OXFORD ECONOMICS

THE ENVIRONMENTAL IMPACT OF DIGITAL OVER CASH PAYMENTS IN EUROPE

WHITE PAPER REPORT FOR THE EUROPEAN DIGITAL PAYMENTS INDUSTRY ALLIANCE

APRIL 2024

EDPIA
The European Digital Payments Industry Alliance

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ABBREVIATIONS

a	annum
ATM	Automated Teller Machine
CCM	Cash Counting Machine
CFC11	trichlorofluoromethane
CiT	Cash in Transit
cm	centimetres
CO2	Carbon Dioxide
CRM	Cash Recycling Machine
DCB	dichlorobenzene
DNB	Dutch National Bank
ECB	European Central Bank
EDPIA	European Digital Payment Industry Alliance
e.g.	for example
eq.	equivalents
EoL	end-of-life
ESG	Environmental, Social and Governance
EU	European Union
g	grams
GHG	Greenhouse Gas
GWP	Global Warming Potential
HIPS	Polymer High-Impact Polystyrene
i.e.	that is
ICT	Information and Communication Technology
ISO	International Organization for Standardization
IT	Information Technology
kBq	kilobecquerel
kg	kilogram
km	kilometres
kWh	kilowatt-hours
LCA	Life-Cycle Assessment
LCIA	Life Cycle Impact Assessment
m^2	square meter
m^3	cubic meter
Mbit/s	megabits per second
Mio.	Million
mm	millimetres
MW	megawatt
MWh	megawatt hour
N	Nitrogen
NFC	Near Field Communication
NOx	Nitric Oxide

P	Phosphorus
PEF	Product Environmental Footprint
PET	Polyethylenterephthalat
PIN	Personal Identification Number
PM	Particulate Matter
POS	point of sale
PSP	Payment Service Provider
PUE	Power Usage Effectiveness
PVC	polyvinylchloride
SO2	Sulfur Dioxide
SPACE	study on the payment attitudes of consumers in the euro area
t	ton
tkm	ton kilometres
TWh	terawatt-hour
UK	United Kingdom
W	watt
WEEE	Waste from Electronical and Electronic Equipment
Wh	watt-hour
yr	year

EXECUTIVE SUMMARY

Digital payments have become increasingly important in the past years. According to a recent study by the European Central Bank (ECB), the share of non-cash payments at point of sale (POS)[1] almost doubled from 21% in 2016 to 41% in 2022 in the euro area.[2] As a result, the total number of non-cash payments—covering all types of payment services—in the euro area increased by 12.5% to €114.2 billion between 2020 and 2021 processing a total value of €197.0 trillion.[3] At the same time, cash remains an important payment alternative in many European countries—in 14 out of 19 euro-area countries, cash is still the most common payment method at POS. Moreover, the share of the digitalisation of the payment system differs substantially across countries. Only 19% of POS transactions were paid in cash in Finland in 2022, while in Malta 77% of POS payments were paid in cash.[4]

Recent studies have indicated that digital payments may have a smaller environmental impact than cash payments. A study by the Dutch National Bank (DNB) analysed that one Dutch debit card transaction in 2015 was estimated to have a global warming potential (GWP) of 0.85 grams (g) of carbon dioxide (CO_2) equivalents, for instance.[5] Furthermore, the DNB showed in a separate paper that the climate impact of an average cash transaction was 4.6 g CO_2 equivalents.[6] Although these estimates were not intended for comparison, the results suggest that cash POS transactions might be more harmful to the environment than digital ones. To explore this further and to ultimately understand how the payments sector can decrease its environmental impact, the European Digital Payment Industry Alliance (EDPIA) commissioned Oxford Economics to carry out this study.

We investigated the environmental impact of both digital and cash payments at a POS in three European countries. The goal of this study was to gain insights into the diverse environmental impacts of an average digital and cash payment at POS in selected European countries in the baseline year 2022. For the analysis, Oxford Economics together with EDPIA chose three different countries all using the euro but with varying digital payment adoption rates: Finland, Italy, and Germany. Finland has the highest digital payment adoption rate, whereas Italy belongs to the countries with one of the lowest adoption rates. Germany was chosen as the third country with a low to medium adoption rate. These countries were also selected as they constitute countries with relevant market sizes and different cultures concerning digital and cash payments.[7] The main research questions were as follows:

[1] In some countries the abbreviation POS also refers to the payment terminal. In our study, we will use POS only as abbreviation for the point of sale. Terminals will be referred to as terminals or POS terminals.
[2] See European Central Bank (2022): "*Study on the payment attitudes of consumers in the euro area (SPACE) – 2022*", Frankfurt am Main: European Central Bank.
[3] See European Central Bank (2022): "*Press Release: Payments statistics: 2021*", retrieved October 25th, 2023.
[4] See European Central Bank (2022): "*Study on the payment attitudes of consumers in the euro area (SPACE) – 2022*", Frankfurt am Main: European Central Bank.
[5] See Lindgreen et al. (2023): "*Author Correction to: Evaluating the environmental impact of debit card payments*", The International Journal of Life Cycle Assessment 28, pp.1799–1801.
[6] See Hanegraaf et al. (2018): "*Life cycle assessment of cash payments*", Amsterdam: De Nederlandsche Bank NV.
[7] For example, the SPACE study that is based on a survey found that while in Germany 30% state cash as their preferred method of payment compared to 41% preferring card or other cashless payments, 18% preferred cash payments in Italy and 58% card

i) Which payment method for settling an average POS transaction in Germany, Italy, and Finland in 2022—cash or non-cash—has a smaller estimated environmental impact? ii) Which are the drivers that cause the highest environmental impact in the cash payment and the digital payment system? iii) Which measures could reduce the environmental impact of both cash and non-cash payments at POS in Europe? To answer these questions, we performed a comparative life-cycle assessment (LCA) of the environmental impact of an average digital payment transaction[8] at POS and an average cash transaction at POS in Germany, Italy, and Finland in 2022.

We performed the LCA based on the ReCiPe 2016 method using the SimaPro software. An LCA should provide a holistic assessment of the environmental impacts of a product or service. The environmental impacts assessed in our study include impacts to air, soil, and water affecting the climate, the environment, resource availability, and human health. Following the International Organization for Standardization (ISO) guidelines for a comparative LCA, we conducted a cradle-to-grave LCA, where we analysed the complete process from the material extraction (the cradle) to production, distribution, and operation until the disposal or recycling (the grave). In addition, our LCA was critically reviewed by a panel of independent experts. To conduct the LCA we used the SimaPro version 9.5.0.1 software (2023), provided by PRé Sustainability. In our modelling, we used the ecoinvent 3.9.1 database (2016) with the system model "allocation, cut-off by classification" and unit processes. The ecoinvent database is a background database that provides data on emissions for a large number of processes, thus easing the data collection process.

We studied two product systems: the digital and the cash payment system at POS. The functional unit of the analysis was making an average payment at POS in 2022. Both product systems that we seek to compare have the same *function*, i.e., to pay for a good or service at a POS in the relevant countries in 2022. The functional unit that is considered focuses on the action of making a payment. It excludes other aspects such as security issues, social acceptance, or barriers to usage. The average payment was calculated by dividing the impact of the total systems—for cash and digital payments—per year by the number of cash and digital POS payments per year, respectively. The average payment has been chosen to ensure comparability across systems.

For the digital payment system, we included cards, payment terminals, data centres, and smartphones as so-called subsystems in our analysis. We assumed that every digital transaction at POS is either made directly with a physical card or a smartphone. Nevertheless, we assumed that a physical card is behind all payments made by smartphone. The seller provides the payment terminal to initiate the transaction. Data centres perform the actual transaction and settle the payment. For all subsystems, we included the production, operation, and end-of-life phase. We did not include any software and development inputs as well as data centre construction activities.

For the cash payment system, we included banknotes, coins, cash-in-transit, cash counting machines, cards, ATMs/CRMs, and data centres as subsystems. To pay with cash at a POS, banknotes and coins are used. These are typically transported by cash-in-transit companies and

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or other cashless option and 7% preferred cash in Finland compared to 83% preferring card or cashless payments (see European Central Bank (2022): "*Study on the payment attitudes of consumers in the euro area (SPACE) – 2022*", Frankfurt am Main: European Central Bank).

[8] It is important to note that we do not study the entire digital and cash payment system. We only consider the relevant functions required to pay for a good or service at a POS.

regularly counted by Cash Counting Machines (CCMs). Cash is typically withdrawn and deposited at Automated Teller Machines (ATMs) or Cash Recycling Machines (CRMs) using a card. The withdrawal or deposition is again processed by data centres. For all subsystems, we included the production, operation, and end-of-life phase. We did not include any software and development inputs, storage of banknotes and coins, coin counting, any other input of cash-in-transit companies than transport trucks, and data centre construction activities.

Data quality was limited. The analysis concerns a complex market activity requiring many data inputs. For some of these, reliable data sources were available, such as the material inputs of banknotes and coins. For others, data availability was limited leading to several assumptions that can limit the reliability of the results. This includes aspects like the number of coins and banknotes used for transactions per country since they cannot be as easily tracked as digital payments, the overall energy usage of data centres since several actors with data centres are involved, and the average distance travelled to an ATM/CRM for the sole purpose of withdrawing money. In light of these limitations and considering the commissioner, we have opted to favour cash over digital payments in our assumptions whenever these were questionable throughout the report. Thus, for example, we assumed that every mobile payment at POS is based on a physical card which increases the environmental impact of digital payments. Moreover, we have performed several sensitivity checks and a Monte-Carlo uncertainty analysis. Nevertheless, it is crucial to keep the limitations concerning data quality in mind when interpreting the results.

Our estimates indicate that a cash POS payment has a larger impact on most analysed impact categories than a digital one in all three countries in 2022. For Germany and Finland, the estimated impact of a cash transaction at POS is larger than the estimated impact of a digital transaction at POS across all 18 impact categories. For Italy, this holds true for all impact categories except ionizing radiation. Here, the estimated impact is larger for the digital payment at POS. In general, the estimated impact of a cash payment is largest in Finland and smallest in Italy. For digital payments the opposite holds true: Here, the largest impact was estimated in Italy and the smallest in Finland. Germany typically ranks in the middle.

The differences in environmental impacts between countries are largely explained by variation in the utilisation of the infrastructure. In Finland, for example, few cash payments are made leading to a higher share of the installed infrastructure being assigned to one average cash transaction at POS. At the same time, the number of cash payments made in Italy is rather high, reducing the impact of the infrastructure assigned to an average cash payment here. In contrast, an average digital transaction has a larger impact in Italy than in the other two countries, because the number of payment terminals is relatively large in Italy compared to the number of digital POS transactions. While the average POS terminal in Italy is used for only 6,456 digital POS transactions, it is used for more than 28,870 in Germany and even 46,152 transactions in Finland.

Moreover, in the case of Finland, the large distances travelled in this country increase the impact of a cash transaction significantly. This holds true for the average distance travelled to ATM/CRM, for example, as well as the overall impact of cash transport. However, there is significant uncertainty concerning the way travelled to ATM/CRM due to the population distribution across urban and rural areas and potential behavioural differences between these two groups. As a result, one should keep this uncertainty in mind when interpreting the results for Finland.

Three important impact categories, global warming potential (GWP), mineral resource scarcity, and ionizing radiation, were examined more closely—given their relevance for POS payments.

- **The estimated impact on GWP was assessed to be significantly lower for a digital payment than for a cash payment made at POS.** We estimated that an average digital payment at POS is associated with the emission of 3.06 g CO_2 equivalents in Germany, 5.39 g CO_2 equivalents in Italy, and 2.20 g CO_2 equivalents in Finland. Considering cash, the estimated emissions are 18.07 g CO_2 equivalents in Germany, 11.50 g of CO_2 equivalents in Italy, and 51.80 g of CO_2 equivalents in Finland. Thus, the impact of a digital payment at POS on GWP is estimated to correspond to 17% of the impact of a cash payment in Germany, 47% in Italy, and 4% in Finland. Yet, the overall environmental impact of both payment systems is rather small. Putting emissions into perspective, in Germany and Italy, the GWP of an average cash POS transaction corresponds to the average carbon emission emitted by one person within just one minute.[9] For Finland's cash system, where the highest GWP was estimated at 51.8 g CO_2 equivalents, this corresponds to streaming Netflix for 60 minutes in Europe, which is estimated to emit around 55 g CO_2 equivalents by Netflix (Carbon Trust, 2021).
- **Our estimated results regarding mineral resource scarcity look similar to the results for GWP with a significantly lower impact for a digital payment than for a cash payment made at POS.** Mineral resource scarcity is measured as the impact of mg copper (CU) equivalents. More specifically, our analysis suggests that an average digital payment at POS is related to the impact of 49.3 mg CU equivalents in Germany, 133.3 mg CU equivalents in Italy, and 44.5 mg CU equivalents in Finland. Moreover, the values for a cash POS payment are 841.8 mg CU equivalents for Germany, 262.5 mg CU equivalents for Italy, and 541.6 mg CU equivalents for Finland. Setting the digital and the cash payment at POS in relation to each other, the outcomes show that the impact of a digital payment at POS equals 14% of the impact of a cash payment at POS in Germany, 51% in Italy, and 8% in Finland.
- **The estimated impact of a digital POS payment on ionizing radiation is larger than a cash POS payment in Italy, but smaller in Germany and Finland.** Ionizing radiation is measured in millibecquerel (mBq) Cobalt-60 (Co-60) equivalents. On the one hand, the estimated impact of an average digital POS transaction is around 38.5 mBq Co-60 equivalents in Germany, 55.0 mBq Co-60 equivalents in Italy, and 40.8 mBq Co-60 equivalents in Finland. On the other hand, the values are 113.4 mBq Co-60 equivalents in Germany, 47.9 mBq Co-60 equivalents in Italy, and 365 mBq Co-60 equivalents in Finland. Whereas the estimated impact of a digital POS transaction amounts 34% of a cash POS transaction in Germany and 11% in Finland, it amounts 115% for Italy. This indicates that when looking at ionizing radiation, a digital transaction appears to have a higher impact than a cash transaction in Italy.

The highest potential to further reduce the environmental impact of the digital payment system lies in the production phase, more specifically the production of terminals and cards. In Italy and Germany, the largest effect is caused in the production phase regarding all impact categories except for ionizing radiation, where the operation phase has the highest effect. The latter holds true

[9] The average carbon emission emitted by one person within one minute can be approximately estimated at 15.22 and 10.84 g CO_2 equivalents in Germany and Italy, respectively (own calculation based on Our World in Data (2023a).

for Finland as well. However, a difference between Finland and Germany as well as Italy lies in the nearly equal effect of the production and operation phase in the impact categories land use, fossil resource scarcity, water consumption, and global warming potential. Whereas the production phase clearly dominates in these categories for Germany and Italy, the effect is balanced between production and operation for Finland. In Italy and Germany, the production of terminals and cards accounts for over 80% of the production phase's GWP and contributes significantly to the other impact categories as well. The higher the utilisation rate of terminals and cards during their lifespan, the lower the global warming impact of an average digital payment POS transaction. This can be mainly achieved by using them for a longer time. Using less material-intensive terminals or recycled cards had a smaller beneficial effect on GWP, for instance, compared to increasing their lifespans. Reducing the number of cards produced can also lower the environmental impact during the production phase. Additionally, further options such as reducing the need for physical cards and terminals at all should be considered. Moreover, any efforts to reduce the energy consumption of data centres can reduce the environmental impact of digital payments—including their transition to more energy-efficient cloud-based data centres. Although the production phase currently dominates the environmental impact, the operation phase is almost solely driven by data centres. Lastly, paper receipts from payment terminals have a large negative impact on the environment, which could be reduced by accelerating the usage of digital receipts.

The highest potential to further reduce the environmental impact of the cash payment system lies in the production and operation phase. In Italy and Germany, the production and operation phase contribute most to the estimated environmental impact depending on the considered impact category. For GWP and ionizing radiation, for example, the production phase is the dominating factor. For others such as marine eutrophication, human non-carcinogenic toxicity, and mineral resource scarcity, the operation phase is most important. While this broadly holds true for Finland as well, the operation phase is more dominating across all impact categories due to the longer distances travelled. In the production phase, the ATM/CRM production is most important. Improving the materials used and extending the life expectancy of ATMs and CRMs could therefore reduce the environmental impact of cash payments at POS. Coin production is another crucial factor. The number of produced coins and the materials used could again reduce the system's impact. During the operation phase, the way and mode travelled to an ATM/CRM is most important. Since this way is significantly larger in Finland, the operation phase is more dominant than in the other two countries. One option to improve the system's impact here would be to promote getting cash in shops that do not require any additional physical infrastructure.

When interpreting the results of our model, it is important to keep in mind the large uncertainties in our assumptions. As mentioned above, we faced limitations on the available data and had to make many assumptions when modelling the digital and cash payment systems. To take this uncertainty into account, we calculated a series of sensitivity checks and a Monte-Carlo uncertainty analysis to check the robustness of our baseline results. One such sensitivity check excluded the way travelled to ATMs/CRMs to withdraw money from the model. Since several data sources had to be combined for modelling the way to an ATM/CRM, the results of these sensitivity are crucial when interpreting the baseline results. Our findings suggest that the baseline results hold in such a sensitivity check for all countries and all impact categories. However, the environmental impact of a cash POS payment decreases significantly in this sensitivity check suggesting that the way travelled to ATMs/CRMs to withdraw money accounts for a significant share of the total impact of a cash POS payment. For example, the estimated impact on GWP drops to 11.6 g CO_2 equivalents in Germany, 6.6 g of CO_2 equivalents in Italy, and 11.6 g of CO_2 equivalents in Finland compared to 18.1 g CO_2 equivalents in Germany, 11.5 g of CO_2 equivalents in Italy, and 51.8 g of CO_2 equivalents in Finland in the baseline. We also modelled a combination of sensitivity checks that merges several checks which reduce the impact of the cash system and increase the impact of the digital system (a "worst case for digital versus best case for cash" scenario). Our estimation suggest that our baseline results hold in Germany and Italy in such a check. However, in Italy, digital POS payments become more damaging than cash in the impact categories global warming, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, land use, and fossil resource scarcity.[10] Finally, our sensitivity checks and Monte-Carlo analysis can only partially take the uncertainty in our assumptions into account.

Digital POS payments could help to reduce the environmental impact of POS payments, but the transformation needs to be shaped and supported. Our study indicates that an average cash payment at POS likely burdened the climate, environment, and human health more than a digital POS payment made at POS in 2022 in Germany, Italy, and Finland. Yet, it should be noted that the overall impact of payments at POS are minor compared to other economic activities. Furthermore, the uncertainty and limitations concerning the presented results should be kept in mind. Additionally, the presented analysis only estimates the environmental impact of both payment options given the current conditions. Other relevant aspects such as social desirability, security, and ease of handling need to be considered as well to compare both payment options holistically. Despite uncertainty and data limitations, we have identified options to improve the environmental impact of both systems. While the major levers concern the industry as discussed above, others can be influenced by policymakers and public institutions. As a result, industry and policymakers should work together to improve the environmental impacts of these systems.

[10] Digital payments also have a larger impact than cash in the category ionizing radiation but this is already the case in the baseline model.

1. INTRODUCTION

1.1 MOTIVATION AND GOAL

Digital payments can have various positive effects on an economy. Although digital payments serve the benefits of reducing fraud, costs, and waste, increasing transaction speed, scalability, and accuracy, and providing real-time cash flow visibility (Forbes, 2023), some customers still prefer cash over paying digitally. For instance, some argue that privacy and anonymity are better ensured when paying in cash and thus, data security does not serve as a problem in cash payments. Furthermore, cash might be easier to handle due to immediate settling or a better overview of their spending (ECB, 2022a). Additionally, no technological literacy is necessary for the usage of cash and cash payments are not dependent on the functioning of software, which is the case for digital payments and thus, serves as another drawback of paying digitally (NTT Data, 2024). However, first estimates show that the Greenhouse Gas (GHG) impact of cash payments may be higher than those of digital payments as digital payments seem to generate less carbon dioxide (CO_2) as shown, for example, by Hanegraad et al. (2018) and Lindgreen et al. (2023). With consumers, businesses, and governments becoming increasingly aware of their behaviour's impact on the natural environment, including CO_2 footprint, habitat impacts, and loss of biodiversity, advancing the adaptation of digital payments can be one step to helping economic actors to reduce their environmental footprint. However, the underlying assumption is that all other factors remain constant, for example, the overall number of point of sale (POS) transactions. Thus, this conclusion only holds ceteris paribus and would not be true if, for instance, the usage of digital payments went hand in hand with an increase in the number of POS payments.

The goal of this study is to gain quantitative insight into the environmental impact of digital compared to cash payments at POS in 2022 using Life-Cycle Assessments (LCAs). This includes one comparative LCA, where the digital payment and the cash payment systems are analysed and compared. The year 2022 was chosen as the reference year as it is the latest year for which reasonable data is available. To understand the impact of digital payments in a variety of settings, the study will focus on three European countries with varying levels of digital payment adoption. The countries selected are Italy with 31% digital payments adoption at POS, Germany with 37%, and Finland with 81% (ECB, 2022a). Besides their varying levels of digital payment adoption, these countries were also selected as they constitute countries with relevant market sizes and different cultures concerning digital and cash payments. For example, the SPACE study (ECB, 2022a) that is based on a survey found that while in Germany 30% state cash as their preferred method of payment compared to 41% preferring card or other cashless payments, 18% preferred cash payments in Italy and 58% card or other cashless option and 7% preferred cash in Finland compared to 83% preferring card or cashless payments (ECB, 2022a). Moreover, all countries use the euro as their currency.

The LCA aims to provide a holistic assessment of the environmental impacts associated with the production, distribution, use and disposal of cash and digital payment systems from cradle to grave. These emissions include environmental impacts on air, soil, and water. Besides identifying the main drivers for environmental impacts, the study also aims to compare the environmental footprints between both the cash and the digital payment system regarding its function to pay for a good or service at POS.

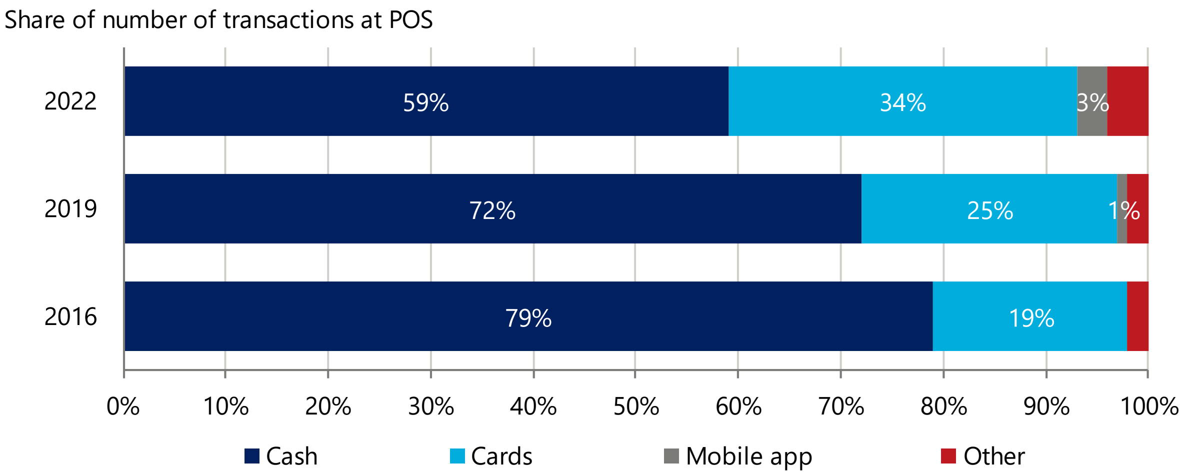
The study was commissioned by the European Digital Payment Industry Alliance (EDPIA), and the results are intended for publication. This can be a source for dialogue with stakeholders such as European policymakers to explore potential options on how to decarbonize the payment system. As the study constitutes an independent analysis commissioned by EDPIA—an association with an interest in promoting digital payments—we have assumed the most conservative assumption whenever no detailed information was available. In other words, assumptions made lean towards favouring cash payments over digital payments. Thus, estimations of the impact of digital over cash payments constitute conservative estimates and are more likely to be biased downward.

1.2 DIGITAL VERSUS CASH PAYMENTS IN EUROPE

In a recent survey, the European Central Bank (ECB) studied the payment attitudes of consumers in the euro area (ECB, 2022a). This so-called Study on the Payment Attitudes of Consumers in the Euro area (SPACE) report shows that cash payments are still the most frequently used payment method at POS in the euro area. Payments made at POS encompass a wide variety of purchases. For instance, consumers have the option to buy everyday items at supermarkets, invest in consumer durables or home services, make transactions at hotels, restaurants, cultural and sports venues, or petrol stations, as well as acquire tickets or other products from vending machines. According to the SPACE study, 54% of all POS transactions in the euro area in 2022 have been initiated to buy day-to-day items—an increase of 3 percentage points from 2019 (ECB, 2022a). Durable goods are also becoming increasingly important considering POS transactions, accounting for 8% of POS transactions in the euro area in 2022 compared to 6% in 2019 (ECB, 2022a).

Although cash remains the most important payment instrument for POS transactions, the relative importance of cash payments has declined over the years from 79% of all POS transactions paid by cash in 2016 to 59% of transactions in 2022 (ECB, 2022a). As an alternative to cash payments, consumers tend to use card payments for POS transactions more often (ECB, 2022a). Additionally, the importance of mobile apps expanded from less than 1% in 2019 to 3% in 2022 (see Figure 1).

FIGURE 1: USAGE OF DIFFERENT POS PAYMENT INSTRUMENTS IN THE EURO AREA



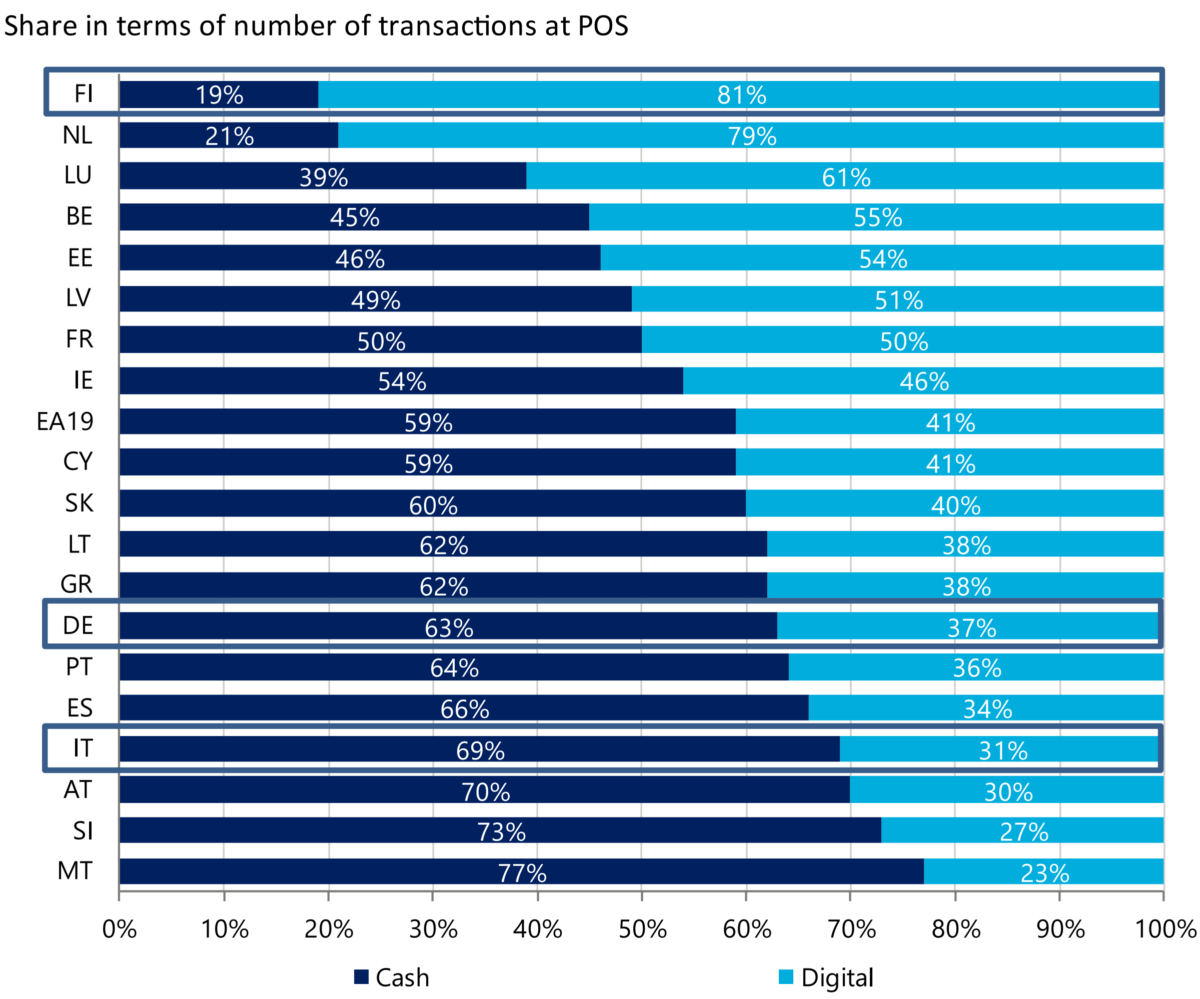
Source: Oxford Economics based on ECB (2022a), chart 2

Cash in POS transactions is mostly used for smaller cash amounts. 81% of POS transactions with a euro amount of €5 or less have been paid in cash (ECB, 2022a). In contrast to that, only 31% of POS transactions with a value of €100 or more have been paid in cash (ECB, 2022a). Yet, the small value transactions at POS are the most common. 59% of all POS transactions had a value of €20 or less (ECB, 2022a).

Comparing digital and cash payments at POS makes the most sense in locations where cash and digital payments are both accepted. According to the SPACE study, on average, 95% of POS transactions in the euro area could be carried out using cash according to respondents in 2022, while in 81% of transactions, it was possible to pay with non-cash payment instruments (ECB, 2022a).

There are significant differences in the payment instruments used in European countries for POS payments. Figure 2 illustrates how the share of cash and digital payments differs between the European countries. Digital payments include card payments, mobile payments, and other payment methods such as mobile apps. The three countries considered in this study are highlighted. Finland has a high adoption of digital payments. Only 19% of POS transactions are settled in cash. Germany shows a lower adoption rate of digital payments since 63% of POS transactions in 2022 are still paid in cash. In Italy, this share is even higher: 69% of POS transactions are paid in cash.

FIGURE 2: SHARE OF CASH AND DIGITAL PAYMENTS USED AT POS IN TERMS OF THE NUMBER OF TRANSACTIONS BY COUNTRY (2022)



Source: Oxford Economics based on ECB (2022a), chart 5

1.3 STRUCTURE OF THE REPORT

The remaining part of the report is structured as follows. In Chapter 2, we specify the goal of our study and the research questions we seek to answer, introduce the publication strategy for the report and explain the standards applied in our analysis. In the following Chapter 3, we elaborate on the scope of the study in detail. This includes specifying the functional unit, the study's product systems, each system's boundaries, our implementation of a sensitivity analysis, data quality requirements, assignment procedures, the calculation, and the critical review of our analysis. The data inventory for our study can be found in Chapter 4. Chapter 5 presents the results of our impact assessment. Chapter 6 contains the interpretation of our results as well as a sensitivity analysis, an uncertainty analysis, and a discussion of the data quality. Finally, Chapter 7 concludes by providing a concise summary of the analysis, and from this, pertinent policy recommendations are deduced.

The appendix to this report contains the following content: Appendix 1 gives an overview of the ReCiPe 2016 impact categories. Next, Appendix 2 provides detailed results of the impact assessment. Appendix 3 contains tables with the main emitting processes for the two payment systems. Detailed characterisation results for all sensitivity checks are displayed in Appendix 4. The pedigree matrices used for the uncertainty analysis are displayed in Appendix 5. The detailed results for the uncertainty analysis are displayed in Source: Oxford Economics

Appendix 6. Finally, Appendix 7 shows the results of this study's critical review.

2. LIFE-CYCLE ASSESSMENT—GOAL

2.1 PROJECT GOAL AND QUESTIONS TO BE ANSWERED

Two studies by the Dutch National Bank (DNB) shed the first light on the difference that specific payment systems can have on the environmental footprint at a POS. One assessed the environmental impacts of cash payments in the Netherlands (Hanegraaf, Jonker, Mandley, & Miedema, Life cycle assessment of cash payments, 2018), while the other study focussed on the environmental impact of debit card payments in the Netherlands (Lindgreen, et al., 2017) with an erratum published a few years later (Lindgreen, et al., 2023). Although some external stakeholders compared the study results with each other, the purpose of the studies was to understand the environmental footprint in each system independently rather than comparing different payment methods. Consequently, our study seeks to build on the two studies published by the DNB but specifically intends to compare cash and non-cash payments. Moreover, the location of analysis differs—while the DNB estimated the impacts for the Netherlands, the countries studied in this report are Germany, Italy, and Finland.

The goal of the study is to identify which payment method at POS—cash or non-cash—is more beneficial from an environmental perspective by comparing the estimated environmental impact of an average cash transaction at POS in Germany, Italy, and Finland in 2022 to an average digital payment at POS in the same countries.[11] Thus, the two product systems studied are the cash payment system and the digital payment system in these three countries for a POS transaction in the baseline year 2022. This is done by estimating the environmental impacts of these two systems throughout their life cycle.

We seek to answer the following research questions:

- Which payment method for settling an average POS transaction in Germany, Italy, and Finland in 2022—cash or non-cash—has a smaller estimated environmental impact?
- Which subsystem[12] within the cash and digital POS payment systems causes the highest environmental impact in the cash payment and the digital payment system? Does this vary between countries and why?
- Considering the results in the three countries, which measures could reduce the environmental impact of both cash and non-cash payments at POS in Europe?

2.2 AUDIENCE AND PUBLICATION

The outcomes will be made public to promote the study results, ensure transparency, and contribute to the literature on LCAs in the payment systems sphere. To substantiate a public comparative statement, the standard mandates a compulsory assessment by impartial specialists (refer to Chapter 3.8).

[11] Although the monetary value of an average POS transaction paid with cash differs from the average POS transaction using cards, comparing an average transaction at POS in both systems with each other is still valid as the environmental impact of a POS transaction paid by card is independent of the transaction value.

[12] Subsystems refer to the different systems part of the larger cash and digital POS payment systems. For example, the cash POS payment system contains the banknotes and coins subsystems among others.

The planned uses of the findings encompass:

- Strengthening knowledge-driven understanding of the environmental footprint of different payment systems.
- Recognising possibilities for improving the environmental impact through the identification of significant areas within the evaluated subsystems' lifecycle (hotspot analysis).
- Sharing the results for educational intentions, to increase transparency and to support governmental decision-making.
- Assisting consumers in deciding which payment option is more environmentally friendly.

The intended audience of the study is first and foremost the members of EDPIA. External audience groups include other stakeholders in the payment ecosystems, supply chain partners, consumers, policymakers, and the public.

2.3 STANDARDS APPLIED

The study is developed following the International Organization for Standardization (ISO) 14040 standards, which are a set of international standards that provide guidelines and principles for conducting an LCA. ISO 14040 (ISO 14040, 2006) and ISO 14044 (ISO 14044, 2006) provide a standardised framework for conducting LCAs, ensuring that assessments are consistent, transparent, and comparable.[13] These standards are widely used by organisations and governments to evaluate and reduce the environmental impacts of products and processes, make informed decisions, and communicate environmental performance to stakeholders.

ISO 14040 and its related standards provide a structured approach to assessing the environmental aspects of products. These include the following steps (Whitehead, Andrews, & Shah, 2015):

- **Goal and Scope Definition:** The first step in an LCA is to clearly define the goals and scope of the assessment. This includes identifying the specific objectives, the system boundaries (what is included and excluded), and the functional unit (the unit of measurement for the product or service being assessed).
- **Inventory Analysis:** This phase involves collecting data on all inputs and outputs associated with the product, process, or service throughout its life cycle. This data includes raw materials, energy consumption, emissions, and waste generation.
- **Life Cycle Impact Assessment:** In this step, the collected inventory data is used to assess the potential environmental impacts. This involves evaluating the environmental consequences of resource use and emissions, such as greenhouse gas emissions, water pollution, and habitat

[13] Although the LCA is performed in line with ISO standards, it should be noted that the underlying methodological approach differs from the Product Environmental Footprint (PEF) method that is recommended by the European Commission (2021). While both approaches aim to analyse the environmental impact of a product's lifecycle holistically, PEFs are based on a more detailed framework with more specific guidelines on how to perform an LCA to increase comparability across studies (Makersite, 2023). Thus, our analysis may not be comparable to a similar PEF study. In our view, using the PEF method in the comparison of payment system can be challenging. According to Weidema (2023), the 2021 PEF method recommends excluding capital goods. Considering the high and varying infrastructure needs in the digital and cash payment POS systems, this could lead to a significant bias in the comparison of these products. There is still an ongoing debate on this topic. In any case, research "suggest that the inclusion of both services and capital, either individually or in combination, leads to overall notable differences in footprint results" (Font Vivanco, 2020).

destruction. Various impact categories, such as climate change, acidification, and eutrophication, are considered.

- **Interpretation:** The interpretation phase involves analysing and interpreting the results of the inventory analysis and impact assessment. It aims to draw conclusions and make recommendations based on the assessment's findings. This phase also includes sensitivity analyses and uncertainty analyses to account for data limitations and assumptions.

To conduct the LCA we used the SimaPro version 9.5.0.1 software (2023), provided by PRé Sustainability. In our modelling, we used the ecoinvent 3.9.1 database (2016) with the system model "allocation, cut-off by classification" and unit processes. The ecoinvent database is a background database that provides data on emissions for a large number of processes, thus easing the data collection process. Since the same database has been used in the study performed by Lindgreen et al. (2017) and (2023), the exact unit processes could be used in our study whenever the information provided was suitable for the presented analysis.[14]

The main data sources used are displayed in Table 1. A summary of the data quality is presented in the last column. Although it was not always feasible to have the highest quality data due to a lack of data availability, the data sources used present the most reliable database that was—to the best of our knowledge—available and suitable for this study. To account for uncertainties regarding data quality and robustness, several sensitivity checks have been performed. The results can be found in Chapter 6.2. Moreover, we have also performed an uncertainty analysis using a Monte Carlo simulation. The results can be found in Chapter 6.3. Lastly, the pedigree matrix, serving as an input for the Monte Carlo simulation details the assessment of data quality and is displayed in the Appendix.

TABLE 1: OVERVIEW OF THE KEY DATA SOURCES

Data Source	Primary use	Examples of indicators used	Impact on subsystems	Data quality
Payment Statistic (ECB, 2022b)	Assignment factors	Numbers of digital payments, terminals, cards, Automated Teller Machines (ATM)/Cash Recycling Machines (CRM) in use	All	High: Based on data provided by national central banks
SPACE report (ECB, 2022a)	Assignment factors	Share of cash, non-cash, and mobile payments	All	Medium to high: Based on a survey commissioned by the ECB
Freight transport statistics (Eurostat, 2021a)	Transport distances for freight	National or international transport distance of product to customer	Most	High: Based on a survey answered by a representative sample and carried out by

[14] Please note that different versions of the ecoinvent database have been used in the studies. While Lindgreen et al. (2017) used the ecoinvent 3.0 database, Lindgreen et al. (2023) used ecoinvent 3.8 and ecoinvent 3.9.1 has been applied in the present study.

Data Source	Primary use	Examples of indicators used	Impact on subsystems	Data quality
				national public authorities
Passenger mobility statistics (Eurostat, 2021b)	Distance to waste treatment facility	Average commuting distance	Included if waste market datasets exclude transport	High: Based on a survey answered by a representative sample and carried out by national public authorities
ECB statistics on cash circulation (ECB, 2023a; ECB, 2023b; ECB, 2023e)	Assignment factors	Banknotes and coins in circulation, share of cash used for transactional purposes	All cash subsystems	High: Based on data provided by national central banks
DNB paper on the impact of cash (Hanegraaf, Jonker, Mandley, & Miedema, Life cycle assessment of cash payments, 2018)	Input to all phases of cash subsystems	Material input, production processes, energy consumed, assumed lifetimes of cash subsystems	Subsystems 5 (banknote), 6 (coins), 7 (Cash in Transit (CiT)), 8 (Cash Counting Machine (CCM)), 10 (ATM/CRM)	Medium: Published study by the Dutch national central bank based on varying degrees of data quality
DNB paper on the impact of debit card payments (Lindgreen, et al., 2017)	Input to all phases of digital subsystems	Material input, production processes, energy consumed, assumed lifetimes of digital subsystems	Subsystems 1 (cards), 3 (payment terminals)	Medium: Published study by the Dutch national central bank based on varying degrees of data quality

Source: Oxford Economics

Lastly, given the commissioner and background of the study, we have assumed the most conservative assumption whenever no detailed information was available leaning towards favouring cash payments over digital payments. Thus, estimations of the impact of digital over cash payments constitute conservative estimates and are more likely to be biased downward.

3. LIFE-CYCLE ASSESSMENT—SCOPE

3.1 FUNCTIONAL UNIT

The functional unit defines what is being studied in an LCA according to ISO norm 14040. More precisely, it is defined as the "quantified performance of a product system for use as a reference unit" (ISO 14040, 2006, p. 4). In the present study, the product studied is a market activity, i.e., the payment at POS. To conduct the payment, different options are available, such as cash payment, card payments, and smartphone payments, for instance.

This study analyses and compares two common payment methods at POS: cash POS payments and digital POS payments. While the cash payment is performed by transferring coins and/or banknotes from customer to supplier in exchange for a good or a service, digital payments studied here are performed by a credit or debit card that is typically tapped on to, swiped through, or inserted into a payment terminal in exchange for a good or service. Smartphone payments that are based on a card are included in the digital payment system.

Both product systems that we seek to compare have the same *function*, i.e., to pay for a good or service at a POS in the relevant countries in 2022. Therefore, the *functional unit* is one average payment at POS. This average payment is calculated by dividing the impact of the total systems—for cash and digital payments—per year by the number of cash and digital POS payments per year, respectively. This could include, for instance, estimating the total energy usage of payment terminals in a given year and dividing it by the total number of digital payments at POS to get the energy used for the payment terminal per average digital POS transaction for that year. Note that our definition of the functional unit excludes other aspects relevant to payments such as security issues, social acceptance, or barriers to usage.

The average payment has been chosen to increase comparability across systems. Comparing both systems in total may be misleading as their utilisation rate might differ. By comparing the average POS payment, it is possible to estimate the environmental impact of both options for the customer given current conditions taking into account aspects like ATM or terminal utilisation, for example. Yet, the average value of cash and non-cash transactions usually differs. Non-cash payments are more commonly used for higher transaction values, whereas smaller transaction values are more likely paid in cash. Regarding the environmental impact, the value of the transaction is mostly relevant for cash transactions as the value influences the number of banknotes and/or coins used in a transaction; however, the value of a digital transaction has mostly no impact on the environmental effect of the payment according to experts—especially regarding the mostly smaller-value POS transactions.[15] Therefore, we decided to calculate the overall system's impact on both subsystems and then assign it to one average POS transaction—whether it is a cash or a non-cash transaction.

Concerning the analysis for the different countries, the functional unit remains the same, i.e., an average transaction at POS. The effective amount of an average payment at POS might differ between countries. Since this also leads to varying results, it is important to note that the analysis presented

[15] Larger-value digital transactions may include extra verification and data processing steps.

here hold for Germany, Italy, and Finland respectively in 2022. Still, as both payment systems provide the same service at a POS, the functional unit picked ensures a reasonable comparison of the estimated environmental impact of one cash payment at a POS with the impact of a digital payment at a POS by country and year given the assumptions stated in the analysis.

In detail, the market segment studied is payments made at POS in Germany, Italy, and Finland in 2022. With 37%, 31%, and 81%, these three countries of interest have varying adoption rates of digital payments at POS (ECB, 2022a). These countries have been chosen due to their varying degrees of digital and cash payments at POS as well as their economic significance for the euro area.

3.2 DESCRIPTION OF PRODUCT SYSTEMS AND SYSTEM BOUNDARIES

3.2.1 Digital Payments: General description of the product system and reference flow

If consumers want to pay for a service at a POS via non-cash means, they initiate a digital transaction at a POS. The customer selects their items for purchase and proceeds to the payment terminal at the checkout counter. They either use their physical payment card, their contactless card, or their smartphone[16] to initiate the payment. The payment terminal collects the transaction data and securely sends it to the data centre for processing. Once the payment is authorised, the data centre sends a confirmation back to the payment terminal. The transaction is completed when the merchant receives the payment in his or her bank account.

The digital transaction process at POS can be complex, but it is streamlined and divided into four key subsystems for clarity and efficiency (see Figure 4). These subsystems work together seamlessly to facilitate secure and convenient payments as displayed in Figure 3.

- **Payment Cards:** Payment cards are a crucial component of the transaction process. These cards can be physical (like credit or debit cards) or virtual (stored in a mobile wallet app, see subsystem Smartphones). When a customer initiates a payment at the POS, they use their payment card by inserting it into the terminal or tapping it, to make a digital payment. The card contains the necessary information for the transaction, such as the cardholder's account details. We include debit and credit cards in our analysis.
- **Smartphones:** In addition to traditional payment cards, consumers can also use smartphones or wearable devices like smartwatches to initiate payments. These devices often support contactless payment methods, such as Near Field Communication (NFC) technology. To pay via smartphone, the customers hold their device near the payment terminal, and the transaction is processed securely. In this study, only smartphone payments at POS are considered whereas other mobile payment methods including for example smartwatches are not covered. Additionally, only those smartphone payments that are based on a debit or credit card (physical or virtual) are studied. Thus, many use cases of smartphone payments are not part of the study, i.e., online purchases, P2P transactions, and other payment services that are not based on a credit or a debit card such as payment via loyalty programs or online payment systems not based on credit or debit cards.
- **Payment Terminals:** Payment terminals are the starting point of the transaction process. These are devices used by consumers to initiate a payment at a physical store. Payment terminals come

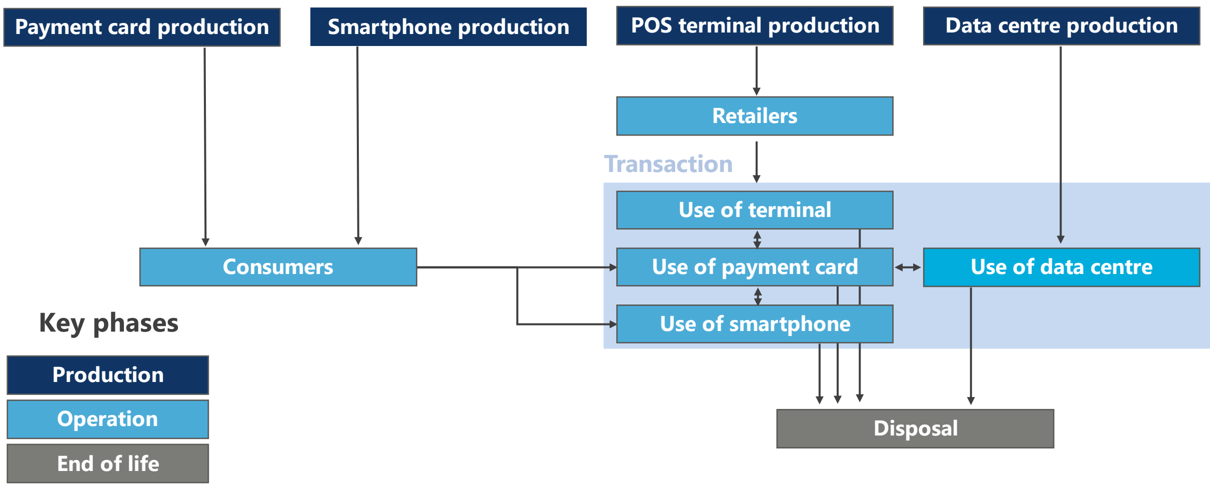
[16] People can also pay using wearables.

in various forms as combined chip card readers and contactless reader payment terminals. When a customer is ready to make a purchase, they interact with the payment terminal by inserting or tapping their payment card, or tapping their smartphone. We include in our analysis dedicated devices only. POS apps on smartphones are not in the scope of this study.

- **Data Centres:** Data centres are the backbone of the digital payment system. They are responsible for processing the transaction data generated by the payment terminal. This data includes information about the purchase, the payment method used, and the authorisation request. Data centres are equipped with robust security measures to ensure that sensitive financial information is protected during transmission and processing.

For all subsystems, the production, operation, and end-of-life (EoL) are considered and assigned to one digital POS transaction in Germany, Italy, and Finland. Moreover, transport and energy consumption are always covered as part of the inputs.

FIGURE 3: PRODUCT SYSTEM FOR DIGITAL PAYMENTS AT POS



Source: Oxford Economics, partially adapted from Lindgreen, et al. (2017)

Table 2 gives an overview of the primary data sources used for the description of the digital payment system. Depending on the preferences of the interview partner, information was either provided through an expert interview or by filling out a questionnaire. All interviews and questionnaires were conducted or collected between August and October 2023. The interviewees were selected based on an assessment of the market leaders in the respective subsystem. To achieve the greatest representativeness possible, we aimed at gathering information for all three countries from the most important players in each field respectively. Considering the rather low number of interviews, we aimed to gain insights representing the overall market as well as possible. Uncertainties concerning data quality and representativeness were estimated using Monte Carlo simulations. The results are displayed in Chapter 6.3 and their inputs, i.e., the pedigree matrix, are displayed in Appendix 4.

TABLE 2: OVERVIEW OF PRIMARY DATA SOURCES – DIGITAL PAYMENTS

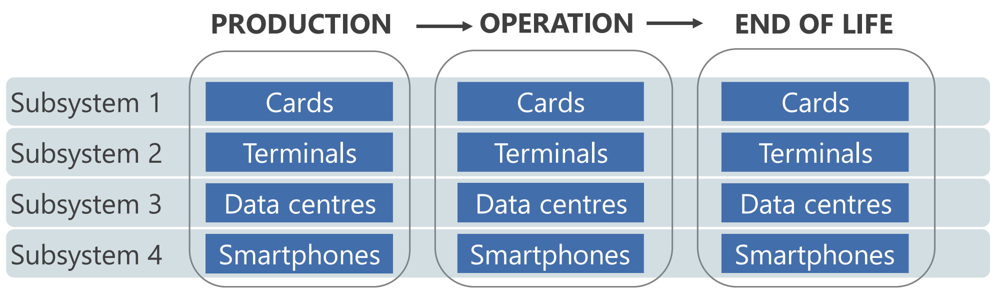
Primary data source	Primary use	Examples of indicators used	Geographic Focus	Data request
Card personalisation company (one of the market leaders)	Production of cards	Location of card and chip production; location of card personalisation; energy used for card personalisation	Italy	Written data request (questionnaire)
POS terminal manufacturer (one of the market leaders)	Terminal production	Material input and energy consumed by terminal per POS transaction, production location, transport modes	Europe	Written data request (questionnaire)
European paper roll manufacturer (one of the market leaders)	Terminal operation	Material inputs for paper receipts	Europe	Confidential report containing interviews
Payment service provider (PSP)	Terminal operation and end-of-life	Energy use for transaction processing; energy use for card personalisation; life expectancy; recycling and refurbishing rates; packaging; transport; servicing of POS terminals	Germany	Expert interview followed by a written data request
PSP	Terminal operation and end-of-life	Energy use for transaction processing; energy use for card personalisation; life expectancy; recycling and refurbishing rates; packaging; transport; servicing of POS terminals	Italy	Expert interview followed by a written data request
PSP	Terminal operation and end-of-life	Energy use for transaction processing; energy use for card personalisation; life expectancy; recycling and refurbishing rates; packaging; transport; servicing of POS terminals	Finland	Expert interview followed by a written data request
PSP	Data centre operation	Data centre location and energy usage	Europe	Expert interviews

Source: Oxford Economics

3.2.2 Digital Payments: Subsystems

As described, the digital payment system is divided into four subsystems (see Figure 4). They are described in the following paragraphs. Differences between the countries under investigation are highlighted. These descriptions are meant to clarify the scope of the study. Detailed steps and inputs included are presented in Chapter 4.

FIGURE 4: OVERVIEW OF SUBSYSTEMS IN THE DIGITAL PAYMENTS ECOSYSTEM



Source: Oxford Economics

SUBSYSTEM 1: CARDS – DIGITAL SYSTEM

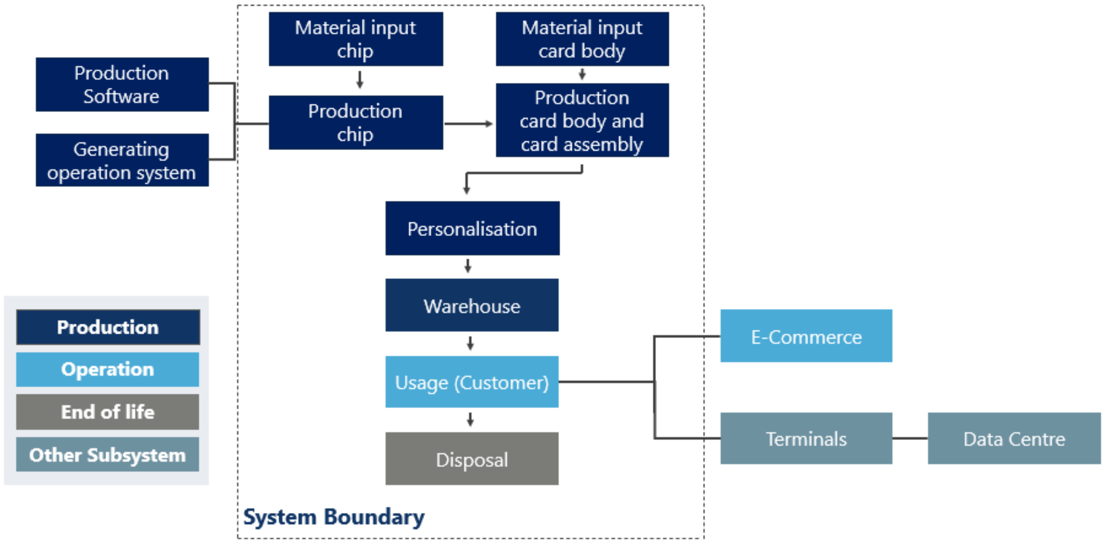
Cards are essential for both systems—the digital and the cash system.[17] In the digital system, customers need cards to make transactions at payment terminals, whereas in the cash system cards enable the withdrawal and deposit of cash. In this paragraph, we consider cards as part of the digital payment system.

Usually, customers receive a physical payment card that is connected to their bank account enabling them to make digital transactions at POS. Having a virtual card only is still very rare (expert interview with a PSP). This is why we decided to leave this case out of our scope and assume that a digital POS transaction is done by using a physical card only or by using a smartphone in addition equipped with the virtual image of a physical card (see Subsystem smartphones). As we assume that payments made without physical cards are reducing the overall impact of digital payments on the environment, our assumption is more conservative and thus more likely to lead to an overestimation of digital payment's environmental impact than an underestimation.

The lifecycle of cards can be displayed as in Figure 5. It is divided into production, operation, and end-of-life phases, whereas the dotted line marks the system boundary of this subsystem. Starting from above, a card body and a chip are produced separately by different companies and assembled afterwards. After the physical assembly data and applications need to be loaded through an operation system (Rankl & Effing, 2010). This—as well as any other software used during the card production phase—is not included in our analysis. After the card production is finalised, the cards are transported to the respective countries to get personalised. Then, after being sent to a warehouse, the cards and a separate letter with the Personal Identification Number (PIN) code are sent to the final owner of the bank account and are, afterwards, ready to use.

[17] Moreover, cards are also used for online purchases but these purchases are not considered in this study.

FIGURE 5: FLOWCHART OF THE CARD SUBSYSTEM



Note: This figure gives a broad overview of the subsystem's lifecycle and indicates what aspects were considered and what was outside the system boundary. Thus, especially transport steps are simplified and do not represent the complexity of the system as modelled in this study. In general, all transport steps were considered either through market processes or through explicit modelling. For detailed information on the transports considered and further aspects of the lifecycle, see Chapter 4.
Source: Oxford Economics based on Rankl & Effing (2010)

During the operation phase, other elements such as terminals and data centres become crucial but the card usage itself does not cause any relevant inputs or outputs. Since terminals and data centres constitute subsystems themselves, no additional inputs or processes are needed for the operation phase of cards in this subsystem.

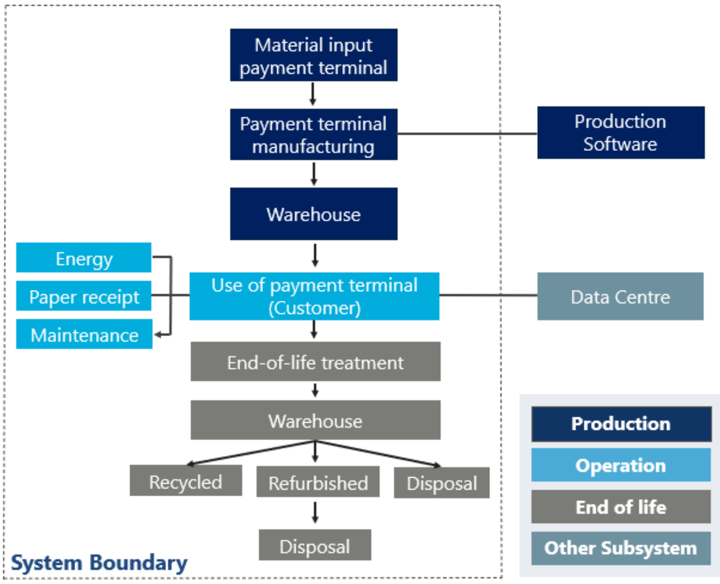
When a card reaches its end-of-life, customers usually destroy the chip to ensure that any personal information will not be misused by cutting the card and disposing of everything in the domestic waste.

Note that we only focus on digital payments at POS. Digital payments done online, for example for e-commerce, are not included in our analysis.

SUBSYSTEM 2: PAYMENT TERMINALS

Payment terminals are a central part of the digital payment system. They are used to conduct the transaction between customers and retailers. As alternative uses of POS terminals (e.g., customer loyalty or club programs that award the customer with points per purchase or offers) are negligible, their environmental footprint can be attributed to the system of digital payments. By assigning the whole terminals' impact to the digital payment system, the analysis over- rather than underestimates the impact of POS terminals, as terminals may be used for other purposes as well. Thus, this once again constitutes a conservative assumption in favour of the cash payment system. Besides their importance for the system, a study by Lindgreen et al. (2023) showed that payment terminals are a crucial factor in the environmental impact of digital payment—especially terminal materials and energy use.

FIGURE 6: FLOWCHART OF THE PAYMENT TERMINAL SUBSYSTEM



Note: This figure gives a broad overview of the subsystem's lifecycle and indicates what aspects were considered and what was outside the system boundary. Thus, especially transport steps are simplified and do not represent the complexity of the system as modelled in this study. In general, all transport steps were considered either through market datasets or through explicit modelling. For detailed information on the transports considered and further aspects of the lifecycle, see Chapter 4.
Source: Oxford Economics partly based on Lindgreen, et al. (2017)

As outlined in Figure 6, upstream processes considered involve the terminal production including the material inputs, production processes and their associated energy consumption. Out of scope is again the development and installation of the software for the operating system. Moreover, transportation from the country of production to the warehouse and the customer is covered. The terminals are mostly produced in Asia and transported by ship or aeroplane to Europe. After that, they are transported with trucks to the customer's warehouses, repackaged and sent to the final customer—the merchant using the terminal as a method for payment at their POS.

In the usage phase, the terminals consume energy. In addition to energy usage, we also consider the input for printing paper receipts as most countries still use paper over electronic receipts. In Germany, for example, the printing of the merchant receipt is mandatory. Furthermore, we consider the maintenance of the terminals, which is mostly done by postal swap according to interviews with a PSP.

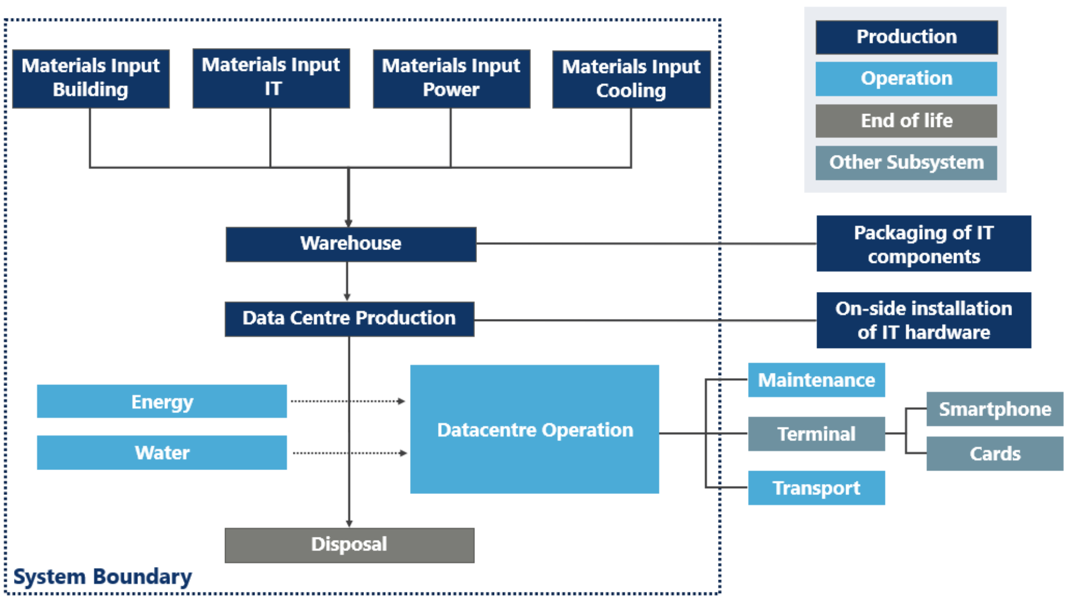
At the end-of-life, terminals are either recycled, refurbished, or disposed of. For recycled terminals, only the transport to the recycling facility is considered. Refurbished terminals are mostly shipped to Asia and disposed of abroad. As terminals fall under the Waste from Electrical and Electronic Equipment (WEEE) directive set out by the European Union (EU), most of the materials used for terminals disposed of in Germany, Italy, and Finland are sorted before the disposal (in 't Groen, Stengs, & Zanneveld, 2017), and therefore treated separately. Paper receipts and packaging are disposed of as well.

SUBSYSTEM 3: DATA CENTRES – DIGITAL SYSTEM

Data centres, like cards, are relevant for both payment systems. Concerning digital payments, data centres process the transaction. They serve as the backbone of the digital payment ecosystem, enabling seamless, secure, and efficient transaction processing while ensuring data integrity and compliance with industry standards. Additionally, they potentially also play a crucial role in the environmental impact of digital payments. Visa and MasterCard, for example, both report in their most recent Environmental, Social and Governance (ESG) reports that data centres accounted for 66% of Visa's total electricity consumption in the financial year 2022 (VISA, 2023) and 10% of MasterCard's total GHG emissions of Scope 1 and 2 (MasterCard, 2023).

Although data centres can vary significantly, their contribution to the impact of digital payments can be summarised in a schematic overview (see Figure 7). First, a data centre needs to be manufactured. The main inputs, according to Lindgreen et al. (2017), are raw materials, as well as other material inputs. In our specification, the material inputs for the power infrastructure, the IT equipment, the cooling system, the racks, and containments as well as the building for the data centre are included.

FIGURE 7: FLOWCHART OF THE DATA CENTRE SUBSYSTEM



Note: This figure gives a broad overview of the subsystem's lifecycle and indicates what aspects were considered and what was outside the system boundary. Thus, especially transport steps are simplified and do not represent the complexity of the system as modelled in this study. In general, all transport steps were considered either through market datasets or through explicit modelling. For detailed information on the transports considered and further aspects of the lifecycle, see Chapter 4.
Source: Oxford Economics based on Lindgreen, et al. (2017) and Whitehead, Andrews, and Shah (2015).

Second, estimates of transporting the input materials for the manufacturing to the site must be included. Following Whitehead, Andrews, and Shah (2015), the omission of on-site facility construction impacts is attributed to the absence of sufficient data and the relatively minor influence it exerts on the outcome. We excluded the packaging of the separate IT components due to a lack of data.

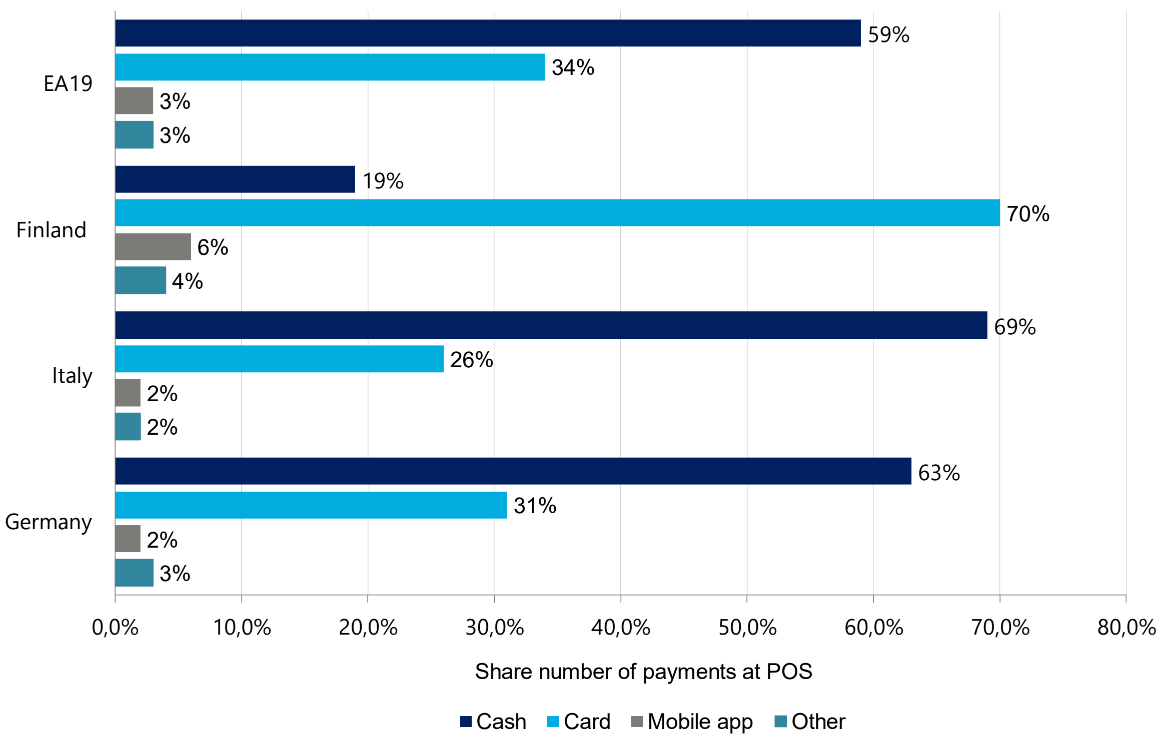
Third, the usage or operation of a data centre for the transaction needs to be considered. As the energy supply of data centres is almost exclusively based on electricity, the emissions produced by the energy usage of data centres heavily depend on the grid emissions factor that varies substantially between European countries (Hintemann, Hinterholzer, & Clausen, 2020). As some data centres may not use the electricity grid but renewable energy sources, assuming the national grid's emission factor corresponds to a very conservative assumption. Furthermore, we consider the water usage for the cooling of the data centres in the operation phase. In the operation phase, maintenance and associated transport are omitted.[18]

Finally, the end-of-life of data centres needs to be considered. This includes the transport of materials and components to the relevant waste treatment sites.

SUBSYSTEM 4: SMARTPHONES

Smartphones are becoming increasingly important for the digital payment system. The SPACE report published by the ECB (2022a) shows that while mobile app payments at POS were not relevant in 2016, they accounted for 1% of the number of POS payments in the euro area in 2019 and 3% in 2022.[19] Considering the countries of interest, the report shows that in 2022, 2% of POS payments in Germany and Italy were conducted by mobile app (see Figure 8). In Finland, mobile app payments are much more popular with a share of 6% out of all POS payments in 2022. The report also shows that mobile app payments are most popular among younger people.

FIGURE 8: SHARE OF PAYMENT INSTRUMENT AT POS



EA 19 refers to euro area 19, i.e., the 19 EU Member States which adopted the euro as their common currency at the time of the analysis. These include Belgium, Germany, Estonia, Ireland, Greece, Spain, France, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Austria, Portugal, Slovenia, Slovakia, and Finland.
Source: Oxford Economics based on ECB (2022a)

[18] The production and usage of the internet network is not considered as separate subsystem since the usage share of POS transactions is very high. Therefore, comparable to modelling road infrastructure, the network infrastructure is considered in the operation phase.

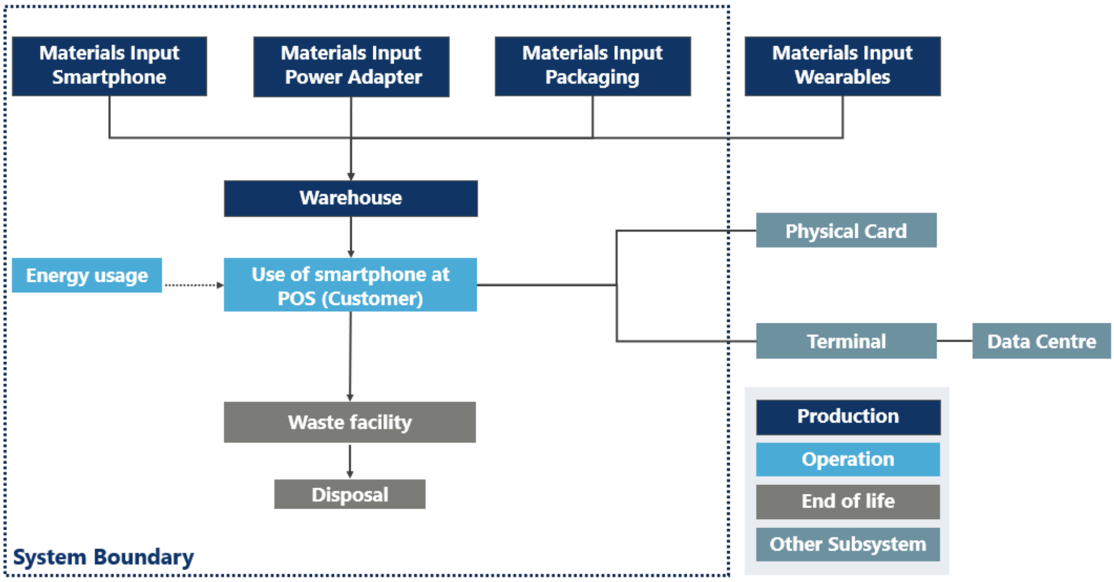
[19] The SPACE report (ECB, 2022a) differentiates between payments made with cash, card, mobile app and other. Mobile app payments may include banks' mobile applications, Apple Pay, Google Pay, other, and country-specific mobile applications.

The subsystem smartphone[20] includes the production of a smartphone covering the material input, energy used, the production of the power adapter, transport from the production location to the relevant country and the customer as well as the packaging of the new smartphone.

The operation phase covers the energy used by the smartphone to conduct an average payment as POS. Other aspects concerning energy usage, such as terminal processing and data centres, are covered in the respective subsystems. We do not consider the energy usage to load the banking card into the e-wallet as we consider it to be negligible—especially after assigning it to one POS transaction. Lastly, the need for internet access varies between providers of mobile payment solutions. For example, Apple Pay does not require internet access, while Google Pay and Samsung Pay require regular access to the internet from time to time to load new tokens (Lowry, 2022). Due to a lack of more specific data, we have omitted impacts caused by internet access through the smartphone. Nevertheless, the internet used by the data centre processing the transaction is still included in the corresponding subsystem 4.

The end-of-life includes the waste treatment process of the smartphone, power adapter and the initial packaging. Transport to the waste facility and energy used during the treatment process are also part of the system.

FIGURE 9: FLOWCHART OF THE SMARTPHONE SUBSYSTEM



Note: This figure gives a broad overview of the subsystem's lifecycle and indicates what aspects were considered and what was outside the system boundary. Thus, especially transport steps are simplified and do not represent the complexity of the system as modelled in this study. In general, all transport steps were considered either through market datasets or through explicit modelling. For detailed information on the transports considered and further aspects of the lifecycle, see Chapter 4.
Source: Oxford Economics

Of course, there are different ways to use smartphones for POS payments. A study performed by Eschelbach et al. (2022) shows that Apple Pay, payment apps provided by banks, and Google Pay are the most common methods used for mobile payments in Germany. Other alternative payment

[20] As the subsystem for smartphones is very simple, a visualisation by a flow chart is omitted.

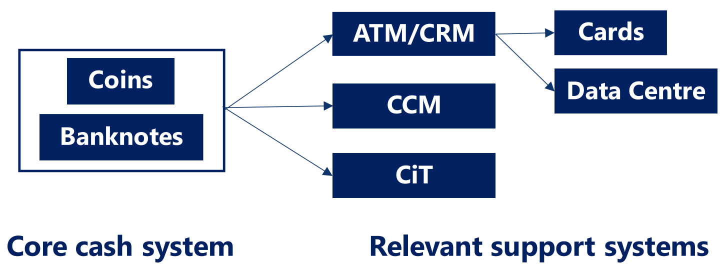
solutions include PayPal or Payback Pay, for example. Yet, as the data used typically do not allow for a differentiation between those smartphone payment methods, we assume every mobile app payment to be a smartphone payment connected to a physical card. Since these methods are mostly used as described above, we consider this a valid assumption. Moreover, as various methods of mobile payments may not be connected to a physical card, reducing their environmental impact, we consider this approach to be conservative.

We do not consider the production of wearables as their usage share is still little according to expert interviews. In Germany, for example, a study by Deutsche Bundesbank found that while 89% of customers owned a smartphone in 2021, only 7% owned a smartwatch and 4% a fitness bracelet with a payment function, respectively (Eschelbach, Lorek, Novotny, Pietrowiak, & Seiler, 2022, p. 20). Of these wearable owners, only 27% have used them to pay in a shop at least once (Eschelbach, Lorek, Novotny, Pietrowiak, & Seiler, 2022, p. 21). In the usage phase, all non-cash payments are considered digital payments—whether done by physical card, E-Wallet, or retail payment apps. Furthermore, the usage share of smartphones includes all mobile payments reported in the SPACE report, which includes all payments using the customer's bank's mobile application, Apple Pay, Google Pay or other methods to carry out the payment (ECB, 2022a).

3.2.3 Cash Payments: General description and reference flow

The cash system can be understood as consisting of a core—the actual cash—and supporting elements that are necessary for the functioning of the cash system. All subsystems are displayed in Figure 10.

FIGURE 10: CENTRAL ELEMENTS OF THE CASH SYSTEM



Source: Oxford Economics

For a consumer to be able to pay with cash at a POS, banknotes and coins need to be produced. Furthermore, the cash must reach the consumer, which is typically done via ATM withdrawals using a payment card and the back-end processing of data centres that authorise the withdrawal and settle it with the consumer's bank.[21] Thus, ATMs, data centres for the back-end processing and cards also need to be produced.

In the usage phase, the cash needs to be distributed between ATMs, retailers, and consumers. Mostly, special CiT companies provide that service for ATMs, CRMs[22] and retailers. They use armoured cash trucks for that service and need to count and sort the cash before recirculating it, which is typically

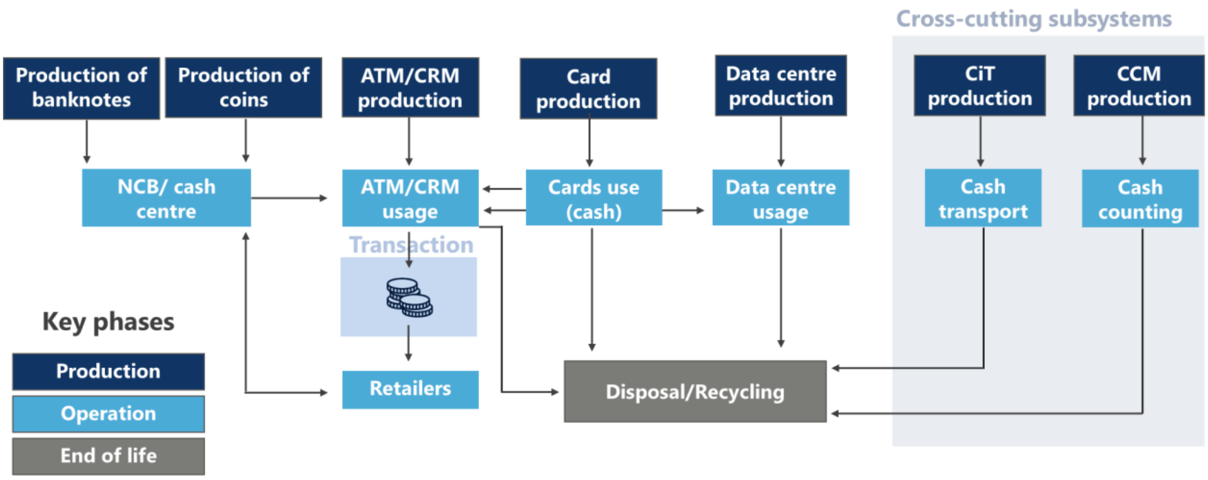
[21] We do not consider withdrawal at the bank counter or cash back at merchants.

[22] CRMs can be used for both – withdrawing and depositing money.

done by CCMs. The withdrawal of cash at an ATM as well as the deposit of money at CRMs is typically done by a consumer using their card.

When coins and banknotes become excessively damaged and reach the end of their life, they need to be withdrawn from circulation. These unfit currency units are typically shredded or melted down for recycling. Similarly, when ATMs, data centres and cards become damaged or non-functional, they are disposed of.

FIGURE 11: PRODUCT SYSTEM FOR A CASH PAYMENT AT POS



Source: Oxford Economics, partially adapted from Hanegraaf, et al. (2018)

Using this description of the cash payment system, we identified seven primary subsystems (see Figure 12):

- **Banknotes and Coins:** Banknotes and coins are two separate subsystems and constitute the centre of the cash transaction system. Banknotes enter circulation after being commissioned and dispensed by the national central banks. Similarly, coins enter circulation after being commissioned and produced. Physical currency is used in daily transactions and exchanged among individuals. They may change hands multiple times during their lifespan and can be used for multiple transactions.
- **ATMs/CRMs**: ATMs and CRMs are deployed at various locations, such as banks, convenience stores, and public areas. The consumer needs to reach the ATM to be able to pay with cash at a POS in a different location. These machines provide consumers with access to cash withdrawals and deposits. ATMs and CRMs are regularly restocked with banknotes and coins by CiT companies. This process involves securely transporting cash to replenish the machines. To withdraw and deposit money, consumers can use their cards at ATMs and CRMs.
- **Cards**: To withdraw cash from ATMs or CRMs, consumers can use their debit or credit cards, which are typically provided by banks after opening a bank account.
- **Data centre:** A withdrawal at an ATM as well as a deposit at a CRM involves back-end processing. For example, when a person wants to withdraw funds from their account, the ATM needs to establish a connection with the relevant systems to verify the person's authorisation and the availability of funds necessary to complete the transaction.

- **CiT companies**: CiT companies are crucial to the cash system as they are responsible for the transportation of valid coins and banknotes during the lifecycle. This may include transporting new banknotes from printing works to the national central banks' headquarters, distributing cash across retailers, ATMs, and CRMs, and transporting damaged banknotes to the central bank's analysis centres, for example. The transport is performed by special armoured and safe vehicles. These cash trucks are built for the sole use of transporting valid coins and banknotes making them fully attributable to the cash system.
- **CCM:** At various steps during a banknote's lifecycle, it needs to be counted. To do this efficiently, CCMs are used, for example by national central banks or by commercial cash handlers. The latter are also CiT companies, but the operation of cash centres is a different business vertical than cash transport. As these machines are produced for the counting of banknotes only, they are a central element of the cash system that should be considered to analyse the environmental impact of cash transactions. To account for the different types of CCMs, we have modelled a typical large CCM as well as a small one.

For all subsystems, the production, operation, and end-of-life are considered and assigned to a cash POS transaction in 2022 in Germany, Italy, and Finland. Again, besides the inputs, transport and energy consumption are always covered.

Table 3 gives an overview of the primary data sources used for the description of the cash payment system. As mentioned in Chapter 3.2.1 on the digital payment system, the interviews and questionnaires were conducted or collected between August and October 2023. To maximize the representativeness and quality of the information collected, we aimed to receive data from a market leader whenever possible. The Monte-Carlo simulations account for data uncertainty and their varying degrees of representativeness. The results are displayed in Chapter 6.3 and the pedigree matrices for the Monte-Carlo simulations can be retrieved from Appendix 4.

TABLE 3: OVERVIEW OF PRIMARY DATA SOURCES – CASH PAYMENTS

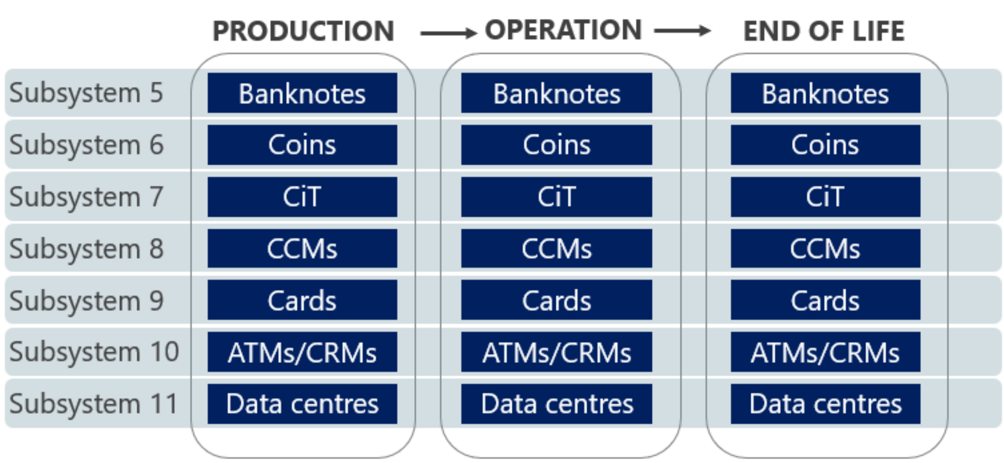
Primary data source	Primary use	Examples of indicators used	Geographic Focus	Data request
ATM/CRM manufacturer (one of the market leaders)	Production and operation of ATM/CRM	Material input, production processes, energy consumed, assumed lifetimes, waste treatment of ATM/CRM	Germany, Italy, and Finland	Written data request
ATM/CRM maintenance provider (one of the market leaders)	Servicing ATM/CRM	Distance travelled for servicing ATM/CRM	Italy	Written data request
Trade association	Cash transport (CiT)	Mileage and lifetime of trucks for cash transport	Germany	Expert interview
CiT company and trade association (one of the market leaders)	Cash transport and counting (CCM, CiT)	Number of CCM in use; milage and lifetime of trucks for cash transport	Italy	Written data request

Source: Oxford Economics

3.2.4 Cash Payments: Subsystems

As described, the cash payment system is divided into seven subsystems (see Figure 12). They are described in detail in the following paragraphs. Differences between the countries under investigation are highlighted.

FIGURE 12: OVERVIEW OF SUBSYSTEMS IN THE CASH PAYMENTS ECOSYSTEM

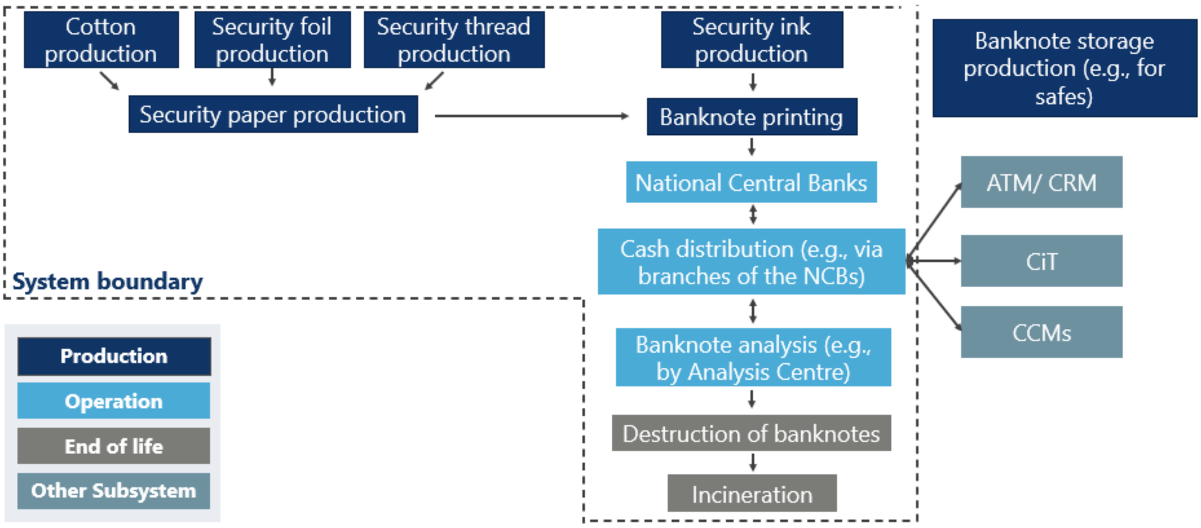


Source: Oxford Economics

SUBSYSTEM 5: BANKNOTES

Euro banknotes are a key element of the cash payments system and thus constitute a key subsystem. They are used for payment in the Eurozone covering all three countries of interest. In general, euro banknotes exist in seven denominations, namely 5-euro, 10-euro, 20-euro, 50-euro, 100-euro, 200-euro, and 500-euro. To evaluate the environmental impact of an average cash POS transaction, an average banknote is constructed using the relevant denominations and weighting them by their relative usage share as described in detail in Chapter 4.

FIGURE 13: FLOWCHART OF THE BANKNOTES SUBSYSTEM



Note: This figure gives a broad overview of the subsystem's lifecycle and indicates what aspects were considered and what was outside the system boundary. Thus, especially transport steps are simplified and do not represent the complexity of the system as modelled in this study. In general, all transport steps were considered either through market datasets or through explicit modelling. For detailed information on the transports considered and further aspects of the lifecycle, see Chapter 4. As secure banknote storage applies to all usage phases, no connecting lines were drawn for simplicity.
Source: Oxford Economics based on Hanegraaf et al. (2018)

This subsystem, including their production, operation, and end-of-life, is presented in Figure 13. The production of banknotes is performed by the national central banks in coordination with the ECB. First, the number of banknotes required for each year is calculated (ECB, 2023a). Then, the production volume of new banknotes is estimated considering the banknotes in circulation, demand, and the number of unfit banknotes. Afterwards, the ECB assigns the actual production volume to each national central bank (ECB, 2023a). In 2023, the ECB initiated the production of 3,141.7 Mio. new banknotes. Out of these, 131.7 Mio. new 5-euro banknotes were produced—commissioned by the national central bank of Greece (ECB, 2023b).

The banknotes are produced in eleven high-security printing plants in Europe (ECB, 2023a). They are then delivered to the various national central banks. Thus, the production process of all euro banknotes is the same—irrespective of their later geographical usage. All euro banknotes are printed on pure cotton fibre paper as displayed in Figure 13. Various security features, such as the watermark and security thread, are incorporated in this stage already (ECB, 2023a). The banknotes are printed using security ink at a banknote printing facility.

The energy usage for the different production processes is included in the LCA. Transport steps concerning the unfinished banknotes are considered as well in this subsystem. Further transport steps are part of subsystem 7. The packaging of the finalised banknotes in special banknote sleeves is also considered.

Given the joint effort to produce and issue euro banknotes by the various national central banks, there are no differences in the production phase for an average transaction across the countries. While some countries have different approaches to producing banknotes than others, each printing work ultimately produces banknotes for the entire euro area.

However, there are some differences in the operational and end-of-life phases between Germany, Italy, and Finland. For those phases, a generalised model is presented in Figure 13. The differences between the systems are described in detail in Chapter 4. Generally, once the banknotes have been issued by the national central banks, they are transported by CiT companies to the branches of the central banks or designated distribution centres that put the banknotes into circulation.

In Germany and Italy, banknotes are distributed through the branches of the respective national central banks (Bank of Italy, 2023b; Deutsche Bundesbank, 2023c). In Finland, however, the central bank provides designated cash management companies with banknotes. These companies are then responsible for distributing cash to ATMs/CRMs and commercial banks, who in turn provide consumers with banknotes (Bank of Finland, 2023b).

During the operation phase, banknotes are handled by CiT companies and counted by cash counting machines. These steps are part of the respective subsystems 7 and 8. We did not cover any inputs used for banknote storage, such as safes.

In Germany, banknotes that are unfit for circulation enter the end-of-life stage and are shredded and sent to an incineration plant (Wagner, 2022). We assume that this is the case for Italy too, as this is the common procedure in the disposal of banknotes. Other banknotes that are still usable are brought back into the cash cycle. In Finland, the cash management and the CiT companies are again responsible for returning banknotes to the central bank. First, banknotes are returned to cash centres in which banknotes are checked and stored. If banknotes are unfit for circulation, the cash centres then return the banknotes to the Bank of Finland, where they are shredded and destroyed in an incineration plant (Bank of Finland, 2023b).

SUBSYSTEM 6: COINS

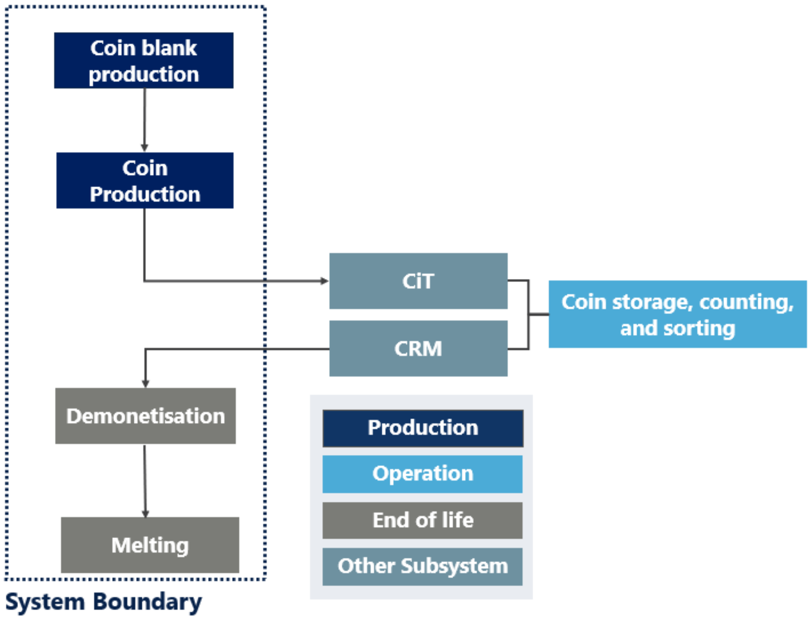
Coins constitute another key component of the cash payment system. In the Eurozone, eight denominations of coins exist: 0.01-euro, 0.02-euro, 0.05-euro, 0.1-euro, 0.2-euro, 0.5-euro, 1-euro, and 2-euro. In contrast to banknotes, the responsibility for coin production lies with the national governments but must be approved by the ECB (ECB, 2023b).

In Germany, coins are issued by the Federal Ministry of Finance, with coinage tasks delegated to the Bundesverwaltungsamt (BVA), a branch of the Federal Ministry of the Interior and Community. The BVA is responsible for procuring the coin blanks and issuing minting orders to Germany’s five state mints, which in turn strike the coin blanks (Bundesverwaltungsamt, 2023). The Bundesbank then purchases coins from the Finance Ministry and distributes them into circulation (Deutsche Bundesbank, 2023c).

The production of coins in Italy is similar to the one in Germany. Coins are issued through the Ministry of Economy and Finance, which commissions the State Printing Works and Mint to mint the coins (Bank of Italy, 2023a). This Istituto Poligrafico e Zecca dello Stato is supposed to also produce the coin blanks according to an expert interview.

In Finland, the life cycle of coins slightly differs from the other two countries. First, the Bank of Finland issues the coins instead of the respective finance ministry (Bank of Finland, 2023a). Second, we assumed that the Mint of Finland, which is responsible for coin production, does not need to procure coin blanks since they produce blanks themselves (Mint of Finland, 2023).

FIGURE 14: FLOWCHART OF THE COIN SUBSYSTEM



Note: This figure gives a broad overview of the subsystem's lifecycle and indicates what aspects were considered and what was outside the system boundary. Thus, especially transport steps are simplified and do not represent the complexity of the system as modelled in this study. In general, all transport steps were considered either through market datasets or through explicit modelling. For detailed information on the transports considered and further aspects of the lifecycle, see Chapter 4.
Source: Oxford Economics, own illustration, based on Hanegraaf, et al. (2018)

The generalised life cycle of a euro coin is illustrated in Figure 14. The production of coins requires several different metals as inputs. The first step in the production process involves the creation of coin blanks by melting the different metals in a furnace and producing a strip of alloy.[23] In the second step of the production process, these blanks are then stamped (struck). Euro coins have a common side and a national side. The national sides differ by the issuing country. We assumed that the differences on the national side do not cause relevant variation in the environmental impact during the striking. After producing coin blanks, the coins are finalised. In these steps transport, material input, and energy usage are parts of the analysis.

Once production has been finished, the coins enter the operation phase and are distributed into the cash system. While the specific agencies and procedures vary among countries, the minted coins are

[23] A coin blank is a flat metal disk that can be turned into a coin by stamping.

typically distributed nationally through the branches of the national central bank or distribution centres. Only in Finland, coins are distributed through the distribution centres used to distribute banknotes as well (Bank of Finland, 2023b). These country-specific transport distances are included in the analysis. As for banknotes, the circulation of coins by CiTs and the depositing of coins at CRMs are covered in the respective subsystems. Coin storage and the counting and sorting of coins are not considered in our analysis due to a lack of data. For new coins entering the cash cycle, packaging was covered by the analysis.

At the end-of-life in Germany, damaged coins can be presented at Bundesbank branches and are eventually sent to the "National Analysis Centre for counterfeits and damaged money" before being devalued and sold for recycling, typically through melting (Zydra, 2015; Deutsche Bundesbank, 2023a). Similarly, damaged coins in Italy can be presented to the branches of the Bank of Italy, which sends the coins back to the State Printing Works and Mint (Bank of Italy, 2023a).

For Finland, we assume that damaged coins will follow the same procedure as damaged banknotes: Once CiT companies return cash to the privately operated cash centres, the cash centres inspect the coins and send damaged coins back to the Bank of Finland. We assume that damaged coins would be demonetised and sent to a melting company for recycling.

Thus, the damaged coins are typically demonetised and melted (Hanegraaf, Jonker, Mandley, & Miedema, Life cycle assessment of cash payments, 2018), with melting being a common method employed to recover the metal content. Therefore, we only modelled transport, the energy used to melt coins, and the disposal of the packaging in the end-of-life phase.

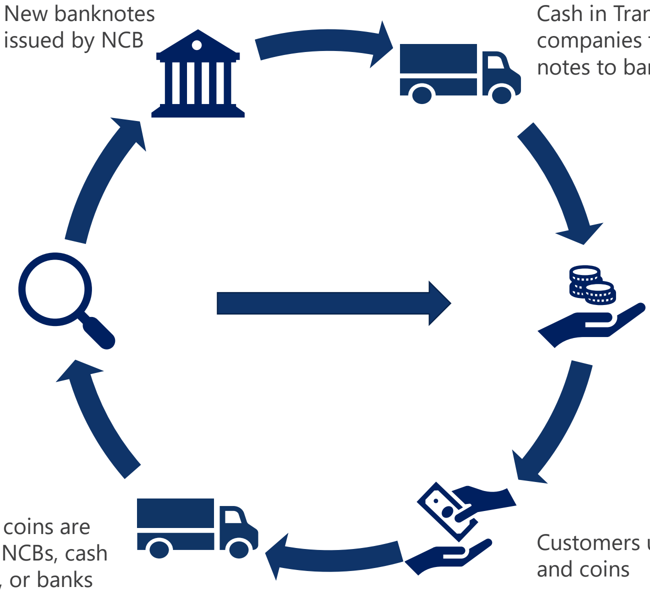
SUBSYSTEM 7: CASH-IN-TRANSIT

In all phases of the banknotes' and coins' lifecycle, privately owned CiT companies play an important role (see Figure 15). CiT companies transport new banknotes and coins from the printing works or coin mints to the central bank headquarters and afterwards to the individual central bank branches or distribution centres. Afterwards, they are put into circulation by retailers, banks, and ATMs/CRMs (Bank of Finland, 2023b). Apart from the transport of cash on its way to circulation, CiT companies handle the circulation of cash—both banknotes and coins—during their respective lifetimes. This service is called pick-up and delivery of cash. They take care of the refilling and managing ATMs and CRMs, transport cash to and from retailers, and deliver cash between commercial banks and/or national banks.[24]

Lastly, CiT companies own the so-called cash centres, where they can count and sort cash using CCMs to manage the retailers' or banks' cash. Additionally, they partly take over the responsibility to check the physical fit and the authenticity of the cash to be sure to only put valid cash back into circulation. However, these checks are also performed by national central banks, banks, and analysis centres. This is why we modelled a separate subsystem for CCMs. Other elements, such as the cash centre building and storage, were not included in the analyses. Transports to the national central bank to check for counterfeits and withdraw unfit money from circulation are also included if the transport is organised by CiT companies.

[24] In so doing, CiT companies trade cash among each other or with the central bank, where companies with a deficit receive cash from companies with a surplus of cash (Hanegraaf, Jonker, Mandley, & Miedema, Life cycle assessment of cash payments, 2018). This has the advantage that no intermediaries need to be included in this process.

FIGURE 15: CIT COMPANIES AS PART OF THE CASH LIFECYCLE



Source: Oxford Economics, partially based on ECB (2017), Figure 1

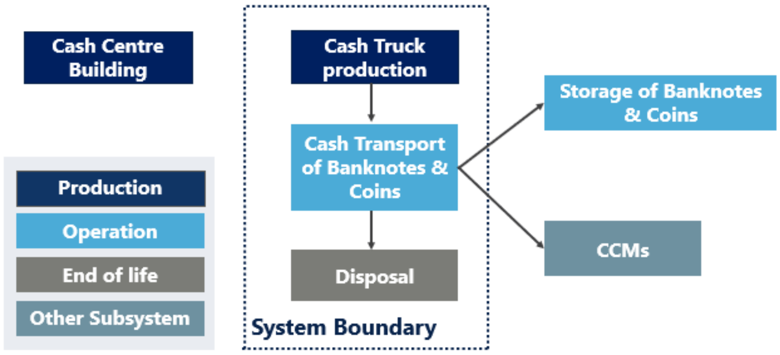
The subsystem CiT was also structured based on a production, operation, and end-of-life phase. The production phase includes the production of the truck and its transport to the CiT companies.

In the operation phase, the ton kilometres (tkm) driven per truck per year were included. Any transport of banknotes or coins ready to use for payments falls into the responsibility of CiT companies, using special armoured and safe vehicles.[25] In the CiT subsystem, only transports of new banknotes and coins starting from the national central bank's headquarters were included. Previous transports that may be carried out by CiT companies as well, such as from the printing works or coin mints to the national central bank's headquarters, were covered in the subsystems of banknotes and coins, respectively.

In the end-of-life phase, the waste treatment of the cash trucks is included.

[25] Some transports may also be carried out by the national banks rather than CiT companies. Since the transports by the national banks were likely carried out using special vehicles equivalent to those of CiT companies, the operator of these cash trucks can either be the national banks or CiT companies.

FIGURE 16: FLOWCHART OF THE CASH-IN-TRANSIT SUBSYSTEM



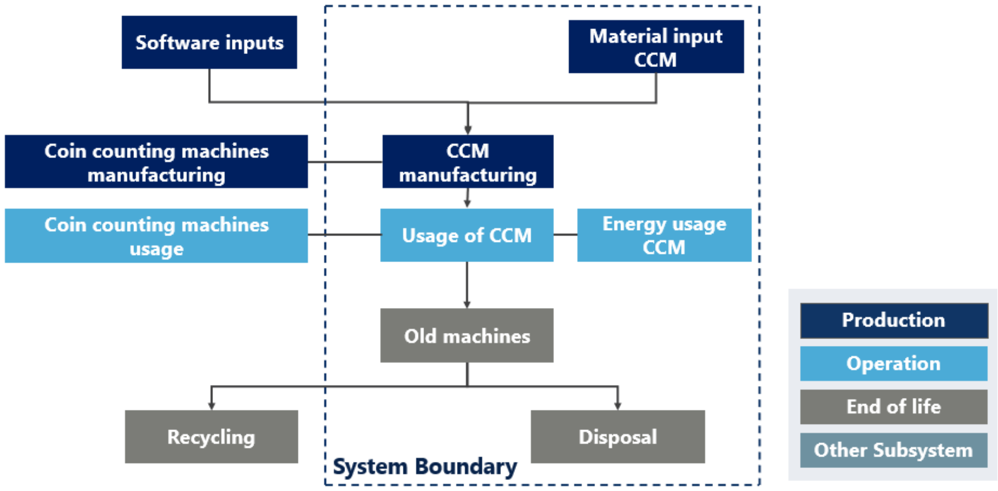
Note: This figure gives a broad overview of the subsystem's lifecycle and indicates what aspects were considered and what was outside the system boundary. Thus, especially transport steps are simplified and do not represent the complexity of the system as modelled in this study. In general, all transport steps were considered either through market datasets or through explicit modelling. For detailed information on the transports considered and further aspects of the lifecycle, see Chapter 4.
Source: Oxford Economics

SUBSYSTEM 8: CASH COUNTING MACHINES

As explained before, CiT companies run cash centres that serve as the logistic hub for the transport of cash. To count and sort cash, they used cash counting machines (CCMs). Moreover, national central banks use—though much larger—cash counting machines in their branches to sort and check cash for counterfeits. The CCMs that count and sort banknotes—both in cash centres run by CiT companies as well as the national central banks—are included in the analysis. We exclude coin counting CCMs due to a lack of data on the number of these machines used.

CCMs count and sort banknotes in addition to checking their physical fit as well as their validity. This is why CCMs need to be approved by the ECB. For our analysis, we picked out two different types of CCMs counting banknotes approved by the ECB. One machine is a rather small model, portable and easy to handle produced by Giesecke+Devrient (2023a). From expert interviews, we learned that these models are used in cash centres of CiT companies. The other model is a large machine, which can count way more banknotes and pack sorted banknotes in small packages preparing them for being stored or sent out. We assumed that these machines are used in central bank branches, where banknotes are counted, checked, sorted, and packed. Again, an example of a large machine is a product by Giesecke+Devrient (2023b).

FIGURE 17: FLOWCHART OF THE CCM SUBSYSTEM



Note: This figure gives a broad overview of the subsystem's lifecycle and indicates what aspects were considered and what was outside the system boundary. Thus, especially transport steps are simplified and do not represent the complexity of the system as modelled in this study. In general, all transport steps were considered either through market datasets or through explicit modelling. For detailed information on the transports considered and further aspects of the lifecycle, see Chapter 4.
Source: Oxford Economics

The lifecycle in Figure 17 is valid for large as well as for small CCMs. In the production phase, we include the material inputs as well as their production. Again, we did not cover any software input that needs to be developed and installed on the machine itself. We did include the packaging of a CCM and its transport to its respective customer operation phase. We also covered the electricity usage of CCMs.

As soon as CCMs reach their end-of-life, old machines are disposed of. From primary sources, we received the information that there does not exist any recycling of old machines.

SUBSYSTEM 9: CARDS – CASH SYSTEM

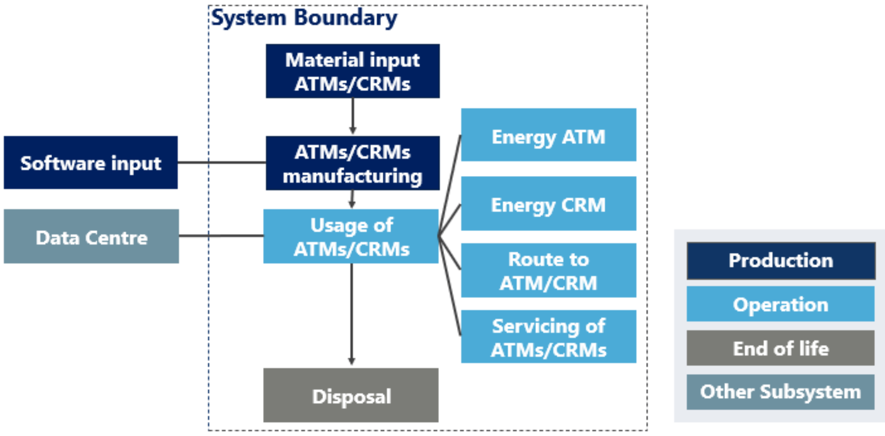
Cards are important in the cash as well as in the digital system. In this paragraph, only the differences in the card lifecycle in cash compared to the already explained digital payment system are highlighted. In the cash payment system, cards are crucial to initiate the link between customer and their bank account. Having either a credit or a debit card makes it possible for customers to withdraw or deposit cash at ATMs or CRMs.

SUBSYSTEM 10: ATMS/CRMS

ATMs and CRMs play a significant role in the cash supply system. On the one hand, these machines ensure that customers can withdraw cash to be able to pay in cash. On the other hand, customers can deposit cash and have it directly transferred to their bank accounts. Here, the main difference between ATMs and CRMs comes into play. At ATMs, customers can only withdraw cash, whereas at CRMs one can withdraw and deposit cash.

In Figure 18, the lifecycle of an ATM and a CRM is displayed. In the production phase, the material input and manufacturing of ATMs and CRMs is included. We treated ATMs and CRMs in the same way. We assumed that the material inputs are the same as well as the production processes. We understand this is a simplifying assumption since CRMs would need to have different material inputs as they can manage deposited cash, i.e., check the quality and the validity of cash, sort it, and give it out at a later point. However, due to data limitations, we followed the study by Hanegraaf et al (2018) and decided to make this assumption. Once again, we did not include the development, programming, or installation of any software on the machines. Transport and packaging were covered by our analysis.

FIGURE 18: FLOWCHART OF THE ATM/CRM SUBSYSTEM



Note: This figure gives a broad overview of the subsystem's lifecycle and indicates what aspects were considered and what was outside the system boundary. Thus, especially transport steps are simplified and do not represent the complexity of the system as modelled in this study. In general, all transport steps were considered either through market datasets or through explicit modelling. For detailed information on the transports considered and further aspects of the lifecycle, see Chapter 4.
Source: Oxford Economics

In the operation phase, the energy usage of ATMS/CRMs, the route to reach an ATM/CRM by the customer, and the servicing of the ATMs/CRMs are considered. The energy usage of ATMs and CRMs differs due to their varying functions and therefore varying active hours. Therefore, we considered the energy usage of ATMs and CRMs separately. Furthermore, we included the distance travelled together with the transport mode for the cardholders to reach the closest ATM or CRM. The mobility shares as well as the modes of transport, which were both covered in our analysis, differ between the countries. Finally, we included the transport necessary for servicing the ATMs and CRMs.

We also took the backend of ATMs and CRMs into account. When cash is deposited or withdrawn at an ATM or CRM, data centres are needed to process the transaction. This is covered in a different subsystem—data centres cash.

As an ATM or CRM reaches its end-of-life, the machines are sent back to the producer. According to expert interviews, machines are not recycled. Rather, the producers themselves or certified partners proceed with the scrapping of old ATMs and CRMs. Therefore, we assumed that all ATMs and CRMs are disposed of in line with WEEE standards (in 't Groen, Stengs, & Zanneveld, 2017).

SUBSYSTEM 11: DATA CENTRES – CASH SYSTEM

Considering a withdrawal at an ATM/CRM, an individual needs to be authorised to access funds from their bank account. This is why the cardholder is asked to enter their PIN after presenting their card. The encrypted information on the PIN is then transferred to the cardholder's bank for authorisation as well as the verification of sufficient funds. If the bank approves the transaction, the ATM or CRM grants authorisation for fund retrieval and the customer gets the cash. After that, the cardholder's financial institution must settle the transaction and reimburse the funds supplied to the ATM owner. A deposit works comparably.

The life cycle of the data centres is the same as explained in the digital payment subsystem 3 – Data Centres. Even the technical process of authorisation, clearing and settlement is quite comparable to a POS transaction explained in detail in the digital data centre subsystem. The difference is that an ATM/CRM withdrawal/deposit only includes the ATM/CRM provider and the cardholder's bank. If the ATM/CRM provider and the cardholder's bank use the same processors—e.g., in the case of a banking group—the authorisation via one (or more) intermediaries and settlement via a clearing system is not required. Therefore, the energy consumption is assumed to be less than for a digital POS transaction.

3.2.5 System boundaries and cut-off criteria: Summary

The system boundaries define the life-cycle stages, processes, and flows considered in the product system providing the system function. In general, all life cycle stages from "cradle to grave" are included and represented in the study. We seek to include transport, packaging, as well as manufacturing processes for all relevant subsystems.

We tried to model the digital and cash payment system as detailed and holistic as possible. As explained in the studied subsystems, we excluded the following elements from our analysis:

- We do not consider the cash register equipment in the study, as it is in our view not a necessary component for the studied function, i.e., to pay for a good or service—neither in the digital nor in the cash system.
- We do not include the possibility of getting cash advances in shops or at POS or withdrawing money at cash counters as we have not identified any further inputs related to these sources of cash that should be considered. However, the implicit assumption is that no additional ways were travelled by customers. Thus, while the explicit exclusion leads to a bias in the average amount withdrawn/deposited, this does not affect the estimated environmental impact which is driven by the total number of ATMs/CRMs and withdrawals/deposits.
- We do not consider any storage impacts in the LCA, e.g., for storing coins and/or banknotes because of a lack of available data.
- We do not include the development and installation of software, or the operating system as available data is rare and we assume the environmental impact to be low compared to the material inputs and the manufacturing. This includes the installation of the virtual image of a banking card into a digital e-wallet as well as the download and update of banking apps which are in part necessary to install the virtual image of a card in the e-wallet.
- We do not consider digital payments with other instruments than (virtual) cards (for example (e.g.), PayPal) due to limited data availability.
- POS apps on smartphones are not in the scope of this study due to limited data availability.
- The need for internet access varies between providers of mobile payment solutions. Due to a lack of more specific data, we omit impacts caused by internet access through the smartphone. Nevertheless, the internet used by the data centre processing the transaction is still included in the corresponding subsystem 4.

- We do not assume any usage share of digital cards because their usage is still very low and assuming the physical card is the more conservative assumption.
- We did not model the building/room for cash centres, and we excluded coin counting CCMs due to a lack of data.
- While modelling data centres, we ignored the on-site facility construction due to the absence of sufficient data and the relatively minor influence.
- We included the packaging for the major products considered in the subsystem data centre but had to exclude it in some cases due to the granularity needed for a detailed packaging approach (e.g., packaging for separate IT components of a data centre) or the lack of information available (e.g., packaging of coins/banknotes in circulation managed by CiT companies).
- We excluded the material inputs contributing less than 1% in terms of mass to the inputs of a data centre due to missing data.[26]

3.3 ALLOCATION PROCEDURE

As we study partially multifunctional processes, the environmental load of the inputs and outputs must be divided among the functions. In general, there are three options for doing this:

- Subdivide the multifunctional process,
- Determine a physical causality for allocation,
- Use the economic revenue as the key to allocation.

Overall, we had to allocate the environmental load of the inputs and outputs for the following multifunctional processes:

- For subsystems 1 and 9 (cards), we used the physical allocation procedure based on the identification of three purposes of payment cards: Digital payments at POS, cash withdrawals and deposits, online or Peer-to-Peer payments. For subsystem 1 we allocated the inputs based on the number of uses of cards for digital payments at POS. For subsystem 9, we allocated the inputs based on the number of uses of cards for cash withdrawals and deposits.
- For subsystems 3 and 11 (data centres), we determined a physical causality for allocation. In detail, we estimated the number of data centres that would be needed to conduct all digital (subsystem 3) and cash (subsystem 11) POS transactions if these data centres were only used for this purpose. The estimation was based on the energy used per data centre per transaction and total capacity of an average data centre. Afterwards, the inputs were assigned to one average digital or cash POS transaction.
- For subsystem 4 (smartphones), we used a similar approach. Here, the total number of smartphones needed to conduct digital payments at POS was estimated if they were only used for this purpose. The estimation was based on electricity usage of one digital POS transaction and capacity of a smartphone. Afterwards, the inputs were assigned to one average digital or cash POS transaction.

[26] We excluded these inputs as we had no detailed information on them. An estimation of their energy and environmental significance was not possible due to missing data. However, we believe the impact of excluding these inputs on the final results to be minor. A cut-off threshold of 1% has been used in other, critically reviewed LCA studies (see e.g. Vilabrille Paz, Ciroth, Mitra, Birnbach, & Wunsch, 2022).

- For subsystem 5 (banknotes), we used the physical causality for allocation. Besides being used for transactions, banknotes are also used for value storage. This was considered by allocating only the banknotes' transaction share to the impact of cash payments at POS. The allocation was based on data on the share of banknotes that are used for transactions in the Euro area. Afterwards, the inputs were assigned to one average digital or cash POS transaction.
- Lastly, for subsystem 6 (coins), we again used physical causality for allocation. Similar to the banknotes, not all coins are used for transactions as some are also hoarded, for example. Thus, we only allocated the share of coin inputs to the cash system that corresponds to the share of coins being used for transactions. Again, afterwards, the inputs were assigned to one average digital or cash POS transaction.

Hence, we only followed the second allocation procedure, i.e. the physical allocation, throughout the analysis.

Furthermore, we used the cut-off method to assign end-of-life impacts in open-loop systems. Under this approach, 100% of the environmental impact resulting from the use of primary materials is attributed to their initial use. Thus, this method assigns potential environmental burdens to the time when they originate, irrespective of any future use. It is more risk averse as no credits for recycling are considered. The positive impacts of recycled materials or inputs stem from avoiding their respective waste treatment.[27]

3.4 DATA QUALITY REQUIREMENTS

Overall, the quality requirements of the data are specified and address all aspects established in the corresponding ISO norm.

- **Time-related coverage:** The reference year for the study is 2022. Accordingly, the data used refers to that year. If we must deviate from the reference year, it is mentioned in the data inventory and accounted for in the Monte Carlo simulation.
- **Geographical coverage:** Data used around the production of raw materials represents the market supply. This either uses global market datasets provided by ecoinvent 3.9.1 or by selecting a geographical area that best represents the specific process. Data for the manufacturing processes represent the market in which the product is produced. Since the cash and digital POS transactions are assessed for Germany, Italy, and Finland, use-phase, and end-of-life data represent the respective country markets; and other geographical markets if the intermediary product or raw product is produced elsewhere.
- **Technology coverage.** Most of the data used in the foreground system represents the status quo of the technology used in the industry. The uncertainty of the fit of the usage of ecoinvent

[27] Our implementation of the cut-off approach as described in the text is based on the ecoinvent implementation of the cut-off approach which ecoinvent recommends as the default system model (see ecoinvent (2024)). There exist other approaches that apply the cut-off at the point, where the residual materials no longer have economic value. In the context of our study, this may be the case for old coins when they are melted down and recycled for future use. We assigned 100% of the primary material inputs of coins to the coin subsystem. If one were to apply the cut-off method according to economic value, one would attribute part of the material input to the subsequent usage as the melted down metals still have economic value. This would lessen the environmental impact of the cash POS system compared to our results. However, as the metals used in coins are not very valuable (they mainly consist of steel, copper, zinc, and nickel as opposed to gold for example, see Chapter 4.2.2), we believe that using an alternative cut-off approach would only have a minor impact on our results.

manufacturing datasets is considered in the Monte Carlo simulation. In the background system, the ecoinvent 3.9.1 database refers to the status quo.

- **Precision:** Concerning the accuracy of the employed data, multiple sensitivity checks have been conducted (see Chapter 6.2). Furthermore, the Monte-Carlo simulation examined the fluctuation of modelled values that significantly impact the outcomes.
- **Completeness:** The acquired data and its utilisation within the model are comprehensively elucidated in the life-cycle inventory. This inventory is a product of an iterative procedure aimed at ensuring comprehensiveness. All pertinent processes within the product system are considered, and input and output data are accessible.
- **Representativeness:** The selected products are representative of the Finish, Italian and German payment systems at POS. They cannot be aggregated to the overall environmental impact of the cash or digital payment system, as especially cash is not only used for transactional purposes.
- **Consistency:** To evaluate all payment systems at POS, an essential factor in guaranteeing their comparability is ensured by using a consistent methodology across all subsystems. Sensitivity checks were conducted to address the assumptions and uncertainties that arose during the process.
- **Reproducibility:** The report provides comprehensive documentation of the methodology and data utilised, enabling any independent researcher to replicate the results.
- **Sources of the data:** Table 1 presents a summary of the key data sources utilised in various subsystems, whereas the ecoinvent 3.9.1 cut-off system model is employed for the background system. Table 2 and Table 3 provide an overview of primary data sources used in the modelling for the digital and the cash system, respectively.
- **Uncertainty:** Uncertainties in the modelling may come from modelling decisions on assignment factors, the applied data (e.g., time, representativeness, etc.) or the used background data set. We examine these aspects in the sensitivity analysis.

3.5 LIFE-CYCLE IMPACT ASSESSMENT

The Life Cycle Impact Assessment (LCIA) is the third step of an LCA according to the ISO 14040 standard (Whitehead, Andrews, & Shah, 2015). The goal of the LCIA is to understand and measure the environmental impact of different products and activities by translating the emissions and extraction of natural resources, as defined by the collected life cycle inventory data, into a limited number of environmental impact scores using characterisation factors (Hauschild & Huijbregts, 2015).

Typically, these characterisation factors are derived at the midpoint and endpoint level. Midpoint characterisation factors, as defined by Goedkoop, et al. (2009), are intermediate environmental impact measures located somewhere along the impact pathway. In contrast, endpoint characterisation factors require modelling of the whole impact pathway up to the area of protection, which can correspond, for example, to human health (Hauschild & Huijbregts, 2015). In general, both approaches are complementary as the midpoint indicators provide a clearer understanding due to their closeness to the environmental flows and, generally, lower assumptions and uncertainties (Hauschild & Huijbregts, 2015). Yet, the endpoint indicators are often more relevant as they directly capture the consequences and reflect the relative importance of environmental changes.

For the LCIA, we employ the established impact assessment method ReCiPe 2016, which is in line with the worldwide standardisation of LCAs laid out by ISO, specifically ISO 14040 and ISO 14044. The main benefit of the ReCiPe 2016 method compared to other LCIA approaches is that it provides harmonised characterisation factors, representative at the global scale, both at the midpoint and endpoint level. Further, the combination of the midpoint and endpoint approach allows for enhanced consistency in the impact pathway modelling (Hauschild & Huijbregts, 2015).

The authors of the ReCiPe 2016 method include in total 18 midpoint impact categories presented in Table 45 in Appendix 1 from which three endpoint-level categories can be derived: human health, ecosystem quality, and resource scarcity. Crucially, at the midpoint level, the ReCiPe 2016 method introduces a reference substance so that the analysed characterisation factor is a dimensionless number that expresses the strength of an amount of a substance relative to that of the reference substance (Goedkoop, et al., 2009). For example, in the case of climate change, the characterisation factor would be the Global Warming Potential (GWP) in kilogram (kg) CO_2 equivalents to air.

To account for different sources of uncertainty and choices, the characterisation factors of the midpoint and endpoint level can be derived according to three cultural perspectives which can be best described as follows (Goedkoop, et al., 2009): The individualist perspective is a short-term optimistic perspective on high adaptive potential through technological progress, thereby allowing to avoid future problems. The hierarchical perspective is the scientific consensus model regarding the time frame and impact mechanisms, assuming that impacts can be avoided with proper management. The egalitarian perspective is the precautious worst-case scenario that views nature as strictly accountable.

Our following analysis focuses on the environmental impact of digital and cash transactions using the midpoint level indicators. This procedure is applied for comparative LCA studies because the ISO 14044 guideline prohibits the weighting of different impact categories as used by the endpoint method. Additionally, we apply the common standard for LCIAs and apply the hierarchical perspective, i.e., the scientific consensus method. Nevertheless, we have computed the baseline using the individualist as well as the egalitarian perspective with the results being displayed in Box 4. Finally, it must be noted that our analysis uses the ReCiPe 2016 method compared to the preceding analysis of the DNB (Lindgreen, et al., 2017; Lindgreen, et al., 2023; Hanegraaf, Jonker, Mandley, & Miedema, 2018) that used the ReCiPe 2008 methodology. Consequently, due to the update to ReCiPe 2016 and the accompanying methodological differences between both methods, the results are not directly comparable (Lindgreen, et al., 2023).

3.6 INTERPRETATION

During the interpretation phase, the results of the impact assessment are discussed, and areas of heightened impact are identified. In addition, the study incorporates the techniques recommended in ISO 14044:2006 to establish and reinforce the reliability and confidence of the LCA results, including the following:

- Sensitivity analysis: Examining how alterations of data assumptions impact the results.
- Uncertainty analysis: Conducting Monte-Carlo simulations to estimate the uncertainty of our impact assessment results.
- Completeness validation: Ensuring that all pertinent information and data required for the interpretation are present and comprehensive.

- Consistency validation: Ensuring that assumptions, methods, and data align with the study's goal and scope.

3.7 UNCERTAINTY ANALYSIS USING MONTE CARLO SIMULATIONS

In LCAs, there can be uncertainty and variability associated with various input parameters such as data on emissions, energy use, material flows, or other process-related factors. Moreover, this study relies extensively on secondary data with varying degrees of uncertainty and many underlying assumptions. While the most critical points are addressed and tested using sensitivity checks (see Chapter 6.2), a Monte Carlo simulation was also applied to additionally test for the uncertainty of the results.

A Monte Carlo simulation is a technique used in LCAs to address the uncertainty and variability in LCA data and results. For each uncertain input parameter, a probability distribution describing the range of possible values and their likelihood is used to account for uncertainty in parameters (i.e., the pedigree matrix). In the Monte Carlo simulation runs, the LCA model is run repeatedly using random samples drawn from the specified probability distributions for each input parameter. Each simulation run generates a set of results that reflect the potential variability in the system. As a result of these simulation runs, a probability distribution of the environmental impact indicators (e.g., greenhouse gas emissions, energy consumption, etc.) is computed that provides a range of possible outcomes. This method can be used to quantify the uncertainty associated with the LCA results.

In our case, we computed 1,000 runs for each Monte Carlo simulation.[28] The results of our analysis are discussed in Chapter 6.3 and the pedigree matrices are displayed in Appendix 4.

3.8 CRITICAL REVIEW

Following the ISO standards, this published comparative study was externally reviewed by a Review Panel. The critical review was conducted by a panel of the following individuals:

- Niels Jungbluth (Chair; ESU-services, Switzerland)
- Erik Roos Lindgreen (Technical expert; Author of one DNB study (Lindgreen, et al., Evaluating the environmental impact of debit card payments, 2017) and the erratum (Lindgreen, et al., 2023))
- Susanne Jorre (Methodological expert; TÜV Rheinland Energy GmbH, Germany)

The report on the critical review is provided in Appendix 7.

[28] We used a random seed value of "325" to ensure reproducibility of our Monte Carlo simulation results.

4. LIFE-CYCLE ASSESSMENT—INVENTORY ANALYSIS

The goal of the inventory analysis is to describe the data used and the calculations applied in detail. Thus, it is transparent to the reader which assumptions and approaches our analysis was based on. In the following, this is laid out for the digital (Chapter 4.1) and the cash payment (Chapter 4.2) systems structured by subsystem similarly to Chapter 3.2. As described before, the subsystems Cards and Data centre are relevant for both the digital and the cash system. Thus, they are described in detail in Chapter 4.1 and only briefly mentioned in Chapter 4.2.

In general, all transport steps within the system boundary as outlined above were included. This was either done by using market datasets that often include transport already or by modelling transport explicitly. To model transports by ship and aeroplane explicitly we used the website SeaRates.com (2023) to estimate distances. For aeroplane transports the website provided by myclimate (2023) was used as well. For distances concerning road transport, we used Google Maps (2023). Moreover, if it was not possible to calculate distances, for example, because the precise production location in one of the relevant countries was not known, one of the following two approaches was chosen. In some cases, the average freight distances by road were used (2021a). In other cases, we chose to use the average commuting distance provided in the passenger mobility statistics (2021b). The reasoning for choosing one approach over the other is described in the respective subsystems in detail.

Regarding the mode of transport, we usually used ecoinvent transport datasets such as “Transport, freight, aircraft, long haul {GLO}| market for transport, freight, aircraft, long haul | Cut-off, U”, for instance. Sometimes, the type of lorry used for transport was unknown. In such cases, we used the ecoinvent dataset “Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U.”

Besides transport, we have also included energy usage in all steps. Like transport, this was either done implicitly by using market datasets that include energy usage or manufacturing processes that cover it. Alternatively, energy usage was also modelled explicitly.

While usually ecoinvent datasets exist that already contain transport and energy usage, we sometimes modelled transport and energy usage separately, if we had access to more specific information. In such cases, we adjusted the original ecoinvent datasets and removed the respective processes from them. These adjusted ecoinvent datasets are marked in our inventory tables. For example, the addition of “WITHOUT ENERGY” in a dataset name indicates the energy input was removed from the ecoinvent dataset because we modelled energy usage separately.

The electricity mixes used in this study and their corresponding emission factors are shown in Table 4.

TABLE 4: ELECTRICITY MIXES USED IN THIS STUDY AND THEIR EMISSION FACTORS

ecoinvent dataset for electricity mix	Kg CO_2 eq. per kWh[29]
Electricity, low voltage {DE}| market for electricity, low voltage | Cut-off, U	0.124
Electricity, low voltage {FI}| market for electricity, low voltage | Cut-off, U	0.066
Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, U	0.109
Electricity, low voltage {GB}| market for electricity, low voltage | Cut-off, U	0.0852
Electricity, low voltage {NL}| market for electricity, low voltage | Cut-off, U	0.138
Electricity, low voltage {FR}| market for electricity, low voltage | Cut-off, U	0.0249
Electricity, low voltage {IR}| market for electricity, low voltage | Cut-off, U	0.218
Electricity, low voltage {CH}| market for electricity, low voltage | Cut-off, U	0.0116
Electricity, medium voltage {DE}| market for electricity, medium voltage | Cut-off, U	0.133
Electricity, medium voltage {FI}| market for electricity, medium voltage | Cut-off, U	0.0632
Electricity, medium voltage {IT}| market for electricity, medium voltage | Cut-off, U	0.114
Electricity, medium voltage {GLO}| market group for electricity, medium voltage | Cut-off, U	0.201
Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	0.0989

Source: Oxford Economics

The inventory typically refers to one unit of the respective subsystem, i.e., one card, one average banknote, or one data centre. Afterwards, an assignment factor is used to assign the impact of one unit to a single average transaction at POS. Please note that the operation phase may differ from the production and end-of-life phases as the reference unit here normally is one year, i.e., energy usage per year, distance travelled for maintenance per year, or ATM withdrawals per year. Therefore, the assignment factor mostly differs as well in the operation phase compared to the other two phases as is described in detail in the following.

4.1 DIGITAL PAYMENTS

To calculate the total number of digital POS payments for Germany, Italy, and Finland, we used the Payment Statistics provided by the ECB (2022b). Specifically, Table 7b in the section country tables displays all cash and cashless transactions that are performed at physical terminals. Thus, transactions done online, for example at virtual terminals, are not included. We calculated the number of digital POS payments for 2021 for each country by adding up POS transactions at terminals located in the reporting country at a) terminals provided by resident Payment Service Providers (PSPs) with cards issued by resident PSPs, b) terminals provided by resident PSPs with cards issued by non-resident

[29] Computed using ReCiPe 2016 v1.1 midpoint, Hierarchist perspective, and excluding long-term emissions.

PSPs, and c) terminals provided by non-resident PSPs with cards issued by resident PSPs.[30] Thus, the number of digital POS payments reached 5.043 billion in Germany, 5.156 billion in Italy, and 1.102 billion in Finland.[31]

The data include debit and credit card payments reported in the respective countries. E-money card payments are not considered. We assume smartphone payments considered in this study, i.e., based on a virtual credit or debit card, to be included in this number as well since these payments are ultimately performed using the card. Based on the SPACE Report by the ECB (2022a) we assumed that 6% of the digital POS transactions are paid using a smartphone in Germany, whereas the share is 7% for Italy and 8% for Finland. To calculate the impact of an average digital POS payment, this number is crucial as the impact has typically been calculated by estimating the impact of the respective subsystem per year per country and dividing it by the total number of digital POS payments. Changes in the number of POS payments would therefore have a high impact on all subsystems. However, due to the high validity of the source, the total number of digital POS payments appears quite robust. Nevertheless, it should be noted that all results only hold for these numbers and increases in the total number of digital payments in the upcoming years would change the results, for instance.

4.1.1 Subsystem 1: Cards – digital system

In this chapter, the inventory for one card is presented. Afterwards, the inventory of one card is assigned to the average POS transaction using the assignment factors displayed as well. Cards are a subsystem in both the digital and cash payment systems. The inventory input for one card is the same in both payment systems, however, the assignment factors differ in the two systems. For the digital system, the inventory of one card is assigned to an average digital POS transaction. For the cash system—presented in Chapter 4.2.5—the inventory of one card is assigned to one average cash POS transaction. The data inventory will be explained in detail in this chapter only.

Production phase

A payment card comprises a card body and a chip. For the analysis presented, debit and credit cards were treated identically as both cards are based on smart card technology. For the **material input**, we use data from Lindgreen et al. (2017). Although these do not represent the newest data, the basic technology used, i.e., smart cards or chip cards, has remained the same. Yet, as the use of recycled plastic might have gone up, we have included a sensitivity check using recycled plastic only (see Chapter 6.2.13). In the more conservative baseline, presented here, the card body consists of an ID-1 card body and an ID-000 card body, which are made of polyvinylchloride (PVC). The card body further

[30] For Finland, the data is not differentiated between POS payments made at terminals abroad and in the reporting country. Instead, the total number of POS transactions has been used. However, considering Germany and Italy, we find a large majority of payments to be reported for terminals located in the reporting country. Since all payments reported must either include a terminal provided by a resident PSP or a card issued by a resident PSP, this is not surprising. Therefore, we assume the total number provided for Finland to be a good approximation of the number of card transactions in the country.

[31] Although it may be counterintuitive to have more digital POS transactions in Italy than in Germany – a country with a significantly larger population – the numbers provided by the payment statistics (ECB, 2022b) also identify more digital POS payments in France and Spain than in Germany. A potential explanation may be tourism. Since Italy, France, and Spain are tourist hotpots in the EU, an explanation for the high number of POS transactions are tourists conducting POS transactions in these countries resulting in an above the population-usual number of POS transactions.

includes copper wires for an antenna inlay for the NFC (Lindgreen, et al., 2017). All the inputs sum up to a weight of the card body of around 4.5 grams (g).[32]
The card chip is made from nickel, copper, gold, glass epoxy (glass fibre), epoxy resin and silicon. The authors calculated the weight of those components by multiplying the surface by the thickness times the density (Lindgreen, et al., 2017). The chip weighs around 0.078 g leading to an overall weight of the card body including the chip of 4.578 g. All ecoinvent datasets chosen and concerned quantities present the material inputs for one card are displayed in Table 5.

For each transport step, the chips/cards are packaged. We assumed that the **packaging** material weighs 5% of the total weight of the product transported—in this first step the chip that is transported to the card body for assembly (PEP, 2023). The packaging itself consists of 10% plastic film, 40% cardboard boxes and 50% tubular particleboards for additional stability (PEP, 2023). After the assembly of the card, we modelled the packaging of the finalized cards again. While the overall approach remained the same, the weight was adjusted to correspond to the weight of the finalised card. For the last transportation step in the production phase, cards are sent to the customer. Here, we assumed that they were sent in an envelope with a window. We also included a second letter with a window that contains the PIN code. Here we modelled both enveloped letters with a total weight of 40 g (20 g each) of which 90% consists of paper and 10% of plastic.

Looking at the **transport** distances during the production phase, card bodies and chips are produced by separate companies and at different locations. The largest global producer of smartcards in terms of revenue is Thales (Emergen Research, 2023). Due to the limitation of data of other smaller suppliers, we decided to only look at the market leader, and only use their data for our model. Thales produces its card bodies in Singapore (Thales, 2022). Furthermore, there exist several chip producers. Again, we focused on the market leader due to a lack of further information. Nearly every second credit or debit card has an implemented chip from Infineon (Hofer, 2020). Infineon has a large production facility in Malaysia. We, therefore, assumed that the chips are produced by Infineon in Malaysia and are transported to the production facility of Thales in Singapore. Thus, the chips are assumed to be transported 700 kilometres (km) by lorry. The chips together with the packaging (discussed below) weigh 0.0823 g, which amounts to 0.000058 tkm.

In Singapore, the chips and the card bodies are assembled and sent to Germany, Italy, and Finland. We assumed that the cards are transported by a freight aircraft to the central hubs in the respective countries, namely Frankfurt (20,600 km), Milan (20,500 km), and Helsinki (18,600 km), as the aeroplane is the transport mode used according to an expert interview. After the personalisation of the cards in the respective countries, they are sent to warehouses for logistic purposes. Since those are unknown national transport distances, we used the average distance of national transport provided by Eurostat (2021a). Lastly, the cards are sent to the customer. Again, we used the average distance of national transport from Eurostat (2021a) to approximate the transport distance.

[32] Rankl and Effing (2010) argue that Polyethylenterephthalat (PET) is a more environmentally friendly substitute to produce the card body, but PVC is still the most widely used product. Therefore, we decided to model our card body with PVC as the material input. Moreover, the authors mention that in the magnetic strip of the card body iron oxide, inks and glue are included. However, the amounts are so low that we as well as Lindgreen et. al (2017) decided not to model them. The same holds for resins and pigments in the ink as well as epoxy resin in the glue used for the assembly.

Apart from the **energy** used in the production of the card body and the chips that are modelled using manufacturing datasets in ecoinvent,[33] we received data on energy usage from a card personalisation company that was modelled as well.

Since all inputs presented are modelled for one card, an **assignment factor** needed to be calculated that determines the share of these inputs that can be attributed to one average digital POS transaction. To calculate the assignment factor, we first calculated the share of cards used for digital POS transactions—assuming that they are used for digital and cash POS transactions as well as online payments. Based on the number of cards issued, number of card payments, number of card payments at POS, and number of withdrawals and deposits published in the Payment Statistics (ECB, 2022b), we have calculated that 57% of card usage can be allocated to digital POS payments in Germany, 59% in Italy, and 60% in Finland.[34] Additionally, the numbers for one card have been multiplied by the total number of cards present in each country divided by the expected lifespan of 3.5 years per card (Lindgreen, et al., 2017). The total numbers of cards were retrieved from the Payment Statistics, which correspond to 174,208,000 cards in Germany, 118,069,000 in Italy and 10,520,000 in Finland in 2021 (ECB, 2022b). This yields the number of cards that need to be produced for digital POS transactions per year per country. Lastly, dividing this by the total number of digital POS payments per country yields the final assignment factor to one average digital POS transaction. We get the following assignment factors: 0.005647 for Germany; 0.003846 for Italy and 0.001646 for Finland. In other words, since there were 174.208 million cards in Germany, 118.069 million in Italy, and 10.520 million in Finland in 2021, each card was used for 101, 153, and 367 total digital POS payments over its lifetime in Germany, Italy, and Finland.[35]

As the assignment factor is crucial for the impact of the whole system, it is important to keep the underlying assumptions in mind. Besides the total number of digital POS payments, the number of cards, expected lifetime, and the share of payments cards attributable to digital POS payments are the decisive factors. Changing these assumptions would impact the estimations for the whole subsystem

[33] See Table 5 for the ecoinvent manufacturing datasets that we used. To model the manufacturing process of PVC materials, glass fiber reinforced plastics, epoxy resin, and silicon, we used the "injection moulding" dataset from ecoinvent. According to the ecoinvent description, injection moulding is "the most important process for producing moldings from thermoplastics, elastomers, and thermosets. To our knowledge, it is the dataset most suited for modelling the manufacturing of plastics in ecoinvent. As a result, we believe that it well suited for modelling the usage of PVC, glass fiber reinforced plastics, and epoxy resin (which turns into a type of plastics) in the manufacturing process. In addition, since the silicone is melted and moulded into shape during the manufacturing process, injection moulding is also suited for modelling the usage of this material during the manufacturing process.
We use the ecoinvent dataset "Metal working, average for copper product manufacturing" to model the use of copper during the manufacturing process. As this dataset specifically models copper products, we believe it is well-suited for this purpose. In addition, we use the ecoinvent dataset "Metal working, average for metal product manufacturing" to model the use of gold and nickel during the manufacturing process, as there is no ecoinvent dataset specific for gold or nickel product manufacturing. However, as gold and nickel are both metals, we believe it approximates the manufacturing process of these materials to a sufficient degree.

[34] 20% of card usage in Germany can be attributed to cash withdrawals and deposits in Germany, 12% in Italy, and 3% in Finland. The remaining usage shares can be attributed to online purchases or P2P payments, for instance.

[35] Please note that cards have not been assigned to the digital POS payments entirely. Instead only 57% in Germany, 59% in Italy, and 60% in Finland have been assigned to digital POS payments as outlined in the text. Thus, considering all cards, the average number of digital POS transactions is quite low. Assuming that only 57%, 59% and 60% of the cards are considered as those cards are only used for digital POS transactions, each card would be used for 177, 260, and 608 digital POS transactions over its lifetime in the respective countries.

decisively. Yet, a sensitivity check on the material input for cards and the Monte Carlo simulation displayed in Chapter 6.3 increase the validity of the overall results.

Operation phase

As mentioned earlier, no material inputs or energy usage of cards were considered during their operation phase.

End-of-life phase

Lastly, cards' end-of-life is modelled by using existing ecoinvent datasets as it is assumed that cards are disposed of in the domestic waste. This assumption was verified during our expert interviews. These datasets include transport to the waste treatment facility and energy used during the process. Moreover, the packaging material is treated with the corresponding waste processes. The assignment factor applied in this phase corresponds to the assignment factor from the production phase.

TABLE 5: INVENTORY TABLE FOR CARDS – DIGITAL SYSTEM

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Production of one card					
Input – card body	Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U	3.486 g			Lindgreen et al. (2017)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	3.486 g			Own selection of manufacturing process (value based on material input)
Input – card body	Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U	0.914 g			Lindgreen et al. (2017)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	0.914 g			Own selection of manufacturing process (value based on material input)
Input – card body	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	0.1 g			Lindgreen et al. (2017)
Manufacturing process	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	0.1 g			Own selection of manufacturing process (value based on material input)
Input – chip	Nickel, class 1 {GLO}| market for nickel, class 1 | Cut-off, U	0.00005164 g			Lindgreen et al. (2017)
Manufacturing process	Metal working, average for metal product manufacturing {GLO}| market for metal working, average for metal product manufacturing | Cut-off, U	0.00005164 g			Own selection of manufacturing process (value based on material input)
Input – chip	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	0.069129 g			Lindgreen et al. (2017)
Manufacturing process	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	0.069129 g			Own selection of manufacturing process (value based on material input)
Input – chip	Gold {GLO}| market for gold | Cut-off, U	0.0000067 g			Lindgreen et al. (2017)
Manufacturing process	Metal working, average for metal product manufacturing {GLO}| market for metal working, average for metal product manufacturing | Cut-off, U	0.0000067 g			Own selection of manufacturing process (value based on material input)
Input – chip	Glass fibre reinforced plastic, polyester resin, hand lay-up {GLO}| market for glass fibre reinforced plastic, polyester resin, hand lay-up | Cut-off, U	0.0000998 g			Lindgreen et al. (2017)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	0.0000998 g			Own selection of manufacturing process (value based on material input)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Input – chip	Epoxy resin, liquid {RoW}| market for epoxy resin, liquid | Cut-off, U	0.00012 g			Lindgreen et al. (2017)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	0.00012 g			Own selection of manufacturing process (value based on material input)
Input – chip	Silicon, electronics grade {GLO}| market for silicon, electronics grade | Cut-off, U	0.009 g			Lindgreen et al. (2017)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	0.009 g			Own selection of manufacturing process (value based on material input)
Packaging from chip production to card body production	Tubular particleboard {RoW}| market for tubular particleboard | Cut-off, U	9.33418E-09 m^3			Based on PEP (2023)
Packaging from chip production to card body production	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	0.001568143 g			Based on PEP (2023)
Packaging from chip production to card body production	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	0.000392036 g			Based on PEP (2023)
Packaging from card body production to country of relevance (logistic hub)	Tubular particleboard {RoW}| market for tubular particleboard | Cut-off, U	2.72524E-07 m^3			Based on PEP (2023)
Packaging from card body production to country of relevance (logistic hub)	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	0.091568143 g			Based on PEP (2023)
Packaging from card body production to country of relevance	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	0.022892036 g			Based on PEP (2023)
Packaging from warehouse to customer (2 envelopes)	Kraft paper {RER}| market for kraft paper | Cut-off, U	36 g			Own assumption based on Deutsche Post (2023)
Packaging from warehouse to customer (2 envelopes)	Polystyrene, general purpose {GLO}| market for polystyrene, general purpose | Cut-off, U	4 g			Own assumption based on Deutsche Post (2023)
Energy usage for card personalisation	Electricity, low voltage {X[36]}| market for electricity, low voltage | Cut-off, U	0.038 kWh			Primary source – card personalisation company
Transport from chip production to card body production	Transport, freight, lorry, unspecified {RoW}| market for transport, freight, lorry, unspecified | Cut-off, U	0.00005763 tkm			Primary source – card personalisation company
Transport from card body production to country of relevance (logistic hub)	Transport, freight, aircraft, long haul {GLO}| market for transport, freight, aircraft, long haul | Cut-off, U	0.09903095 tkm	0.098550214 tkm	0.089416291 tkm	Primary source – card personalisation company

[36] X represents country specific processes for Germany, Italy, and Finland.

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Transport from logistic hub to warehouse	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.00043747 tkm	0.000644182 tkm	0.000523999 tkm	Own assumption based on primary source – card personalisation company
Transport from warehouse to customer	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.00405664 tkm	0.005973507 tkm	0.004859046 tkm	Own assumption based on primary source – card personalisation company
Assignment factor of one card (production) $= \frac{\left(\frac{nr.of\ cards\ in\ 2021}{lifespan}\right)}{nr.of\ digital\ POS\ transactions\ per\ year} * card\ share\ of\ digital\ POS\ payments$		0.005647	0.003846	0.001646	Based on ECB (2022b) and (2022a), Hanegraaf et al. (2018)
End-of-life of one card					
Output – card body	Waste polyvinylchloride {X}| market for waste polyvinylchloride | Cut-off, U	3.486 g			Own selection of end-of-life process (value based on material input)
Output – card body	Waste polyvinylchloride {X}| market for waste polyvinylchloride | Cut-off, U	0.914 g			Own selection of end-of-life process (value based on material input)
Output – card body	Scrap copper {Europe without Switzerland}| market for scrap copper | Cut-off, U	0.1 g			Own selection of end-of-life process (value based on material input)
Output – chip (nickel)	Scrap steel {Europe without Switzerland}| market for scrap steel | Cut-off, U	0.00005164 g			Own selection of end-of-life process (value based on material input)
Output – chip	Scrap copper {Europe without Switzerland}| market for scrap copper | Cut-off, U	0.069129 g			Own selection of end-of-life process (value based on material input)
Output – chip (gold)	Scrap steel {Europe without Switzerland}| market for scrap steel | Cut-off, U	0.0000067 g			Own selection of end-of-life process (value based on material input)
Output – chip (glass fibre reinforced plastic)	Waste glass {X}| market for waste glass | Cut-off, U	0.0000998 g			Own selection of end-of-life process (value based on material input)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Output – chip (epoxy resin)	Waste plastic, mixture {X}| market for waste plastic, mixture | Cut-off, U	0.00012 g			Own selection of end-of-life process (value based on material input)
Output – chip (silicon)	Waste plastic, mixture {X}| market for waste plastic, mixture | Cut-off, U	0.009 g			Own selection of end-of-life process (value based on material input)
Total packaging (tubular particleboard)	Waste wood, untreated {X}| market for waste wood, untreated | Cut-off, U	1.18E-04 kg			Own selection of end-of-life process (value based on material input)
Total packaging (corrugated board box)	Waste paperboard {X}| market for waste paperboard | Cut-off, U	9.31E-05 kg			Own selection of end-of-life process (value based on material input)
Total packaging (packaging film)	Waste plastic, mixture {X}| market for waste plastic, mixture | Cut-off, U	2.33E-05 kg			Own selection of end-of-life process (value based on material input)
Total packaging (kraft paper)	Waste paperboard {X}| market for waste paperboard | Cut-off, U	3.60E-02 kg			Own selection of end-of-life process (value based on material input)
Total packaging	Waste polystyrene {X}| market for waste polystyrene | Cut-off, U	4.00E-03 kg			Own selection of end-of-life process (value based on material input)
Assignment factor of one card (end-of-life) $= \frac{\left(\frac{nr.\,of\ cards\ in\ 2021}{lifespan}\right)}{nr.\,of\ digital\ POS\ transactions\ per\ year} * card\ share\ of\ digital\ POS\ payments$		0.005647	0.003846	0.001646	Based on ECB (2022b) and (2022a), Hanegraaf et al. (2018)

Source: Oxford Economics

4.1.2 Subsystem 2: Terminals

In this chapter, the inventory for one payment terminal is presented for the production and end-of-life phases. To assign it to an average digital POS transaction, an assignment factor is estimated and applied afterwards. The reference unit for the operation phase differs and thus, the assignment factor as well. The approach is described in detail in the following and a comprehensive summary inventory table of all inputs used is displayed in Table 7.

Production phase

For the **material input** of one payment terminal, we used data from Lindgreen et. al (2017), who deducted the material input for a typical terminal using web-based references (tear-down of payment terminals on Youtube) and expert interviews with a terminal manufacturer. According to their research, a typical payment terminal consists of a polycarbonate casing, an LCD screen, a rubber keypad, a lithium battery or power supply, thermal printing paper, and internal electrical components such as the printed circuit board and integrated circuits. We excluded the paper roll Lindgreen et. al (2017) considered, as the printing paper was accounted for separately. Overall, the terminal modelled in the production phase weighs 0.254 kg without packaging.

As the terminal used by Lindgreen et. al (2017) is not produced anymore, we also performed a sensitivity check with a newer terminal. A payment terminal manufacturer provided us with the data. As we were not able to gather data on the models of terminals currently used in the three countries and the newer terminal is significantly more energy-efficient and uses less material, we chose to stick with the data of Lindgreen et. al (2017) as it is the more conservative assumption. The results of the sensitivity check in 6.2.2 that the type of terminal modelled indeed has a notable environmental effect.

We included data from a payment terminal producer on the **packaging**. According to our expert, the payment terminal is packed using 0.05 kg of packaging film and 0.19 kg of a corrugated board box. The PSP repack the terminals before sending them out to their customers. According to a PSP active in all three countries, the PSP packaging of a terminal typically consists of 0.05 kg of packaging film and 0.2 kg of a corrugated board box in Italy as well as Finland and 0.19 kg in Germany.

For the **transport** of a payment terminal to a merchant, we first considered the transport of a terminal from its production location to Europe. Following an interview with a leading POS terminal producer, we assumed Vietnam to be the production location. 85% of the terminals are shipped by plane to a European freight airport and 15% are transported with a container ship to a European port. From there, terminals are transported to the warehouse of a PSP in each country of which the location was shared with us by a PSP. The final distance from the warehouse to the merchant was modelled with data from a PSP.

For each input, a manufacturing process was added to account for **energy** and other inputs during the manufacturing process, except for the ones that already include a processed good, such as an integrated circuit. As the ecoinvent dataset for the power supply does not include the electricity used to produce the product, we added the heat and electricity from the ecoinvent dataset "market for liquid crystal display, minor components, auxiliaries and assembly effort".

To assign one payment terminal to an average digital POS transaction, we calculated an **assignment factor** by using the number of payment terminals published in the payment statistics (ECB, 2022b) and dividing it by the average lifespan of a terminal. The overall number of terminals in the respective countries was 927,826 for Germany, 4,148,706 for Italy and 135,984 for Finland. Thereby, the numbers for Germany and Italy are from 2021 and for Finland from 2020. This gave us the average number of produced payment terminals per year for digital POS transactions. According to our experts, the average lifespan of a terminal is 5 to 6 years. We used 5 years as the more conservative option. Furthermore, given we had data on how many terminals were refurbished in 2022 by a PSP, we extended the lifespan of the refurbished terminals by another 5 years. Thus, the average lifespan including the share of refurbished terminals was 5.57 years in Germany, 5.11 years in Italy, and 5.70 years in Finland, where refurbishing rates are highest. To assign the total number of produced terminals per year to one digital POS transaction, we divided it by the total number of digital POS transactions in 2021 used before and published again in the payment statistics (ECB, 2022b). As a result, 0.00003 newly produced POS terminals were assigned to an average digital POS transaction in Germany, 0.00016 in Italy, and 0.00002 in Finland. In other words, each terminal is used for 28,870 digital POS transactions per lifetime in Germany, 6,355 in Italy, and 46,152 in Finland.

The assignment factor sums up several critical assumptions that have a significant effect on the estimated environmental impact of the subsystem. The most critical aspects here concern the number of terminals, the number of digital payments, and the lifetime of terminals. While the first two aspects were retrieved from the payment statistics (ECB, 2022b) with high validity, the lifetime was estimated and depends on several assumptions including refurbishment of terminals, for example. Thus, as mentioned before, an additional sensitivity check was performed adjusting the lifetime of terminals by assuming no refurbishment and thus shortening the expected lifetime (see Chapter 6.2.3). The check does not influence the overall outcome of the two systems. Lastly, uncertainties regarding data robustness were also accounted for in the Monte-Carlo simulation displayed in Chapter 6.3.

Operation phase

In the operation phase, terminals print receipts and use energy as well as the internet for processing digital POS transactions and they need to be maintained.

To be able to print receipts, the printing paper needs to be manufactured first. According to information retrieved by a European paper roll manufacturer, printing paper consists of paper and a plastic core. Thus, the **materials** modelled to produce the receipt paper roll are lightweight coated paper and polypropylene for the core. The paper share of one receipt is assumed to weigh 0.108 g, which corresponds to a receipt length of 18 centimetres (cm), while the whole paper roll is 80 m long and weighs 48 g. For one paper receipt, 0.108 g of paper and 0.009 g of plastic for a core are used. Furthermore, we added 13.3 mg/g Bisphenol-A for one paper receipt, following Biedermann, Tschudin and Grob (2010).[37]

For the **packaging** of the paper roll, we assigned the packaging film (low-density polyethene) for a 4-pack of the paper roll to one receipt, which is 0.001665 g.

To **assign** this information to one digital POS transaction, we had to make assumptions on the share of receipts printed per transaction as no primary data was available. In Germany, the printing of a

[37] Note that in recent years Bisphenol-A has been banned by the EU and consequently replaced by Bisphenol-S. As there is no Bisphenol-S process in ecoinvent, we have modelled paper receipts using Bisphenol-A instead.

merchant receipt is mandatory. In Italy and Finland, electronic receipts are also accepted. Additionally, a consumer receipt may be printed in all three countries. According to a survey conducted by global polling company Toluna of 6,375 consumers throughout France, Germany, Italy, Spain, Sweden, and the United Kingdom (UK) in 2019, 54% of European consumers prefer paper receipts (ChoosePaper, 2020). Thus, we assumed, that 1.54 paper receipts are printed per digital POS transaction in Germany (mandatory merchant receipt plus in 54% of cases customer receipt), and 1.08 paper receipts are printed per transaction in Italy and Finland (54% of merchant and customer receipts each). The latter assumes that the merchant receipts are printed when the customer demands a paper receipt. Again, we performed sensitivity checks on this in Chapter 6.2.5 using two receipts per transaction in all three countries.

For the maintenance of a terminal, customers mainly use postal swap according to interviews with a PSP. We assumed that the terminals are swapped twice per lifetime. The **transport** distance was retrieved from the PSP.

In terms of **energy** usage, the market datasets used in ecoinvent account for the energy usage for paper roll production. Apart from that, terminals use energy for their operation. As terminal providers advise merchants to never disconnect the terminal from the power supply (Worldline, 2021), we assumed the terminals to be switched on 24 hours (Lindgreen, et al., 2017). The amount of electricity used depends on the mode or process of a terminal. Table 6 was retrieved from Lindgreen, et al. (2017) and lists the energy use and normal duration of a specific process a terminal can perform.

TABLE 6: ELECTRICITY USE AND TIMES FOR A TERMINAL PER PROCESS

Process	Energy use in Watt	Duration
Standby mode	0.20	Rest of the day, 23.55 hours
Merchant enters amount	1.53	0.00168 hours (6 sec)
Display: your card, please	3.44	0.00168 hours (6 sec)
NFC Transaction	3.73	0.00168 hours (6 sec)
*Printing**	*30.00*	*0.00080* hours *(3 sec)*
Other: time to go in standby mode etc.*	*1.53*	*0.01200* hours *(42 sec)*
Other: time to go in standby mode etc.	1.53	0.01040 hours (39 sec)
*Total energy use**	40.43	-
Total energy use	10.43	-

Source: Lindgreen, et al. (2017)

Based on the number of terminals and the number of digital POS transactions published in the ECB Payment Statistic (ECB, 2022b), we could calculate the average number of digital transactions per terminal per day, which is 14.2 in Germany, 3.4 in Italy, and 17.64 in Finland. We further included the energy used for printing a receipt (in italic words) only for the assumed share of receipts printed as explained above. The rest of the day, meaning when the terminal does not process any transactions but is connected to power, the terminal uses energy according to its standby mode. We further modelled the local electricity mix as low voltage according to ecoinvent.

Next, we included the ecoinvent dataset "Internet access, work, 0.2 megabits per second (Mbit/s) {CH}| internet access, work, 0.2 Mbit/s | Cut-off, U" for the time the terminal needs to be online to process a transaction. This includes the production share for a router and its electricity consumption.

End-of-life phase

The packaging and the paper receipts are disposed of using corresponding waste **treatment** processes. In the end-of-life of payment terminals, we differentiated recycled, refurbished, and "normally" disposed terminals. The share for each category was retrieved from a PSP and based on each country's data for 2022. The "normally" disposed of terminals are processed according to the WEEE standards (in 't Groen, Stengs, & Zanneveld, 2017). For these terminals, all components were assigned waste treatment processes in SimaPro. For the recycled terminals, we only included transportation to the recycling site in the model and no specific treatment processes.

Refurbishing terminals was assumed to lengthen the lifespan of a terminal by another 5 years. Especially for the refurbished ones, we assumed that after reaching the end of their lifetime, they are exported to Asia for reuse and disposed of in these countries. Since the terminals' end-of-life is not perfectly known and we needed to account for the possibility that terminals are disposed of in Asia (Lindgreen, et al., 2017), we chose this assumption as the conservative baseline for our model. Sensitivity checks in Chapter 6.2.4 were performed for the case that all terminals are either disposed of in the three countries or recycled as well as the possibility that terminal components in Asia are disposed of using open burning—the waste treatment with the worst environmental impact.

All terminals are **transported** from the customer to the warehouse (distances were given by a PSP), and then from there to the waste treatment facility, which we approximated by using country-specific commuting distances (Eurostat, 2021b). For Finland, we used data from Latvia as no country-specific data were available. For the refurbished terminals we assumed to be shipped to Asia, we included the transport from the warehouses to the port of Rotterdam—the main European port—and from there to the port of Malaysia.

The **assignment factors** for the paper receipts are based on the ones in the operation phase; the ones for the packaging are based on the assignment factors in the production phase. For the terminals, the assignment factors were adjusted following the refurbishment and recycling rates retrieved from a PSP. The recycling rates in 2022 were 4% in Germany, 7% in Italy, and 17% in Finland, while the refurbishment rates were 11% in Germany, 2% in Italy, and 14% in Finland (PSP).

TABLE 7: INVENTORY TABLE FOR TERMINALS

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Production of one payment terminal					
Input – Payment Terminal	Power supply unit, for desktop computer {GLO}| market for power supply unit, for desktop computer | Cut-off, U	0.054421769 pieces			Lindgreen et al. (2017)
Input – Payment Terminal	Battery cell, Li-ion, NMC111 {GLO}| market for battery cell, Li-ion, NMC111 | Cut-off, U	30 g			Lindgreen et al. (2017)
Input – Payment Terminal	Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	152.06 g			Lindgreen et al. (2017)
Manufacturing Process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	152.06 g			Own selection of manufacturing process (value based on material input)
Input – Payment Terminal	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	5 g			Lindgreen et al. (2017)
Manufacturing Process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	5 g			Own selection of manufacturing process (value based on material input)
Input – Payment Terminal	Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for glass fibre reinforced plastic, polyamide, injection moulded | Cut-off, U	4.15 g			Lindgreen et al. (2017)
Input – Payment Terminal	Silicone product {RER}| market for silicone product | Cut-off, U	21.98 g			Lindgreen et al. (2017)
Manufacturing Process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	21.98 g			Own selection of manufacturing process (value based on material input)
Input – payment terminal	Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	0.001960784 pieces			Lindgreen et al. (2017)
Input – payment terminal	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	10 g			Lindgreen et al. (2017)
Manufacturing Process	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	10 g			Own selection of manufacturing process (value based on material input)
Input – payment terminal	Printed wiring board, mounted mainboard, desktop computer, Pb free {GLO}| market for printed wiring board, mounted mainboard, desktop computer, Pb free | Cut-off, U	30 g			Lindgreen et al. (2017)
Input – payment terminal	Integrated circuit, logic type {GLO}| market for integrated circuit, logic type | Cut-off, U	2.578 g			Lindgreen et al. (2017)
Input – payment terminal	Integrated circuit, memory type {GLO}| market for integrated circuit, memory type | Cut-off, U	0.03 g			Lindgreen et al. (2017)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Electricity for power supply manufacturing	Electricity, medium voltage {GLO}| market group for electricity, medium voltage | Cut-off, U	1.4989 kWh			Based on electricity used in the ecoinvent market process “market for liquid crystal display, minor components, auxiliaries and assembly effort”
Heat for power supply manufacturing	Heat, district or industrial, natural gas {GLO}| market group for heat, district or industrial, natural gas | Cut-off, U	3.8477 MJ			Based on electricity used in the ecoinvent market process “market for liquid crystal display, minor components, auxiliaries and assembly effort”
Heat for power supply manufacturing	Heat, district or industrial, other than natural gas {GLO}| market group for heat, district or industrial, other than natural gas | Cut-off, U	0.9691 MJ			Based on electricity used in the ecoinvent market process “market for liquid crystal display, minor components, auxiliaries and assembly effort”
Packaging	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	0.05 kg			Primary source – terminal manufacturer
Packaging	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	0.1 kg			Primary source – terminal manufacturer
Repackaging	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	0.05 kg			Primary source – PSP
Repackaging	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	0.19 kg	0.2 kg	0.2 kg	Primary source – PSP
Transport from production (Vietnam) to freight airport in Luxembourg (85% shipped by air)	Transport, freight, aircraft, long haul {GLO}| market for transport, freight, aircraft, long haul | Cut-off, U	2.58 tkm			Primary source – PSP
Transport from production (Vietnam) to port in Marseille (15% shipped by sea)	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	0.63 tkm			Primary source – PSP
Transport from airport/port to warehouse	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.28 tkm	0.2 tkm	0.52 tkm	Primary source – PSP
Transport from airport/port to warehouse (some shipped by sea)	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	-	-	0.03 tkm	Primary source – PSP
Transport from distribution centres to customers	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.2 tkm	0.77 tkm	0.47 tkm	Primary source – PSP
Assignment factor for one payment terminal (production) $= \frac{\left(\frac{nr.\,of\ terminals\ in\ 2021}{lifespan}\right)}{nr.\,of\ digital\ POS\ transactions\ per\ year}$		3.463797E-05	1.573422E-04	2.166731E-05	Based on ECB (2022b) and (2022a) and primary source – PSP

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Operation – one paper receipt [38] (payment terminal)					
Input – paper receipt	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	0.009 g			Retrieved from a European paper roll manufacturer
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	0.009 g			Own selection of manufacturing process (value based on material input)
Input – paper receipt	Paper, woodcontaining, lightweight coated {RER}| market for paper, woodcontaining, lightweight coated | Cut-off, U	0.108 g			Retrieved by a European paper roll manufacturer
Input – paper receipt	Bisphenol A, powder {GLO}| market for bisphenol A, powder | Cut-off, U	1.44E-03 g			Biedermann, Tschudin and Grob (2010)
Packaging	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	0.001665 g			Retrieved from a European paper roll manufacturer
Assignment factor of one paper receipt (payment terminal operation) $= nr.of\ paper\ receipts\ printed\ per\ transatction$		1.54	1.08	1.08	Own assumptions based on Choose Paper (2020) and primary source – European paper roll manufacturer
Operation – maintenance of one payment terminal					
Transport – maintenance (mostly postal swap, twice per lifetime)	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.0711390 tkm	0.0002995 tkm	0.0001653 tkm	Primary source – PSP
Assignment factor for one payment terminal (operation) $= \frac{\left(\frac{nr.of\ terminals\ in\ 2021}{lifespan}\right)}{nr.of\ digital\ POS\ transactions\ per\ year}$		3.463797E-05	1.573422E-04	2.166731E-05	Based on ECB (2022b) and (2022a) and primary source – PSP
Operation – electricity per terminal per day					
Electricity per terminal per day – without printing	Electricity, low voltage {X[39]}| market for electricity, low voltage | Cut-off, U	0.000433 kWh	0.000104 kWh	0.000538 kWh	Lindgreen et al. (2017)
Electricity per terminal per day – printing only	Electricity, low voltage {X}| market for electricity, low voltage | Cut-off, U	0.000578 kWh	0.000097 kWh	0.000504 kWh	Lindgreen et al. (2017)

[38] In Germany the merchant is obligated to print the receipt. We made the assumption that the customer wants a printed receipt in 54 % of the cases. Whereas, in Italy and Finland we assumed that the merchant and the customer printed receipt in 54 % of the cases.

[39] X represents country specific processes for Germany, Italy, and Finland.

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Electricity per terminal per day – non-processing time	Electricity, low voltage {X}| market for electricity, low voltage | Cut-off, U	0.004746 kWh	0.004788 kWh	0.004736 kWh	Lindgreen et al. (2017)
Assignment factor for one payment terminal (operation) $= \frac{nr. of\ terminals\ in\ 2021}{nr. of\ digital\ POS\ transactions\ per\ year}$		1.93E-04	8.05E-04	1.23E-04	Based on ECB (2022b) and (2022a)
Operation – internet access per day					
Energy – transmission of data via the internet	Internet access, work, 0.2 Mbit/s {CH}| internet access, work, 0.2 Mbit/s | Cut-off, U	0.015440 hours			Lindgreen et al. (2017)
Assignment factor for one payment terminal (operation)		1			
End-of-life of one payment terminal – without recycling and refurbishing					
Output – payment terminal (power supply)	Used industrial electronic device {CH}| treatment of used industrial electronic device, manual dismantling | Cut-off, U	80 g			Own selection of end-of-life process (value based on material input)
Output – payment terminal	Used Li-ion battery, without transport {GLO}| market for used Li-ion battery | Cut-off, U	30 g			Own selection of end-of-life process (value based on material input)
Output – payment terminal (polycarbonate)	Waste plastic, mixture, without transport {X}| market for waste plastic, mixture | Cut-off, U	152.06 g			Own selection of end-of-life process (value based on material input)
Output – payment terminal	Waste polypropylene, without transport {X}| market for waste polypropylene | Cut-off, U	5 g			Own selection of end-of-life process (value based on material input)
Output – payment terminal (glass fibre reinforced plastic)	Waste plastic, mixture, without transport {X}| market for waste plastic, mixture | Cut-off, U	4.15 g			Own selection of end-of-life process (value based on material input)
Output – payment terminal (silicone)	Waste plastic, mixture, without transport {X}| market for waste plastic, mixture | Cut-off, U	21.98 g			Own selection of end-of-life process (value based on material input)
Output – payment terminal	Used liquid crystal display {CH}| treatment of used liquid crystal display, manual dismantling | Cut-off, U	10 g			Own selection of end-of-life process (value based on material input)
Output – payment terminal	Scrap copper {Europe without Switzerland}| treatment of scrap copper, municipal incineration | Cut-off, U	10 g			Own selection of end-of-life process (value based on material input)
Output – payment terminal (printed wiring board)	Electronics scrap from control units {RER}| treatment of electronics scrap from control units | Cut-off, U	30 g			Own selection of end-of-life process (value based on material input)
Output – payment terminal (integrated circuit, logic type)	Electronics scrap from control units {RER}| treatment of electronics scrap from control units | Cut-off, U	2.578 g			Own selection of end-of-life process (value based on material input)
Output – payment terminal (integrated circuit, memory type)	Electronics scrap from control units {RER}| treatment of electronics scrap from control units | Cut-off, U	0.03 g			Own selection of end-of-life process (value based on material input)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Transport from warehouse to waste treatment (incinerated in the respective countries)	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.0134 tkm	0.0151 tkm	0.0261 tkm	Primary source – PSP
Assignment factor for one payment terminal without recycling and refurbishing (end-of-life) $= \left(\frac{\left(\frac{nr.of\ terminals\ in\ 2022}{lifespan}\right)}{nr.of\ digital\ POS\ transactions\ per\ year} \right) * (1 - share\ recycled - share\ refurbished)$		2.94E-05	1.43E-04	1.51E-05	Based on ECB (2022b) and (2022a) and primary source – PSP
End-of-life of one payment terminal – only refurbished					
Output – payment terminal (as a whole)	Used industrial electronic device {RoW}| market for used industrial electronic device | Cut-off, U	345.798 g			Primary source – PSP
Transport from warehouse to port of Rotterdam	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.3858 tkm	0.5192 tkm	- [40]	Own calculation based on primary source – PSP
Transport from the port of Rotterdam to the port of Malaysia	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	7.4508 tkm	7.4508 tkm	9.7263 tkm	Own calculation based on primary source – PSP
Assignment factor for one payment terminal only refurbished (end-of-life) $= \left(\frac{\left(\frac{nr.of\ terminals\ in\ 2022}{lifespan}\right)}{nr.of\ digital\ POS\ transactions\ per\ year} \right) * share\ refurbished$		3.94E-06	3.59E-06	3.01E-06	Based on ECB (2022b) and (2022a) and primary source – PSP
End-of-life of one payment terminal – only recycled					
Transport from warehouse to recycling company	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.0165 tkm	0.3952 tkm	0.1 tkm	Primary source – PSP
Assignment factor for one payment terminal only refurbished (end-of-life) $= \left(\frac{\left(\frac{nr.of\ terminals\ in\ 2022}{lifespan}\right)}{nr.of\ digital\ POS\ transactions\ per\ year} \right) * share\ recycled$		1.25873E-06	1.07866E-05	3.59246E-06	Based on ECB (2022b) and (2022a) and primary source – PSP
End-of-life of packaging and repackaging and transportation from customer to warehouse (payment terminal)					

[40] Since Helsinki is located close to the sea, we added the distance from Helsinki to Rotterdam, which is overcome by ship, to the subsequent transport step.

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Packaging and repackaging (packaging film)	Waste polyvinylchloride {Europe without Switzerland}| market group for waste polyvinylchloride | Cut-off, U	0.1 kg			Own selection of end-of-life process (value based on material input)
Packaging and repackaging (corrugated board box)	Waste paperboard {Europe without Switzerland}| market group for waste paperboard | Cut-off, U	0.29 kg	0.3 kg	0.3 kg	Own selection of end-of-life process (value based on material input)
Transport from customer to warehouse for disposal/recycling	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.4010 tkm	0.0247 tkm	0.25 tkm	Primary source – PSP
Assignment factor for packaging and repackaging (end-of-life payment terminal) $= \frac{\left(\frac{nr.\,of\ terminals\ in\ 2021}{lifespan}\right)}{nr.\,of\ digital\ POS\ transactions\ per\ year}$		3.463797E-05	1.573422E-04	2.166731E-05	Based on ECB (2022b) and (2022a) and primary source – PSP
End-of-life of paper receipt (payment terminal)					
Output – one paper receipt (polypropylene)	Waste graphical paper {X}| market for waste graphical paper | Cut-off, U	0.009 g			Own selection of end-of-life process (value based on material input)
Output – one paper receipt (paper)	Waste graphical paper {X}| market for waste graphical paper | Cut-off, U	0.108 g			Own selection of end-of-life process (value based on material input)
Output – one paper receipt (bisphenol A)	Waste graphical paper {X}| market for waste graphical paper | Cut-off, U	0.00144 g			Own selection of end-of-life process (value based on material input)
Packaging – one paper receipt (packaging film)	Waste plastic, mixture {X}| market for waste plastic, mixture | Cut-off, U	0.00167 g			Own selection of end-of-life process (value based on material input)
Assignment factor of one paper receipt (end-of-life payment terminal) $= nr.\,of\ paper\ receipts\ printed\ per\ transatction$		1.54	1.08	1.08	Own assumptions based on Choose Paper (2020) and primary source – European paper roll manufacturer

Source: Oxford Economics

4.1.3 Subsystem 3: Data centres – digital system

In this chapter, the inventory for one data centre is displayed for the production and end-of-life phase and assigned to the average digital POS transaction by applying an assignment factor presented as well. The operation phase largely refers to the inputs per year and thus the assignment factor differs. The inventory for one data centre is used in the cash payment system as well (see Chapter 4.2.7) since data centres are also a subsystem there. However, the assignment factors of data centres applied in the digital and cash payment systems differ because the utilisation of data centres in a POS transaction varies between the digital and cash payment systems.

Production phase

Only a few studies exist on the material input for data centres. One of the main reasons is that they differ substantially and are "very complex and heterogeneous constructs" (Fichter & Hintemann, 2014, p. 847). To account for this, several sensitivity checks have been performed for this subsystem (see Chapter 6.2.6 to Chapter 6.2.10) and an uncertainty analysis using a Monte-Carlo simulation was applied (see Chapter 6.3.2).

The production of data centres can be divided into four main components. Those are the IT equipment, the cooling infrastructure, the power supply, and the building (Laurent, Dal Maso, Wang, Zhu, & Prata Dias, 2020).

One detailed and extensive analysis of the **material input** for the information technology (IT) equipment, the cooling infrastructure, and the power supply in an average data centre in Germany was conducted by Fichter and Hintemann (2014). The study develops an approach enabling the computation of data centre quantities across different size categories and their mean equipment composition, encompassing IT components alongside infrastructure elements like cooling systems and power provisions. This methodology facilitates precise assessments of the materials comprising the equipment within more than 53,000 data centres situated in Germany in 2008.

They distinguish between the quantities of materials used in the following components:

- IT equipment including stand-alone servers (tower servers), blade servers, rack servers, unix server/mainframe, network, 2.5-inch network storage, 3.5-inch network storage,
- Power infrastructure including a single- and three-phase uninterruptible power supply, batteries, generators, transformers, and power cables,
- Racks and containment including server and network racks as well as cold- and hot-aisle containments,
- Cooling equipment including split devices/rack-cooling devices, space cooling systems, including pumps, and coolants.

According to interviews with several PSP representatives, most players in the processing of digital transactions use data centres with a medium size as well as more and more cloud data centres with larger sizes. If we only consider medium-sized data centres (501-5,000 servers) and large data centres (over 5,000 servers), the raw materials displayed in Table 8 need to be considered for one average data centre.

TABLE 8: BULK MATERIAL INPUT FOR DATA CENTRE EQUIPMENT

	Materials in medium-sized data centres (total in t)	Materials in large data centres (total in t)	Materials used in one average data centre (in t)
Number of data centres considered	*370*	*50*	*1*
Iron[41]	11,100	16,200	354
Copper	4,000	5,500	121
Aluminium	1,400	2,100	46
Circuit boards	2,300	3,200	70
Plastics (PVC, Epoxy, …)[42]	2,300	3,200	70
Miscellaneous[43]	1,400	1,800	40

Source: Oxford Economics based on Fichter and Hintemann (2014)

For the average lifetime of the data centre equipment, Lindgreen et. al (2017) assume an expected lifetime of three to five years for the IT equipment as well as mostly 20 years for the power and the cooling equipment. We used that information to calculate the weighted average lifetime of the components modelled in the publication by Fichter and Hintemann (2014), which is 11.5 years.

Input materials used in the building of data centres are mainly concrete, reinforced steel, and aluminium (Laurent, Dal Maso, Wang, Zhu, & Prata Dias, 2020). We used the Building Hall Steel Construction in ecoinvent to account for the materials used in the building of data centres. The average floor space of the data centres reviewed by Fichter and Hintemann (2014), 1,242.86 m^2, was used to adjust the building to our purposes. The default lifetime is 50 years. Transport and energy usage to produce the materials are included in the used ecoinvent market datasets.

To assign the material inputs to one POS transaction, we had to compute an **assignment factor**. As we based our information on the material inputs used in data centres on data gathered in Germany, we also tried to use German data to deduct an assignment share of these material inputs per POS transaction. According to a study by Bitkom, in 2022, around 3,000 data centres[44] consumed 18 billion kilowatt-hours (kWh) of electricity (Rohleder, 2023). Thus, an average data centre would consume 6 Mio. kWh per year.[45] According to our upper bound energy usages for one POS transaction deduced further below in the description of the operation phase, this would result in the following:

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[41] Based on the material inputs used for this aggregation, we assume that 63% of the iron is actually steel and the rest is iron.
[42] Based on the material inputs used for this aggregation, we assume 43% is PVC, 41% is synthetic rubber and 16% is epoxy.
[43] The exact material input for the category "Miscellaneous" cannot be assessed. Given the materials used in each of the components, we assume that 31% is lead, 24% ceramics, 22% glass, 13% sulfur acid, and 10% silicon monoxide. Overall, all materials contributing more a minimum of 1% of mass in the data centres are considered.
[44] In that definition, a data centre comprises at least 10 racks or server cabinets or has a connected load of more than 40 kW.
[45] This is a rather conservative estimate. A case study in Sweden reports an annual consumption of 10.04 Mio. kWh per year (Honée, Hedin, St-Laurent, & Fröling, 2012) and a comparative study published in Environmental Research Letters assumes an average energy consumption of 24.05 kWh per year (Siddik, Shehabi, & Marston, 2021) – both would result in much lower usage shares than the ones calculated below.

- In Germany, 4,792 Mio. POS transactions could theoretically be processed by an average data centre. Given the number of POS transactions published in the national bank's payment statistics (ECB, 2022b), this would mean that approx. 1.05 data centres would be needed to process all POS transactions in the given year. Hence, the assignment factor for a single POS transaction for the data centre building would be 4.2E-12 and for the rest components 1.8E-11. Thus, the average data centre building would be engaged in more than 269.6 billion digital POS transactions in Germany over the course of its lifetime and the rest of the components in more than 55.1 billion digital POS transactions.
- In Italy, 4,233 Mio. POS transactions could theoretically be processed by an average data centre. Given the number of POS transactions published in the national bank's payment statistics (ECB, 2022b) this would mean that approx. 1.22 data centres would be needed to process all POS transactions in the given year. Hence, the assignment factor for a single POS transaction for the data centre building would be 4.7E-12 and for the rest components 2.1E-11. Thus, the average data centre building would be engaged in more than 211.6 billion digital POS transactions in Italy over the course of its lifetime and the rest of the components in more than 48.6 billion digital POS transactions.
- In Finland, 3,624 Mio. POS transactions could theoretically be processed by an average data centre. Given the number of POS transactions published in the national bank's payment statistics (ECB, 2022b) this would mean that approx. 0.30 data centres would be needed to process all POS transactions in the given year. Hence, the assignment factor for a single POS transaction for the data centre building would be 5.5E-12 and for the rest components 2.4E-11. Thus, the average data centre building would be engaged in more than 181.2 billion digital POS transactions in Finland over the course of its lifetime and the rest of the components in more than 41.6 billion digital POS transactions.

Operation phase

Many environmental impact assessments of data centres focus on energy usage, primarily due to the constant and substantial power requirements of equipment within data centres, which operate around the clock (Whitehead, Andrews, & Shah, 2015). These continuous power requirements lead to significant environmental impacts, driving efforts within the data centre industry primarily towards reducing energy consumption during their operational activities. The energy supply of data centres is almost exclusively based on electricity. The emissions produced by the energy usage of data centres therefore depend on the grid emissions factor that varies substantially between European countries (Hintemann, Hinterholzer, & Clausen, 2020).

Publicly available datasets on the energy performance of data centres are limited (Brocklehurst, 2022). One major challenge is to approximate the energy usage for a card payment because many different stakeholders are involved. These use different data centres and cloud service providers to process a payment, making it complicated to assign the energy consumption of the data centre to one POS transaction. This is why we had to make some simplifying assumptions about the relevant stakeholders to consider. To account for that, several sensitivity checks have been performed with varying levels of energy usage (see Chapters 6.2.6, 6.2.7, and 6.2.8).

For the processing of a transaction, separate messages for authorisation, clearing and settling of a transaction are used. Typically, several players are active in the card payment process and one actor is involved in multiple stages of the process (European Commission, 2020). For simplicity, we assumed that the following entities mostly consume energy to process a typical digital card-based payment[46]:

- **PSP—as an acquirer or issuing processor:** PSPs offer both acquiring processing services for merchants and issuing processing services for issuing banks or issuers.
- **Card scheme:** The card scheme, also known as the card network or payment network, acts as an intermediary that facilitates communication, standardisation, and coordination between the various participants involved in the payment process.
- **Issuing Bank:** Issuing banks, also known as card issuers, are financial institutions that provide payment cards, such as credit cards and debit cards, to customers. They are responsible for underwriting the credit risk associated with the cards, setting cardholders' credit limits, and managing cardholders' accounts.

If the payment is not initiated by a physical card but an e-wallet, the process is essentially the same, because we assumed that every e-wallet is connected to a physical card.

To calculate the average **energy** consumption of data centres for a typical POS transaction, we first approximated the energy needed for a POS transaction by summing up the watt-hour (Wh) used per transaction for the card scheme, the issuing bank, and the PSP (or the so-called "Netzbetreiber" in Germany). In particular, we used a top-down approach where we approximated the average energy consumption for the three stakeholders by dividing the total energy consumption of the data centres by their total processed transactions.[47]

It is important to note that in this process we do not consider the energy consumption of the acquiring bank as in the payment process it is mostly captured by the acquiring processor, while the acquiring bank only performs the crediting of payments on the merchants' accounts. Hence, their energy consumption is neglectable. Further, E-Wallet providers are not considered because, according to an expert interview, no online connection of the phone is required during a POS transaction.

The average influence of card schemes is estimated using their respective market share per country. For Germany, the domestic Girocard represents the most important scheme with a share of 75% followed by Visa (13%) and Mastercard (11%) (Worldpay, 2023). In Italy, the domestic solution of Bancomat (45%) is the leading card scheme, again sharing the market with Visa (34%) and Mastercard (20%) (Worldpay, 2023). As no domestic card scheme exists in Finland, Visa and Mastercard share the market with 55% and 45%, respectively (Worldpay, 2023). We decided to not include energy consumption from domestic scheme switches as no specific data was available, and any estimations would lower the quality of this analysis. Using the non-financial reports of Visa and Mastercard, we

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[46] Of course, the merchant also needs an acquiring bank to settle the transaction and receive the payment on the bank account. The acquiring banks, also known as merchant banks, are financial institutions that partner with businesses to process electronic payments, such as credit card and debit card transactions. The business partners are again, PSPs focusing on the acquiring processing. As PSP handle most of the acquiring processing for the acquiring banks, they are omitted as major player for the energy usage in a digital POS transaction.

[47] Data centres of the three stakeholders are likely to process also other activities (e.g., storage of customer data). Therefore, the following estimation strategy has to rely on the conservative assumption that the data centres' resulting energy consumption is only due to the processing of financial payments. Hence, the used estimates present an upper bound on the true energy consumed of data centres used in the payment processes.

approximated their respective energy consumption per transaction by a top-down approach, i.e., dividing the total reported energy consumption in data centres by the total number of transactions processed in the network. This top-down approach was proposed by Leopold and Englesson (2017). This yields an average electricity consumption of 0.590 and 0.453 Wh per transaction for Visa and Mastercard, respectively.[48] This difference was expected given that Mastercard's data centres seem to operate more efficiently as shown by their lower Power usage effectiveness (PUE) of 1.39—compared to Visa's PUE of 1.48 (Mastercard (2023); Visa (2023)). Combining this with the market shares of Visa and Mastercard within the countries yields the average energy consumption for a POS transaction by a card scheme:[49]

- Germany: 0.127 Wh per Transaction
- Italy: 0.292 Wh per Transaction
- Finland: 0.53 Wh per Transaction

To approximate the average energy consumption of PSPs (or NSP in the German case), we again used the top-down approach. For the PSPs, we focussed on the energy use of the companies Nexi and Worldline. Both companies provide extensive services as issuing processors, merchant acquirers, and merchant processors in all three countries. Hence, their services provide the key element in the data processing chain and, therefore, should provide a good indication of the average energy consumption needed for a POS transaction by a PSP in the digital payment process. On average, using both companies' non-financial reports, Nexi utilizes 0.456 Wh per transaction, whereas Wordline uses 0.669 Wh per transaction.[50] For the baseline calculation, we used the more conservative Worldline data to approximate a PSP's energy use for a digital POS transaction.

Issuing banks have provided no data regarding their data centres' consumption. According to an expert interview, the involvement of issuing banks' data centres in the payment process considerably depends on contractual agreements between the issuing bank and third-party providers such as Nexi and Worldline. If the issuing bank fully delegates the processing of card transactions to a third-party provider, their involvement in the processes is very low. If the issuing bank processes payments internally, then, despite some additional data transfer and storage, their internal data centre energy consumption for payments should be comparable to one of the third-party providers. Hence, the issuing bank's energy consumption is approximated using the average energy consumption per POS transaction of the issuing processors (i.e., the PSP) in the calculation. Again, this yields, on average, an energy consumption of 0.456 Wh per transaction for the issuing bank.

Summing over the energy consumption of the card schemes, the issuing banks, and the PSPs, the average energy consumption for a POS transaction among the three players yielded an estimated energy usage for processing a digital POS transaction of 1.3 Wh in Germany, 1.4 Wh in Italy, and 1.7 Wh in Finland.

[48] Visa consumed a total of about 114,216,667 kWh and processed 192.5 billion transactions in 2022 (VISA, 2023). MasterCard's data centres consumed a total of 57,010,000 kWh and processed 125.7 billion transactions in 2022 (MasterCard, 2023).
[49] These difference in consumption are to expect, given the high usage of, for example, the Girocard in Germany.
[50] Nexi consumed a total of about 15,464,823.9 kWh and processed 33.9 billion transactions in 2022 (Nexi, 2023). Worldline's internal and external data centres consumed a total of 47945277.8 kWh and processed about 71.7 billion transactions in 2022 (Wordline, 2023).

While our approach to estimating the energy consumption per digital transaction only gives a rough indication of the true average energy consumed per POS transaction, the results perform in the range of bottom-up approaches[51] and are also highly comparable to the results of Lindgreen et al. (2017). Lindgreen et al. (2017) estimate an average energy consumption for a POS transaction of about 1.1 Wh per transaction. Our inputs are slightly higher and therefore more conservative, as we—in contrast to Lindgreen et al. (2017)—included the issuing bank's and the international card scheme's energy consumption. Since PSPs increasingly rely on cloud services which are supposed to consume less energy than internally operated data centres, our modelled energy usage is again a rather conservative one. On the other hand, we did not include the energy consumption of national card schemes which potentially underestimates the energy consumption in Italy and potentially in Germany.

To account for that, we included a sensitivity check using the following assumptions to account for our potential over- and underestimation of the data centre's energy consumption:

- We used the average PSP energy consumption for all acquiring and issuing services involved in a digital transaction (0.562441 Wh per transaction) (Nexi, 2023; Wordline, 2023).
- We used the average international card scheme energy consumption as a proxy for all card schemes—both international and national (0.523437 Wh per transaction) (Nexi, 2023; Wordline, 2023).
- We used 1/3 of the PSP lower bound energy consumption as a proxy for the acquiring bank's energy consumption, since according to Lindgreen et al. (2017) the acquiring bank consumes 1/3 of the acquiring host. We added 2.5% of the PSP lower bound energy consumption for the issuing bank since according to Lindgreen et al. (2017) the acceptance payment provider consumes 5% of the acquiring host and according to expert interviews, the issuing bank consumes even less. This yields 0.163468 Wh per transaction for all banks involved.

The results of this sensitivity check can be found in Chapters 6.2.6 to 6.2.8.

For the baseline scenario, we furthermore assumed that the data centres for digital payment processing are mainly located in the EU including the UK. According to experts, this is a reasonable assumption given that data security regulations are very different in the EU and the rest of the World. As data centres are not distributed equally among the European countries, we assumed that the data centres' electricity grid corresponds to the installed capacity. This is given by:

[51] We also tried to calculate the energy consumption by looking at the energy use of data centres used for processing transactions in each country, assume a certain share of the energy used by the whole data centre for processing POS transactions only and divide this by the actual processed POS transactions in that data centre. A drawback of this approach is that the outcome highly depends on the expert guess on the usage share of energy for POS transaction processing and it excludes energy consumed by cloud data centres, which are more and more used. The bottom-up approach led to a 2.33 times smaller energy consumption of PSPs in Germany compared to a 1.008 higher energy consumption in Finland compared to our lower bound estimates.

TABLE 9: APPROXIMATED DATA CENTRE GRID SHARE BASED ON INSTALLED CAPACITY

Country	Capacity in Megawatts (MW)	Grid Share
UK	711	36%
Germany	510	26%
Netherlands	365	19%
France	204	10%
Ireland	94	5%
Switzerland	68	3%

Source: Deutscher Bundestag (2021), S. 9

It is crucial to note that we relied on the electricity grid and did not assume a significantly higher share of renewable energies such as reported, for example, in the annual reports of the card schemes or PSPs as they utilise power purchase agreements and renewable energy certificates. Hence, to a significant share, grid electricity instead of on-site generated renewables was used. Again, considering the impact of data centres' electricity usage on the compared systems, we followed this approach as it constitutes the more conservative assumption by rather overestimating the impact of the digital system than underestimating it.

To account for the uncertainties in the collected data, we conducted some sensitivity checks. One was to use country-specific grid factors for the PSP and the issuing bank as expert interviews revealed that the location of the PSPs' and the issuing banks' data centres is mostly in the country itself—except for cloud-based data centres (see Chapter 6.2.9 and 6.2.10). Furthermore, we increased the overall energy usage by a factor of 1.75 to account for the possibility that the energy consumption for cooling and auxiliary equipment would not be included in the ESG reports used for our analysis (see Chapter 6.2.6).[52]

Furthermore, we included the ecoinvent dataset "Internet access, work, 0.2 Mbit/s {CH}| internet access, work, 0.2 Mbit/s | Cut-off, U". We assumed the same time as the terminal needs to be online to process a transaction (see the inventory of payment terminals).

Apart from energy, data centres also consume **water** if—as is often the case in medium to larger size data centres—cooling-tower-based chillers are used instead of air-cooled chillers. Along with other studies (Siddik, Shehabi, & Marston, 2021), we used an average water consumption of 1.8 m^3 per Megawatt hour (MWh) —to estimate the direct water footprint of the data centres included in processing a digital transaction. Using the upper bound of kWh consumed, this gave us the average water consumption per digital POS transaction for each country.

End-of-life phase

For the data centres' end-of-life, we used the ecoinvent treatment dataset "Used industrial electronic device {CH}| treatment of used industrial electronic device, manual dismantling | Cut-off, U" and the

[52] According to Montevecchi, et al. (2020, p. 57), the total energy consumption of data centres in the EU in 2018 was 76.8 Terawatt-hours (TWh)/a of which 43.8 TWh/a accrued to IT components (e.g., servers) and the remaining part of infrastructure (e.g., cooling). Hence, a factor of 1.75 to account for cooling should be appropriate.

transport to a waste treatment facility, again approximated with commuting distances (Eurostat, 2021b). The used market dataset for the data centre building already includes the disposal and does not need to be modelled explicitly.

TABLE 10: INVENTORY TABLE FOR DATA CENTRES – DIGITAL SYSTEM

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Production of one data centre – IT equipment, cooling infrastructure, power supply					
Input – IT equipment, cooling infrastructure, power supply	Steel, unalloyed {GLO}| market for steel, low-alloyed | Cut-off, U	223.02 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Metal working, average for steel product manufacturing {GLO}| market for metal working, average for steel product manufacturing | Cut-off, U	223.02 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Cast iron {GLO}| market for cast iron | Cut-off, U	130.98 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Metal working, average for metal product manufacturing {GLO}| market for metal working, average for metal product manufacturing | Cut-off, U	130.98 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	120.81 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	120.81 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	45.78 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Metal working, average for aluminium product manufacturing {GLO}| market for metal working, average for aluminium product manufacturing | Cut-off, U	45.78 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Printed wiring board, mounted mainboard, desktop computer, Pb free {GLO}| market for printed wiring board, mounted mainboard, desktop computer, Pb free | Cut-off, U	70.22 t			Based on Fichter and Hintemann (2014)
Input – IT equipment, cooling infrastructure, power supply	Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U	30.19 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	30.19 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Synthetic rubber {GLO}| market for synthetic rubber | Cut-off, U	28.79 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	28.79 t			Own selection of manufacturing process (value based on material input)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Input – IT equipment, cooling infrastructure, power supply	Epoxy resin, liquid {RoW}| market for epoxy resin, liquid | Cut-off, U	11.23 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	11.23 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Lead {GLO}| market for lead | Cut-off, U	12.33 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Metal working, average for metal product manufacturing {GLO}| market for metal working, average for metal product manufacturing | Cut-off, U	12.33 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Ceramic tile {GLO}| market for ceramic tile | Cut-off, U	9.55 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	9.55 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Glass fibre {GLO}| market for glass fibre | Cut-off, U	8.75 t			Based on Fichter and Hintemann (2014)
Input – IT equipment, cooling infrastructure, power supply	Sulfuric acid {RoW}| market for sulfuric acid | Cut-off, U	5.17 t			Based on Fichter and Hintemann (2014)
Input – IT equipment, cooling infrastructure, power supply	Silicone product {RoW}| market for silicone product | Cut-off, U	3.98 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	3.98 t			Own selection of manufacturing process (value based on material input)
Assignment factor of material of one data centre (production) $= \frac{\left(\frac{theoretical\ nr.\ of\ data\ centre\ for\ all\ POS\ transactions}{average\ lifespan\ of\ materials}\right)}{nr.\ of\ digital\ POS\ transactions\ per\ year}$		1.81436E-11	2.05409E-11	2.39900E-11	Based on ECB (2022b), Fichter and Hintemann (2014) and Lindgreen et al. (2017)
Production of one data centre – IT building					
Input – building	Building, hall, steel construction {CH}| building construction, hall, steel construction | Cut-off, U	1242.86 m^2			Based on Laurent et al. (2020) and Lindgreen et al. (2017)
Assignment factor of building of one data centre (production) $= \frac{\left(\frac{theoretical\ nr.\ of\ data\ centre\ for\ all\ POS\ transactions}{lifespan\ of\ building}\right)}{nr.\ of\ digital\ POS\ transactions\ per\ year}$		4.173E-12	4.72441E-12	5.51770E-12	Based on ECB (2022b), Laurent et al. (2020) and Fichter and Hintemann (2014)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Operation of one data centre per year – water consumption for cooling					
Water consumption for cooling	Water, cooling, unspecified natural origin, ReR	0.0018 m^3/kWh			Siddik, Shehabi and Marston (2021)
Assignment factor of one data centre in operation, water consumption for cooling (operation) $= average\ energy\ consumption\ per\ POS\ transaction\ in\ kWh$		0.001251905	0.001417324	0.001655309	Based on Nexi (2023), Worldline (2023) and primary source – PSP
Operation of one transaction processed – energy usage and internet access					
Energy – card scheme	Data centre average electricity mix	0.000127023 kWh	0.000292441 kWh	0.000530426 kWh	Based on Nexi (2023), Worldline (2023) and primary source – PSP
Energy – issuing bank	Data centre average electricity mix	0.000456189 kWh			Based on Nexi (2023), Worldline (2023) and primary source – PSP
Energy – payment service provider	Data centre average electricity mix	0.000668693 kWh			Based on Nexi (2023), Worldline (2023) and primary source – PSP
Transmission of data via the internet	Internet access, work, 0.2 Mbit/s {CH}| internet access, work, 0.2 Mbit/s | Cut-off, U	0.01544 h			Based on the payment terminal subsystem
Assignment factor of one transaction processed, energy usage & internet access (operation)		1			
End-of-life of one data centre					
Overall output	Used industrial electronic device {CH}| treatment of used industrial electronic device, manual dismantling | Cut-off, U	701 t			Own selection of end-of-life process (value based on material input)
Transport to the waste treatment facility	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	3622.768 tkm			Based on Eurostat (2021a)
Assignment factor of material of one data centre (production) $= \frac{\left(\frac{theoretical\ nr.of\ data\ centre\ for\ all\ POS\ transactions}{average\ lifespan\ of\ materials}\right)}{nr.of\ digital\ POS\ transactions\ per\ year}$		1.81436E-11	2.05409E-11	2.39900E-11	Based on ECB (2022b), Fichter and Hintemann (2014) and Lindgreen et al. (2017)

Source: Oxford Economics

4.1.4 Subsystem 4: Smartphones

This subsystem presents the inventory of one smartphone in the production and end-of-life phase and the assignment factor used to assign the inventory to the average digital POS transaction. The reference unit for the operation phase in inputs per year, i.e., energy usage and the assignment factor are adjusted accordingly. In general, smartphones are assumed to be used additionally to the other inputs in the digital payment system. Thus, implicitly, all smartphone payments also include the impact of the terminal, data centre, and card covered by the other subsystems. As 6%, 7%, and 8% of the digital POS transactions are conducted by smartphones in Germany, Italy, and Finland respectively, we added the material inputs for a smartphone for that fraction of payments. In other words, it is assumed that all smartphone payments are based on virtual debit or credit cards. Although in practice there may be payments not involving any card, we decided to build the model on this simplifying assumption due to a lack of data availability and because it constitutes the more conservative approach.

Production phase

For the **material** inventory of the subsystem smartphone, we mainly used the ecoinvent dataset "Consumer electronics, mobile device, smartphone {GLO}| market for consumer electronics, mobile device, smartphone | Cut-off, U" in the production phase. A power adapter is already part of the dataset. In detail, the process models the production of one smartphone (Fairphone 1 from 2014). The display of the smartphone is 4.3 inches, and the total weight is 163.45 g. The energy used to produce the smartphone is also included in the production process. A detailed overview of all ecoinvent datasets used, the values for Germany, Italy, and Finland as well as the sources are displayed in the detailed inventory table in Table 11.

Additionally, the **packaging** of the smartphone was included. The largest part of the packaging is assumed to be a corrugated board box (120 g), while some packaging film was included as well (10 g) per average smartphone (Apple Inc., 2017)).

Finally, the **transport** of the smartphone from production to consumer was modelled. As outlined in Boyo (2022), most smartphones are produced in China. We therefore modelled the international transport from Beijing to the respective countries. According to Sánchez, Proske, and Baur (2022), the baseline assumption for Fairphones is that 50% of the phones are transported by ship and 50% by aeroplane. The worst-case assumption stated is 10% transport by ship and 90% transport by plane. As Fairphone can be assumed to be more environmentally friendly than the average smartphone producer the worst-case scenario has been modelled for the average smartphone. Moreover, the constitutes the most conservative assumption. Thus, international transport by aeroplane was modelled assuming that smartphones are transported from Beijing to the biggest freight airport in the respective countries (Frankfurt for Germany, Milan for Italy, and Helsinki for Finland). For transport by ship, the distance has been calculated from Beijing to the biggest freight ports in the respective countries (Hamburg for Germany, Gioia Tauro for Italy, and Helsinki for Finland). To account for the national transport to the customer, the average distance for national transport in the respective countries was assumed (Eurostat, 2021a). The assumed mode of transport is by lorry.

To calculate the impact of smartphone production on the average digital POS payment, it is crucial to determine what part of the smartphone is used for the payments—i.e., the **assignment factor**.

Skipping this process would lead to the implicit assumption that smartphones are only used and produced to conduct digital POS payments. To calculate this assignment factor, the following steps have been performed:

- Step 1: Using the smartphones' battery statistics the share of total screen time spent in the wallet out of total screen time has been used as a starting point to approximate total energy usage for smartphone payments at POS. Based on a sample of three, we estimated that 3.77% of total screen time is spent in the wallet app. Thus, we further assumed, that 3.77% of the energy used can be assigned to the wallet.[53]
- Step 2: Next, smartphone energy usage was estimated. A period of ten days has been taken as a period of reference. During these days, we estimated that the average smartphone would go through 6.3 full charging cycles based on a study by Sánchez, Proske, and Baur (2022) who assume that the average smartphone is fully charged 230 times per year. According to the same study, an average charging cycle requires 18.4 Wh. Thus, total energy usage per year and smartphone was estimated to be 4,232 Wh. For the ten days chosen, the total energy usage is estimated as 116 Wh.
- Step 3: In this step, we estimated the energy usage per smartphone transaction. Combining the results of steps 1 and 2, we found that during a period of 10 days, 4.37 Wh could be assigned to smartphone payments (116 Wh total energy usage * 3.77% payments share). As smartphones in our sample conducted 10.67 payments during these 10 days, on average, 0.35 Wh were assigned to a single transaction.[54]
- Step 4: Now that the average energy consumed per transaction is estimated, we approximated the total number of smartphones needed to conduct all transactions per country per year if these smartphones were just used for digital POS transactions only. This approach is like the one applied in the subsystem data centre. Instead of taking the total number of smartphones per country and estimating their differing average usage shares for POS transactions, we estimated how many average smartphones would be needed per year to conduct all digital POS transactions by country. The average smartphone refers to average energy usage and charging cycles as stated above. Afterwards, these smartphones only used for digital transactions are fully assigned to all POS transactions conducted by smartphones per country in 2021. The total number of smartphone payments per country was calculated using the total number of digital POS payments per country (ECB, 2022b) and the smartphone share as displayed in Figure 8 (ECB, 2022a). In Germany and Italy, the share of POS payments conducted by smartphones out of all payments at POS was only 2%, but 6% in Finland. Thus, the total number of smartphone payments at POS was estimated to be 280.2 Mio. in Germany in 2021, 343.7 Mio. in Italy, and 82.7 Mio. in Finland. This resulted in the need for almost 23 smartphones used only for POS payments in Germany (280

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[53] To approximate the energy usage that can be attributed to an average smartphone payment at POS we only used energy consumed by the smartphone wallet. Although in some cases banking apps are required for authentication, they have not been considered due to a lack of data. To include this, we would need information on the share of card providers requiring a banking app to enable mobile payments at POS, the share of the apps' energy usage that can be assigned to POS transactions as the app is presumably used for other purposes such as bank transfers, P2P transfers and online payments as well, frequency and energy usage of updates and average lifetime of a banking app installed on a smartphone.

[54] Although the sample size is quite small and the number of smartphone payments may differ widely, we assumed that the average energy used per transaction should remain constant. Thus, more payments would, for example, also result in a higher assignment of energy used and thus, leading to the same result.

Mio. smartphone payments/12 Mio. payments per average smartphone), a little over 28 in Italy (344 Mio. smartphone payments/12 Mio. payments per average smartphone) and almost 7 in Finland (83 Mio. smartphone payments/12 Mio. payments per average smartphone).

- Step 3: Next, the usage share used for one smartphone transaction at POS was calculated. This was done by dividing the total number of smartphones needed by the number of digital POS payments paid by smartphones overall. For all countries, this resulted in a factor of 8.21E-08, i.e., 0.0000082% of a smartphone could be attributed to a smartphone POS payment in 2021.
- Step 4: To assign the material input of a smartphone to a POS transaction conducted by a smartphone, the average lifetime needs to be considered well. Skipping this step would imply that all payments conducted by smartphones per year correspond to the total number of smartphone payments in the device's lifetime. Thus, the factor presented in the previous step needs to be divided by the life expectancy of a smartphone. Assuming a lifetime of three years (European Environmental Bureau, 2019), the assignment factor reduces further to 2.74E-08. In other words, 0.0000027% of the material input of a smartphone should be assigned to an average smartphone POS transaction per country and year.
- Step 5: Lastly, we accounted for the fact that smartphones are only used on a fraction of digital POS payments. Thus, as we consider the average digital POS transaction per country, country-specific shares need to be included. As highlighted in the SPACE report (ECB, 2022a), 6% of the digital POS transactions in Germany are conducted using a smartphone, whereas 7% and 8% constitute the corresponding shares for Italy and Finland, respectively. To estimate the impact of one average digital payment, we therefore assume that 6%, 7%, and 8% of the digital payments are conducted using a smartphone as well. We calculated the usage share of material of a smartphone for one POS transaction by dividing it by the expected lifetime of the smartphone. Multiplying this usage share with the assignment factor displayed in step 4 yields the final assignment factor presenting the part of a new smartphone that can be attributed to an average digital payment at POS in 2021 in the respective countries. Again, this took into account that most digital POS transactions do not involve a smartphone. The final values for the relevant countries are 1.52E-09 for Germany, 1.82E-09 for Italy, and 2.05E-09 for Finland. Note that—in contrast to the previous steps—the assignment factors differ between the countries reflecting the variation in smartphones used to conduct digital POS transactions. The more payments are conducted using a smartphone (i.e., 8% in Finland), the higher the assignment of a new smartphone to the average digital POS transaction.

Operation phase

For the operation phase, only **energy usage** was covered. Starting from the energy use per average smartphone transaction as described above (0.3 Wh), this was **assigned** to the average digital POS transaction by multiplying this number with the share of the digital transaction paid by smartphone out of all digital transactions based on the SPACE report (ECB, 2022a). As the need for internet access varies between providers of mobile payment solutions and due to a lack of data, we have omitted all impacts caused by internet access through the smartphone. For example, Apple Pay does not require internet access, while Google Pay and Samsung Pay require regular access to the internet from time to time to load new tokens (Lowry, 2022). Nevertheless, the internet used by the data centre processing the transaction is still included in the corresponding subsystem 4.

End-of-life phase

For end-of-life, the smartphone and the power adapter were modelled based on existing ecoinvent datasets. These include **transport** to the waste treatment facility and **energy** used during the process. Moreover, the **packaging material** was treated with the corresponding waste processes, i.e., waste paperboard for the corrugated board box and waste polyethene for the packaging film. The **assignment factor** applied in this phase corresponds to the assignment factor from the production phase.

TABLE 11: INVENTORY TABLE FOR SMARTPHONES

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Production of one smartphone					
Input – Smartphone (incl. adapter)	Consumer electronics, mobile device, smartphone {GLO}| market for consumer electronics, mobile device, smartphone | Cut-off, U	1 piece			Based on Lindgreen et al. (2017)
Packaging	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	120 g			Apple Inc. (2017)
Packaging	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	10 g			Apple Inc. (2017)
Transport from Bejing to Hamburg (Germany), Milan (Italy), Helsinki (Finland) (shipped by sea)	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	0.618535084 tkm	0.473235957 tkm	0.646943978 tkm	Based on Sanches, Proske and Baur (2022)
Transport from Bejing to Hamburg (Germany), Gioia Tauro (Italy), and Helsinki (Finland) (shipped by air)	Transport, freight, aircraft, long haul {GLO}| market for transport, freight, aircraft, long haul | Cut-off, U	2.060019 tkm	2.1392505 tkm	1.6638615 tkm	Based on Sanches, Proske and Baur (2022)
Transport from the country of relevance to the customer (national)	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.026704 tkm	0.0393223 tkm	0.03198605tkm	Based on Eurostat (2021a)
Assignment factor of one smartphone (production) $= \frac{\left(\frac{theoretical\ nr.of\ smartphones\ for\ all\ POS\ transactions}{lifespan}\right)}{nr.of\ digital\ POS\ transactions\ by\ smartphone\ per\ year} * fraction\ of\ digitial\ payment\ transaction\ made\ with\ smartphone$		1.52E-09	1.82E-09	2.05E-09	Based on our assumptions, Sánchez, Proske, and Baur (2022), ECB (2022b), ECB (2022a), European Environmental Bureau (2019)
Operation of one payment – energy usage					
Energy usage per smartphone payment at POS	Electricity, low voltage {X[55]}| market for electricity, low voltage | Cut-off, U	3.4731E-04 kWh			Own calculation based on Sánchez, Proske and Baur (2022)

[55] X represents country specific processes for Germany, Italy, and Finland.

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Assignment factor of payment (operation) $= fraction\ of\ digitial\ payment\ transaction\ made\ with\ smartphone$		0.0555556	0.0666667	0.075	Based on ECB (2022a)
End-of-life of one smartphone					
Output – Smartphone	Used smartphone {GLO}| market for used smartphone | Cut-off, U	0.157866709 kg			Own selection of end-of-life process (value based on material input)
Output – Smartphone adapter	Used cable {GLO}| market for used cable | Cut-off, U	0.01316 kg			Own selection of end-of-life process (value based on material input)
Packaging (corrugated board box)	Waste paperboard {X}| market for waste paperboard | Cut-off, U	120 g			Own selection of end-of-life process (value based on material input)
Packaging (packaging film)	Waste polyethylene {X}| market for waste polyethylene | Cut-off, U	10 g			Own selection of end-of-life process (value based on material input)
Assignment factor of one smartphone (production) $= \frac{\left(\frac{theoretical\ nr.of\ smartphones\ for\ all\ POS\ transactions}{lifespan}\right)}{nr.of\ digital\ POS\ transactions\ by\ smartphone\ per\ year} * fraction\ of\ digitial\ payment\ transaction\ made\ with\ smartphone$		1.52E-09	1.82E-09	2.05E-09	Based on our assumptions, Sánchez, Proske, and Baur (2022), ECB (2022b), ECB (2022a), European Environmental Bureau (2019)

Source: Oxford Economics

4.2 CASH PAYMENTS

The number of cash payments has been estimated using the payment statistics provided by the ECB (ECB, 2022b) and the SPACE report (ECB, 2022a). First, the number of digital payments has been calculated as outlined in the previous chapter on digital payments. Taking this number and the shares of different payment methods as reported in the SPACE report (see Figure 2) we then calculated the total number of cash payments in 2021 for Germany to be 8.965 billion, for Italy to be 12.030 billion, and for Finland to be 0.275 billion. It should be noted that these estimations are based on a combination of the payment statistics and a survey introducing some uncertainty on the values calculated. However, due to a lack of alternatives, we considered this approach to be the most valid. Nevertheless, as these numbers affect all subsystems for the cash analysis, this aspect is not negligible. To increase the validity of our results, several sensitivity checks have been performed in Chapters 6.2.14 to 6.2.15 and an uncertainty analysis was undertaken as described in Chapter 6.3.

4.2.1 Subsystem 5: Banknotes

In this chapter, the inventory for one average fictional banknote is presented. Moreover, as banknotes are used for several transactions the estimation of the assignment factor is displayed.

The starting point for the production phase as well as the operation and end-of-life phase was the study by Hanegraaf et al. (2018). Here, an average fictional banknote was calculated consisting of all banknotes weighted by the respective denominations shares in the Netherlands. In detail, the absolute inputs used for banknote production are divided by the total number of produced banknotes, resulting in the inputs for the average banknote. 200- and 500-euro banknotes were not considered in the study. As a result, the average fictional banknote consisted of 0.815 g of cotton, 0.082 g of ink, 0.010 g of thread, and 0.049 g of foil. For copper and steel, average global shares for recycled material were used. Thus, the overall weight of the fictional average Dutch banknote was 0.956 g.

In principle, it could be assumed that the average fictional banknote is identical in the Netherlands and the euro area. Yet, the distribution of banknote denominations differs across countries, which leads to variations in the weight of the average fictional banknote. Thus, we use the distribution of banknote denominations in the euro area instead of the one in the Netherlands.[56] Since expert interviews have confirmed that the relative material inputs are proportional to each denomination's weight, the inputs from the Dutch study (Hanegraaf, Jonker, Mandley, & Miedema, Life cycle assessment of cash payments, 2018) could be used by only adjusting for the overall weight to reflect the distribution across denominations as used in this study.

Based on Zamora-Pérez (2021), we have assumed that only 5-, 10-, 20-, and 50-euro banknotes are used for transactional purposes. The other denominations—100, 200, and 500 euros—are assumed to be mainly used for value storage and thus ignored in the analysis. The distribution of small denominations is provided by the ECB (2023c) and corresponds to 8.8%, 12.5%, 20.1% and 58.6% from 5€ banknote to 50€ banknote. The corresponding weights per banknote and denomination are 0.71 g,

[56] There was no data available on the distribution of banknote denominations in the individual countries.

0.72 g, 0.81 g, and 0.92 g from 5€ banknote to 50€ banknote respectively (Hanegraaf, Jonker, Mandley, & Miedema, Life cycle assessment of cash payments, 2018).

Based on this distribution, we have estimated that the average fictional banknote of the euro area weighted 0.855 g in 2021—89% of the fictional average banknote from Hanegraaf et al. (2018). The **inputs** for the average banknote analysed in this study were cotton, ink, thread, and foil including average global shares for recycled copper and steel.[57] Additionally, further inputs were considered, including for example processing, packaging, transport, and energy use. Most of these data were also taken from Hanegraaf et al. (2018). All details on the inputs modelled and their weight are displayed in Table 12.

In addition, we have estimated the **packaging** ourselves. For this, the format of banknotes was needed, which was published by the ECB (2023f). Using each denomination's circulation share, our average banknote is 133.26 mm long and 71.82 mm wide. 100 banknotes are usually packed in one sleeve out of brown or white paper with a height of 12 mm (Wikipedia, 2023a). 10 of these bundles are typically put into one package with a height of 130 mm (Wikipedia, 2023a). Using the average load of a EUR-flat pallet (IMPARGO, 2023), we assumed that approximately 100 packets of 10-sleeved banknote packages fit on a pallet. Furthermore, we assumed that each of the 10 sleeved-banknotes packages is wrapped with plastic foil as well as the 100 packets that are put on a EUR-flat pallet. Assuming that one square meter (m^2) of the film has an average weight of 0.11 tonnes (abfallscout, 2023), we can calculate the packaging material for one packed EUR-flat pallet and divide it by the number of banknotes that fit onto that pallet, i.e., 100,000. As a result, one average banknote needs 2 g of kraft paper, 0.0059 g of packaging film and 0.00001 pieces of a EUR-flat pallet for its packaging.

The analysis also explicitly included **transport** whenever it was not already included in ecoinvent market datasets. Since banknotes are produced in several European countries for the whole euro area (as outlined in Chapter 3), most transportation steps were identical for the countries considered. Only those transportation steps concerning the distribution of finished banknotes differed between the countries. In general, transportation steps considered were the transport of fair-trade cotton to the paper mill[58], the transport of banknote paper from the paper mill to the printing works, and the transport of finalised banknotes from printing works to the respective national bank's headquarters.[59]

Concerning the transport of fair-trade cotton, the origin of the product was unknown. Thus, the three most common supplying countries of organic cotton—Mali, Senegal, and Burkina Faso—have been assumed to deliver the fair-trade cotton used for banknotes. This is in line with Hanegraaf et al. (2018). The average distance from these countries to the biggest freight port in Europe, Rotterdam, is 4,874 km. Multiplying this by the weight of the cotton transported (0.0344 g or 3.44E-08 t) yielded the tkm needed (0.000168 tkm). Additionally, the cotton was assumed to be transported from Rotterdam to the paper mills distributed in Europe by lorry. To approximate the distance travelled, the average

[57] Please note that the assumed weights per average banknote correspond the data stated by Hanegraaf et al. (2018). The correction for the weight per input was implemented via the assignment factor. All details and the precise formular applied to estimate the assignment facto rare stated in Table 12.

[58] Here, only the transport of fairtrade cotton was modelled as transport for traditional and organic cotton were already included in the respective market processes.

[59] All further transport steps – including, for example, distribution of banknotes to ATMs/CRMs and retail – are covered by a separate subsystem, namely CiT companies.

distance between Rotterdam and paper mills supplying the active ECB's printing works has been calculated.[60] Thus, on average, fair-trade cotton is also transported about 690 km by a lorry on land (2.37E-05 tkm).

Next, transport from the paper mill to printing works was estimated. Here, the average distance between the paper mills and the most relevant printing works was calculated.[61] Overall, the average distance corresponded to 873 km (0.00075 tkm).

In the last transportation step covered in the production phase of the subsystem banknote, banknotes were transported from printing works to the respective central bank's headquarters.[62] This transport distance varied between Germany, Italy and Finland. Generally, at least a part of the transport was assumed to be carried out by a lorry. In Germany, all printing works deliver banknotes to the Bundesbank by truck. The average distance was 1,229 km. In Italy, printing works delivered banknotes to the Bank of Italy. Most of these transports were performed by truck with an average distance of 1,555 km. However, part of the transport was also done by ship, with an average distance of 20 km. Similarly, transports to the Bank of Finland were done by truck with an average distance of 2,581 km and by ship with an average distance of 81 km.

For **energy** use, the modelling was based on Hanegraaf et al. (2018). It was included explicitly whenever no suitable manufacturing process was available in ecoinvent or it was not included in the (market) dataset. All datasets and precise quantities by country are displayed in the respective inventory table at the end of this subchapter.

To assign these inputs for one average banknote to one average cash POS transaction in the relevant countries, an **assignment factor** was calculated. The assignment factor describes how many new banknotes need to be produced for the average cash POS transaction, i.e., the inverse of the total number of transactions that an average banknote is involved in during its lifetime.

The first element needed was the number of banknotes used for transactions circulating in each of the relevant countries. Although the total number of banknotes circulating is provided by the ECB (2023c), it is challenging to calculate the number of banknotes used for transactions at a country level for several reasons. First, banknotes fulfil multiple tasks and are not only produced for transactions. As outlined in a study by Zamora-Pérez (2021), the share of banknotes in circulation used for transactions in the euro area corresponds to between 20 and 22% of the overall value of banknotes in circulation. The rest of the banknotes are either used for storing value in the euro area (28-50%) or held abroad

[60] Paper mills considered include Papierfabrik Louisenthal (Louisenthal 1, Gmund am Tegernsee, Germany), Polska Wytwórnia Papierów Wartościowych (Karczunkowska 30, Warsaw, Poland), Europafi (Cité Banque de France, Vic-le-Comte, France), Burgos Paper Mill (Avda. Costa Rica, 2. 09001 Burgos, Spain), Oberthur Paper Mill (Wezenweg 2, 7339 GS Ugchelen, Netherlands), and Portals Paper Mill (Overton Mill, Overton, Basingstoke RG25 3JG, United Kingdom).

[61] Printing works considered include Giesecke + Devrient (Leipzig, Johannisgasse 16, Germany), IMBIA (Madrid, Av. De Dorca 294, Spain), Bank of Greece (Chalandri, Mesogion 341, Greece), Bank of France (Chamalieres, Bd Duclaux 10, France), Bank of Italy (Rome, Via Tuscolana 417, Italy), Bundesdruckerei (Berlin, Kommandantenstraße 18, Germany), Österreichische Banknoten & Sicherheitsdruck GmbH (Wien, Garnisongasse 15, Austria), Valora (Alenquer, Estr. Do Banco de Portugal, Protugal), Oberthur Fiduciaire SAS (Chantepie, Rue du breil 20, France), Oberthur Fiduciaire AD (Sofia, Boulevard tsarigradsko shose 17, Bulgaria), De La Rue Currency (Gateshead, Team valles tranding estate kingway S, United Kingdom), De La Rue Currency (Loughton, Langston rd, United Kingdom), and Polska Wytwornia Papierow Wartosciowych (Warsaw, Karczunkowska 30, Poland).

[62] The final transportation step from the national central banks' headquarters to their branches is assigned to the subsystem of CiT companies and not considered here.

(30-50%). Second, since the euro is a global currency, another challenge is to estimate the actual number of banknotes circulating at a country level. Although some numbers are provided by the ECB, they contain negative values for some countries since banknotes issued by the local national central bank may be exceeded by the number of banknotes returned. One potential explanation may be tourists who bring cash to a country that is later returned.

Considering these challenges, we calculated the number of banknotes circulating at a country level and used for transactions as follows: As mentioned before, we have assumed that only 5-, 10-, 20-, and 50-euro banknotes are used for transactional purposes. The value of these "small" banknotes circulating corresponds to 53% of all banknotes in circulation. We further reduced the number of banknotes considered by taking into account that only 21% of banknotes are used for transactions in the euro area (Zamora-Pérez, 2021).[63] For the euro area, these calculations led to an estimate of 8.9 billion banknotes that are used for transactions. Considering the share of denominations, this includes 0.79 billion 5-euro banknotes, 1.1 billion 10-euro banknotes, 1.8 billion 20-euro banknotes, and 5.3 billion 50-euro banknotes.

Next, these numbers needed to be assigned to the countries of interest. To approximate the number of banknotes circulating in Germany, Italy, and Finland, we estimated each country's share of cash POS payments out of all cash POS payments paid in the euro area. This was done by first summing up the total number of POS payments paid by cash in each euro country according to the methodology outlined for the countries analysed. Afterwards, these numbers were added up to get the total number of POS payments paid by cash in the euro area. Dividing each country's number of POS payments paid by cash by the overall number of cash POS payments in the euro area yields the final share, i.e., each country's share of POS payments paid by cash in the euro area.

Overall, it is estimated that 60.5 billion POS payments were paid with cash in the euro area in 2021. Out of these, 14% of the cash POS payments were paid in Germany, 19% in Italy, and 0.4% in Finland.[64] Assuming that the number of banknotes in circulation by country that are used for transactions depends on the number of cash POS transactions in that country, banknotes have been assigned according to this share of cash POS transactions. As a result, 1,275.5 Mio. banknotes used for transactions have been assigned to Germany, 1,704.7 Mio. banknotes have been assigned to Italy, and 38,4 Mio. have been assigned to Finland. Taking this number of banknotes assigned to transactions per country and dividing it by the average number of cash POS transactions yields the average number of banknotes used per cash POS transaction per country. As described above, the number of cash POS transactions was estimated to be 8.965 billion for Germany, 12.030 billion for Italy, and 0.275 billion for Finland. Thus, in all three countries, about 0.14 average banknotes were used per transaction.

[63] The "small" denominations that are not used for transactions within the euro area may be circulating outside the euro area due to tourism, for example. Assuming that an identical share of each small denomination is used for transactions in the euro area, we arrived at an estimate of 21%.

[64] It may not be intuitive to assign more cash POS payments to Italy than to Germany – a much larger country. However, these estimates are based on the number of digital POS payments made by each country combined with the shares of different payment types at POS. Here, the number of digital POS payments in Italy exceeds the number of digital POS payments in Germany leading to the results as displayed above.

Next, the number of banknotes in circulation used for transactions by country was divided by the average banknote's life expectancy. We estimated this using a weighted average of the life expectancy of the respective denominations based on Deutsche Bundesbank (2023b). This step is necessary as not all banknotes used in a POS transaction are newly produced and thus, used for this transaction only. Instead, banknotes are typically used for several transactions. In general, the smaller the denomination, the shorter its life expectancy. Considering only 5-, 10-, 20-, and 50-euro banknotes, the life expectancy of the fictional average banknote considered in this study was 3.03 years. Accordingly, 420.7 Mio. fictional average banknotes were produced for transactions in Germany per year. In Italy, 562.2 Mio. were produced for transactions, and in Finland, 12.7 Mio. were produced for transactions per year. Finally, to assign the banknotes that need to be newly produced per year to one average POS transaction, we divided the number of newly produced banknotes by the total number of cash POS transactions per country per year. As a result, in each of the three countries, about 0.046 new banknotes could be assigned to one average POS transaction. In other words, the average banknote used for transactions is used in about 22 transactions at POS over the average lifetime.[65]

Since there is some uncertainty regarding the lifetime of the average banknote—especially since the introduction of the more robust series—we included a sensitivity check in which we doubled the lifetime of the average banknote to 6.06 years. As a result, the implicit assumption in this sensitivity check is that each banknote is used for about 43 transactions at POS over its lifetime.

Operation phase

During the operation phase, banknotes are counted and transported, for example to ATMs/CRMs and retailers. These aspects were covered in the analysis as well. However, they were estimated in separate subsystems, namely CCMs and CiT companies.

End-of-life phase

In the end-of-life phase, all inputs considered in the production phase including the packaging are disposed of. The precise waste treatment processes applied are displayed in the inventory table in Table 12. These waste treatment processes represent the waste treatment of one fictional average banknote. Thus, to assign these to one average cash POS transaction, the same **assignment factor** to one average cash POS transaction was applied as in the production phase (0.042).

Transport from the waste treatment facility was considered as well. In Germany, old banknotes are transported from the Deutsche Bundesbank analysis centre in Mainz—where they are shredded—to a waste incinerator in Ludwigshafen. The distance travelled was thus 87.6 km or 0.00008 tkm per average banknote. In Italy, old banknotes were assumed to be directly transported from the Bank of Italy branches to the closest local waste incinerators. The average distance travelled from the branches to the incinerators was 70.43 km or 0.00007 tkm per average banknote. Lastly, in Finland banknotes

[65] Please note that the assignment factor stated in the inventory table also contains a correction factor for the weight of an average banknote leading to a divergance from the assignment factor stated in the text. This is because the inputs stated in the literature refer tot he average Dutch banknote (Hanegraaf, Jonker, Mandley, & Miedema, 2018). However, the weight of the banknote modelled in this study differs because of varying distributions across denominations. Thus, as outlined in the formular for the assignment factor, only 89% of the material inputs' weights were modelled for this study.

were transported from the Bank of Finland to the biggest waste-to-energy incinerator Vantaa Energy. The distance travelled here was 15.9 km or 0.00002 tkm per average banknote.

Lastly, **energy** was used in the banknotes' end-of-life. Although some waste processes already contain energy usage, it was partly also modelled explicitly. Data for energy usage were taken from Hanegraaf et al. (2018). In particular, 0.37 Wh of heat and 0.91 Wh of electricity are used to treat one average banknote. As before, data on transport and energy usage needed to be assigned to one average cash POS transaction. Again, the assignment factor described above was applied.

TABLE 12: INVENTORY TABLE FOR BANKNOTES

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Production of one fictional banknote					
Input – Cotton production (traditional cotton)	Fibre, cotton {GLO}| market for fibre, cotton | Cut-off, U	0.4140127389 g			Hanegraaf et al. (2018)
Input – Cotton production (organic cotton)	Fibre, cotton, organic {GLO}| market for fibre, cotton, organic | Cut-off, U	0.2420382166 g			Hanegraaf et al. (2018)
Input – Cotton production (fair trade cotton)	Fibre, cotton {RoW}| fibre production, cotton, ginning | Cut-off, U	0.0343949045 g			Hanegraaf et al. (2018)
Input – Cotton production	Polyethylene terephthalate, granulate, amorphous {GLO}| market for polyethylene terephthalate, granulate, amorphous | Cut-off, U	0.0007961783 g			Hanegraaf et al. (2018)
Input – Foil production	Polyester-complexed starch biopolymer {GLO}| market for polyester-complexed starch biopolymer | Cut-off, U	0.0152866242 g			Hanegraaf et al. (2018)
Input – Foil production	Aluminium, primary, ingot {RoW}| market for aluminium, primary, ingot | Cut-off, U	0.0101910828 g			Based on Hanegraaf et al. (2018)
Input – Foil production	Polyester resin, unsaturated {RER}| market for polyester resin, unsaturated | Cut-off, U	0.0229299363 g			Based on Hanegraaf et al. (2018)
Manufacturing process	Extrusion, plastic film, without electricity {RER}| extrusion, plastic film | Cut-off, U	0.0382165605 g			Own selection of manufacturing process (value based on material input)
Manufacturing process	Metal working, average for aluminium product manufacturing, without electricity {RER}| metal working, average for aluminium product manufacturing | Cut-off, U	0.0101910828 g			Own selection of manufacturing process (value based on material input)
Input – Tread production	Aluminium, primary, ingot {RoW}| market for aluminium, primary, ingot | Cut-off, U	0.0058280255 g			Based on Hanegraaf et al. (2018)
Input – Tread production	Polyester-complexed starch biopolymer {GLO}| market for polyester-complexed starch biopolymer | Cut-off, U	0.0043184713 g			Hanegraaf et al. (2018)
Manufacturing process	Extrusion, plastic film, without electricity {RER}| extrusion, plastic film | Cut-off, U	0.0043184713 g			Own selection of manufacturing process (value based on material input)
Manufacturing process	Metal working, average for aluminium product manufacturing, without electricity {RER}| metal working, average for aluminium product manufacturing | Cut-off, U	0.0058280255 g			Own selection of manufacturing process (value based on material input)
Input – Paper production	Sulfate pulp, bleached {RoW}| market for sulfate pulp, bleached | Cut-off, U	0.0324840764 g			Based on Hanegraaf et al. (2018)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Input – Paper production	Chemi-thermomechanical pulp {GLO}| market for chemi-thermomechanical pulp | Cut-off, U	0.0407643312 g			Hanegraaf et al. (2018)
Input – Paper production	Paper, newsprint {RER}| market for paper, newsprint | Cut-off, U	0.8152866242 g			Based on Hanegraaf et al. (2018)
Input – Paper production	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	0.0034777070 g			Based on Hanegraaf et al. (2018)
Input – Paper production	Polyethylene terephthalate, granulate, amorphous {GLO}| market for polyethylene terephthalate, granulate, amorphous | Cut-off, U	0.0006242038 g			Hanegraaf et al. (2018)
Input – Paper production	Paper, newsprint {RER}| market for paper, newsprint | Cut-off, U	0.8089171975 g			Based on Hanegraaf et al. (2018)
Input – Ink production	Printing ink, offset, without solvent, in 47.5% solution state {RoW}| market for printing ink, offset, without solvent, in 47.5% solution state | Cut-off, U	0.0630573248 g			Based on Hanegraaf et al. (2018)
Input (Banknote printing)	Acetone, liquid {RoW}| market for acetone, liquid | Cut-off, U	0.1057324841 g			Based on Hanegraaf et al. (2018)
Input (Banknote printing)	Waste newspaper {GLO}| market for waste newspaper | Cut-off, U	0.0681528662 g			Hanegraaf et al. (2018)
Input (Banknote printing)	Polyethylene terephthalate, granulate, amorphous {GLO}| market for polyethylene terephthalate, granulate, amorphous | Cut-off, U	0.0184713376 g			Hanegraaf et al. (2018)
Input (Banknote printing)	Polyethylene, low density, granulate {GLO}| market for polyethylene, low density, granulate | Cut-off, U	0.0050445860 g			Hanegraaf et al. (2018)
Input (Banknote printing)	Corrugated board box {RER}| corrugated board box production | Cut-off, U	0.1082802548 g			Based on Hanegraaf et al. (2018)
Input (Banknote printing)	Waste paperboard, sorted {GLO}| market for waste paperboard, sorted | Cut-off, U	0.0038853503 g			Hanegraaf et al. (2018)
Input (Banknote printing)	Nickel, class 1 {GLO}| market for nickel, class 1 | Cut-off, U	0.0028343949 g			Based on Hanegraaf et al. (2018)
Input (Banknote printing)	Polyethylene terephthalate, granulate, amorphous {GLO}| market for polyethylene terephthalate, granulate, amorphous | Cut-off, U	0.0028343949 g			Hanegraaf et al. (2018)
Input (Banknote printing)	Printed paper, without paper, toner, electricity {Europe without Switzerland}| operation, printer, laser, colour, per kg printed paper | Cut-off, U	0.956 g			Hanegraaf et al. (2018)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Packaging	Kraft paper {RER}| market for kraft paper | Cut-off, U	0.002 kg			Own assumptions based on Wikipedia (2023a), IMPARGO (2023) and abfallscout (2023)
Packaging	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	0.000005929 kg			Own assumptions based on Wikipedia (2023a), IMPARGO (2023) and abfallscout (2023)
Packaging	EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, U	0.00001 pieces			Own assumptions based on Wikipedia (2023a), IMPARGO (2023) and abfallscout (2023)
Transport from fair trade cotton production to port	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	0.000167644 tkm			Own calculations based on Hanegraaf et al. (2018)
Transport from port in Europe to paper mill (fair trade cotton)	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	2.37194E-05 tkm			Own calculations based on Hanegraaf et al. (2018)
Transport paper production from paper mill to printing works)	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.000751659 tkm			Own calculations based on Hanegraaf et al. (2018)
Transport banknote production from printing works to central bank HQ (by lorry)	Transport, freight, lorry, unspecified, WITHOUT LORRY {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.003911815 tkm	0.004884995 tkm	0.007956536 tkm	Own calculations based on Hanegraaf et al. (2018)
Transport banknote production from printing works to central bank HQ (by ship)	Transport, freight, sea, ferry {GLO}| market for transport, freight, sea, ferry | Cut-off, U	-	0.000063639 tkm	0.000257736 tkm	Own calculations based on Hanegraaf et al. (2018)
Electricity for cotton production	Electricity, medium voltage {GLO}| market group for electricity, medium voltage | Cut-off, U	0.015286624 Wh			Hanegraaf et al. (2018)
Electricity for foil production	Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	0.008917197 Wh			Based on Hanegraaf et al. (2018)
Heat for foil production	Heat, district or industrial, natural gas {RER}| market group for heat, district or industrial, natural gas | Cut-off, U	2.420382166 J			Based on Hanegraaf et al. (2018)
Electricity for thread production	Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	0.001636943 Wh			Based on Hanegraaf et al. (2018)
Heat for thread production	Heat, district or industrial, natural gas {RER}| market group for heat, district or industrial, natural gas | Cut-off, U	0.452229299 J			Based on Hanegraaf et al. (2018)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Electricity for paper production	Electricity, medium voltage {X[66]}| market group for electricity, medium voltage | Cut-off, U	0.049681529 Wh			Based on Hanegraaf et al. (2018)
Electricity for banknote printing	Electricity, medium voltage {X}| market for electricity, medium voltage | Cut-off, U	1.477707006 Wh			Based on Hanegraaf et al. (2018)
Assignment factor for one transaction (banknote production) $= \frac{\left(\frac{nr.of\ (small)\ banknotes\ in\ circulation\ used\ for\ transactions}{lifespan}\right)}{nr.of\ cash\ POS\ transactions\ per\ year} * correction\ factor\ material\ input$		0.041950*	0.041780*	0.041080*	Based on ECB (2022b) and (2022a) and (2023c), Hanegraaf et al. (2018), Zamora-Pérez (2021)
Operation – see cash counting machines and cash-in-transit companies					
End-of-life of one average banknote					
Output – cotton (traditional cotton)	Waste textile, soiled {CH}| treatment of waste textile, soiled, municipal incineration | Cut-off, U	0.4140127389 g			Own selection of end-of-life process (value based on material input)
Output – cotton (organic cotton)	Waste textile, soiled {CH}| treatment of waste textile, soiled, municipal incineration | Cut-off, U	0.2420382166 g			Own selection of end-of-life process (value based on material input)
Output – cotton (fair trade cotton)	Waste textile, soiled {CH}| treatment of waste textile, soiled, municipal incineration | Cut-off, U	0.0343949045 g			Own selection of end-of-life process (value based on material input)
Output – cotton	Waste polyethylene terephthalate {CH}| treatment of waste polyethylene terephthalate, municipal incineration | Cut-off, U	0.0007961783 g			Own selection of end-of-life process (value based on material input)
Output – foil (polyester-complexed starch biopolymer)	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, municipal incineration | Cut-off, U	0.0152866242 g			Own selection of end-of-life process (value based on material input)
Output – foil (polyester resin)	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, municipal incineration | Cut-off, U	0.0229299363 g			Own selection of end-of-life process (value based on material input)
Output – foil	Scrap aluminium {Europe without Switzerland}| treatment of scrap aluminium, municipal incineration | Cut-off, U	0.010191083 g			Own selection of end-of-life process (value based on material input)

[66] X represents country specific processes for Germany, Italy, and Finland.

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Output – ink (treatment printing ink)	Waste paint {Europe without Switzerland}| treatment of waste paint, municipal incineration | Cut-off, U	0.063057325 g			Own selection of end-of-life process (value based on material input)
Output – paper production (sulfate pulp)	Waste graphical paper {CH}| treatment of waste graphical paper, municipal incineration | Cut-off, U	0.032484076 g			Own selection of end-of-life process (value based on material input)
Output – paper production (chemi-thermomechanical pulp)	Waste graphical paper {CH}| treatment of waste graphical paper, municipal incineration | Cut-off, U	0.040764331 g			Own selection of end-of-life process (value based on material input)
Output – paper production (paper newsprint)	Waste graphical paper {CH}| treatment of waste graphical paper, municipal incineration | Cut-off, U	0.815286624 g			Own selection of end-of-life process (value based on material input)
Output – paper production	Waste polyethylene terephthalate {CH}| treatment of waste polyethylene terephthalate, municipal incineration | Cut-off, U	0.000624204 g			Own selection of end-of-life process (value based on material input)
Output – paper production (corrugated board box)	Waste paperboard {CH}| treatment of waste paperboard, municipal incineration | Cut-off, U	0.003477707 g			Own selection of end-of-life process (value based on material input)
Output – paper production (paper newsprint)	Waste graphical paper {CH}| treatment of waste graphical paper, municipal incineration | Cut-off, U	0.808917197 g			Own selection of end-of-life process (value based on material input)
Output – tread production	Scrap aluminium {Europe without Switzerland}| treatment of scrap aluminium, municipal incineration | Cut-off, U	0.005828025 g			Own selection of end-of-life process (value based on material input)
Output – tread production (polyester-complexed starch biopolymer)	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, municipal incineration | Cut-off, U	0.004318471 g			Own selection of end-of-life process (value based on material input)
Output – banknote printing production (acetone)	Municipal solid waste {DE}| treatment of municipal solid waste, incineration | Cut-off, U	0.1057324841 g			Own selection of end-of-life process (value based on material input)
Output – banknote printing production (newspaper)	Waste graphical paper {CH}| treatment of waste graphical paper, municipal incineration | Cut-off, U	0.068152866 g			Own selection of end-of-life process (value based on material input)
Output – banknote printing production	Waste polyethylene terephthalate {CH}| treatment of waste polyethylene terephthalate, municipal incineration | Cut-off, U	0.018471338 g			Own selection of end-of-life process (value based on material input)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Output – banknote printing production	Waste polyethylene {CH}| treatment of waste polyethylene, municipal incineration | Cut-off, U	0.005044586 g			Own selection of end-of-life process (value based on material input)
Output – banknote printing production (corrugated board box)	Waste paperboard {CH}| treatment of waste paperboard, municipal incineration | Cut-off, U	0.108280255 g			Own selection of end-of-life process (value based on material input)
Output – banknote printing production	Waste paperboard {CH}| treatment of waste paperboard, municipal incineration | Cut-off, U	0.00388535 g			Own selection of end-of-life process (value based on material input)
Output – banknote printing production (nickel)	Scrap aluminium {CH}| treatment of scrap aluminium, municipal incineration | Cut-off, U	0.002834395 g			Own selection of end-of-life process (value based on material input)
Output – banknote printing production	Waste polyethylene terephthalate {CH}| treatment of waste polyethylene terephthalate, municipal incineration | Cut-off, U	0.002834395 g			Own selection of end-of-life process (value based on material input)
Output – packaging (kraft paper)	Waste paperboard {X}| market for waste paperboard | Cut-off, U	0.002 kg			Own selection of end-of-life process (value based on material input)
Output – packaging (packaging film)	Waste polyethylene {X}| market for waste polyethylene | Cut-off, U	0.000005929 kg			Own selection of end-of-life process (value based on material input)
Output – packaging (euro pallet)	Waste wood, untreated {X}| market for waste wood, untreated | Cut-off, U	0,00022 kg			Own selection of end-of-life process (value based on material input)
Transport from the centre for analysis to the waste incinerator	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.00008375 tkm	0.00006733 tkm	0.0000152 tkm	Own calculations based on Hanegraaf et al. (2018)
Output – shredding, granulating, and compacting of banknotes	Polyethylene terephthalate, granulate, amorphous {GLO}| market for polyethylene	0.003181818 g			Based on Hanegraaf et al. (2018)
Heat for shredding, granulating, and compacting of banknotes	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler modulating >100kW | Cut-off, U	0.000413636 kWh			Based on Hanegraaf et al. (2018)
Electricity for shredding, granulating, and compacting of banknotes	Electricity, medium voltage {X}| market for electricity, medium voltage | Cut-off, U	0.001027273 kWh			Based on Hanegraaf et al. (2018)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Assignment factor for one transaction (banknote production) $= \frac{\left(\frac{nr.of\ (small)\ banknotes\ in\ circulation\ used\ for\ transactions}{lifespan}\right)}{nr.of\ cash\ POS\ transactions\ per\ year} * correction\ factor\ material\ input$		0.041950	0.041780	0.041080	Based on ECB (2022b) and (2022a) and (2023c), Hanegraaf et al. (2018), Zamora-Pérez (2021)

Note: *The assignment factor stated in the table includes a correction factor for the material inputs. As described in the formula, only 89% of the material inputs should be used since the inputs were taken for the Dutch average banknote that differs in its weight due to varying distributions in denominations. Thus, the final value entered in SimaPro—multiplying the assignment factor and the inputs—is correct.

Source: Oxford Economics

4.2.2 Subsystem 6: Coins

The inventory of one average fictional coin is presented in this chapter. An assignment factor is applied wherever necessary to estimate the impact of one average cash POS transaction.

Production phase

Similar to the approach applied in the subsystem banknotes, an average fictional coin was estimated in the first step. The main material **inputs** are steel, copper, aluminium, zinc, tin, and nickel. Based on a study by the European Society of Clinical Microbiology and Infectious Diseases (2020) as well as ECB (2023d) and Wikipedia (2023b), the composition of each denomination was calculated. All inputs per denomination are displayed in Table 13. The ecoinvent datasets chosen are based on Hanegraaf et al. (2018) and include shares of recycled steel and copper according to global estimates.

TABLE 13: COMPOSITION OF DIFFERENT EURO COIN DENOMINATIONS

Denomination	Material
1-cent, 2-cent, and 5-cent coins	94.35% steel and 5.65% copper **1-cent coin**: 2.116g steel and 0.184g copper **2-cent coin**: 2.8152g steel and 0.2448g copper **5-cent coin**: 3.6064g steel and 0.3136 copper
10-cent, 20-cent, and 50-cent coins	89% copper, 5% aluminium, 5% zinc, and 1% tin (Nordic gold) **10-cent coin**: 3.649g copper, 0.205g aluminium, 0.205g zinc, and 0.041g tin **20-cent coin**: 5.1086g copper, 0.287g aluminium, 0.287g zinc, and 0.0574g tin **50-cent coin**: 6.942g copper, 0.39g aluminium, 0.39g zinc, and 0.078g tin
1-euro and 2-euro coins	*Gold part*: 75% copper, 20% zinc, and 5% nickel *Silver part*: 75% copper and 25% nickel (cupronickel) **1-euro coin**: Diameter: 23.25 mm, edge width: 3 mm Core: 75% copper and 25% nickel Edge: 75% copper, 20% zinc, and 5% nickel Total composition: 75% copper, 8.991% zinc, 16.009% nickel **2-euro coin**: Diameter 25.75 mm, edge width: 4 mm Core: 75% copper, 20% zinc, and 5% nickel Edge: 75% copper and 25% nickel Total composition: 75% copper, 9.503% zinc, 15.497% nickel

Source: Oxford Economics based on European Society of Clinical Microbiology and Infectious Diseases (2020), ECB (2023d), and Wikipedia (2023b)

To calculate the average coin, the denominations' distribution is relevant. The source used for the distribution was ECB (2023e) in July 2021.[67] Although coins are produced by each country—in contrast to banknotes—their long lifetime of 30 years makes a distribution across the euro area (and beyond) likely. Thus, similarly to the approach for banknotes, the total number of coins issued in the eurozone has been used as a starting point. The final average euro coin consisted of 1.796 g of steel, 1.938 g of copper, 0.068 g of aluminium, 0.145 g of zinc, 0.014 g of tin, and 0.13 g of nickel. We also added manufacturing processes to produce the average euro coin. A detailed overview of the products and

[67] July 2021 was chosen since the data used to calculate the number of cash POS transactions and to assign coins in circulation in the relevant countries (ECB, 2022b) refer to 2021.

processes used as well as quantities and sources are displayed in the detailed inventory table in Table 14.

Additionally, we also added the **packaging** of euro coins assuming that kraft paper and euro pallets are used. Coins are packed in paper rolls. Using the share per denomination and the normed length and diameter of paper rolls per denomination (Euro-Informationen, 2023), we calculated the average paper roll for approximately 44.88 average coins that have a diameter of 20.16 mm and a length of 1.84 mm including the paper bead. If the paper weighs 70 g/m², the paper used for an average roll weighs 8.15 g. We then assumed that paper rolls were packed in paper cartons. Given the weight, we assumed that they are packed in small-sized cartons (25 x 17.5 x 10 cm) (Lizenzero, 2023) that have space for 75 average coin rolls. Using the average load of a EUR-flat pallet (IMPARGO, 2023), we calculated that 22 cartons fit on a EUR-flat pallet. As a result, 0.201 g of paper for the paper roll and the carton as well as 0.0000135 EUR-flat pallets are used for an average coin.

Only two **transportation** steps were modelled in the production phase of euro coins. These were transportation from coin blank producers to coin mints and from the coin mints to the national central bank's headquarters. Other transports were either included in the market datasets or are covered by the subsystem CiT companies. Since coins are produced locally in contrast to banknotes, distances were much smaller, and all travelled by lorry. For Germany, the average distance travelled between coin blank producers and coin mints was 433 km (0.00177 tkm per average coin). For Italy, the average distance was zero as coin blanks and coin mints were already produced at the national central bank's headquarters. For Finland, coin blanks were also produced in the same place as the coins. Thus, no transportation was modelled here as well. For transport from coin producer to the national central bank, the distance travelled in Germany was 361 km (0.00166 tkm per average coin).[68] As described, the transport distance in Italy was again zero. In Finland, the distance travelled was 1.5 km (0.000007 tkm). Again, the transport of one coin in the production phase was then assigned to one average cash POS transaction using the assignment factor described above.

Lastly, **energy** consumption that was not already included in the ecoinvent market dataset was modelled for the production phase based on Hanegraaf et al. (2018). 0.918 kWh was used to produce one average fictional coin. Combining this value again with the assignment factor led to the desired value.

These inputs were used to construct the average euro coin. To estimate the impact of one average cash POS transaction, an **assignment factor** needed to be added. Similar to the subsystem banknotes, assigning the number of coins used for cash transactions on a country level was challenging. Overall, 141.2 billion euro coins are in circulation in the euro area. Although coins are typically not used for value storage, a study published by the Deutsche Bundesbank (2015) shows that only 36% of the coins in circulation in Germany are used for transaction purposes. The rest of the coins are mainly hoarded. Therefore, we have assigned 36% of the coins issued to transactions in the euro area, i.e., 50.8 billion coins. Moreover, although coins have a life expectancy of 30 years, some coins get damaged and need to be replaced. Two factors need to be considered: Error coins may be

[68]Here, the weight of the packaging material for coins has been considered as well.

produced during the minting process leading to an overhead production.[69] Second, not all coins returned to central banks may be reissued since some may be unfit for circulation due to dirtiness, corrosion, and mechanical damage, for example (Banque Centrale du Luxembourg, no date).[70] Combing both elements, we assume that the number of coins in circulation (and used for transactions) corresponds to only 70% of the coins produced (for transactions). This overhead production needs to be assigned for transactions as well whenever necessary. Thus, to get 50.8 billion coins used for transactions and circulating in the euro area, 72.6 billion euro coins had to be produced. While it may be the case that (some of) the overhead production of coins is melted down and recycled again, we fully assign this overhead production to the coin subsystem, in line with our cut-off approach described in chapter 3.2.5. To estimate the impact of this assignment choice, and to account for the critical assumptions underlying this approach, we conducted a sensitivity check in which we set the overhead production of coins to zero (see Chapter 6.2.15).

Next, the total number of coins produced and circulating for cash POS transactions needed to be estimated per country. Similar to the approach on banknotes, the total number of coins produced and circulating in the euro area was assigned to the countries of interest using the respective shares of total cash POS transactions in the euro area. Since 14% of all cash POS transactions in the euro area took place in Germany, 7.2 billion coins used for transactions (10.3 billion coins including overhead production) were assigned to the country. With 19% of cash POS transactions being conducted in Italy, 13.8 billion coins have been assigned to Italy including overhead production and 9.6 billion excluding overhead production. Lastly, 0.3 billion coins were assigned to Finland including overhead production and 0.2 billion coins excluding overhead production, as only 0.4% of cash POS transactions in the euro area took place here.

Dividing the total number of coins produced for transactions (i.e., including overhead production) by their expected lifespan—30 years[71]—yields the average number of coins that are newly produced per year. For Germany, about 333 Mio. coins are produced per year, for Italy about 444 Mio. coins, and for Finland roughly 10 Mio. Dividing these numbers again by the total number of cash POS transactions per year yields the assignment factor desired for material inputs indicating the number of newly produced coins needed for an average cash POS transaction. In Germany, Italy, and Finland, about 0.037 average coins are newly produced for a cash POS transaction on average.[72] Thus, we estimate, that every year 4.10 new coins are produced for transactions in Germany (incl. overhead production). Due to the higher number of cash POS transactions and the lower number of people, 7.79 new coins per person are estimated to be produced for transactions in Italy per year (incl. overhead production).

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[69] Although no data for euro coins were available US data show that in 2007 only 74.9% of coins produced were issued (Jenkins, 2014). However, this rate improved to 99.3% in 2014. Thus, we assumed that only 74.9% of the coins produced were issued up until 2007, 87.1% of the produced coins were issued between 2008 and 2013 (average rate between the years), and since 2014, 99.3% of the coins produced were also issued.

[70] Since no data were available, we assumed that 5% of the coins returned to central banks are unfit for circulation and thus, only 95% re-enter circulation. To replace the 5%, new coins need to be produced.

[71] An interview with a coin producer revealed that banknotes have an average lifetime of 30-31 years. We chose the 30 years as it is the more conservative choice from the digital subsystem's point of view.

[72] To get the average number of coins involved in a transaction – not the number of newly produced coins in the average transaction – the overhead production should not be included. This leaves 7.2 billion coins used for transactions in Germany, 9.6 billion in Italy, and 0.2 billion in Finland. Divided by the number of POS transactions per year results in roughly 0.8 average coins being involved in the average cash POS transaction.

Lastly, in Finland we estimate that 1.86 new coins are produced for transactions per person per year (incl. overhead production).

For packaging and transport of newly produced coins, overhead production was not considered. Thus, the number of produced coins excluding overhead production was divided by life expectancy, resulting in 232 million new coins being packaged and transported per year in Germany. Similarly, 311 million coins are packaged and transported per year in Italy and 7 million in Finland. Dividing these numbers again by the total number of cash POS transactions per year yields the assignment factor desired for packaging and transport in the production phase. In Germany, Italy, and Finland, about 0.026 average coins are newly packaged and transported for a cash POS transaction on average per year.[73] In other words, each average coin issued and used for transactions is used in 37 POS transactions over its lifespan. While 37 transactions might seem unintuitively small, only POS transactions are considered, and the variance in the number of transactions might be quite large. In other words, we estimate that in 2022 there were 86 coins per person used for transactions in Germany, 164 in Italy, and 39 in Finland (all excl. overhead production). Thus, considering the life expectancy of 30 years, 2.9 coins are estimated to be produced for transactions per person in Germany (excl. overhead), 5.5 in Italy (excl. overhead), and 1.3 in Finland (excl. overhead).

Operation phase

During the operation phase coins are transported, for example to ATMs/CRMs and retailers. These aspects were covered in the analysis as well. However, they were estimated in a separate subsystem, namely CiT companies.

End-of-life phase

At the end-of-life, euro coins are melted, and the material **output** is reused for other products (Hanegraaf, Jonker, Mandley, & Miedema, Life cycle assessment of cash payments, 2018). Therefore, no material outputs of the coins were considered in the end-of-life phase. Yet, outputs from **packaging** were modelled in line with the packaging inputs. Additionally, **transport** to the melting facility was included. Since no exact data on the distance were available, average commuting distances were used (Eurostat, 2021b). Lastly, energy usage for coin melting was modelled in line with Hanegraaf et al. (2018). As before, all details on the datasets used and quantities applied are displayed in the detailed inventory table below. Afterwards, these values were multiplied with the assignment factor described above to model the impact on one average cash POS transaction.

[73] To get the average number of coins involved in a transaction – not the number of newly produced coins in the average transaction – the overhead production should not be included. This leaves 7.2 billion coins used for transactions in Germany, 9.6 billion in Italy, and 0.2 billion in Finland. Divided by the number of POS transactions per year results in roughly 0.8 average coins being involved in the average cash POS transaction.

TABLE 14: INVENTORY TABLE FOR COINS

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Production of one fictional coin					
Input – fictional coin blank	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	1.79629 g			Hanegraaf et al. (2018)
Input – fictional coin blank	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	1.93806 g			Based on Hanegraaf et al. (2018)
Input – fictional coin blank	Aluminium, primary, liquid {GLO}| market for aluminium, primary, liquid | Cut-off, U	0.06801 g			Based on Hanegraaf et al. (2018)
Input – fictional coin blank	Zinc {GLO}| market for zinc | Cut-off, U	0.14446 g			Hanegraaf et al. (2018)
Input – fictional coin blank	Tin {GLO}| market for tin | Cut-off, U	0.01360 g			Hanegraaf et al. (2018)
Input – fictional coin blank	Nickel, class 1 {GLO}| market for nickel, class 1 | Cut-off, U	0.13021 g			Based on Hanegraaf et al. (2018)
Manufacturing process	Metal working, average for metal product manufacturing {GLO}| market for metal working, average for metal product manufacturing | Cut-off, U	4.09062 g			Own selection of manufacturing process (value based on material input)
Manufacturing process	Metal working, average for metal product manufacturing, without energy {RER}| metal working, average for metal product manufacturing | Cut-off, U	4.09062 g			Own selection of manufacturing process (value based on material input)
Electricity for fictional coin production	Electricity, medium voltage {X}| market for electricity, medium voltage | Cut-off, U	0.917948720 Wh			Based on Hanegraaf et al. (2018)
Assignment factor for one transaction (coin production) $= \frac{\left(\frac{nr.of\ coins\ in\ curculation}{lifespan}\right)}{nr.of\ cash\ POS\ transactions\ per\ year}$		0.038324182	0.038169308	0.037529161	Based on ECB (2022b) and (2022a), Hanegraaf et al. (2018), Deutsche Bundesbank (2015)
Production of one fictional coin – packaging and transportation					
Packaging	Kraft paper {RER}| market for kraft paper | Cut-off, U	0.000200983 kg			Own assumptions based on Euro-Informationen (2023), Lizenzero (2023), IMPARGO (2023)
Packaging	EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, U	0.000013504 pieces			Own assumptions based on Euro-Informationen (2023), Lizenzero (2023), IMPARGO (2023)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Transport from coin blank producer to coin mint	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.00177 tkm	-[74]	-[75]	Own calculations based on Hanegraaf et al. (2018)
Transport from coin mint to national central bank HQ	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0,00166 tkm	-	0.000007 tkm	Own calculations based on Hanegraaf et al. (2018)
Assignment factor for one transaction (coin production) $= \frac{\left(\frac{nr.\,of\ coins\ in\ curculation\ (without\ overhead)}{lifespan}\right)}{nr.\,of\ cash\ POS\ transactions\ per\ year}$		0.026826927	0.026718516	0.026270413	Based on ECB (2022b) and (2022a), Hanegraaf et al. (2018), Deutsche Bundesbank (2015)
Operation – see cash counting machines and cash-in-transit companies					
End-of-life of one fictional coin					
Packaging (kraft paper)	Waste paperboard {X}| market for waste paperboard | Cut-off, U	0.00020 kg			Own selection of end-of-life process (value based on material input)
Packaging (euro pallet)	Waste wood, untreated {X}| market for waste wood, untreated | Cut-off, U	0.00030 kg			Own selection of end-of-life process (value based on material input)
Transport from the Central Bank HQ to the melting facility	Transport, freight, lorry, unspecified, WITHOUT LORRY {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.00034361 tkm	0.00024789 tkm	0.00006504 tkm	Own calculations based on Hanegraaf et al. (2018)
Assignment factor for one transaction (coin production) $= \frac{\left(\frac{nr.\,of\ coins\ in\ curculation\ (without\ overhead)}{lifespan}\right)}{nr.\,of\ cash\ POS\ transactions\ per\ year}$		0.026826927	0.026718516	0.026270413	Based on ECB (2022b) and (2022a), Hanegraaf et al. (2018), Deutsche Bundesbank (2015)
End-of-life of one fictional coin – melting					
Electricity for coin melting	Electricity, medium voltage {X}| market for electricity, medium voltage | Cut-off, U	0.00007 kWh			Based on Hanegraaf et al. (2018)
Assignment factor for one transaction (coin production) $= \frac{\left(\frac{nr.\,of\ coins\ in\ curculation}{lifespan}\right)}{nr.\,of\ cash\ POS\ transactions\ per\ year}$		0.038324182	0.038169308	0.037529161	Based on ECB (2022b) and (2022a), Hanegraaf et al. (2018), Deutsche Bundesbank (2015)

Source: Oxford Economics

[74] In Italy coin blanks and coins are produced at the national central bank.

[75] In Finland coin blanks and coins are produced in the same location.

4.2.3 Subsystem 7: Cash-in-Transit

In this chapter, the inventory for Cash-in-Transit companies is displayed and the assignment factor used to estimate the impact of one average cash POS transaction is presented. While the production and end-of-life phases refer to on CiT truck, the operation phase considers inputs for one year of operation. The assignment factors are applied accordingly to estimate everything based on one average cash POS transaction.

Production phase

CiT companies use special armoured vehicles that are solely used to safely transport cash and can, therefore, be completely attributed to the cash payment system. We modelled a cash truck based on the approach of Hanegraaf et al. (2018), as cash trucks differ from normal trucks or lorries. The authors developed the **material** input for a cash truck using a passenger car reinforced with steel. An average cash truck weighs around 3.5 t (Böwing, 2013).[76] Therefore, the inputs in our model for the cash transport subsystem are 1,945 kg reinforced steel (Hanegraaf, Jonker, Mandley, & Miedema, Life cycle assessment of cash payments, 2018) and a passenger car where we adjusted the weight to 1,500 kg to arrive at an overall weight of around 3.5 t. We removed the waste treatment in the passenger car dataset to model the vehicle's end-of-life explicitly. All details on the modelling of the subsystem are displayed in Table 15.

We included the **transport** of the produced cash truck to the customers by considering a lorry as a transport vehicle, the weight of the cash truck and the average national freight distances in 2021 (Eurostat, 2021a).

The **assignment factor** for cash transport was calculated using the distance that banknotes and coins are transported in one year. We estimated this number starting with the total km driven by cash trucks per country per year. In Finland, the Bank of Finland recently reported that the km travelled in cash supply amounted to over 9 Mio. in 2020 (Bank of Finland, 2021). In Germany, we calculated that all trucks drove about 72.4 Mio. km per year based on information from a trade association (BDGW/BDSW/BDLS, 2023).[77] In Italy, the estimation was based on information provided by a leading CiT company. Here, all cash trucks drive more than 186.7 Mio. km per year.[78] To get the tkm transported, we furthermore assumed an average load weight of 448 kg per truck based on the information provided by Böwing (2013) and a load factor of 64% as recommended by the EU (2021). Next, we divided the tkm cash transported per year by the total tkm a cash truck drives over its lifetime. For Germany and Italy, this was—again—based on the data provided by the trade association and the CiT company, respectively. In Germany, trucks drive 30,000 km per year with an expected lifetime of 8 years. In Italy, trucks drive 133,334 km on average per year with an expected lifetime of 9 years. For Finland, this information was not available. Thus, we chose to use the same numbers as for

[76] We have decided to model the vehicle as a truck and not as a van because trucks have a lower fuel use per tkm compared to vans and, therefore, represents a lower environmental impact, i.e., this approach represents a more conservate approach relative to the digital payment system as it reduces the impact of the cash system.

[77] Data were provided by a trade association stating that more than 2,400 trucks were active with an average of 30,000 km driven per truck per year.

[78] Data were provided by a leading CiT company stating that 1,400 trucks were active with an average of more than 133,000 km driven per truck per year.

Germany, as these constitute the conservative estimate. As a result, we have calculated the number of fully consumed cash trucks needed for cash transport in one year per country. We found that more than 281 cash trucks would be needed in Germany, 154 in Italy, and 37.4 in Finland. Dividing this by the number of cash transactions yielded the final assignment factors: 3.257E-08 in Germany, 1.270E-08 in Italy, and 1.343E-07in Finland. Thus, a cash transporter supports almost 32 million cash POS transactions in Germany over its lifetime, almost 78 million cash POS transactions in Italy, and more than 7 million in Finland.

Operation phase

During the operation phase, we modelled the transportation of cash by CiT companies that transport cash between ATMs, banks, and retailers. From our approximated cash truck, we excluded the lorry production and the end-of-life in this dataset to only cover the road wear, fuel consumption etc., as the production was modelled as outlined in the production phase.

For calculating the **transport** in the operation phase, we used the estimated tkm all cash transporters drive per year from above. Since transports in the production and end-of-life phase of coins and banknotes were already covered in these subsystems, we then subtracted these distances. Out of the 281 fully consumed cash trucks needed per year in Germany, 266 were assigned to the operation phase of cash and thus modelled in this subsystem. The remaining 15 cash trucks were attributed to the production and end-of-life of coins and banknotes and therefore modelled in these subsystems. In Italy, 151 out of the 154 cash trucks were attributed to the operation phase, and in Finland 36.7 out of the 37.4 cash trucks were. To assign this to one average cash transaction, we divided this distance by the number of cash POS transactions per country per year. As a result, more than 28.6 Mio. tkm was attributed to cash transports in the operation phase in Germany, more than 81.15 Mio. tkm in Italy, and about 3.95 Mio. tkm in Finland.

End-of-life phase

The end-of-life of cash trucks was modelled by applying the corresponding treatment processes to the input processes in SimaPro. The same assignment factor as in the production phase was used.

TABLE 15: INVENTORY TABLE FOR CASH-IN-TRANSIT

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Production of one cash truck					
Input – cash truck	Reinforcing steel {GLO}| market for reinforcing steel | Cut-off, U	1,945 kg			Hanegraaf et al. (2018)
Manufacturing process	Metal working, average for steel product manufacturing {GLO}| market for metal working, average for steel product manufacturing | Cut-off, U	1,945 kg			Own selection of manufacturing process (value based on material input)
Input – cash truck	Passenger car, diesel, without waste treatment {GLO}| passenger car production, diesel | Cut-off, U	1,500 kg			Based on Hanegraaf et al. (2018)
Transport of cash truck to customer	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	312.806 tkm	461.9745 tkm	374.13 tkm	Based on Eurostat (2021a)
Assignment factor for one cash truck (production) $= \frac{\left(\frac{Total\ tkm\ driven\ during\ operation}{lifetime\ of\ a\ cash\ truck * average\ load}\right)}{nr.of\ cash\ POS\ transactions\ per\ year} + \frac{\left(\frac{Total\ tkm\ driven\ during\ production\&EoL\ for\ cash}{lifetime\ of\ a\ cash\ truck * average\ load}\right)}{nr.of\ cash\ POS\ transactions\ per\ year}$		3.13327E-08	1.28486E-08	1.35609E-07	Based on ECB (2022b) and (2022a), Bank of Finland (2021), BDGW/BDWS/BDLS (2023), Böwing (2023) and primary source – CiT company
Operation of all cash trucks per year					
Transport for cash handling for circulation	Transport, freight, lorry, unspecified, WITHOUT LORRY {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	28602250.95 tkm	81151930.13 tkm	3947899.93 tkm	Primary source – CiT company
Assignment factor for all cash trucks per year (operation $= \frac{1}{nr.of\ cash\ POS\ transactions\ per\ year}$		1.12E-10	8.31E-11	3.63E-09	Based on ECB (2022b) and (2022a)
End-of-life of one cash truck					
Output – cash truck	Scrap steel {Europe without Switzerland}| market for scrap steel | Cut-off, U	1,945 kg			Own selection of end-of-life process (value based on material input)
Output – cash truck	Passenger car, diesel, only waste treatment {GLO}| passenger car production, diesel | Cut-off, U	1,500 kg			Own selection of end-of-life process (value based on material input)

Assignment factor for one cash truck (production) $= \frac{\left(\frac{Total\ tkm\ driven\ during\ operation}{lifetime\ of\ a\ cash\ truck * average\ load}\right)}{nr.of\ cash\ POS\ transactions\ per\ year} + \frac{\left(\frac{Total\ tkm\ driven\ during\ production\&EoL\ for\ cash}{lifetime\ of\ a\ cash\ truck * average\ load}\right)}{nr.of\ cash\ POS\ transactions\ per\ year}$	3.13327E-08	1.28486E-08	1.35609E-07	Based on ECB (2022b) and (2022a), Bank of Finland (2021), BDGW/BDWS/BDLS (2023), Böwing (2023) and primary source – CiT company

Source: Oxford Economics

4.2.4 Subsystem 8: Cash counting machines

In this chapter, the inventory of CCMs and the assignment factor applied to estimate the impact of one cash POS transaction are described. Since two different models have been covered—as outlined in Chapter 3.2—the first part refers to small CCMs, while the second part concerns the inventory of large CCMs.

Production phase – small CCMs

Due to the unavailability of primary data and the limitation of open-accessible sources, our **material inputs** were estimated based on desk research and assumptions. We found that Giesecke+Devrient is one of the leading manufacturers of CCMs (Global View Research, 2023). Therefore, we modelled the CCMs as close as possible to the information sheet of one of the EU-certified small CCMs, the ProNote 1.5 (Giesecke+Devrient, 2023a). We added information from a CCM patent to validate our modelling assumptions (McDonald & Hengeveld, 1987).

The model CCM (Giesecke+Devrient, 2023a) weighs 9 kg and has the following dimensions: 33.5×29.0×27.0 centimetres (cm) (height × width × depth). We used the dimensions to approximate an outer casing made of common polymer high-impact polystyrene (HIPS). Through the calculation of the surface and assuming a thickness of 1 cm, we have calculated a volume of 0.0053 cubic metres (m^3). The final weight of the HIPS outer casing was then based on the density of the material leading to a calculated weight of 5.6 kg (Aqua-calc, 2023). Furthermore, the machines include a motor for the feeding mechanism. Those motors are made from copper (Amazon, 2023a) and steel and typically weigh about 280 g (Amazon, 2023b). We assumed that the copper comes from a copper cable inside the motor, making up about 10% of the weight, so the amount of copper used in one motor was estimated to be 28 g. The other 90% were modelled and assumed to be steel. We also included a microprocessor as well as a power adapter. Furthermore, we included a display and a keyboard. Lastly, we included some additional steel giving the machine stability and more robustness, leading to an overall weight of 9 kg. All details on the modelling of small CCMs are displayed in Table 16.

Before the newly produced CCMs are transported, they are **packaged**. We assumed that the machines were wrapped in plastic and then put into a board box. The calculations we made were based on the volume of the machine.

Transport information was again retrieved from one of the market leaders—Giesecke + Devrient. The company has production facilities all over the globe, including a couple of local production facilities in Germany, Italy, and Finland (Giesecke+Devrient, 2023c). We, therefore assumed that the CCMs are produced and transported nationally and thus, we used the average distance of national transport (Eurostat, 2021a).

To calculate the **assignment factor** for one small CCM to an average cash POS transaction, we first approximated the overall number of small CCMs in Germany and Finland based on information we received from one of the leading CiT companies in Italy and the number of banknotes in circulation in each of the three countries. This resulted in the overall number of 814 small CCMs in Germany in 2022, 1,088 small CCMs in Italy and 24 small CCMs in Finland. Using these numbers and the average lifespan of 5 years of a small CCM (estimated by our primary source), we then divided the number of small CCMs in use per country by the lifespan of a small CCM and by the number of cash POS transactions per year in that country.[79] Lastly, we assumed that all banknotes circulating in the Eurozone are counted by small CCMs. Thus, to assign the production of the machines only to those banknotes used for transactions, we multiplied the CCM assignment per average POS transaction from before by the share of banknotes used for small transactions out of all banknotes circulating in the Eurozone. As a result, the assignment factor for Germany is 1.49E-08, for Italy 1.48E-08, and for Finland 1.46E-08. We consider this approach to be conservative, as banknotes used for transactions are likely counted more frequently than other banknotes in circulation.

As the number of small CCMs is hard to estimate, we included two sensitivity checks in Chapters 6.2.11 and 6.2.12. One simply runs the model without any small CCMs, the other calculates the number of CCMs by using information from the ECB study again. According to the study, approximately 150,000 banknote handling machines were in use in Europe in the second half of 2016 (Deinhammer & Ladi, 2017). If we use the share of banknotes in circulation in a country of the European banknotes as weight, we can calculate a new number of CCMs in use, which is 94,806 CCMs in Germany, 27,916 in Italy and 2,240 in Finland.

Operation phase – small CCMs

In the operation phase, we included the **energy** that is consumed by the small CCMs during their usage. Through desk research, we found that an average small CCM has an electricity usage of 90 W per hour. During that time, it can count up to 60,000 banknotes (ZENY, 2023). Therefore, the electricity usage of a small CCM per counted banknote is 0.0015 Wh. To scale this number up to the whole system, we multiplied the 0.0015 Wh by the number of banknotes checked per year based on Deinhammer and Ladi (2017). Overall, all small CCMs consumed approximately 3,381 kWh of energy in Germany, 4,519 kWh in Italy, and 101 kWh in Finland.

To assign the energy usage to one average cash POS transaction, total energy usage is divided by the number of cash POS transactions per country per year. The total number of cash POS transactions is around 9 billion in Germany, around 12 billion in Italy and around 275 million in Finland.

End-of-life phase – small CCMs

Lastly, the end-of-life of small CCMs is modelled by modelling existing treatment processes that correspond best to the material inputs. The assignment factor was identical to the factor used in the production phase. Again, all details are in the inventory table in Appendix 1.

Production phase – large CCMs

The material input modelling approach of a large CCM was similar to small CCMs, adjusting for the size. We again use a model from Giesecke+Devrient 2023b – BPS M3 (Giesecke+Devrient, 2023b). This large CCM weighs 1,859 kg and measures 1.488x6.518x1.020 m (height × width × depth). Using these data points, we modelled the outer casing made of common HIPS and assumed that the machine was made from three units of the same size. Again, assuming a thickness of 1 cm, we estimated a volume

[79] We assumed that all banknotes in circulation are counted by small CCMs, for example, at the beginning of banknotes' lifecycle by CiT companies. Thus, since only small banknotes used for transactions are considered in the analysis, we include only their usage share of small CCMs in the LCA. Since no information on their precise usage share is available it is assumed that all banknotes in circulation are counted equally often. Considering that banknotes used for transactions are likely counted more frequently than other banknotes this approach is considered conservative.

of 0.139353 m^3 per large CCM or 443.13 kg (Aqua-calc, 2023). Furthermore, the machines include a motor for the feeding mechanism. Based on desk research, we approximated that about 100 motors are used in a large CCM (Giesecke+Devrient, 2017). Those motors are made from copper (Amazon, 2023a) as well as steel and typically weigh about 280 g (Amazon, 2023b). Considering that 100 motors are used in one large CCM, the total amount of copper is 2.8 kg. The other 90% are modelled by steel, which amounts to 25.2 kg for 100 motors.

Furthermore, we included more microprocessors than in the small machine. We estimated the number of microprocessors to be 100. For comparison, an average personal computer has about 100-200 microprocessors (Tessloff, 2023). In addition, we also included a display, a keyboard as well as a power adapter. Following the product description, the large CCM weighs about 1.8 t. We added additional steel to the model to reach that weight. All inputs are displayed in detail in Table 17.

The large CCMs need **packaging** for the transport to the customer. We assumed that the machines were wrapped in plastic and then put into a board box. The calculations were made based on the overall volume of the machine.

The **transport** is the same as for small CCMs. Yet, we accounted for the higher weight and the different packaging material.

To calculate the **assignment factor**, we approximated the number of large CCMs in use due to a lack of more precise data. Assuming that large CCMs are mainly used in national central bank branches with one CCM per branch, we have estimated that 30 large CCMs are in use in Germany, 37 in Italy and 6 in Finland. The average lifetime of these machines is assumed to be 15 years. This is again a rather conservative assumption as the literature suggests a lifetime of 10 years would be a valid assumption as well (Giesecke+Devrient, 2022). The assignment factor is calculated in the same way as for small CCMs, except for changing the overall number of CCMs in use. Combining all the numbers, we get the following assignment factors: 1.83E-10 in Germany; 1.68E-10 in Italy; and 1.19E-09 in Finland.

Operation phase – large CCMs

In the operation phase, we included the **energy** that is consumed by the large CCMs during their usage. We used information from Hanegraaf et al (2018), namely that the electricity usage of a large CCM per Mio. counted banknotes is 207.6 kWh. Thus, the electricity usage of a large CCM per one counted banknote is 0.2076 Wh. To scale this number up to the whole system, we multiplied the 0.2076 Wh by the number of banknotes checked by these machines based on Deinhammer and Ladi (2017). The electricity usage of all considered large CCMs to count banknotes for transactional purposes is approximately 423,409 kWh in Germany, 565,881 kWh in Italy, and 12,741 kWh in Finland.

The **assignment** to one average cash POS transaction is performed by dividing total energy usage per year by the number of cash POS transactions per year. The total number of cash POS transactions is around 9 billion in Germany, around 12 billion in Italy and about 275 million in Finland.

End-of-life phase – large CCMs

The end-of-life of large CCMs is modelled in the same way as the end-of-life of small CCMs, adjusting for varying weights. The assignment factor was again taken from the production phase.

TABLE 16: INVENTORY TABLE FOR SMALL CCMS

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Production of one small CCM					
Input – small CCM (outer casing)	Polystyrene, high impact {GLO}| market for polystyrene, high impact | Cut-off, U	5.64 kg			Aqua-calc (2023)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	5.64 kg			Own selection of manufacturing process (value based on material input)
Input – small CCM (stability purposes and 90 % of motor)	Steel, unalloyed {GLO}| market for steel, unalloyed | Cut-off, U	1.0505 kg			Own assumption based on Giesecke+Devrient (2023a)
Manufacturing process	Metal working, average for steel product manufacturing {GLO}| market for metal working, average for steel product manufacturing | Cut-off, U	1.0505 kg			Own selection of manufacturing process (value based on material input)
Input – small CCM (10 % of the motor)	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	0.028 kg			Amazon (2023a) and (2023b)
Manufacturing process	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	0.028 kg			Own selection of manufacturing process (value based on material input)
Input – small CCM	Integrated circuit, logic type {GLO}| market for integrated circuit, logic type | Cut-off, U	0.0595 kg			Own assumption based on Giesecke+Devrient (2023a)
Input – small CCM	Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	1.275 kg[80]			Own assumption based on Giesecke+Devrient (2023a)
Manufacturing process	Assembly of liquid crystal display, auxiliaries and energy use {GLO}| assembly of liquid crystal display, auxiliaries and energy use | Cut-off, U	1.275 kg			Own selection of manufacturing process (value based on material input)n
Input – small CCM	Power adapter, for laptop {GLO}| market for power adapter, for laptop | Cut-off, U	1 piece			Own assumption based on Giesecke+Devrient (2023a)
Input – small CCM	Keyboard {GLO}| market for keyboard | Cut-off, U	0.59 kg[81]			Own assumption based on Giesecke+Devrient (2023a)
Packaging	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	0.465 kg			Own assumption based on Giesecke+Devrient (2023a)
Packaging	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	0.036 kg			Own assumption based on Giesecke+Devrient (2023a)

[80] This amount corresponds to 25 % of the display in SimaPro.
[81] This amount corresponds to 50 % of the keyboard in SimaPro.

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Transport from the production facility to the customer	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.865 tkm	1.273 tkm	1.036 tkm	Based on Eurostat (2021a)
Assignment factor of one small CCM (production) $= \frac{\left(\frac{nr.of\ small\ CCM}{lifespan}\right)}{nr.of\ cash\ POS\ transactions\ per\ year} * \frac{nr.BN\ in\ circulation\ in\ Eurozone}{nr.small\ BN\ in\ circulation\ in\ Eurozone}$		1.49E-08	1.48007E-08	1.45525E-08	Based on ECB (2022b) and (2022a), Zamora-Perez (2021), primary source – CiT company
Operation – electricity to count banknotes for transactions per year (small CCM)					
Electricity	Electricity, low voltage {X[82]}| market for electricity, low voltage | Cut-off, U	3.38E+03 kWh	4.52E+03 kWh	1.02E+02 kWh	ZENY (2023)
Assignment factor of electricity to count banknotes for transactions per year (small CCM operation) $= \frac{1}{nr.of\ cash\ POS\ transactions\ per\ year}$		1.11541E-10	8.31209E-11	3.62976E-09	Based on ECB (2022b) and (2022a)
End-of-life of one small CCM					
Output – small CCM (outer casing)	Waste polystyrene {X}| market for waste polystyrene | Cut-off, U	5.64 kg			Own selection of end-of-life process (value based on material input)
Output – small CCM	Scrap steel {Europe without Switzerland}| market for scrap steel | Cut-off, U	1.0505 kg			Own selection of end-of-life process (value based on material input)
Output – small CCM	Scrap copper {Europe without Switzerland}| market for scrap copper | Cut-off, U	0.028 kg			Own selection of end-of-life process (value based on material input)
Output – small CCM (integrated circuit)	Waste electric and electronic equipment {GLO}| market for waste electric and electronic equipment | Cut-off, U	0.0595 kg			Own selection of end-of-life process (value based on material input)
Output – small CCM	Used liquid crystal display {GLO}| market for used liquid crystal display | Cut-off, U	1.275 kg			Own selection of end-of-life process (value based on material input)
Output – small CCM (power adapter)	Waste electric and electronic equipment {GLO}| market for waste electric and electronic equipment | Cut-off, U	0.357 kg			Own selection of end-of-life process (value based on material input)
Output – small CCM (keyboard)	Waste electric and electronic equipment {GLO}| market for waste electric and electronic equipment | Cut-off, U	0.59 kg			Own selection of end-of-life process (value based on material input)
Packaging (corrugated board box)	Waste paperboard {X}| market for waste paperboard | Cut-off, U	0.465 kg			Own selection of end-of-life process (value based on material input)

[82] X represents country specific processes for Germany, Italy, and Finland.

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Packaging (packaging film)	Waste polyethylene {X}| market for waste polyethylene | Cut-off, U	0.036 kg			Own selection of end-of-life process (value based on material input)
Assignment factor of one small CCM (production) $= \frac{\left(\frac{nr. of\ small\ CCM}{lifespan}\right)}{nr. of\ cash\ POS\ transactions\ per\ year} * \frac{nr. BN\ in\ circulation\ in\ Eurozone}{nr. small\ BN\ in\ circulation\ in\ Eurozone}$		1.49E-08	1.48007E-08	1.45525E-08	Based on ECB (2022b) and (2022a), Zamora-Perez (2021), primary source – CiT company

Source: Oxford Economics

TABLE 17: INVENTORY TABLE FOR LARGE CCMS

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Production of one large CCM					
Input – large CCM (outer casing)	Polystyrene, high impact {GLO}| market for polystyrene, high impact | Cut-off, U	443.13 kg			Aqua-calc (2023)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	443.13 kg			Own selection of manufacturing process (value based on material input)
Input – large CCM (stability purposes and 90 % of motor)	Steel, unalloyed {GLO}| market for steel, unalloyed | Cut-off, U	541.483 kg			Own assumption based on Giesecke+Devrient (2023b)
Manufacturing process	Metal working, average for steel product manufacturing {GLO}| market for metal working, average for steel product manufacturing | Cut-off, U	541.483 kg			Own selection of manufacturing process (value based on material input)
Input – large CCM (10 % of the motor)	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	2.8 kg			Amazon (2023a) and (2023b)
Manufacturing process	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	2.8 kg			Own selection of manufacturing process (value based on material input)
Input – large CCM	Integrated circuit, logic type {GLO}| market for integrated circuit, logic type | Cut-off, U	5.95 kg			Own assumption based on Giesecke+Devrient (2023b)
Input – large CCM	Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	1 piece			Own assumption based on Giesecke+Devrient (2023b)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Manufacturing process	Assembly of liquid crystal display, auxiliaries and energy use {GLO}| assembly of liquid crystal display, auxiliaries and energy use | Cut-off, U	5.1 kg			Own selection of manufacturing process (value based on material input)
Input – large CCM	Power adapter, for laptop {GLO}| market for power adapter, for laptop | Cut-off, U	1 piece			Own assumption based on Giesecke+Devrient (2023b)
Input – large CCM	Keyboard {GLO}| market for keyboard | Cut-off, U	1 piece			Own assumption based on Giesecke+Devrient (2023b)
Packaging	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	175.72 kg			Own assumption based on Giesecke+Devrient (2023b)
Packaging	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	13.6 kg			Own assumption based on Giesecke+Devrient (2023b)
Transport from the production facility to the customer	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	108 tkm	159 tkm	130 tkm	Eurostat (2021a)
Assignment factor of one large CCM (production) $= \frac{\left(\frac{nr.of\ large\ CCM}{lifespan}\right)}{nr.of\ cash\ POS\ transactions\ per\ year} * \frac{nr.BN\ in\ circulation\ in\ Eurozone}{nr.small\ BN\ in\ circulation\ in\ Eurozone}$		1.83E-10	1.68E-10	1.19E-09	Based on ECB (2022b) and (2022a), Zamora-Perez (2021), primary source – CiT company
Operation – electricity to count banknotes (large CCM)					
Electricity	Electricity, low voltage {X}| market for electricity, low voltage | Cut-off, U	423409.38 kWh	565881.02 kWh	12741.24 kWh	Hanegraaf et al. (2018)
Assignment factor of electricity to count banknotes for transactions per year (small CCM operation) $= \frac{1}{nr.of\ cash\ POS\ transactions\ per\ year}$		1.11541E-10	8.31209E-11	3.62976E-09	Based on ECB (2022b) and (2022a)
End-of-life of one large CCM					
Output – large CCM (outer casing)	Waste polystyrene {X}| market for waste polystyrene | Cut-off, U	443.13 kg			Own selection of end-of-life process (value based on material input)
Output – large CCM	Scrap steel {Europe without Switzerland}| market for scrap steel | Cut-off, U	541.483 kg			Own selection of end-of-life process (value based on material input)
Output – large CCM	Scrap copper {Europe without Switzerland}| market for scrap copper | Cut-off, U	2.8 kg			Own selection of end-of-life process (value based on material input)
Output – large CCM (integrated circuit)	Waste electric and electronic equipment {GLO}| market for waste electric and electronic equipment | Cut-off, U	5.95 kg			Own selection of end-of-life process (value based on material input)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Output – large CCM	Used liquid crystal display {GLO}| market for used liquid crystal display | Cut-off, U	5.1 kg			Own selection of end-of-life process (value based on material input)
Output – large CCM (power adapter)	Waste electric and electronic equipment {GLO}| market for waste electric and electronic equipment | Cut-off, U	0.357 kg			Own selection of end-of-life process (value based on material input)
Output – large CCM (keyboard)	Waste electric and electronic equipment {GLO}| market for waste electric and electronic equipment | Cut-off, U	1.18 kg			Own selection of end-of-life process (value based on material input)
Packaging (corrugated board box)	Waste paperboard {X}| market for waste paperboard | Cut-off, U	175.72 kg			Own selection of end-of-life process (value based on material input)
Packaging (packaging film)	Waste polyethylene {X}| market for waste polyethylene | Cut-off, U	13.6 kg			Own selection of end-of-life process (value based on material input)
Assignment factor of one large CCM (production) $= \frac{\left(\frac{nr.of\ large\ CCM}{lifespan}\right)}{nr.of\ cash\ POS\ transactions\ per\ year} * \frac{nr.BN\ in\ circulation\ in\ Eurozone}{nr.small\ BN\ in\ circulation\ in\ Eurozone}$		1.83E-10	1.68E-10	1.19E-09	Based on ECB (2022b) and (2022a), Zamora-Perez (2021), primary source – CiT company

Source: Oxford Economics

4.2.5 Subsystem 9: Cards – cash system

The whole inventory including the production phase, which covers material inputs, packaging, electricity usage and transport, as well as the operation phase and the end-of-life, is explained in detail in Chapter 4.1.1.

However, the **assignment factor** differs between both subsystems. As described in Chapter 4.1.1, it is first necessary to calculate how much of an average card can be attributed to the cash payment system, considering that cards are used for digital POS payments, cash POS payments, and online payments. We estimated that 20% of card usage can be attributed to cash withdrawals and deposits and thus to the cash payment system in Germany, while in Italy and Finland, only 12% and 3% can be attributed to that use respectively. Furthermore, the numbers for one card have been multiplied by the total number of cards present in each country divided by the expected lifespan of 3.5 years per card (Lindgreen, et al., 2017), yielding the number of cards that need to be produced for cash withdrawals and deposits per year per country. As mentioned in chapter 4.1.1 previously, 174,208,000 cards are present in Germany, 118,069,000 in Italy and 10,520,000 in Finland in 2021 (ECB, 2022b). Lastly, dividing this by the total number of cash POS payments per country yields the final assignment factor to one average cash POS transaction. We get the following assignment factors: 0.001098 for Germany, 0.000331 for Italy, and 0.000354 for Finland. Thus, over its lifetime, a card is involved in 180 cash POS transactions in Germany, 357 cash POS transactions in Italy, and 91 cash POS transactions in Finland.[83]

[83] Please note that cards have not been assigned to the cash POS payments entirely. Instead only 20% in Germany, 12% in Italy, and 3% in Finland have been assigned to digital POS payments as outlined in the text. Thus, considering all cards, tkhe average number of digital POS transactions is quite low. Assuming that only 20%, 12% and 3% of the cards are considered as those cards are only used for digital POS transactions, each card would be used for 911, 3,021, and 2,827 digital POS transactions over ist lifetime in the respective countries.

TABLE 18: INVENTORY TABLE FOR CARDS – CASH SYSTEM

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Production of one card					
Input – card body	Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U	3.486 g			Lindgreen et al. (2017)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	3.486 g			Own selection of manufacturing process (value based on material input)
Input – card body	Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U	0.914 g			Lindgreen et al. (2017)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	0.914 g			Own selection of manufacturing process (value based on material input)
Input – card body	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	0.1 g			Lindgreen et al. (2017)
Manufacturing process	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	0.1 g			Own selection of manufacturing process (value based on material input)
Input – chip	Nickel, class 1 {GLO}| market for nickel, class 1 | Cut-off, U	0.00005164 g			Lindgreen et al. (2017)
Manufacturing process	Metal working, average for metal product manufacturing {GLO}| market for metal working, average for metal product manufacturing | Cut-off, U	0.00005164 g			Own selection of manufacturing process (value based on material input)
Input – chip	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	0.069129 g			Lindgreen et al. (2017)
Manufacturing process	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	0.069129 g			Own selection of manufacturing process (value based on material input)
Input – chip	Gold {GLO}| market for gold | Cut-off, U	0.0000067 g			Lindgreen et al. (2017)
Manufacturing process	Metal working, average for metal product manufacturing {GLO}| market for metal working, average for metal product manufacturing | Cut-off, U	0.0000067 g			Own selection of manufacturing process (value based on material input)
Input – chip	Glass fibre reinforced plastic, polyester resin, hand lay-up {GLO}| market for glass fibre reinforced plastic, polyester resin, hand lay-up | Cut-off, U	0.0000998 g			Lindgreen et al. (2017)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	0.0000998 g			Own selection of manufacturing process (value based on material input)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Input – chip	Epoxy resin, liquid {RoW}| market for epoxy resin, liquid | Cut-off, U	0.00012 g			Lindgreen et al. (2017)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	0.00012 g			Own selection of manufacturing process (value based on material input)
Input – chip	Silicon, electronics grade {GLO}| market for silicon, electronics grade | Cut-off, U	0.009 g			Lindgreen et al. (2017)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	0.009 g			Own selection of manufacturing process (value based on material input)
Packaging from chip production to card body production	Tubular particleboard {RoW}| market for tubular particleboard | Cut-off, U	9.33418E-09 m^3			Based on PEP (2023)
Packaging from chip production to card body production	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	0.001568143 g			Based on PEP (2023)
Packaging from chip production to card body production	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	0.000392036 g			Based on PEP (2023)
Packaging from card body production to country of relevance (logistic hub)	Tubular particleboard {RoW}| market for tubular particleboard | Cut-off, U	2.72524E-07 m^3			Based on PEP (2023)
Packaging from card body production to country of relevance (logistic hub)	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	0.091568143 g			Based on PEP (2023)
Packaging from card body production to country of relevance	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	0.022892036 g			Based on PEP (2023)
Packaging from warehouse to customer (2 envelopes)	Kraft paper {RER}| market for kraft paper | Cut-off, U	36 g			Own assumption based on Deutsche Post (2023)
Packaging from warehouse to customer (2 envelopes)	Polystyrene, general purpose {GLO}| market for polystyrene, general purpose | Cut-off, U	4 g			Own assumption based on Deutsche Post (2023)
Energy usage for card personalisation	Electricity, low voltage {X[84]}| market for electricity, low voltage | Cut-off, U	0.038 kWh			Primary source – card personalisation company
Transport from chip production to card body production	Transport, freight, lorry, unspecified {RoW}| market for transport, freight, lorry, unspecified | Cut-off, U	0.00005763 tkm			Primary source – card personalisation company

[84] X represents country specific processes for Germany, Italy, and Finland.

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Transport from card body production to country of relevance (logistic hub)	Transport, freight, aircraft, long haul {GLO}| market for transport, freight, aircraft, long haul | Cut-off, U	0.09903095 tkm	0.098550214 tkm	0.089416291 tkm	Primary source – card personalisation company
Transport from logistic hub to warehouse	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.00043747 tkm	0.000644182 tkm	0.000523999 tkm	Own assumption based on primary source – card personalisation company
Transport from warehouse to customer	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	0.00405664 tkm	0.005973507 tkm	0.004859046 tkm	Own assumption based on primary source – card personalisation company
Assignment factor of one card (production) $= \frac{\left(\frac{nr.of\ cards\ in\ 2021}{lifespan}\right)}{nr.of\ cash\ POS\ transactions\ per\ year} * card\ share\ of\ digital\ POS\ payments$		0.001098	0.000331	0.000354	Based on ECB (2022b) and (2022a), Hanegraaf et al. (2018)
End-of-life of one card					
Output – card body	Waste polyvinylchloride {X}| market for waste polyvinylchloride | Cut-off, U	3.486 g			Own selection of end-of-life process (value based on material input)
Output – card body	Waste polyvinylchloride {X}| market for waste polyvinylchloride | Cut-off, U	0.914 g			Own selection of end-of-life process (value based on material input)
Output – card body	Scrap copper {Europe without Switzerland}| market for scrap copper | Cut-off, U	0.1 g			Own selection of end-of-life process (value based on material input)
Output – chip (nickel)	Scrap steel {Europe without Switzerland}| market for scrap steel | Cut-off, U	0.00005164 g			Own selection of end-of-life process (value based on material input)
Output – chip	Scrap copper {Europe without Switzerland}| market for scrap copper | Cut-off, U	0.069129 g			Own selection of end-of-life process (value based on material input)
Output – chip (gold)	Scrap steel {Europe without Switzerland}| market for scrap steel | Cut-off, U	0.0000067 g			Own selection of end-of-life process (value based on material input)
Output – chip (glass fibre reinforced plastic)	Waste glass {X}| market for waste glass | Cut-off, U	0.0000998 g			Own selection of end-of-life process (value based on material input)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Output – chip (epoxy resin)	Waste plastic, mixture {X}| market for waste plastic, mixture | Cut-off, U	0.00012 g			Own selection of end-of-life process (value based on material input)
Output – chip (silicon)	Waste plastic, mixture {X}| market for waste plastic, mixture | Cut-off, U	0.009 g			Own selection of end-of-life process (value based on material input)
Total packaging (tubular particleboard)	Waste wood, untreated {X}| market for waste wood, untreated | Cut-off, U	1.18E-04 kg			Own selection of end-of-life process (value based on material input)
Total packaging (corrugated board box)	Waste paperboard {X}| market for waste paperboard | Cut-off, U	9.31E-05 kg			Own selection of end-of-life process (value based on material input)
Total packaging (packaging film)	Waste plastic, mixture {X}| market for waste plastic, mixture | Cut-off, U	2.33E-05 kg			Own selection of end-of-life process (value based on material input)
Total packaging (kraft paper)	Waste paperboard {X}| market for waste paperboard | Cut-off, U	3.60E-02 kg			Own selection of end-of-life process (value based on material input)
Total packaging	Waste polystyrene {X}| market for waste polystyrene | Cut-off, U	4.00E-03 kg			Own selection of end-of-life process (value based on material input)
Assignment factor of one card (end-of-life) $= \frac{\left(\frac{nr. of\ cards\ in\ 2021}{lifespan}\right)}{nr. of\ cash\ POS\ transactions\ per\ year} * card\ share\ of\ digital\ POS\ payments$		0.001098	0.000331	0.000354	Based on ECB (2022b) and (2022a), Hanegraaf et al. (2018)

Source: Oxford Economics

4.2.6 Subsystem 10: ATMs/CRMs

For the production and end-of-life phase, the inventory of one ATM/CRM is presented in this chapter. To assign it to one cash POS transaction, the estimated assignment factor is described. Moreover, for the operation phase, all inputs are described for one year and assigned to an average cash POS transaction using the corresponding assignment factor.

Production phase

Customers can withdraw cash at ATMs as well as at CRMs, but only deposit cash at CRMs. As mentioned earlier and as also assumed by Hanegraaf et al. (2018)., ATMs and CRMs were assumed to have the same material inputs and only differ in their energy usage.

The **material input** of an ATM/CRM was based on Hanegraaf et al. (2018) and validated by a leading manufacturer. The machines were divided into two parts. The upper part is the head module with all the electronics included, and the bottom part includes a steel-safe containing cassettes with banknotes. Like Hanegraaf et al. (2018), we made a simplifying assumption on the material inputs, namely that an average ATM or CRM consists of a display, a computer and 700 kg of reinforcing steel for the safe. All details on the modelling of ATMs/CRMs are displayed in the detailed inventory table in Appendix 1.

Before the transport, the newly produced machines are **packaged** in plastic. To calculate the packaging material that is needed, we used the dimensions of an average machine, which are 0.945x1.025x0.5 m (height × width × depth) (Leichsenring, 2018), inducing a surface of 3.9 m^2. Assuming that the machines are wrapped twice, we estimated that 0.441 kg of plastic film is needed to package one ATM/CRM. Furthermore, we assumed the machine was packaged with an additional layer of kraft paper (2.3 kg). Next, the package is wrapped by polyethylene terephthalate (PET) straps weighing 10 g per meter, leading to an estimate of 57.8 g of plastic required. Lastly, the machines are transported on a EUR pallet, which was considered as well.

According to information provided by a leading ATM/CRM manufacturer, the major manufacturers of ATMs/CRMs have production facilities in Europe. Therefore, we assumed **transport** distances according to the average distance of international transport (Eurostat, 2021a) for the transport between the production facility and the customer. The mode of transport is an average lorry.

To **assign** the production of one ATM/CRM to one average cash POS transaction, we started with the overall number of ATMs and CRMs[85] per country provided by the Payment Statistics (ECB, 2022b). There it is stated that 80,864 ATMs and CRMs were installed in Germany, 45,529 in Italy, and 1,935 in Finland. Please also note that all data are for 2021 except for Finland. Here, the numbers are from 2020 because the Payment Statistic does not provide values for 2021. However, these numbers indicate the sum of ATMs and CRMs. Thus, to get specific numbers for ATMs and CRMs respectively, we used percentage shares that were given by a primary source (ATM/CRM manufacturer).[86] We then divided the number of ATMS/CRMs by their average lifespan of 10 years (Hanegraaf, Jonker, Mandley,

[85] The Payment Statistics from the ECB (2022b) lists the total aggregated number of ATMs and CRMs in Table 6 under "terminals provided by resident PSPs – ATMs – located in the reporting country" in 2021.
[86] The exact percentage shares cannot be given here due to data confidentiality.

& Miedema, Life cycle assessment of cash payments, 2018) and by the number of cash POS transactions for each country. We estimated an assignment factor of 9.02E-07 for Germany, 3.78E-07 for Italy, and 7.02E-07 for Finland. Thus, on average each ATM/CRM is used for about 1.1 Mio. cash POS transactions in Germany, 2.6 Mio. cash POS transactions in Italy, and 1.4 Mio. cash POS transactions in Finland. The underlying assumption is that the whole ATM/CRM can be fully attributed to cash POS transactions. As we assume that all cash withdrawn or deposited is used for cash transactions as POS sooner or later, we deem this assumption valid even if, for example, cash is in the first step withdrawn as a gift.

Operation phase

In the operation phase, we covered the way to get to the ATM or CRM, the transport for servicing the machines, and their energy consumption.

To be able to pay in cash at a POS, people need to go to an ATM or CRM to withdraw money. Concerning the **transport** to reach the ATM or CRM, distances differ between the relevant countries: In Germany, the average distance is 1.7 km (Deutsche Bundesbank, 2023d), which can be used to approximate the distances in the other two countries, i.e. 2.6 km in Italy and 13.2 km in Finland.[87] It should be noted however, that this represents average distance to ATM/CRM, not average distance travelled to ATM/CRM which would be more suitable here. This can be important if one assumes that people living closer to an ATM/CRM withdraw money more often than people living further away, for instance. Then, the average distance travelled to ATM/CRM would be smaller than the average distance alone. However, on the contrary some literature also suggests that people living in rural areas with presumably longer distances to the next ATM/CRM withdraw money more often than people living in urban areas (Deutsche Bundesbank, 2020). This could, for example, be caused by the fact that people prefer to pay with cash in rural areas (ECB, 2020). Either way it should be kept in mind, that we used the average distance here since there were no data on the average distance travelled available.

In addition to the distance, we included the mode of transport that is used based on the mobility shares in the relevant countries (see Table 19). For example, 58% of the distances travelled to ATMs were done by car in Germany. However, not all ways travelled to ATMs can be attributed to cash withdrawals only, as they are often combined with the way to work or grocery shopping, for instance. Accounting for that, the last column of Table 19 states the share of ways travelled to ATM that can fully be attributed to cash withdrawal, i.e., is not related to any other purpose of travel. For instance, 10.37% of car travels to ATMs can be attributed to that purpose only, and 33% of ways travelled to ATMs by foot (Deutsche Bundesbank, 2022). This means that the distance travelled can be fully attributed to the cash withdrawal or deposit. Because of a lack of data for Italy and Finland, the same shares were assumed for these countries. Combining the average distance, mode of transport, and share travelled with the sole purpose of withdrawing or depositing cash, we calculated the average distance travelled per person and the mode to get to the next ATM or CRM that can be attributed to ATM/CRM usage. Since only those ways are considered that can be fully attributed to ATM withdrawal, these impacts are rather underestimated, since part of the remaining ways to get to ATM

[87] The numbers for Italy and Finland are approximated by the following formula: $\sqrt{\frac{Area\ in\ km^2}{Number\ of\ ATMs\ and\ CRMs}}$, which comes from a study by the Danish Payments Council (2016). Data for Finland were roughly confirmed by the Danish Payments Council (2016) who estimate the average distance to ATM in Finland to be 14.4 km. Thus, our estimate is rather conservative.

should also be accounted for. Our approach therefore constitutes a conservative assumption. For the transport by passenger car, we corrected for a load factor of 1.2 for Germany, 1.17 for Italy, and 1.74 for Finland (Eurostat, 2021).[88] Thus, we assumed that whenever people drive to the ATM/CRM for the only reason to withdraw or deposit money, 1.2, 1.17, and 1.74 people were also driving to the ATM. This means, less than 100% of the trip can be attributed to one person's withdrawals or deposits. However, trips travelled just to withdraw or deposit money at an ATM/CRM may not be representative in terms of vehicle load as they may not compare with a trip to go grocery shopping, drive to work or on vacation, for instance. Nevertheless, correcting for the average vehicle load constitutes the most conservative assumption once again. We also performed a sensitivity check fully excluding the way to ATM displayed in Chapter 6.2.1.

There are of course other options to receive cash, i.e., in shops or at the bank counter. Thus, part of the cash used for POS transactions was not retrieved from the ATM/CRM in the first place. Although these aspects were not considered explicitly, they do not cause an overestimation of ATM's/CRM's impact. This is because we used the number of withdrawals/deposits as stated in the payment statistics (ECB, 2022b). Since they do not include cash in shops or received at the bank counter, the number of withdrawals—and thus also ways travelled to ATM/CRM—is still correct. Instead, our approach implicitly overestimates the value of cash withdrawn, as part of these withdrawals were received at shops or bank counters. However, as the amount withdrawn does not affect the system's environmental impact, our estimations are not biased concerning this issue. This is because, implicitly, it is assumed that for cash in shops and at bank counters no additional ways are travelled.

TABLE 19: TRANSPORT MODE TO GET TO THE NEXT ATM/CRM

Transport type	Germany	Italy	Finland	Share of which this transport mode is solely used to get to an ATM/CRM[89]
Car	58%	62%	61%	10.34%
Motorcycle	-	3%	-	10.34%
Bike	11%	3%	7%	16.67%
By foot	21%	21%	23%	33.34%
Public transport	10%	11%	6%	12.5%
Other	-	-	3%	15%

Sources: Oxford Economics based on infas, DLR and IVT Research (2019), Mims (2022), Traficom (2023), Deutsche Bundesbank (2022)

[88] As no data on the average load factor for Finland were provided, it was approximated by the average load factor of Latvia constituting the second highest load factor stated with 1.74.

[89] We get the share from the table "Der Weg zu Geldautomat und Bankschalter", where we take the ratio of "gesonderter Gang von zu Hause aus" divided by "ingesamt" because this is the only category, where customers travel on purpose to get to an ATM or CRM, whereas in the other categories customers run other errands and in addition to that, include the way to an ATM or CRM (Deutsche Bundesbank, 2022).

In addition, **transport** for servicing one ATM or CRM was included. Based on the information of an ATM servicing company in Italy that stated that the average call rate per ATM/CRM is about 5 times per year and that the average distance travelled to the onsite service is 54 km per intervention, we calculated that about 260 km are driven to service one ATM/CRM per year. We assumed the same numbers for Germany and Finland.

The **energy** consumption of ATMs and CRMs differs because CRMs consume more energy than ATMs. In general, both machines are connected to power all day. They are either in an active state, where ATMs consume 310 watts (W) and CRMs 330 W or in an idle state, where ATMs consume 110 W and CRMs 120 W, as reported by the leading manufacturer. We know that an average withdrawal takes around 1:15 minutes and an average deposit takes around 4 minutes. To estimate the overall energy usage of an ATM, we used the withdrawal data from the Payment Statistics (ECB, 2022b)[90], stating that there were 1,590 Mio. withdrawals in Germany, 841 Mio. in Italy and 55 Mio. in Finland. Since withdrawals can be done at ATMs and CRMs and there is no differentiation in the Payment Statistics (ECB, 2022b), we assigned these numbers using the share of ATMs and CRMs in a country based on information from a leading ATM manufacturer.[91] Based on this information and the total number of ATMs per country, the total energy usage of ATMs per year per country could be estimated.

For the energy usage of CRMs, we summed up the share of CRM withdrawals (46% of all withdrawals) and the total number of deposits (ECB, 2022b).[92] Again, based on this information and the total number of CRMs per country, the total energy usage of CRMs per year per country could be estimated. As before, all quantities are displayed in the detailed inventory table in Appendix 1.

To **assign** all the usage information to one cash POS transaction, we divided them by the total number of cash POS transactions per year in each country. The total number of cash POS transactions is around 9 billion in Germany, around 12 billion in Italy and around 275 million in Finland.

End-of-life phase

In the end-of-life phase, we modelled the waste treatment best corresponding to the inputs. One of the leading ATM manufacturers confirmed that ATMs and CRMs are not recycled.

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[90] To cover all ATM withdrawals at terminals located in the reporting countries, we take a sum over the following variables in Table 7b from the Payment Statistics (ECB, 2022b) for all respective countries: "at terminals provided by resident PSPs with cards issued by resident PSPs – ATM cash withdrawals at terminal located in the reporting country" + "at terminals provided by resident PSPs with cards issued by non-resident PSPs – ATM cash withdrawals at terminal located in the reporting country" + "at terminals provided by non-resident PSPs with cards issued by resident PSPs – ATM cash withdrawals at terminal located in the reporting country".

[91] The source estimated the share of ATMs to be 54% of all machines and thus 46% CRMs.

[92] To cover all ATM deposits at terminals located in the reporting countries, we take a sum over the following variables in table 7b from the Payment Statistics (ECB, 2022b) for all respective countries: "at terminals provided by resident PSPs with cards issued by resident PSPs – ATM cash deposits at terminal located in the reporting country" + "at terminals provided by resident PSPs with cards issued by non-resident PSPs – ATM cash deposits at terminal located in the reporting country" + "at terminals provided by non-resident PSPs with cards issued by resident PSPs – ATM cash deposits at terminal located in the reporting country".

TABLE 20: INVENTORY TABLE FOR ATMS/CRMS

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Production of one ATM/CRM					
Input – ATM/CRM	Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	1 piece			Hanegraaf et al. (2018)
Manufacturing process	Assembly of liquid crystal display, auxiliaries and energy use {GLO}| market for assembly of liquid crystal display, auxiliaries and energy use | Cut-off, U	5.1 kg			Own selection of manufacturing process (value based on material input)
Input – ATM/CRM	Computer, desktop, without screen {GLO}| market for computer, desktop, without screen | Cut-off, U	1 piece			Hanegraaf et al. (2018)
Input – ATM/CRM	Reinforcing steel {GLO}| market for reinforcing steel | Cut-off, U	700 kg			Hanegraaf et al. (2018)
Manufacturing process	Metal working, average for steel product manufacturing {RER}| metal working, average for steel product manufacturing | Cut-off, U	700 kg			Own selection of manufacturing process (value based on material input)
Packaging (PVC straps)	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	57.8 g			Own assumption based on YouTube (2014)
Manufacturing process	Injection moulding {RER}| market for injection moulding | Cut-off, U	57.8 g			Own selection of manufacturing process (value based on material input)
Packaging	Kraft paper {RER}| market for kraft paper | Cut-off, U	2.3 kg			Own assumption based on YouTube (2014)
Packaging (plastic wrap)	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	0.441 kg			Own assumption based on YouTube (2014)
Packaging	EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, U	1 piece			Own assumption based on YouTube (2014)
Transport from production to customer	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	239.3885 tkm	449.1314 tkm	347.5951 tkm	Based on Eurostat (2021a)
Assignment factor of one ATM/CRM (production) $= \frac{\left(\frac{nr.\,of\ ATMs\ and\ CRMs}{lifespan}\right)}{nr.\,of\ cash\ POS\ transactions\ per\ year}$		9.02E-07	3.78E-07	7.02E-07	Based on ECB (2022b) and (2022a), Hanegraaf et al. (2018)
Operation of all ATMs/CRMs per year – energy usage, transport for servicing and transport to reach the next ATM/CRM					

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Energy usage – ATM	Electricity, low voltage {X[93]}| market for electricity, low voltage | Cut-off, U	45654024.82 kWh	25582689.22 kWh	1130595.84 kWh	Primary source – ATM/CRM manufacturer
Energy usage – CRM	Electricity, low voltage {X}| market for electricity, low voltage | Cut-off, U	44455428.95 kWh	26443468.45 kWh	1105436.91 kWh	Primary source – ATM/CRM manufacturer
Transport for servicing	Transport, passenger car, EURO 5 {RER}| market for transport, passenger car, EURO 5 | Cut-off, U	20981782.08 km	11813409.63 km	502074.45 km	Primary source – ATM/CRM maintenance provider
Transport to reach the next ATM/CRM by car[94]	Transport, passenger car {RER}| market for transport, passenger car | Cut-off, U	147521458.17 km	146938594.54 km	28217169.66 km	infas, DLR and IVT Research (2019), Mims (2022), Traficom (2023), Deutsche Bundesbank (2022b)
Transport to reach the next ATM/CRM by bicycle	Transport, passenger, bicycle {CH}| transport, passenger, bicycle | Cut-off, U	59383930.80 km	13487471.96 km	9135033.60 km	infas, DLR and IVT Research (2019), Mims (2022), Traficom (2023), Deutsche Bundesbank (2022b)
Transport to reach the next ATM/CRM by public transport (bus)	Transport, regular bus {CH}| transport, regular bus | Cut-off, U	29632700.00 km	37016514.87 km	5860800.00 km	infas, DLR and IVT Research (2019), Mims (2022), Traficom (2023), Deutsche Bundesbank (2022b)
Transport to reach the next ATM/CRM by motor scooter	Transport, passenger, motor scooter {CH}| transport, passenger, motor scooter | Cut-off, U	-	8318620.43 km	-	infas, DLR and IVT Research (2019), Mims (2022), Traficom (2023), Deutsche Bundesbank (2022b)
Assignment factor of electricity to count banknotes for transactions per year (small CCM operation) $= \frac{1}{nr. of\ cash\ POS\ transactions\ per\ year}$		1.11541E-10	8.31209E-11	3.62976E-09	Based on ECB (2022b) and (2022a)
End-of-life of one ATM/CRM					
Output – ATM/CRM	Used liquid crystal display {GLO}| market for used liquid crystal display | Cut-off, U	5.1 kg			Own selection of end-of-life process (value based on material input)
Output – ATM/CRM (computer)	Used industrial electronic device {CH}| market for used industrial electronic device | Cut-off, U	11.3 kg			Own selection of end-of-life process (value based on material input)
Output – ATM/CRM	Waste reinforcement steel {CH}| market for waste reinforcement steel | Cut-off, U	700 kg			Own selection of end-of-life process (value based on material input)
Packaging (PVC straps)	Waste polypropylene {Europe without Switzerland}| market group for waste polypropylene | Cut-off, U	57.8 g			Own selection of end-of-life process (value based on material input)

[93] X represents country specific processes for Germany, Italy, and Finland.

[94] We excluded „walking" and „other" from our analysis.

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Packaging (kraft paper)	Waste paperboard {Europe without Switzerland}| market group for waste paperboard | Cut-off, U	2.3 kg			Own selection of end-of-life process (value based on material input)
Packaging (packaging film)	Waste polyvinylchloride {Europe without Switzerland}| market group for waste polyvinylchloride | Cut-off, U	0.441 kg			Own selection of end-of-life process (value based on material input)
Packaging (euro pallet)	Waste wood, untreated {DE}| market for waste wood, untreated | Cut-off, U	22 kg			Own selection of end-of-life process (value based on material input)
Assignment factor of one ATM/CRM (production) $= \frac{\left(\frac{nr.\,of\ ATMs\ and\ CRMs}{lifespan}\right)}{nr.\,of\ cash\ POS\ transactions\ per\ year}$		9.02E-07	3.78E-07	7.02E-07	Based on ECB (2022b) and (2022a), Hanegraaf et al. (2018)

Source: Oxford Economics

4.2.7 Subsystem 11: Data centres – cash system

The inventory of data centres was explained in detail in Chapter 4.1.3 for digital payments. Therefore, we only elaborate on the differences between data centres for the cash and digital payment systems in this paragraph. According to interviews with technical experts from PSPs responsible for the data processing of terminals and ATMs to banks, we confirmed that the general procedure to process a deposit or a withdrawal is comparable to a digital POS transaction. According to expert interviews, most people withdraw money from their house bank. Hence, intermediate steps such as authorisation and clearing systems at other banks do not occur. Therefore, energy consumption should be less than the one of a digital POS transaction. For the calculation, we relied on the expert guess that the energy consumption for the back-end processing of an ATM/CRM is 25% of the one for processing a digital POS transaction. This results in an average **energy** consumption of 0.3 Wh per withdrawal/deposit in Germany, 0.4 Wh per withdrawal/deposit in Italy, and 0.4 Wh per withdrawal/deposit in Finland.

The **assignment factor** for the inputs and outputs are calculated the same way as in Subsystem 3: Data centres for digital payments, using the different energy consumptions and the total number of cash deposits and withdrawals at ATMs and CRMs instead of digital POS transactions. In the operation phase, the assignment is the reciprocal of the number of cash POS transactions per year and country.

TABLE 21: INVENTORY TABLE FOR DATA CENTRES – CASH SYSTEM

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Production of one data centre – IT equipment, cooling infrastructure, power supply					
Input – IT equipment, cooling infrastructure, power supply	Steel, unalloyed {GLO}| market for steel, low-alloyed | Cut-off, U	223.02 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Metal working, average for steel product manufacturing {GLO}| market for metal working, average for steel product manufacturing | Cut-off, U	223.02 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Cast iron {GLO}| market for cast iron | Cut-off, U	130.98 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Metal working, average for metal product manufacturing {GLO}| market for metal working, average for metal product manufacturing | Cut-off, U	130.98 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	120.81 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	120.81 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	45.78 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Metal working, average for aluminium product manufacturing {GLO}| market for metal working, average for aluminium product manufacturing | Cut-off, U	45.78 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Printed wiring board, mounted mainboard, desktop computer, Pb free {GLO}| market for printed wiring board, mounted mainboard, desktop computer, Pb free | Cut-off, U	70.22 t			Based on Fichter and Hintemann (2014)
Input – IT equipment, cooling infrastructure, power supply	Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U	30.19 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	30.19 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Synthetic rubber {GLO}| market for synthetic rubber | Cut-off, U	28.79 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	28.79 t			Own selection of manufacturing process (value based on material input)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Input – IT equipment, cooling infrastructure, power supply	Epoxy resin, liquid {RoW}| market for epoxy resin, liquid | Cut-off, U	11.23 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	11.23 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Lead {GLO}| market for lead | Cut-off, U	12.33 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Metal working, average for metal product manufacturing {GLO}| market for metal working, average for metal product manufacturing | Cut-off, U	12.33 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Ceramic tile {GLO}| market for ceramic tile | Cut-off, U	9.55 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	9.55 t			Own selection of manufacturing process (value based on material input)
Input – IT equipment, cooling infrastructure, power supply	Glass fibre {GLO}| market for glass fibre | Cut-off, U	8.75 t			Based on Fichter and Hintemann (2014)
Input – IT equipment, cooling infrastructure, power supply	Sulfuric acid {RoW}| market for sulfuric acid | Cut-off, U	5.17 t			Based on Fichter and Hintemann (2014)
Input – IT equipment, cooling infrastructure, power supply	Silicone product {RoW}| market for silicone product | Cut-off, U	3.98 t			Based on Fichter and Hintemann (2014)
Manufacturing process	Injection moulding {GLO}| market for injection moulding | Cut-off, U	3.98 t			Own selection of manufacturing process (value based on material input)
Assignment factor of material of one data centre (production) $= \frac{\left(\frac{nr.\,of\ data\ centre\ for\ all\ ATM\&CRM\ withdrawals\&deposits}{average\ lifespan\ of\ materials}\right)}{nr.\,of\ ATM\&CRM\ withdrawals\&deposits}$		8.8190E-13	4.4197E-13	1.2888E-12	Based on ECB (2022b), Fichter and Hintemann (2014) and Lindgreen et al. (2017)
Production of one data centre – IT building					
Input – building	Building, hall, steel construction {CH}| building construction, hall, steel construction | Cut-off, U	1242.86 m^2			Based on Laurent et al. (2020) and Lindgreen et al. (2017)
Assignment factor of building of one data centre (production) $= \frac{\left(\frac{nr.\,of\ data\ centre\ for\ all\ POS\ transactions}{lifespan\ of\ building}\right)}{nr.\,of\ digital\ POS\ transactions\ per\ year}$		2.0284E-13	1.0165E-13	2.9641E-13	Based on ECB (2022b), Laurent et al. (2020) and Fichter and Hintemann (2014)

Input	Dataset	Amount			Source
		Germany	Italy	Finland	
Operation of one data centre per year – water consumption for cooling and energy					
Water consumption for cooling	Water, cooling, unspecified natural origin, ReR	9.82E+02 m^2	6.60E+02 m^2	4.41E+01 m^2	Siddik, Shehabi and Marston (2021)
Energy	Data centre average electricity mix	545,548.95 kWh	366,883.81 kWh	24,498.57 kWh	Based on Nexi (2023), Worldline (2023) and primary source – PSP
Assignment factor of water consumption and energy (data centre operation) $= \frac{1}{nr. of\ cash\ POS\ transactions\ per\ year}$		1.12E-10	8.31E-11	3.63E-09	Based on ECP (2022b) and (2022a)
Operation of one transaction (withdrawal/deposit) processed – internet access					
Transmission of data via the internet	Internet access, work, 0.2 Mbit/s {CH}| internet access, work, 0.2 Mbit/s | Cut-off, U	0.02083 h			Based on the payment terminal subsystem
Assignment factor of internet access (operation)		1			
End-of-life of one data centre					
Overall output	Used industrial electronic device {CH}| treatment of used industrial electronic device, manual dismantling | Cut-off, U	701 t			Own selection of end-of-life process (value based on material input)
Transport to the waste treatment facility	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	3622.768 tkm			Based on Eurostat (2021a)
Assignment factor of material of one data centre (production) $= \frac{\left(\frac{nr. of\ data\ centre\ for\ all\ ATM\&CRM\ withdrawals\&deposits}{average\ lifespan\ of\ materials}\right)}{nr. of\ ATM\&CRM\ withdrawals\&deposits}$		8.8190E-13	4.4197E-13	1.2888E-12	Based on ECB (2022b), Fichter and Hintemann (2014) and Lindgreen et al. (2017)

Source: Oxford Economics

5. LIFE-CYCLE ASSESSMENT—IMPACT ASSESSMENT

In this chapter, we present and analyse the results of our impact assessment. The environmental impact of a typical transaction—both cash and digital—at POS is calculated using the ReCiPe 2016 (H) Midpoint method. This method was chosen to ensure comparability with previous studies on the environmental impact of payment systems.[95] In addition, we used the Midpoint version of ReCiPe 2016 instead of the Endpoint method, as the ISO norm prohibits the weighting of different impact categories in comparative LCA studies.

We start our analysis by looking at the impact of each payment system on its own in Chapter 5.1. The results are presented first for all impact categories of the ReCiPe 2016 method. Afterwards, we focus on three selected impact categories which we examine in more detail. In Chapter 5.2, we continue our analysis by comparing the digital and cash payment systems. Again, we start by looking at all impact categories before examining three selected ones more closely.

All absolute characterisation results are contained in Appendix 2.

5.1 CONTRIBUTION ANALYSIS

5.1.1 Digital POS Payment

The characterisation results of the digital payment system can be found in Table 22.

TABLE 22: OVERALL CHARACTERISATION RESULTS OF ONE DIGITAL POS PAYMENT FOR EACH COUNTRY

Impact category	Unit	Germany	Italy	Finland
Global Warming	kg $C0_2$ eq	3.055E-03	5.39E-03	2.20E-03
Stratospheric ozone depletion	kg CFC_{11} eq	1.423E-09	2.22E-09	1.09E-09
Ionizing radiation	kBq Co-60 eq	3.845E-05	5.50E-05	4.07E-05
Ozone formation, Human health	kg NO_x eq	8.956E-06	1.59E-05	5.91E-06
Fine particulate matter formation	kg PM2.5 eq	4.660E-06	9.57E-06	3.69E-06
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.294E-06	1.65E-05	6.13E-06
Terrestrial acidification	kg SO2 eq	1.140E-05	2.16E-05	8.90E-06
Freshwater eutrophication	kg P eq	3.211E-07	6.84E-07	2.52E-07
Marine eutrophication	kg N eq	1.084E-07	2.70E-07	6.37E-08
Terrestrial ecotoxicity	kg 1,4-DCB	3.047E-02	5.66E-02	2.77E-02
Freshwater ecotoxicity	kg 1,4-DCB	1.080E-05	2.81E-05	9.19E-06
Marine ecotoxicity	kg 1,4-DCB	5.547E-05	1.47E-04	4.96E-05

[95] See e.g. Hanegraaf et al. (2018) and Lindgreen et al. (2023).

Impact category	Unit	Germany	Italy	Finland
Human carcinogenic toxicity	kg 1,4-DCB	5.757E-05	1.21E-04	4.98E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	2.300E-03	4.39E-03	2.04E-03
Land use	m2a crop eq	5.685E-04	5.11E-04	2.78E-04
Mineral resource scarcity	kg Cu eq	4.934E-05	1.33E-04	4.45E-05
Fossil resource scarcity	kg oil eq	8.574E-04	1.42E-03	6.12E-04
Water consumption	m3	3.066E-05	4.88E-05	2.27E-05

Source: Oxford Economics

As an alternative to the characterisation values, the results can also be presented in form of normalised results (see Box 1).

BOX 1: NORMALISED RESULTS

Normalised values relate the impact of an average payment to the average emission or contribution per person within the respective impact category. It is important to keep in mind that a large, normalised impact on indicator A is not necessarily more harmful to the environment than a small, normalised impact on indicator B. It simply relates the value to the average per-person emissions in that category in 2010. The following values are used for normalisation in ReCiPE 2016:

- Fossil resource scarcity: oil equivalents (eq.) per person in 2010
- Mineral resource scarcity: kg Cu (copper) eq. per person in 2010
- Marine eutrophication: kg nitrogen (N) to marine water eq. per person in 2010
- Marine ecotoxicity: kg 1,4-Dichlorobenzene (DCB) emitted to seawater eq. per person in 2010
- Land use: m^2·annual crop eq. per person in 2010
- Terrestrial acidification: kg Sulfur dioxide (SO2) eq. per person in 2010
- Terrestrial ecotoxicity: kg 1,4-DCB emitted to industrial soil eq. per person in 2010
- Freshwater eutrophication: kg Phosphorus (P) to freshwater eq. per person in 2010
- Freshwater toxicity: kg 1,4-DCB emitted to freshwater eq. per person in 2010
- Water consumption: m^3 consumed per person in 2010
- Global warming: kg CO_2 eq. per person in 2010
- Human non-carcinogenic toxicity: kg 1,4-DCB emitted to urban air eq. per person in 2010
- Human carcinogenic toxicity: kg 1,4-DCB emitted to urban air eq. per person in 2010
- Ionizing radiation: Kilobecquerel (kBq) Co-60 emitted to air eq. per person in 2010
- Stratospheric ozone depletion: kg Trichlorofluoromethane (CFC11) eq. per person in 2010
- Ozone formation: kg nitric oxide (NOx) eq. per person in 2010
- Fine particulate matter (PM) formation: kg PM2.5 eq. per person in 2010

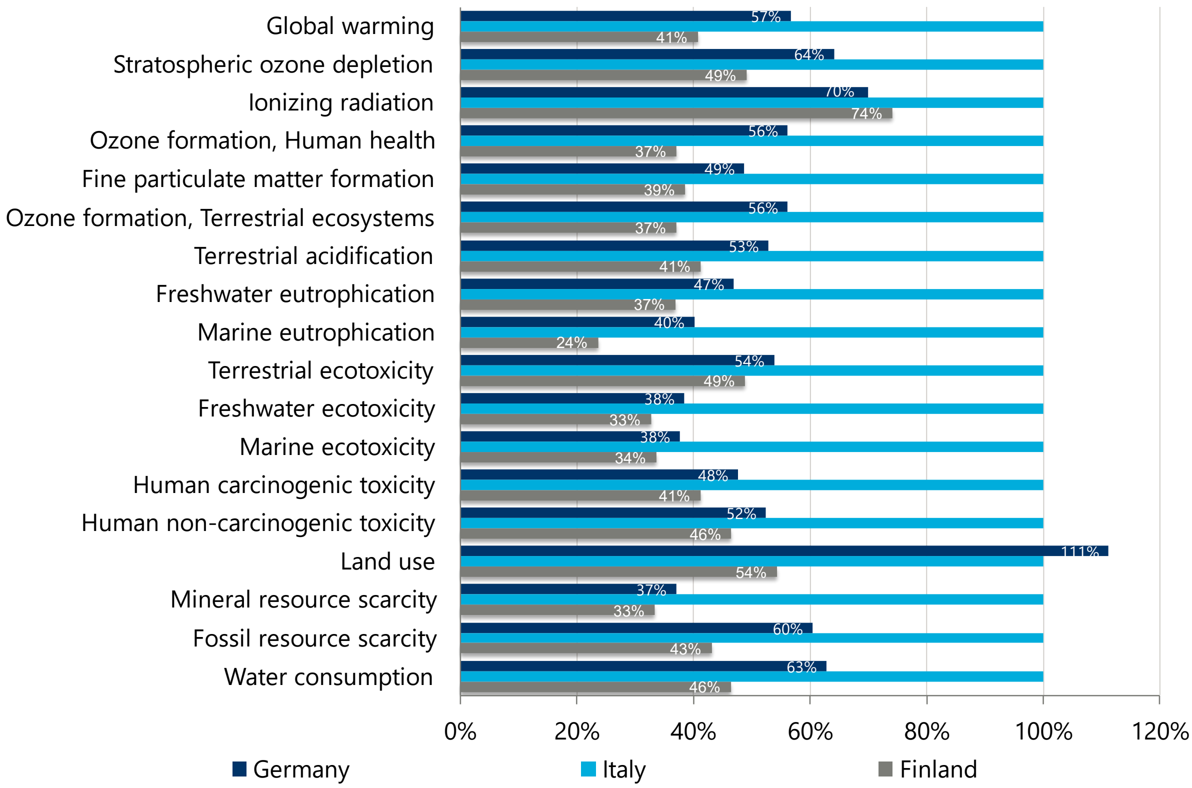
All values refer to global estimates. For more information on the approach and precise values used see National Institute for Public Health and the Environment (2020) and PRé Sustainability (2022).

The robustness of these indicators varies depending on the research behind each impact category. Thus, it would be wrong to assume that all the results for each impact category are similarly robust.

Considering the limitations of normalised results, we estimated that the largest normalised impact of one digital POS payment occurs in the impact category “human carcinogenic toxicity.” In addition, other categories with a relatively large impact are “terrestrial ecotoxicity”, “marine ecotoxicity”, “fossil resource scarcity”, “global warming”, “ozone formation, human health”, “fine particulate matter formation”, “ozone formation, terrestrial ecosystems”, terrestrial acidification”, “freshwater eutrophication”, and “freshwater ecotoxicity.” Our results suggest that a digital POS payment only has a relatively minor impact on the categories “stratospheric ozone depletion”, “ionizing radiation”, “marine eutrophication”, “human non-carcinogenic toxicity”, “land use”, “mineral resource scarcity”, and “water consumption.”

Figure 19 presents the relative estimated impacts across countries by impact category.

FIGURE 19: IMPACT CATEGORIES IN COUNTRY COMPARISON FOR ONE DIGITAL POS PAYMENT

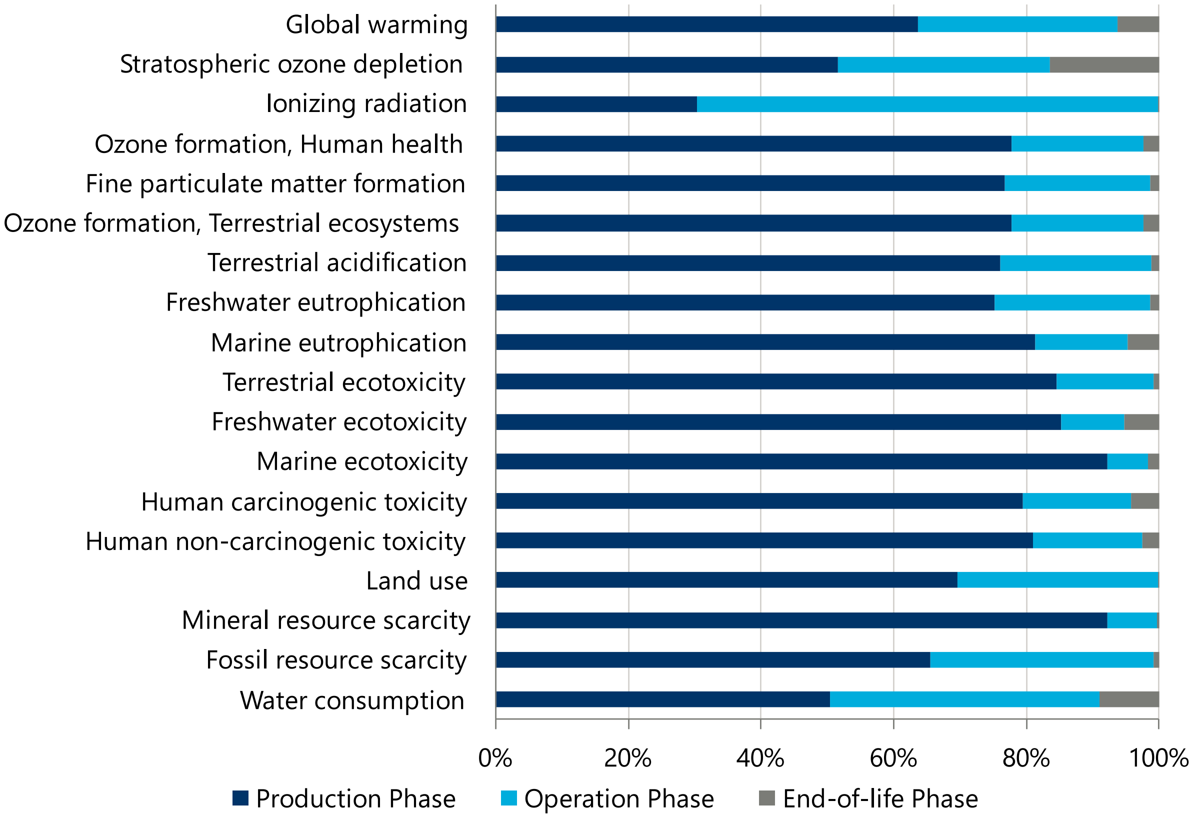


Source: Oxford Economics

The estimated impact was largest in Italy across all impact categories except land use. Here, the impact was larger in Germany. For the other impact categories the estimates for Germany typically rank in the middle. For ionizing radiation, stratospheric ozone depletion, and water consumption, the estimated impact in Germany is 70, 64, and 63% of the estimated impact in Italy, for instance. The difference is largest for mineral resource scarcity, marine ecotoxicity, and freshwater ecotoxicity where the impact in Germany is only 37, 38, and 38% of that in Italy. The estimated impact is typically lowest in Finland. Here, the estimated impact on marine eutrophication, freshwater ecotoxicity, and mineral resource scarcity are only 24, 33, and 33% of the impact estimated in Italy. Only considering ionising radiation, Finland ranks in the middle while the estimated impact is lowest in Germany.

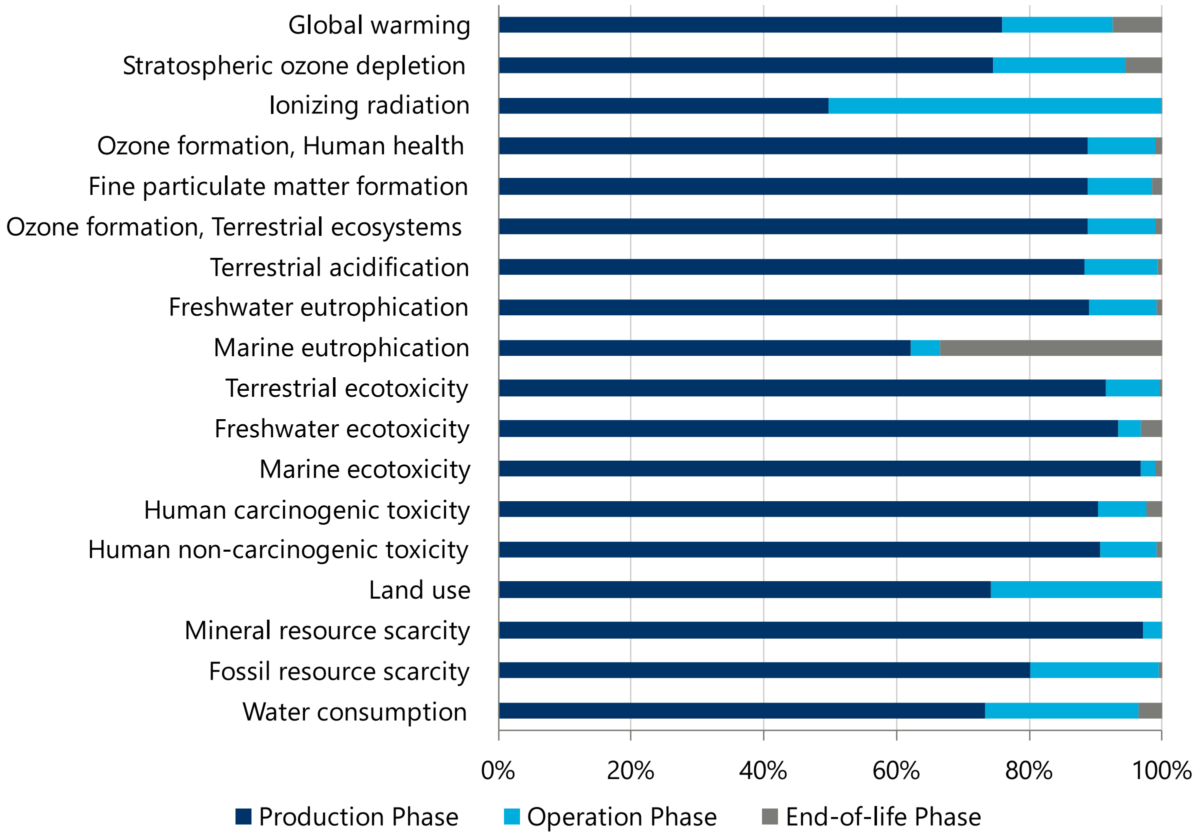
The life-cycle stage contributions of one digital POS payment in the three countries are shown in Figure 20 to Figure 22.

FIGURE 20: LIFE-CYCLE STAGE CONTRIBUTION OF ONE DIGITAL POS PAYMENT IN GERMANY



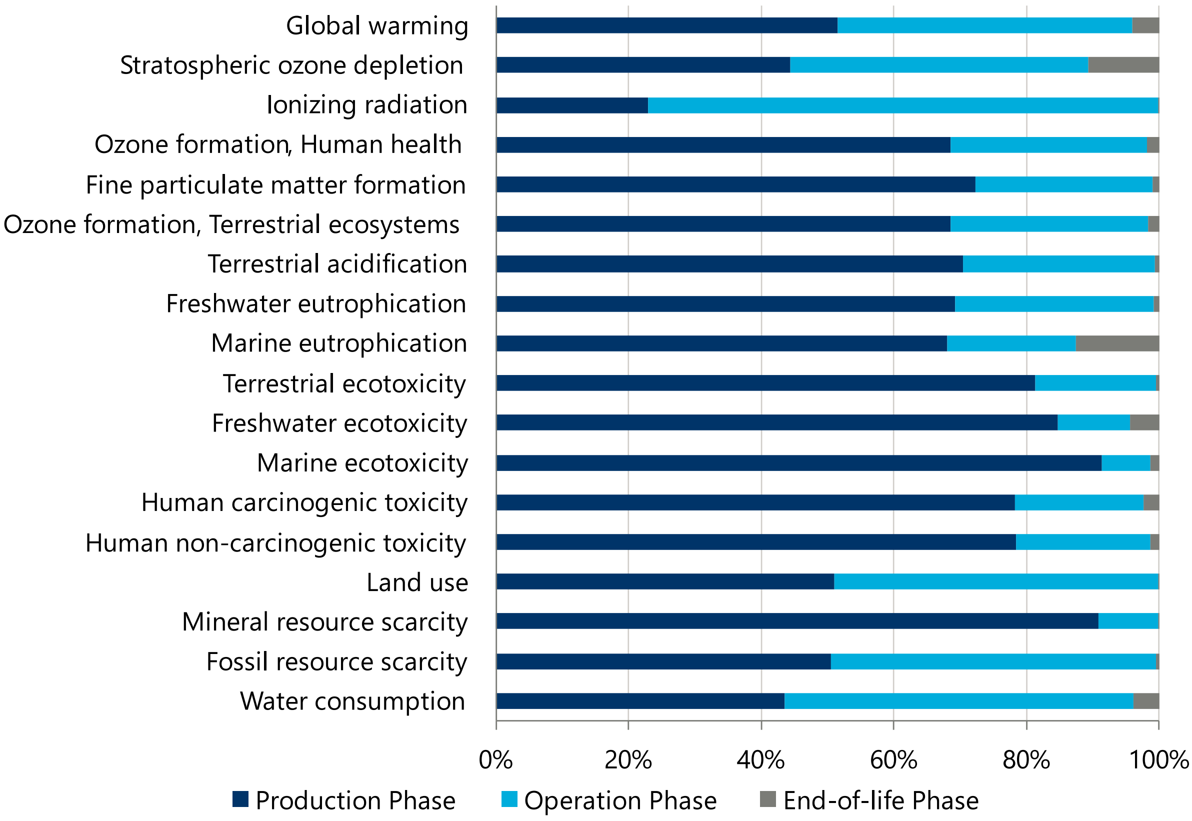
Source: Oxford Economics

FIGURE 21: LIFE-CYCLE STAGE CONTRIBUTION OF ONE DIGITAL POS PAYMENT IN ITALY



Source: Oxford Economics

FIGURE 22: LIFE-CYCLE STAGE CONTRIBUTION OF ONE DIGITAL POS PAYMENT IN FINLAND



Source: Oxford Economics

First, it is noticeable that for almost all impact categories, in Germany and Italy, the largest effect is caused in the production phase followed by the operation phase. According to our results, the production phase is responsible for between around 50% to 90% of the total lifetime impact in most categories in Germany. In Italy, the production phase causes between around 60% to 95% of the total lifetime impact in most categories. One exception in both countries is "ionizing radiation" for which the operation phase causes the largest impact. In comparison, the operation phase has a relatively larger impact in Finland compared to Germany and Italy. In Finland, the operation phase is responsible for the largest impact in the categories "stratospheric ozone depletion", "ionizing radiation", and "water consumption". The impact of the end-of-life phase is small or negligible in most cases. One exception is the category "marine eutrophication" in Italy, where the end-of-life phase is responsible for a third of the total impact.

Concerning the production phase in Germany and Finland, our results show that the main impact in this phase is generally caused by data centre and terminal production, followed by card production. In Germany, the largest impact is caused by data centre production in some categories and by terminal production in others. For example, terminal production is the most relevant factor in the categories "marine ecotoxicity", "freshwater eutrophication", and "freshwater ecotoxicity". In Italy, the production phase of terminals is the most important factor across all categories measured.

To produce the data centre, our analysis shows that especially the printed wiring board and copper used are largely responsible for the environmental impact. The key terminal inputs causing the environmental impact described are the printed wiring board, the integrated circuits, and the power supply unit. Further important elements include the lithium-ion battery, the polycarbonate casing, copper, and the LED display. For cards, transport by aeroplane, the kraft paper packaging, and copper inputs appear to be the most important factors driving the environmental impact in the production phase.

The main impact in the operation phase is generally largely caused by data centre usage and partly by terminal usage in all three countries. A significant part of the impact of data centre contribution in this phase is caused by its electricity usage while the impact of terminal usage is mainly due to receipt printing as mentioned in the previous chapter.

The largest contributors to the impact of the end-of-life phase are the terminals' and cards' end-of-life. While in Germany and Finland, the end-of-life of the paper receipt is most decisive, the packaging of the terminal is most relevant in Italy. For cards, the most important elements during the end-of-life phase are the waste paperboard, waste PVC, and waste polystyrene mainly used for the card body and packaging.

5.1.2 Cash POS Payment

We now look at the environmental impact of the cash payment system. Similarly, the characterisation results for the specific impact categories per country are shown in Table 23.

TABLE 23: OVERALL CHARACTERISATION RESULTS OF ONE CASH POS PAYMENT FOR EACH COUNTRY

Impact category	Unit	Germany	Italy	Finland
Global Warming	kg $C0_2$ eq	1.807E-02	1.15E-02	5.18E-02
Stratospheric ozone depletion	kg CFC_{11} eg	8.036E-09	5.27E-09	1.87E-08
Ionizing radiation	kBq Co-60 eq	1.134E-04	4.79E-05	3.65E-04
Ozone formation, Human health	kg NO_x eq	4.691E-05	3.64E-05	1.51E-04
Fine particulate matter formation	kg PM2.5 eq	3.254E-05	2.59E-05	7.05E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	4.957E-05	3.87E-05	1.61E-04
Terrestrial acidification	kg SO2 eq	8.518E-05	7.06E-05	1.68E-04
Freshwater eutrophication	kg P eq	1.710E-06	8.02E-07	1.85E-06
Marine eutrophication	kg N eq	1.490E-06	1.33E-06	2.11E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.867E-01	3.56E-01	5.73E-01
Freshwater ecotoxicity	kg 1,4-DCB	5.863E-05	4.27E-05	1.63E-04
Marine ecotoxicity	kg 1,4-DCB	2.621E-04	2.20E-04	5.20E-04
Human carcinogenic toxicity	kg 1,4-DCB	9.214E-04	5.77E-04	1.74E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.222E-02	1.97E-02	3.04E-02
Land use	m2a crop eq	1.085E-03	8.86E-04	2.06E-03
Mineral resource scarcity	kg Cu eq	3.418E-04	2.62E-04	5.42E-04

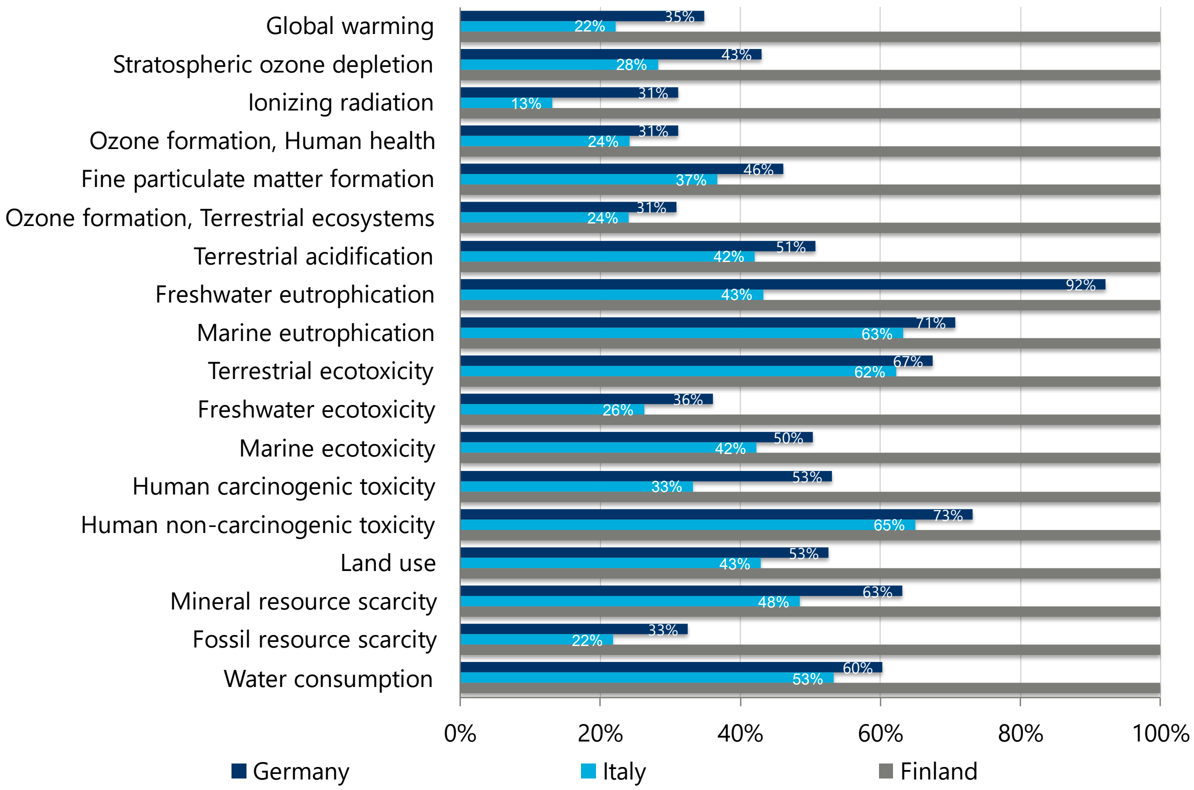
Impact category	Unit	Germany	Italy	Finland
Fossil resource scarcity	kg oil eq	4.788E-03	3.22E-03	1.47E-02
Water consumption	m3	1.856E-04	1.64E-04	3.08E-04

Source: Oxford Economics

As for the digital payment system, the largest normalised impact of the cash payment system is estimated in the category “human carcinogenic toxicity” across all three countries, followed by “terrestrial ecotoxicity.” Other categories with noticeable impacts are “global warming”, “ozone formation, human health”, “fine particulate matter formation”, “ozone formation, terrestrial ecosystems”, “terrestrial acidification”, “freshwater eutrophication”, “freshwater ecotoxicity”, “marine ecotoxicity”, and “fossil resource scarcity.”

Furthermore, the country comparison for the impact of one cash POS transaction is displayed in Figure 23, where Finland is set to 100%. This is different to Figure 19, where Italy was set to 100%. However, the decision rule is the same as before, which to set the country to 100%, which has the largest impact in most of the categories.

FIGURE 23: IMPACT CATEGORIES IN COUNTRY COMPARISON FOR ONE CASH POS PAYMENT

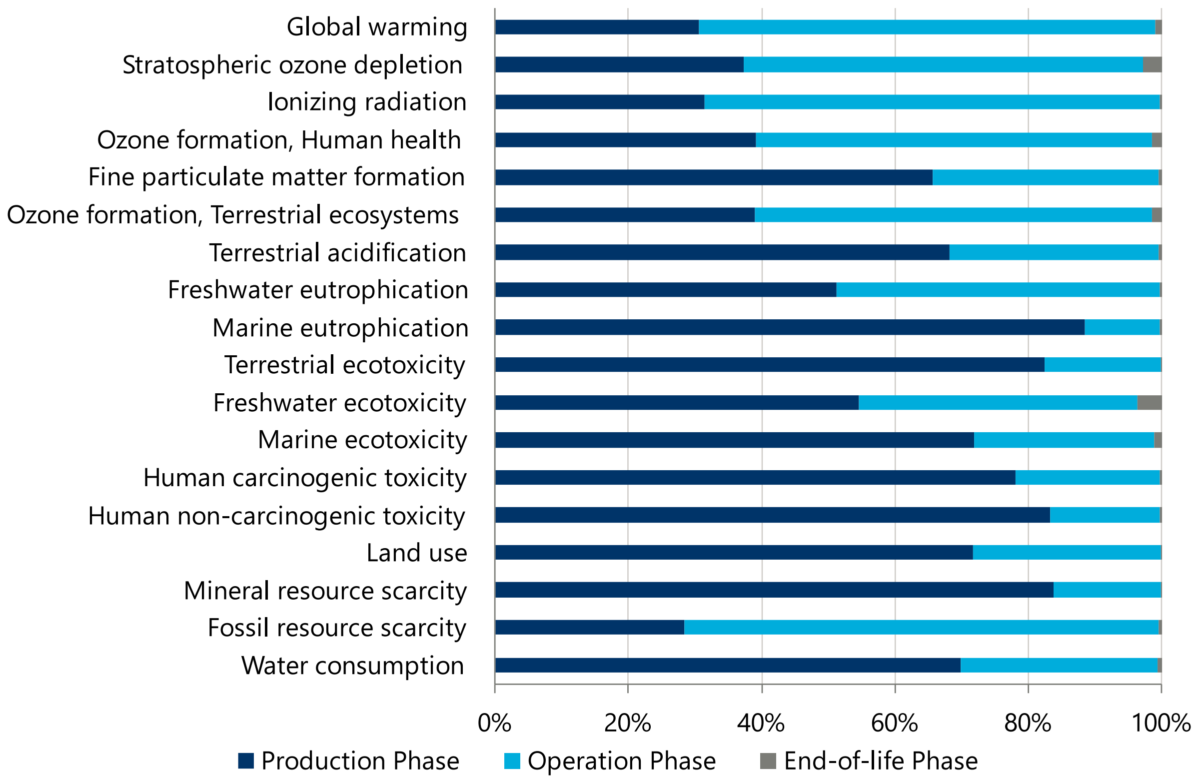


Source: Oxford Economics

The largest impact of an average cash transaction at POS on most categories is estimated in Finland, followed by Germany. Considering freshwater eutrophication, for instance, the estimated impact in Germany is 92% of that in Finland. Other examples include human non-carcinogenic toxicity with 73% of the estimate for Finland and ozone formation, terrestrial ecosystems with 31% of the estimated impact. Furthermore, the smallest impact was estimated in Italy across all impact categories. The estimated impact on ionizing radiation, global warming, and freshwater ecotoxicity in Italy, for example, is just 13, 22, and 43% of the estimated impact in Finland.

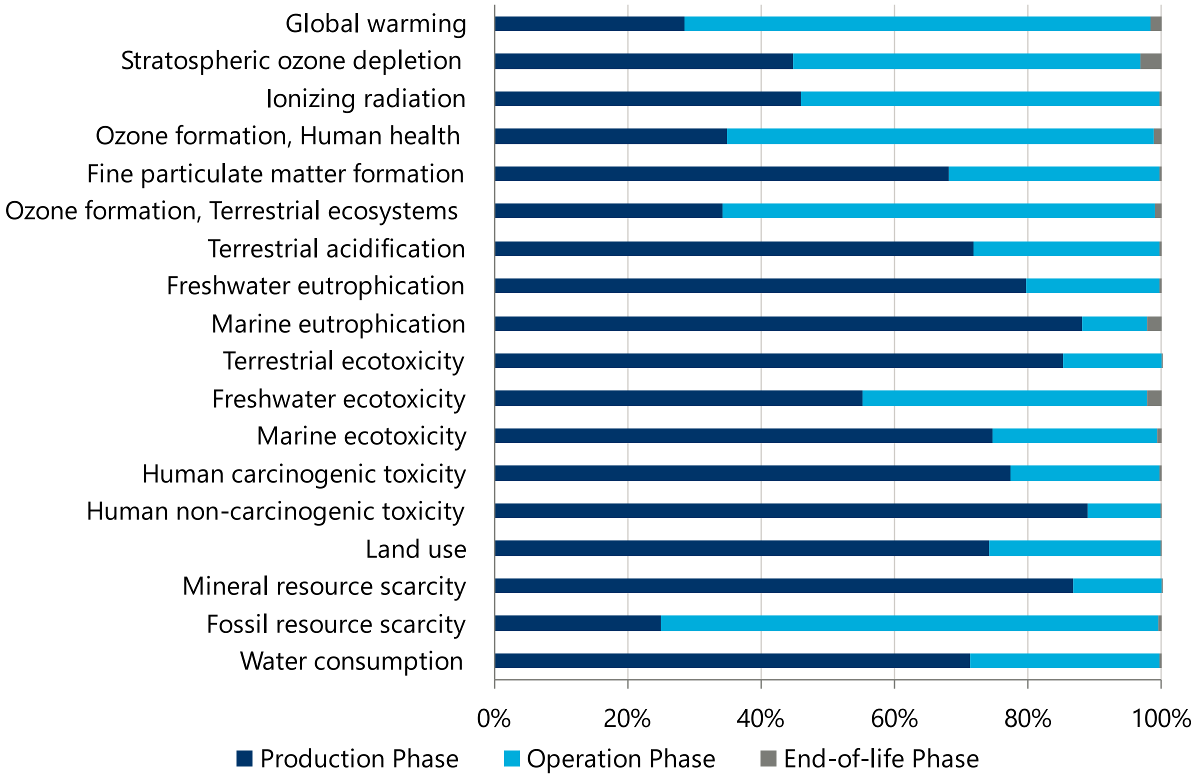
The life-cycle stage contributions of one cash POS payment in the three countries are shown in Figure 24 to Figure 26.

FIGURE 24: LIFE-CYCLE STAGE CONTRIBUTION OF ONE CASH POS PAYMENT IN GERMANY



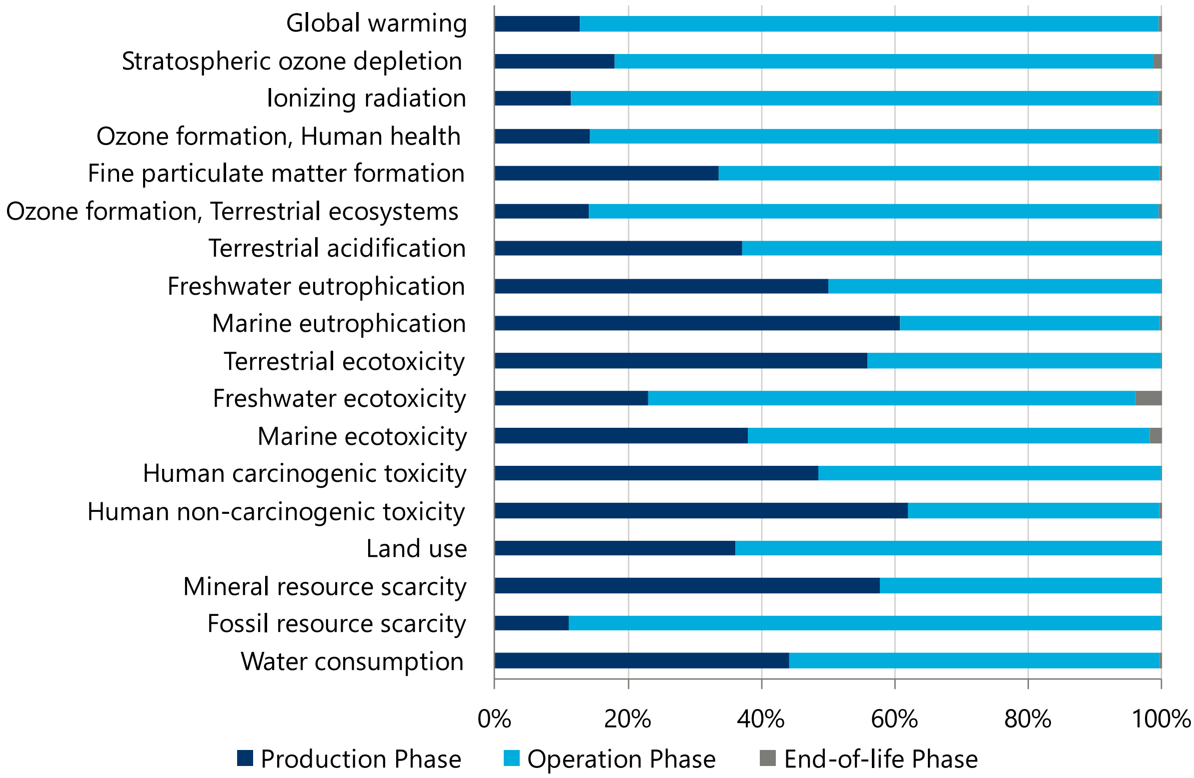
Source: Oxford Economics

FIGURE 25: LIFE-CYCLE STAGE CONTRIBUTION OF ONE CASH POS PAYMENT IN ITALY



Source: Oxford Economics

FIGURE 26: LIFE-CYCLE STAGE CONTRIBUTION OF ONE CASH POS PAYMENT IN FINLAND



Source: Oxford Economics

The figures show that in Germany and Italy, the production and operation phases in the cash payment system cause the largest impact. While in some categories our results show that the production phase is more important, in others the operation phase contributes a larger impact. In comparison, the operation phase is the most relevant in most categories in Finland. The end-of-life phase only has a very minor impact across all categories in the three countries.

During the production phase, we estimate that the ATM/CRM subsystem is the main contributor in Germany, especially for the impact on human carcinogenic toxicity, followed by coin production with a large impact on human carcinogenic toxicity, terrestrial, and marine ecotoxicity, and the cash transport subsystem with a large impact on human carcinogenic toxicity. In Italy, the largest impact in the production phase is caused by the coin subsystem, followed by the ATM/CRM and the cash transport subsystems. In Finland, the largest contributors during the production phase are also the ATM/CRM subsystem, the cash transport subsystem, and the coins subsystem.

The relatively larger impact of the cash payment system's operation phase in Finland compared to Germany and Italy is mainly driven by the ATM/CRM subsystem, more specifically by the distance travelled by the customer to the ATM/CRM to withdraw cash. The dominance of the operation phase in Finland can be explained by the much larger calculated distance customers need to travel to get to the next ATM/CRM (see Box 2 for a more detailed analysis). While the average distance in Germany and Italy was calculated to be 1.7 and 2.3 km respectively, it was 13.2 km in Finland. Additionally, cash transport usage contributes a small but noticeable amount regarding some impact categories too.

5.1.3 Detailed analysis for selected impact categories

In this chapter, we analyse the environmental impact of digital and cash POS payments in more detail for three select impact categories. We chose the three categories according to the following selection criteria: high relevance for the system under study according to literature; high environmental relevance; level of robustness according to literature; closeness of the digital and the cash POS payments' impacts in a certain category according to our analysis. To assess whether a certain impact category has a high relevance for the systems under study, we rely on guidance published by the International Telecommunication Union (see International Telecommunication Union (2014)). The guidance by the ITU on information and communication technology (ICT) goods is well suited for our study because many of our considered systems can be classified as ICT goods, such as data centres, terminals, cash counting machines, and others.

Following these criteria, we identified three important impact categories that we analyse in more detail in the following. The first category is "global warming potential". This category was chosen because the ITU assesses it as the most important category and the only one that needs to be evaluated mandatorily. In addition, this category has been the focus of much scientific research and its quantification through models is considered robust (see e.g., Parisi et al. (2020)).

The second category is "mineral resource scarcity". This category was chosen as the depletion of minerals in general and rare earths in particular are an important environmental issue. This holds especially true as metals and minerals play are an important input factor for cash as well as digital payments at POS. It is also one of the impact categories that the ITU highlights in its guidance.

The third selected category is "ionizing radiation". The ITU also considers this category as important to evaluate (International Telecommunication Union (2014)). In addition, the difference between the digital and cash impacts was smallest in this category and in Italy the impact on ionizing radiation was even larger for digital than cash POS transactions. This impact category is considered to have a medium to high robustness (Parisi et al. (2020)).

Global warming potential

Digital POS payment

In this subchapter, the contribution of the production, operation, and end-of-life phases on the global warming potential (GWP) of cash and digital payments and the impact of their different subsystems are presented in more detail. Figure 27 shows the GWP contribution in grams of CO_2 equivalents of each phase in the digital payment process. The estimated total GWP impact is 3.06 g of CO_2 equivalents in Germany, 5.39 g of CO_2 equivalents in Italy, and 2.2 g of CO_2 equivalents in Finland. By scaling these numbers with the total number of digital POS transactions, the climate change impact of the total digital POS payment system in a country can be approximated. This approach yields a climate change impact of the entire digital payments system of about 15.4 Mio. kg CO_2 equivalents (or about 0.0023% of total CO_2 emissions in 2022 based on Our World in Data (2023b)) in Germany, 27.8 Mio. kg CO_2 equivalents (0.0082%) in Italy, and 2.4 Mio. kg CO_2 equivalents (0.0067%) in Finland.[96]

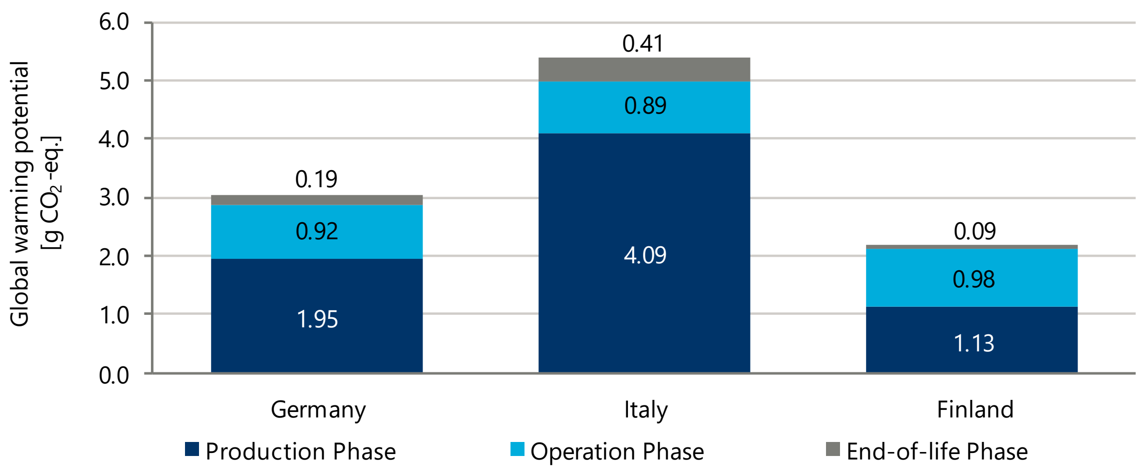
[96] The annual CO_2 emissions of each country are taken from Our World in Data (2023b).

For all three countries, the production phase has the largest environmental impact, followed by the operation phase. The end-of-life phase does not play a crucial role in all three countries. The relative importance of the production phase for the GWP of the average digital POS payment is highest in Italy with 76% of the total GWP impact, followed by Germany with 64%, and Finland with 52%. The importance of the production phase in Italy is driven by the large number of terminals used in Italy. While Italy sees a similar amount of digital POS transactions per year as Germany, in 2021, there were more than four times as many terminals in use in Italy relative to Germany, according to our estimation (see Chapter 4). More specifically, the data from the payment statistics indicates that the number of terminals is 4.1 Mio. in Italy that are used for 5,156 Mio. digital POS payments compared to just 0.97 Mio. terminals in Germany that are used for 5,043 Mio. digital POS payments (ECB, 2022b).[97]

The operation phase is most important in Finland (44% of the total GWP impact of an average digital POS payment), and least important in Italy (17%). Germany again is in the middle with the operation phase contributing 30%. These differences in shares are mainly caused by the varying impact of the production phase across the three countries, as the absolute impact of an average digital POS payment is similar in all countries and ranges from 0.89 g of CO_2 equivalents in Italy to 0.98 g of CO_2 equivalents in Finland.

The end-of-life phase is relatively unimportant in all countries, contributing only 4% (Finland) to 8% (Italy) to the overall effect on GWP.

FIGURE 27: GLOBAL WARMING POTENTIAL OF AN AVERAGE DIGITAL POS PAYMENT BY PHASE



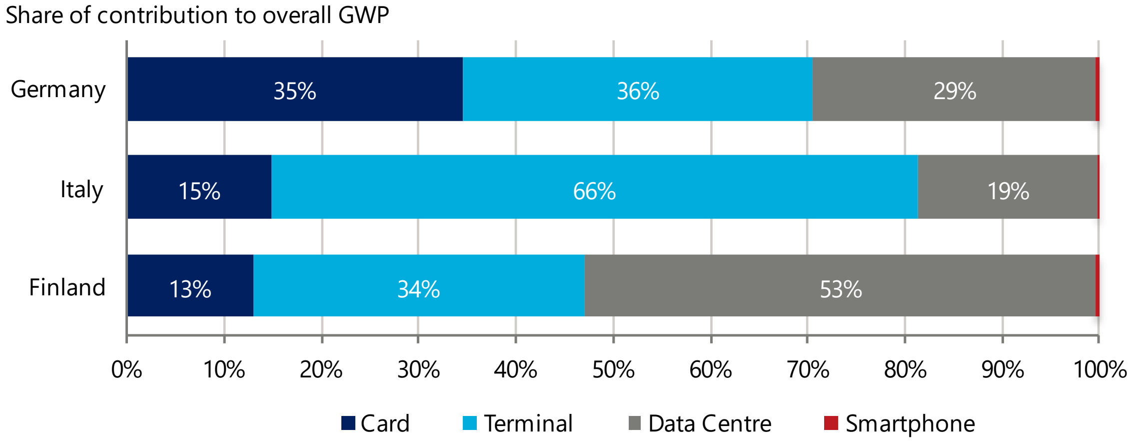
Source: Oxford Economics

Figure 28 illustrates the share of contribution to the total GWP impact in each country by subsystem. One notices that the subsystems' shares differ substantially by country. Our results indicate that data centres contribute more than half of the total GWP impact in Finland. In Italy, two-thirds of the total GWP impact stems from terminals. As mentioned earlier, this is caused by the much larger number of terminals in use in Italy (more than four times as many terminals as in Germany), while having only around 2% more digital transactions. In Germany, cards, terminals, and data centres contribute a comparable share to the total GWP impact of the digital POS payment system. The card subsystem's

[97] Note that we consider both payments made with cards issued by resident PSPs as well as non-resident PSPs (see Chapter 4.1). Thus, payments made by foreigners in the country are also included.

relative impact is higher in Germany compared to the other two countries because 1.47 times as many cards were issued in Germany as in Italy, while the share of digital POS payments is comparable. Finally, our results show that smartphones only have a negligible impact on the total GWP impact, from around 0.17% in Italy to 0.29% in Finland.

FIGURE 28: SHARE OF GLOBAL WARMING POTENTIAL BY DIGITAL SUBSYSTEMS



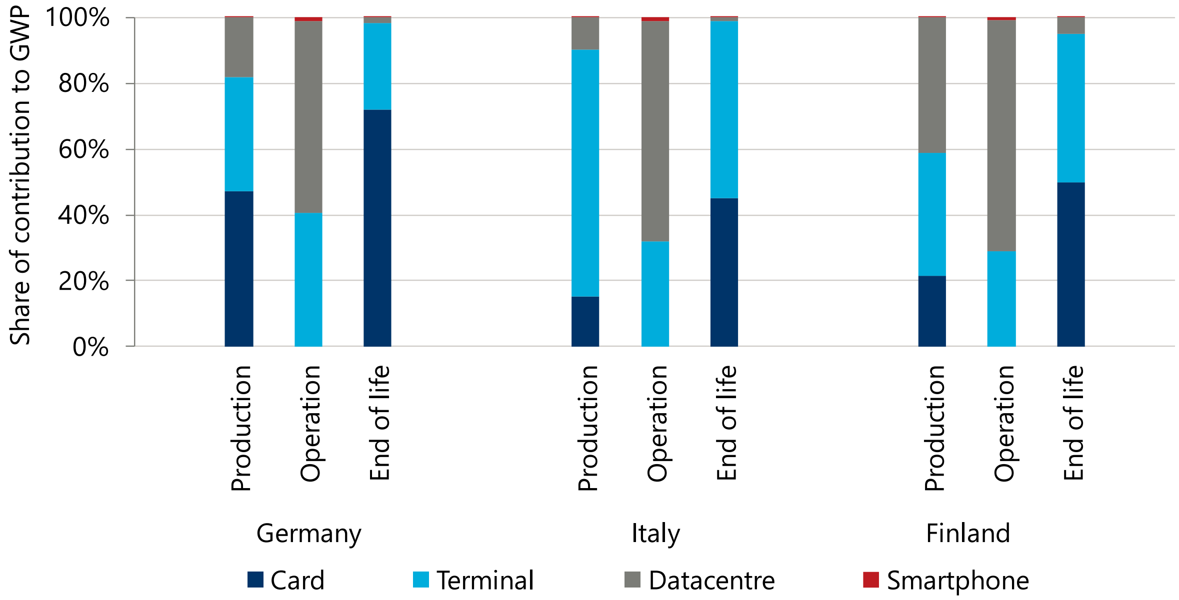
Source: Oxford Economics

Figure 29 illustrates the contribution of the digital subsystems in each phase to the overall GWP impact. Our results show that in Germany the impact during the production phase is dominated by the impact of the production of cards and terminals. They contribute 47% and 35% of the production phase's GWP impact, respectively. 18% of the GWP impact in the production phase is caused by data centres. For Italy, we can see that Italy's GWP impact in the production phase is dominated by the impact of the production of terminals. 75% of the GWP impact is caused by this subsystem's impact. Cards and data centres contribute minor shares of 15% and 10%, respectively. In Finland, our results indicate that the GWP impact of cards, terminals, and data centres have a contribution of 21%, 37%, and 41%, respectively. Smartphones do not have a noticeable GWP impact in the production phase in any country.

For the operation phase, we calculate that data centres' impact accounts for the majority of the GWP impact in all three countries. Their contribution to the operation phase's GWP impact ranges from 59% in Germany to 70% in Finland. Furthermore, terminals have a significant GWP impact in the operation phase in all countries—29% in Finland, 32% in Italy, and 40% in Germany. According to our results, the most important impact during the operation phase of terminals was the printing of paper receipts in all three countries. The energy consumption of terminals only has a small effect compared to the paper receipts. Again, smartphones only have a small impact in the operation phase in all countries up to around 1%.

Our results show that the card and terminal subsystems are the most important ones regarding the GWP impact during the end-of-life phase. In Germany and Finland, the card subsystem is the most important one, accounting for 72% and 50% of the GWP impact during the end-of-life phase, respectively. In Italy, the terminal subsystem is the most crucial, causing 54% of the GWP impact during the end-of-life phase. Data centres only play a minor role, accounting for 0.9 to 5.1% of the GWP impact during the end-of-life phase across the three countries.

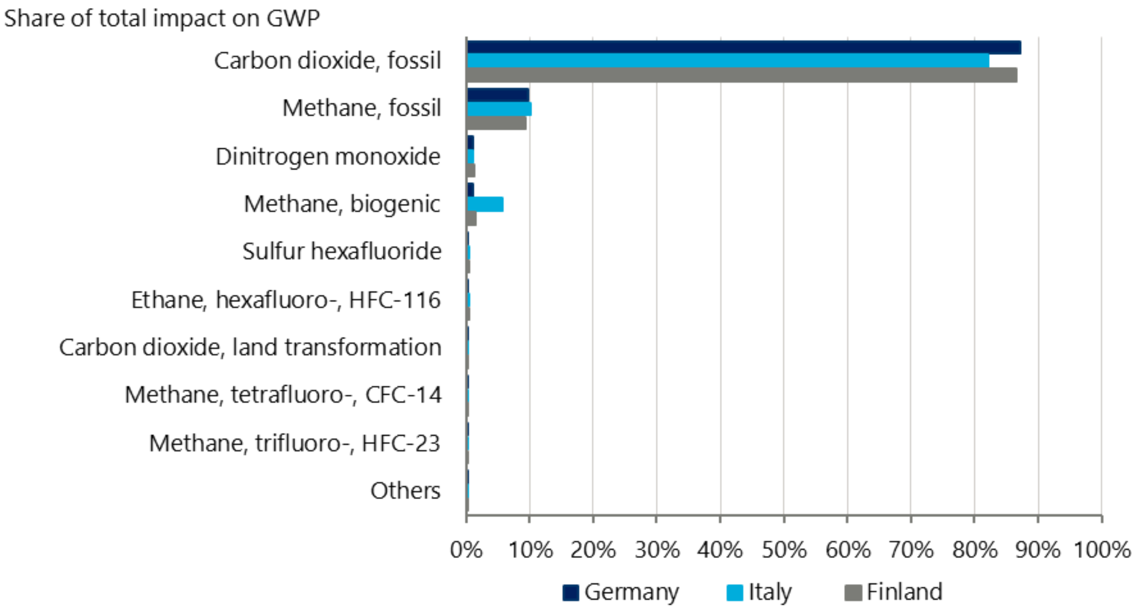
FIGURE 29: GLOBAL WARMING POTENTIAL OF AN AVERAGE DIGITAL POS PAYMENT BY PHASE AND SUBSYSTEM



Source: Oxford Economics

The main emissions for GWP of the digital POS payment system are displayed in Figure 30. Across all countries, it is estimated that carbon dioxide (fossil) and methane (fossil) contribute most to GWP. For Italy, also methane (biogenic) also contributes a significant share of emissions for the GWP of the digital payment system.

FIGURE 30: MAIN EMISSIONS FOR GWP IN THE DIGITAL SYSTEM



Source: Oxford Economics

The phase during which most fossil carbon dioxide is emitted is the production phase in Germany. Within this phase, the production of cards and terminals are particularly impactful. In Italy and Finland, the most important phases are also production, but the production of terminals is by far the most impactful in Italy and the production of data centres is most impactful in Finland.

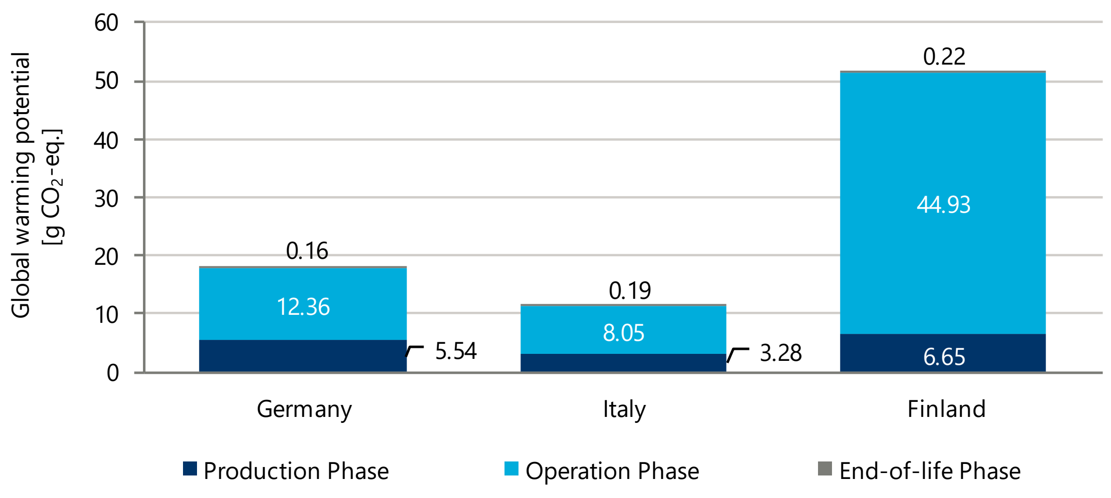
The main emitting processes for GWP of the digital POS payment system can be found in Table 64 Appendix 3.

Cash POS payment

Turning to the average cash POS payment, Figure 31 shows the GWP contribution of each phase in the three countries. According to our results, the total GWP impact amounts to 18.1 g of CO_2 equivalents in Germany, 11.5 g of CO_2 equivalents in Italy, and 51.8 g of CO_2 equivalents in Finland. Scaling these numbers with the total number of cash POS transactions yields the climate change impact of the total cash POS payment system in a country. This approach yields a climate change impact of the entire cash payments system of about 162.0 Mio. kg CO_2 equivalents (or about 0.024% of total CO_2 emissions in 2021 based on Our World in Data (2023b)) in Germany, 138.5 Mio. kg CO_2 equivalents (0.041%) in Italy, and 14.3 Mio. kg CO_2 equivalents (0.04%) in Finland.[98] Thus, the climate change impact of the total cash POS payment system is an order of magnitude larger than the digital system in all three countries.

In all three countries, the most important phase is the operation phase, which accounts for 68% of the total GWP impact in Germany, 70% in Italy, and 87% in Finland. The reason for the importance of the operation phase lies in the distance travelled to reach an ATM/CRM to withdraw or deposit cash. As previously mentioned, the significantly higher impact of the operation phase in Finland is driven by the long average distances to the closest ATM. Furthermore, the capacity utilisation for the cash infrastructure is much lower in Finland, because only 20% of POS payments are made in cash, which also contributes to the high GWP impact per transaction of the operation phase. We estimate that the GWP impact of the end-of-life phase is minor in all three countries.

FIGURE 31: GLOBAL WARMING POTENTIAL OF CASH POS PAYMENT BY PHASE



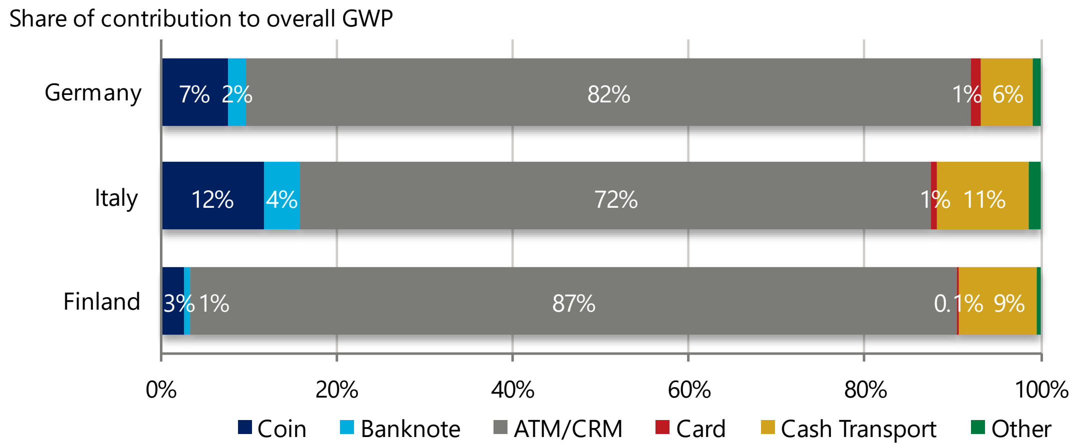
Source: Oxford Economics

[98] The annual CO_2 emissions of each country are taken from Our World in Data (2023b).

Figure 32 analyses which subsystem is the most important for the total GWP impact across all phases. In all three countries, our results indicate that the ATM/CRM subsystem is the main contributor to the total GWP impact—accounting for between 72% of the total GWP impact in Italy and 87% in Finland. As explained above, this result is mainly driven by the way travelled to ATMs/CRMs to withdraw or deposit cash.

Other important subsystems are the cash transport subsystem and the coin subsystem. In contrast, our results indicate that the banknote subsystem, the card subsystem, the small and large CCM subsystems and the data centre subsystem only play a minor role in the impact of an average cash POS transaction.

FIGURE 32: SHARE OF GLOBAL WARMING POTENTIAL BY CASH SUBSYSTEMS



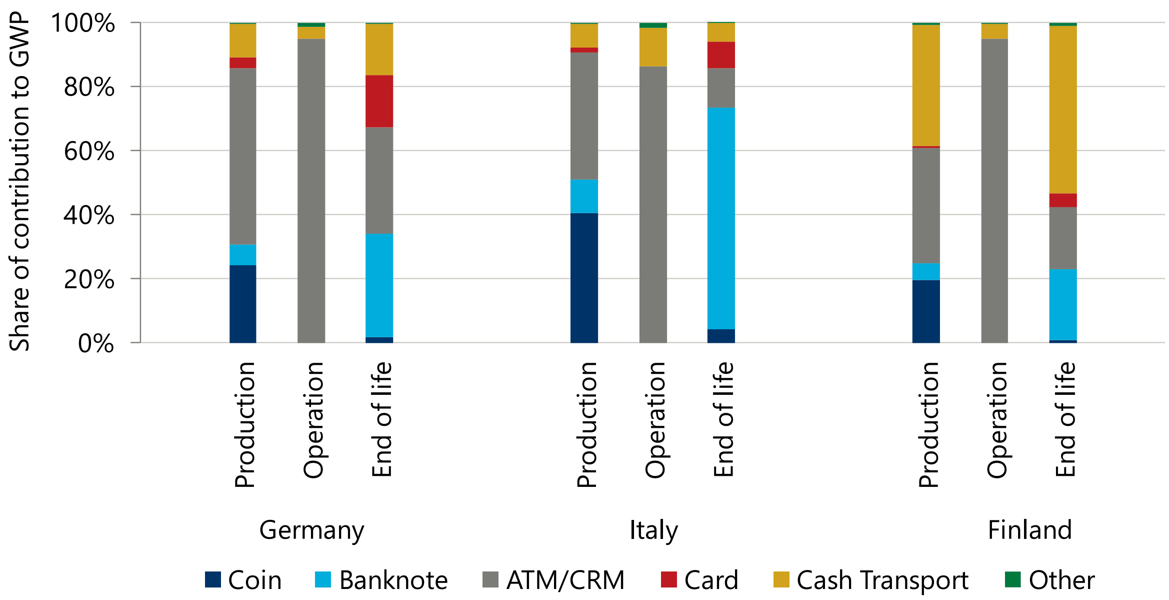
Source: Oxford Economics

In Figure 33, we illustrate the contribution of the digital subsystems in each phase to the GWP impact in that phase. We can see that in the production phase, ATMs and CRMs are among the most relevant contributors to the GWP impact in all three countries, accounting for about 55% in Germany, 40% in Italy, and 36% in Finland—mostly because of the steel needed in its construction and the corresponding metal working process. As a result, ATMs and CRMs are the largest contributors in the production phase in Germany. In Italy, it is only surpassed by the coin subsystem accounting for 41%. In Finland, only the cash transport subsystem has a larger impact share (38%). The share of the GWP impact in the production phase accounted for by the cash transport subsystem is much smaller in the other countries (Germany 10% and Italy 7%).

Looking at the operation phase, the ATM/CRM subsystem is even more important (see Figure 33). In all three countries, our results show that ATMs/CRMs—i.e., the way to them, their energy usage, and maintenance—account for about 86-95% of the operation phases' GWP impact followed by a much smaller share for cash transport (4-12%). As explained before, travelling to an ATM/CRM is especially important in Finland, where transport distances are usually higher.

Finally, our results indicate that in the end-of-life phase, banknotes and ATMs/CRMs—and cash transport in Finland—account for most of the GWP impact. Banknotes have a relatively high impact in this phase because their lifespan is much shorter than that of coins. The high share accounted for by the cash transport subsystem in Finland is again due to the long distances in this country which leads to cash trucks reaching their end-of-life mileage sooner than cash trucks in other countries. In Germany, cards also contribute a noticeable share of 16% to the end-of-life GWP as comparably more cards are in use in Germany compared to the other countries. For example, while about 911 cash POS transactions were assigned to a card in Germany, 3,022 were assigned to a card in Italy, and 2,827 to a card in Finland making the assignment of one card to an average POS transaction by far the largest in Germany.[99] The small and large CCM subsystems and the data centre subsystem are not relevant in the end-of-life phase of any country.

FIGURE 33: GLOBAL WARMING POTENTIAL OF CASH POS PAYMENT BY PHASE AND SUBSYSTEM

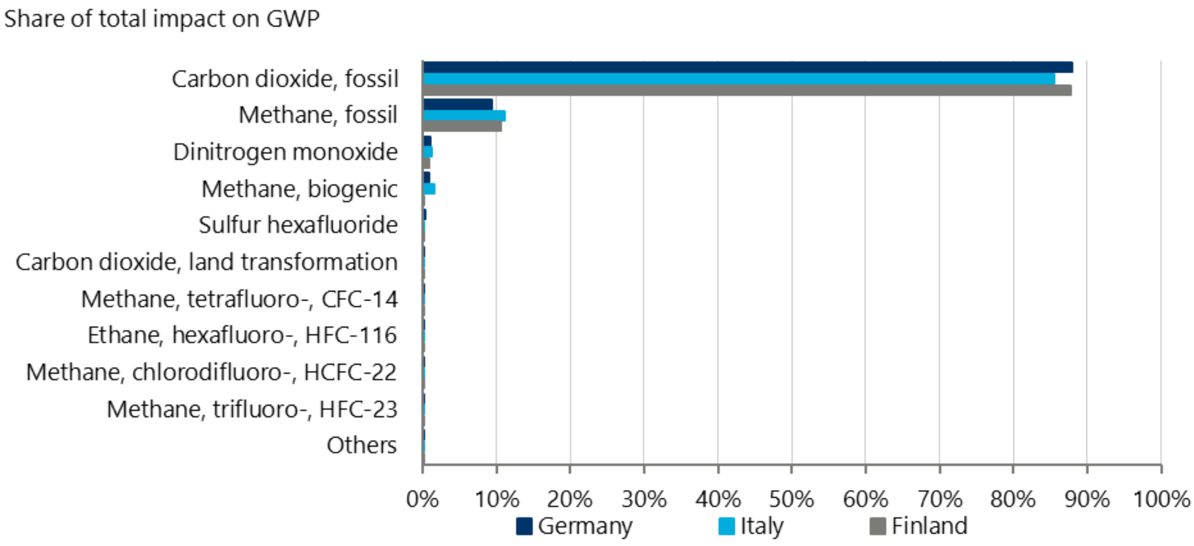


Source: Oxford Economics

The main emission for GWP of the cash POS payment system are displayed in Figure 34. As for the digital POS payment system, it is estimated that fossil carbon dioxide and fossil methane contribute with around 85% and 10%, respectively, most to GWP in all three countries.

[99] The high assignment of a card to a cash POS transaction in Germany is mainly caused by two aspects. First, there are relatively many cards in Germany. While one card supports about 51 cash POS transactions in Germany, almost 102 cash payments are supported in Italy. Although one card supports only about 26 transactions in Finland, the second aspect leads to the assignment numbers as stated in the text. That is, in Germany 20% of the card is allocated to the cash payment system at POS whereas this share is only 12% in Italy and 3% in Finland. In these countries, cards are used relatively more often for digital POS transactions and non-POS transactions such as online purchases.

FIGURE 34: MAIN EMISSIONS FOR GWP IN THE CASH SYSTEM



Source: Oxford Economics

In Germany, the operation phase is the highest emitting phase of fossil carbon dioxide. Within this phase, it is mostly the ATM/CRM subsystem that is responsible for their emission, in particular during the way to ATM/CRM to withdraw/deposit cash. The same is true for Italy and Finland.

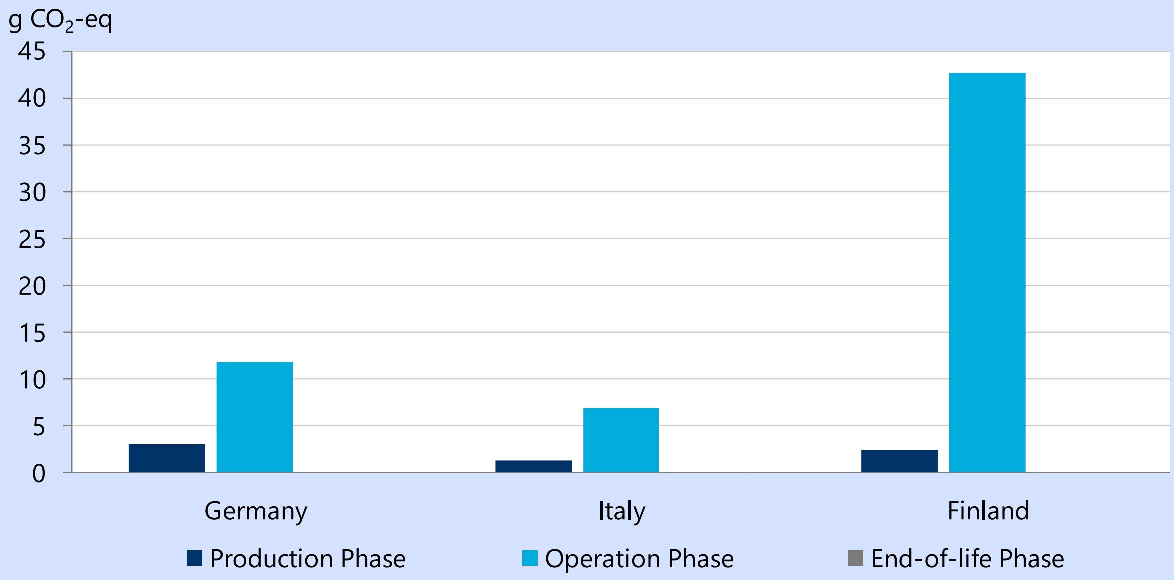
Table 65 in Appendix 3 shows the main emitting processes regarding GWP for the cash POS payment system.

BOX 2: A CLOSER LOOK AT THE ATM/CRM SUBSYSTEM

According to our results, the ATM/CRM subsystem is the subsystem with the largest share of the total GWP impact of an average cash POS payment. In this box, we analyse this subsystem in more detail.

The GWP impact of the ATM/CRM subsystem in the different phases and across the three countries is presented in Figure 35. As one can see, our results show that the largest GWP impact of this subsystem occurs in the operation phase. We estimate that one average cash POS transaction causes a GWP impact of 11.76 g of CO_2 equivalents in Germany, 6.94 g of CO_2 equivalents in Italy, and 42.72 g of CO_2 equivalents in Finland. In contrast, the end-of-life phase of the ATM/CRM subsystem is irrelevant in all countries.

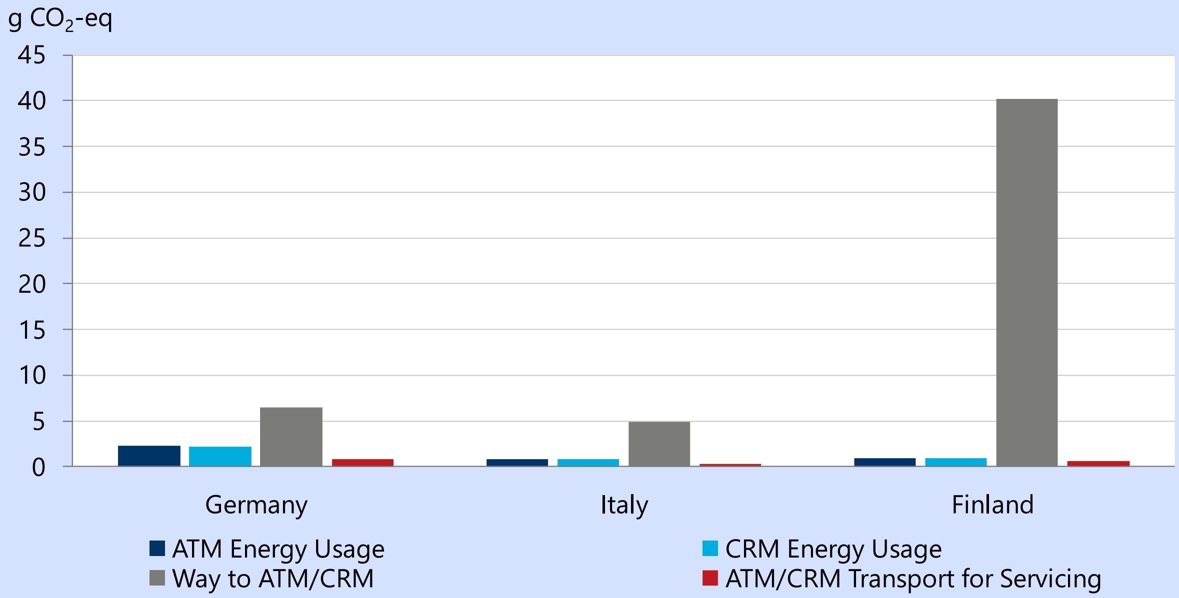
FIGURE 35: GLOBAL WARMING POTENTIAL OF THE ATM/CRM SUBSYSTEM



Source: Oxford Economics

Looking further at the operation phase of the ATM/CRM subsystem in the three countries in Figure 36, our results indicate that the way travelled to ATMs and CRMs to withdraw and deposit cash is the main driver of the large GWP impact of this subsystem's operation phase. The impact in Finland is particularly large, as our data suggests that the average distance to the closest ATM/CRM is 13.2 km in Finland compared to 1.7 km and 2.6 km in Germany and Italy, respectively. The energy usage of ATMs and CRMs is the next most important component, accounting for 38% of the GWP impact of this subsystem's impact in the operation phase in Germany, 24% in Italy, and only 5% in Finland. The GWP impact of servicing ATMs and CRMs is of minor importance in all three countries.

FIGURE 36: GLOBAL WARMING POTENTIAL OF THE OPERATION PHASE OF THE ATM/CRM SUBSYSTEM



Source: Oxford Economics

Mineral resource scarcity

Digital POS payment

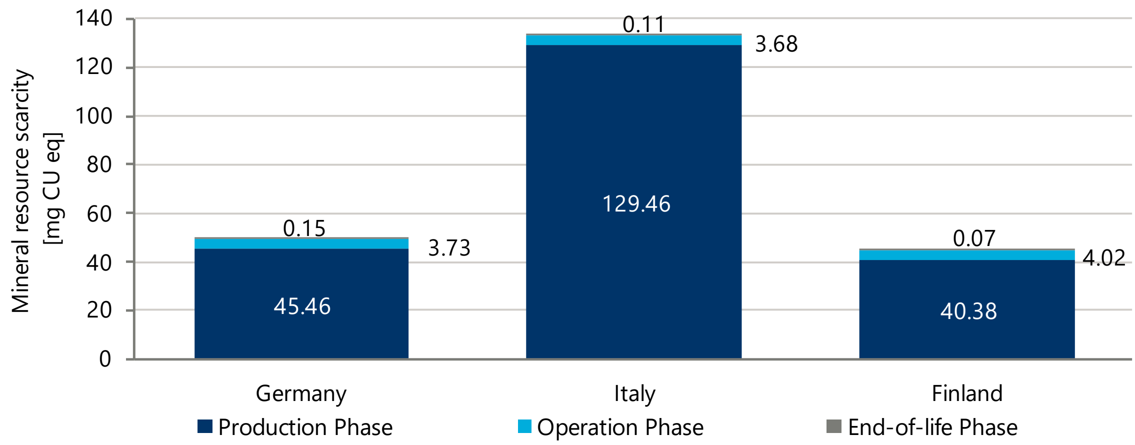
In this subchapter, we look at the contribution of the production, operation, and end-of-life phases of cash and digital payments on the mineral resource scarcity and the impact of their different subsystems. The overall picture that emerges is roughly similar to the one for the GWP impact. Figure 37 depicts the impact contribution in mg CU (copper) eq. of each phase in the three different countries. According to our results, the total impact of an average digital POS payment amounts to 49.3 mg CU eq. in Germany, 133.3 mg CU eq. in Italy, and 44.5 mg CU eq. in Finland. The production phase is responsible for the largest impact, followed by the operation phase. The end-of-life phase only has a minor impact in the three countries.

The share of the production phase among the total impact on mineral resource scarcity is estimated to be largest in Italy (97%), followed by Germany (92%), and Finland (91%). The operation phase is most important in Finland with 9% of the total impact of an average digital POS payment on mineral resource scarcity, and least important in Italy (3%). Germany ranks in the middle with the operation phase contributing 8%. Compared to our results for the GWP impact, the production phase is even more dominant for this impact category.[100]

Again, the end-of-life phase is relatively unimportant in all countries, contributing less than 0.5% to the total impact on mineral resource scarcity in all three countries.

[100] As a reminder, we estimated the share of the production phase among the total GWP impact to be 64% in Germany, 76% in Italy, and 52% in Finland.

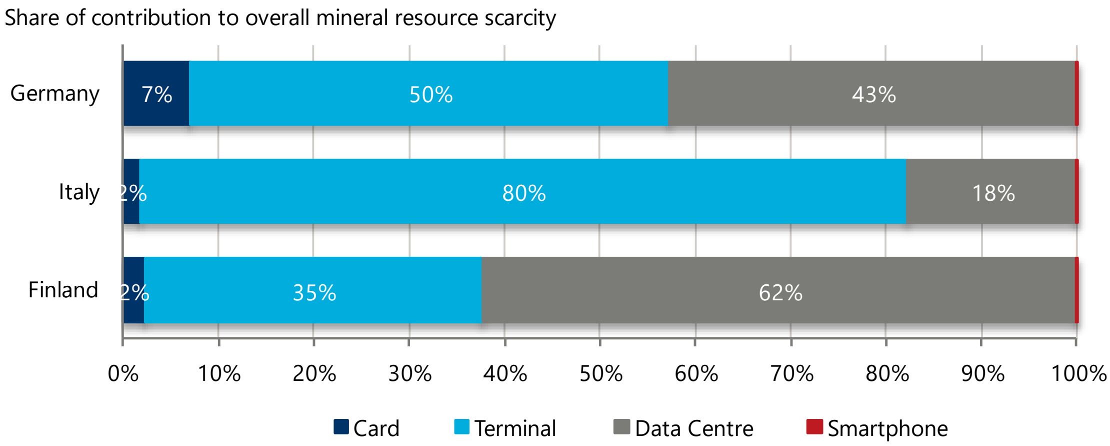
FIGURE 37: MINERAL RESOURCE SCARCITY OF DIGITAL POS PAYMENT BY PHASE



Source: Oxford Economics

The share of contribution of each of the four subsystems to overall mineral resource scarcity in the three countries is shown in Figure 38. Our results indicate that the importance of the terminal and data centre is roughly equal in Germany. In contrast, the terminal subsystem is much more important in Italy (80% of the overall impact on mineral resource scarcity), whereas in Finland the data centre subsystem is the most important one. Comparing the results on mineral resource scarcity with those on GWP, one can notice that the card subsystem is less important across all three countries for mineral resource scarcity than on GWP. At the same time, the data centre subsystem has a relatively larger impact on mineral resource scarcity than on GWP. Finally, as in the case of GWP, our results show that smartphones only have a negligible impact on mineral resource scarcity.

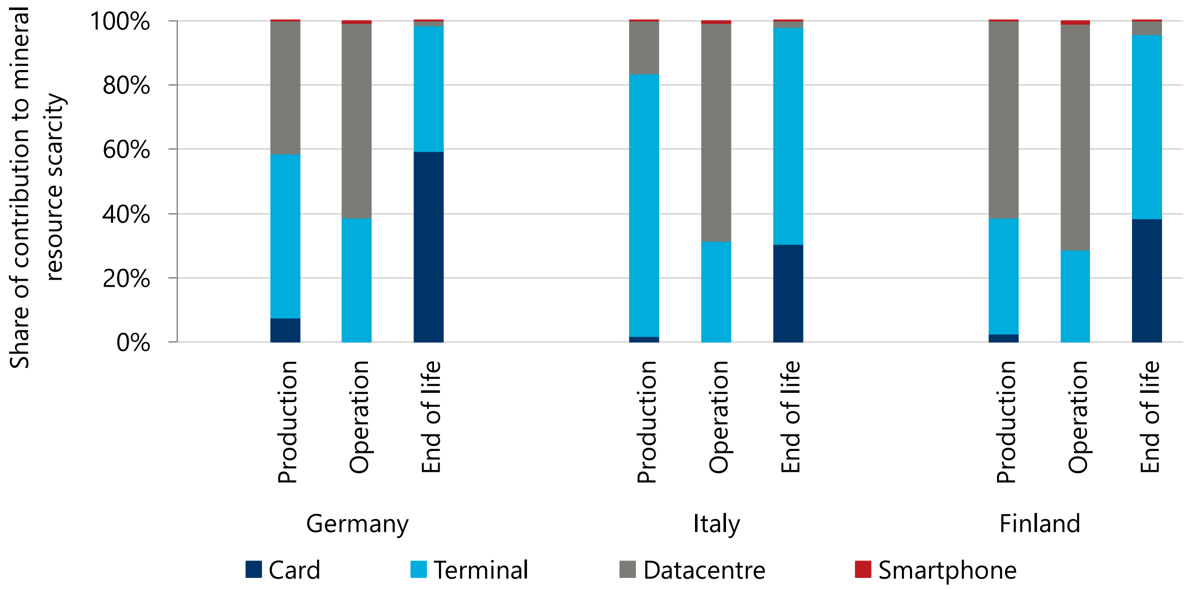
FIGURE 38: SHARE OF MINERAL RESOURCE SCARCITY BY DIGITAL SUBSYSTEMS



Source: Oxford Economics

The contribution of the digital subsystems in each phase to the overall impact on mineral resource scarcity in that phase is shown in Figure 39. In comparison to the results on GWP, the importance of the data centre subsystem has increased during the production phase in all three countries. In contrast, the share of the card subsystem during the production phase has decreased in all countries. The results for the operation phase are similar to the GWP results. In the three countries, the most important subsystem in this phase is the data centre subsystem. Terminals are also very relevant in this phase. In the end-of-life phase, the importance of the card subsystem for mineral resource scarcity has slightly decreased compared to its importance for GWP. Instead, the terminal subsystem has become even more important. As in the case of GWP, the smartphone subsystem does not play a relevant role in any phase in the three countries.

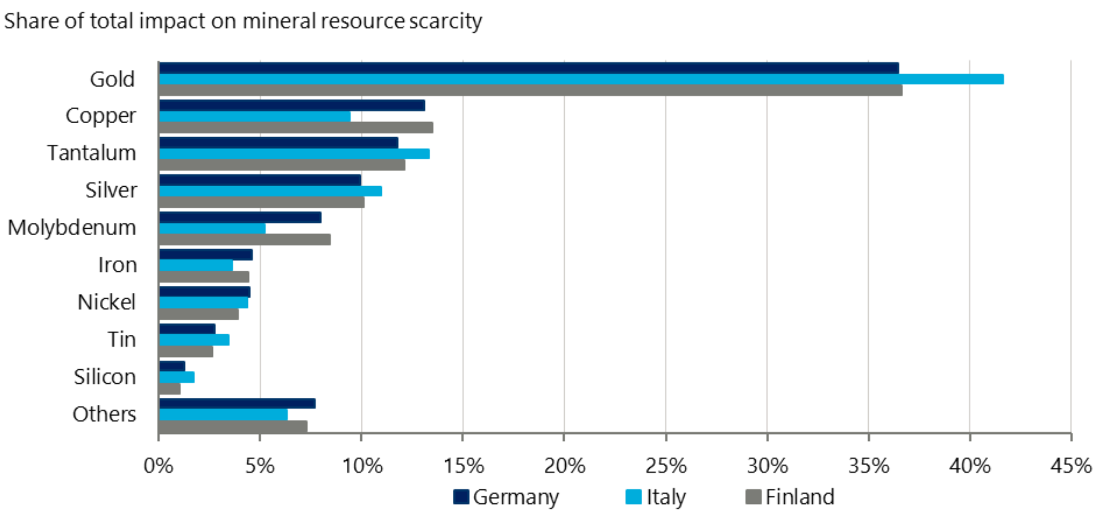
FIGURE 39: MINERAL RESOURCE SCARCITY OF DIGITAL POS PAYMENT BY PHASE AND SUBSYSTEM



Source: Oxford Economics

The main emissions for mineral resource scarcity of the digital POS payment system are displayed in Figure 40. Compared to the emissions for the GWP, the main emissions for mineral resource scarcity are more evenly spread. Overall, gold has the largest impact on resource scarcity with over 35% across all countries, followed by copper, tantalum, and silver.

FIGURE 40: MAIN EMISSIONS FOR MINERAL RESOURCE SCARCITY IN THE DIGITAL SYSTEM



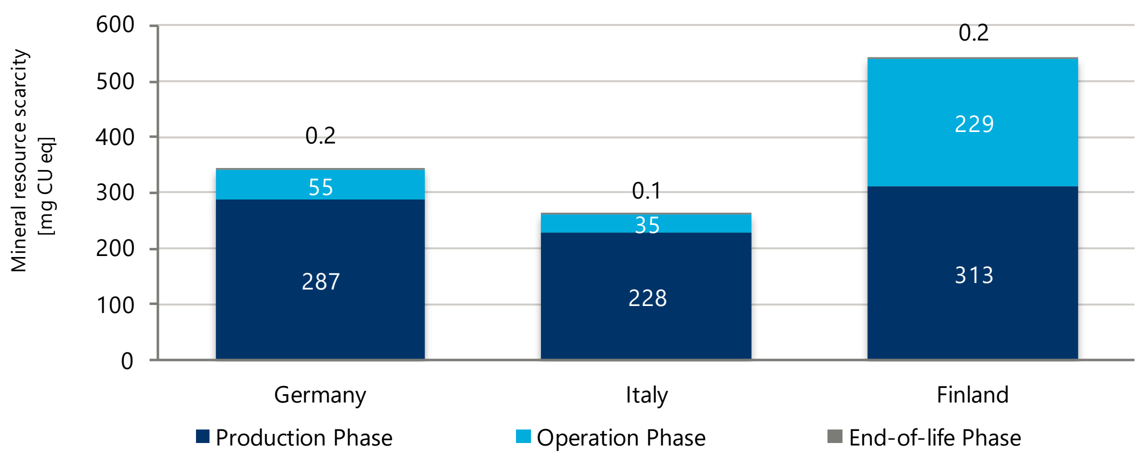
Source: Oxford Economics

The main emitting processes regarding mineral resource scarcity of the digital POS payment system are displayed in Table 66 in Appendix 3.

Cash POS payment

Figure 41 shows the impact of a cash POS payment on mineral resource scarcity by phase and country. Our results suggest that the total impact on mineral resource scarcity equals 841.8 mg CU eq. in Germany, 262.5 mg CU eq. in Italy, and 541.6 mg CU eq. in Finland. Compared to the results on GWP, the production phase has become much more important in all three countries. Its share of the total impact on mineral resource scarcity is 84% in Germany, 87% in Italy, and 58% in Finland.[101] The impact of the end-of-life phase on mineral resource scarcity remains minor in all three countries.

FIGURE 41: MINERAL RESOURCE SCARCITY OF CASH POS PAYMENT BY PHASE

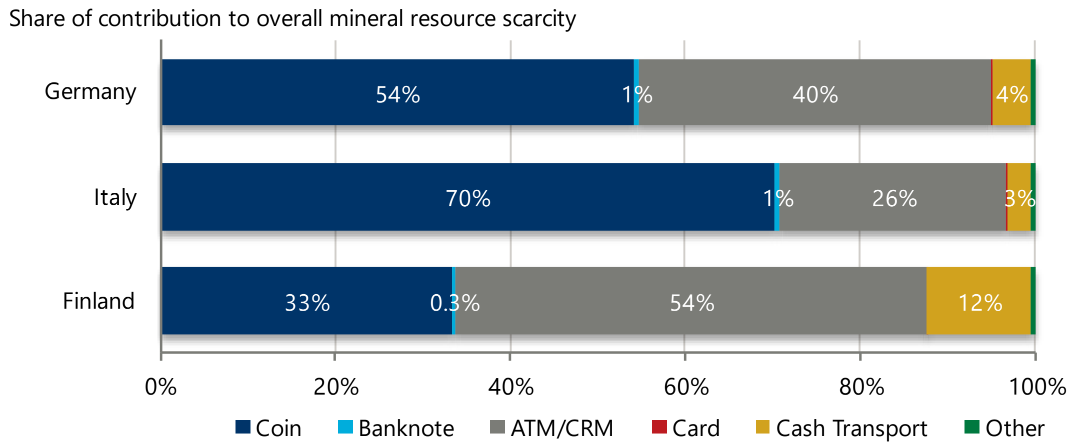


Source: Oxford Economics

The share of the contribution by one cash POS payment to overall mineral resource scarcity is shown in Figure 42. In Germany and Italy, coins are the most important subsystems contributing 54% and 70% to the total impact on mineral resource scarcity respectively. In Finland, coins rank second with 33% contribution. Here, ATMs/CRMs contribute most to the overall impact with 54%. In Germany and Italy, this subsystem contributes 40% and 26% respectively. The is in contrast to the overall GWP impact that is clearly dominated by ATMs/CRMs impact with around 70-90%. Furthermore, cash transport contributes 4% in Germany, 3% in Italy, and 12% in Finland. Other subsystems including cards, banknotes, CCMs, and only contribute little to the overall impact on mineral resource scarcity.

[101] The corresponding shares for GWP were 31% in Germany, 28% in Italy, and 13% in Finland.

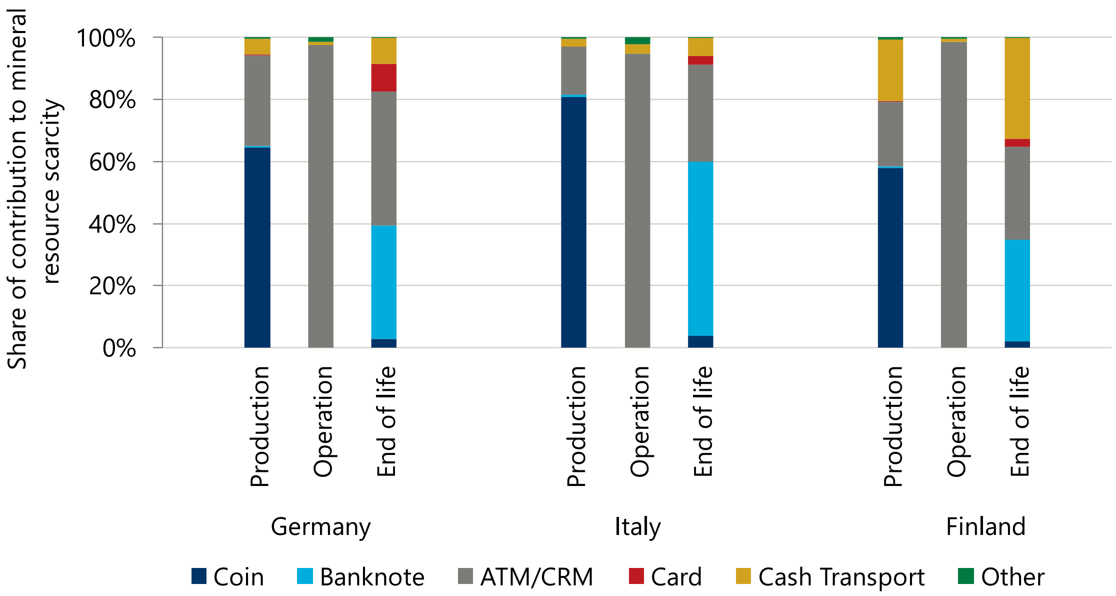
FIGURE 42: SHARE OF MINERAL RESOURCE SCARCITY BY CASH SUBSYSTEMS



Source: Oxford Economics

The contribution of the cash subsystems to the impact on mineral resource scarcity in each phase is illustrated in Figure 43. Our results show that coins are dominating the impact in the production phase across all countries. This is in contrast to the impact in GWP. Furthermore, ATMs/CRMs and cash transport are meaningful contributors in the production phase. The impact of the operation phase on mineral resource scarcity is mostly driven by ATMs/CRMs with more than 90% of contribution share in all three countries. In the end-of-life phase, banknotes and ATMs/CRMs have the largest impact. Only in Finland, the end-of-life of cash transport has a large contribution to the phase's impact on mineral resource scarcity as well.

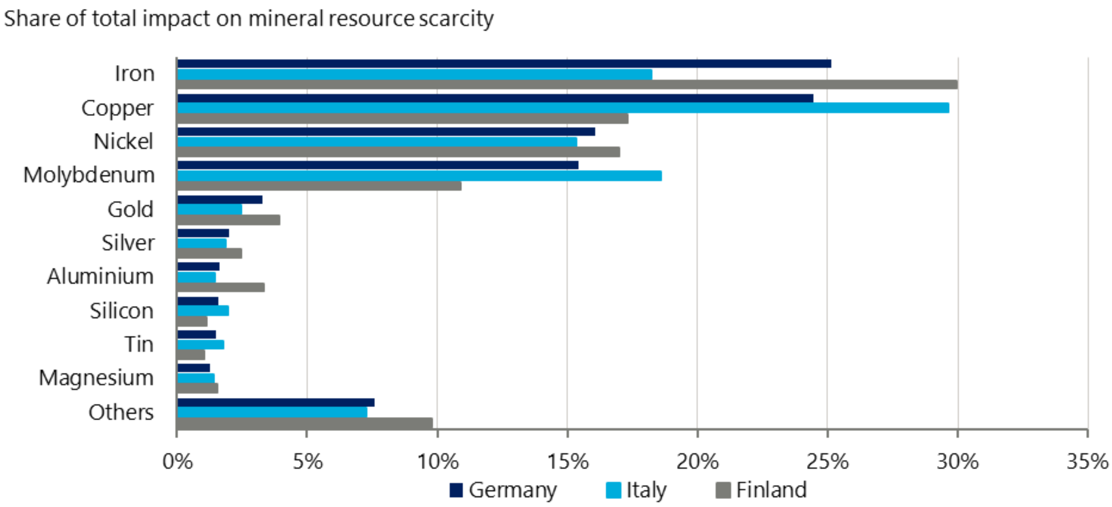
FIGURE 43: MINERAL RESOURCE SCARCITY OF CASH POS PAYMENT BY PHASE AND SUBSYSTEM



Source: Oxford Economics

The main emissions for mineral resource scarcity of the cash POS payment system are displayed in Figure 44. As in the digital payment system, the contributors for mineral resource scarcity impact are more widespread across compartments than in the GWP case. For the cash system, especially iron and copper, which are used for the production of coins, have the highest impact on mineral resource scarcity. However, other metals such as nickel and molybdenum also contribute a significant share to the mineral resource scarcity impact of cash POS payments.

FIGURE 44: MAIN EMISSIONS FOR MINERAL RESOURCE SCARCITY IN THE CASH SYSTEM



Source: Oxford Economics

Table 67 in Appendix 3 show the main processes regarding mineral resource scarcity for the cash POS payment systems.

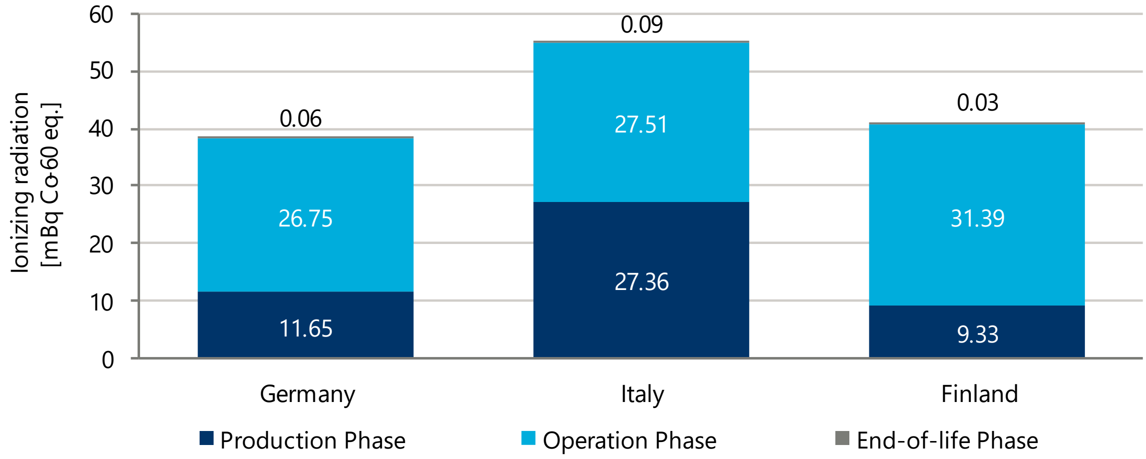
Ionizing radiation

Digital POS payment

Finally, we turn to the impact category "ionizing radiation." Figure 45 shows the total estimated impact on this category by phase and country. Our results suggest that an average POS payment produces a total impact on ionizing radiation of 38.5 mBq (millibecquerel) Co-60 (Cobalt-60) equivalents in Germany, 55 mBq Co-60 in Italy, and 40.8 mBq Co60 equivalents in Finland. Ionizing radiation in the digital system is comparatively high in Italy due to the high number of terminals produced.

In all three countries, the operation phase is the most important one, followed by the production phase, and the end-of-life phase. Compared to GWP and mineral resource scarcity, where the production phase was the most important, the operation phase is much more relevant when it comes to ionizing radiation. It accounts for 70% of the total impact in Germany, 50% in Italy, and 77% in Finland. Equivalent to the two other impact categories, the end-of-life phase is mostly irrelevant in the three countries.

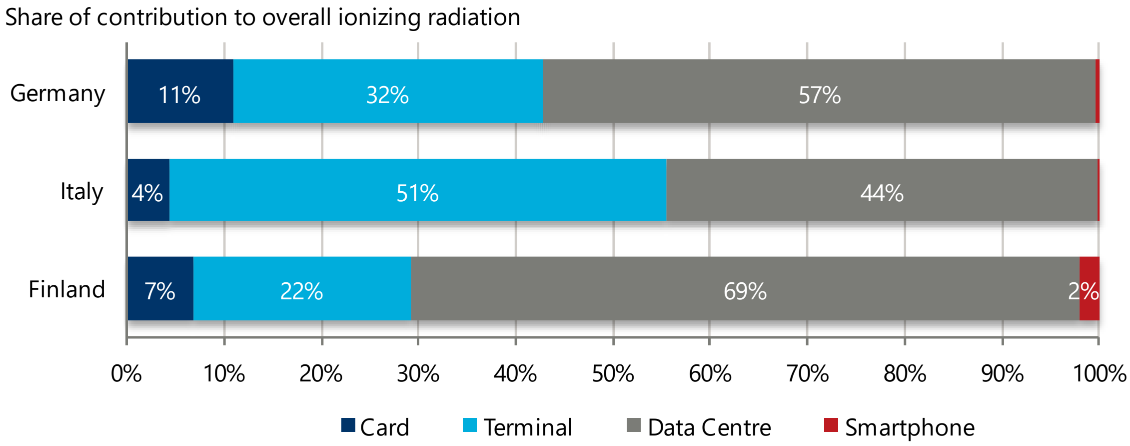
FIGURE 45: IONIZING RADIATION OF DIGITAL POS PAYMENT BY PHASE



Source: Oxford Economics

The estimated share of contribution of each subsystem to overall ionizing radiation in the three countries is shown in Figure 46. Compared to GWP and mineral resource scarcity, the share of the data centre subsystem has increased and makes up between 44% of the total impact in Italy and 69% in Finland. In contrast, the share of the terminal subsystem has decreased compared to the impact on GWP and mineral resource scarcity, only making up between 22% (Finland) and 51% (Italy) of the total impact on ionizing radiation.

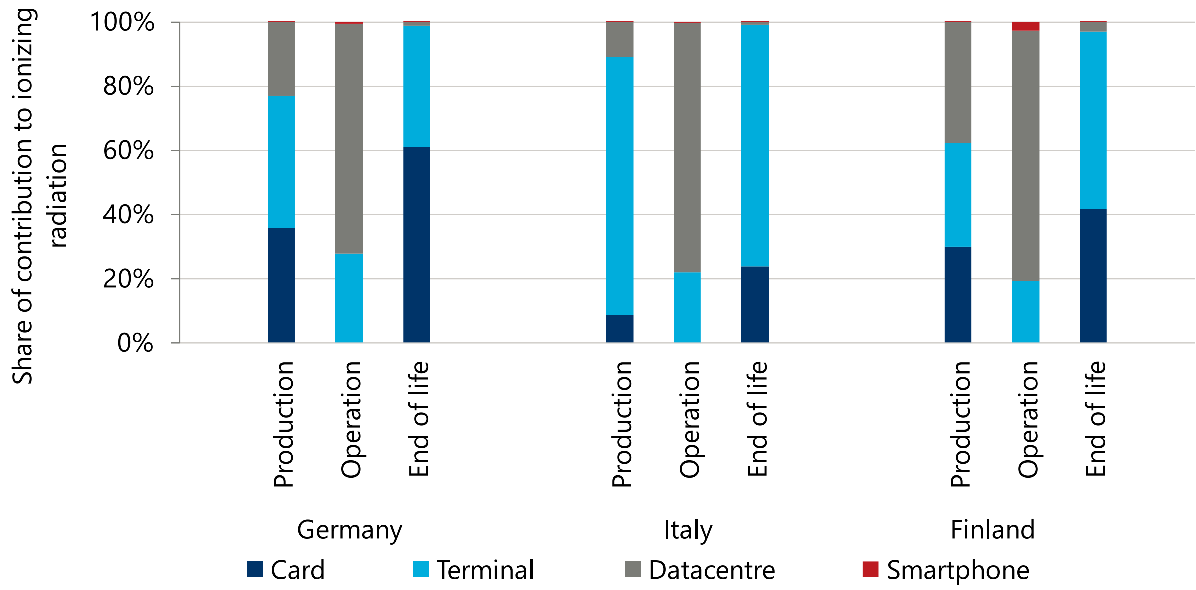
FIGURE 46: SHARE OF IONIZING RADIATION BY DIGITAL SUBSYSTEMS



Source: Oxford Economics

The contribution of the digital subsystems to the overall impact on ionizing radiation in each phase is shown in Figure 47. The results for ionizing radiation are similar to those for GWP. Concerning the production phase, the card, terminal, and data centre subsystems have comparable shares in Germany in Finland. In contrast, the production phase in Italy is dominated by the terminal subsystem. In the operation phase, the impact on ionizing radiation is mainly caused by the data centre subsystem. In the end-of-life phase, the card and terminal systems are the most relevant ones in all three countries.

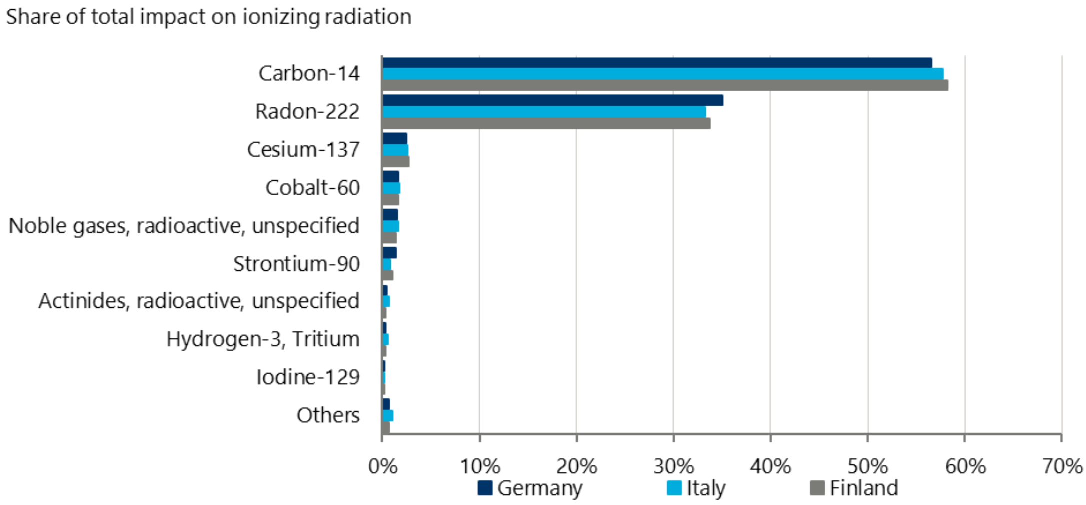
FIGURE 47: IONIZING RADIATION OF DIGITAL POS PAYMENT BY PHASE AND SUBSYSTEM



Source: Oxford Economics

The main emissions for ionizing radiation of the digital POS payment system are displayed in Figure 48. Across all countries, carbon-14 and radon-222 are estimated to be the leading contributors to ionizing radiation. Other isotopes, such as cesium-137 or cobalt-60, only contribute a minor share with each under 3% of the total impact.

FIGURE 48: MAIN EMISSIONS FOR IONIZING RADIATION IN THE DIGITAL SYSTEM



Source: Oxford Economics

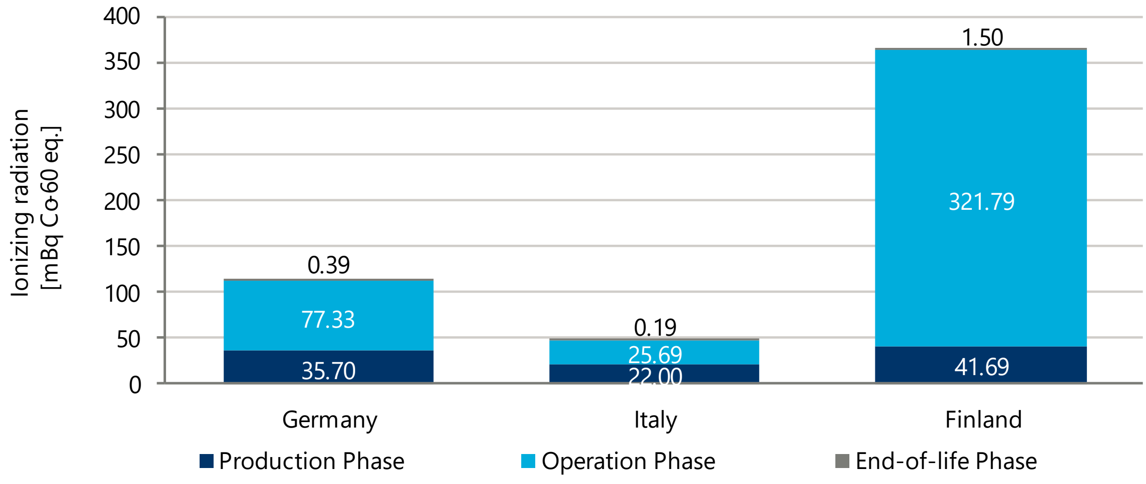
The main emitting processes for ionizing radiation of the digital POS payment system are displayed in Table 68 in Appendix 3.

Cash POS payment

The impact of a cash POS payment on ionizing radiation by phase and country is shown in Figure 49. Our results show that the total impact amounts to 113.4 mBq Co-60 equivalents in Germany, 47.9

mBq Co-60 equivalents in Italy, and 365 mBq Co-60 equivalents in Finland. Ionizing radiation in the cash system in Italy is lower than in other countries mainly due to the local electricity mix that produces less ionizing radiation since it is not as reliant on nuclear energy.

FIGURE 49: IONIZING RADIATION OF CASH POS PAYMENT BY PHASE

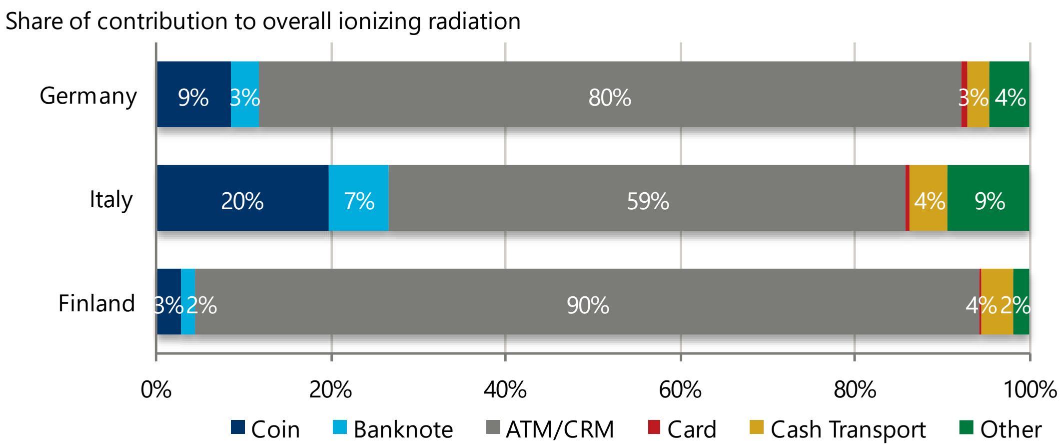


Source: Oxford Economics

The operation phase accounts for the largest share of the total impact in all three countries. Its share is particularly large in Finland, where it is responsible for 88% of the total impact on ionizing radiation. The end-of-life phase is of minor relevance in all countries.

Figure 50 depicts the share of contribution to overall ionizing radiation for each subsystem. Again, the results are largely similar to those for GWP. The ATM/CRM subsystem accounts for the largest share in all three countries. Another important subsystem is the coin subsystem. Compared to the impact on GWP and mineral resource scarcity, small and larger CCMs as well as data centres (subsumed under the "Other" category in the figure) have a larger share of the total impact on ionizing radiation.

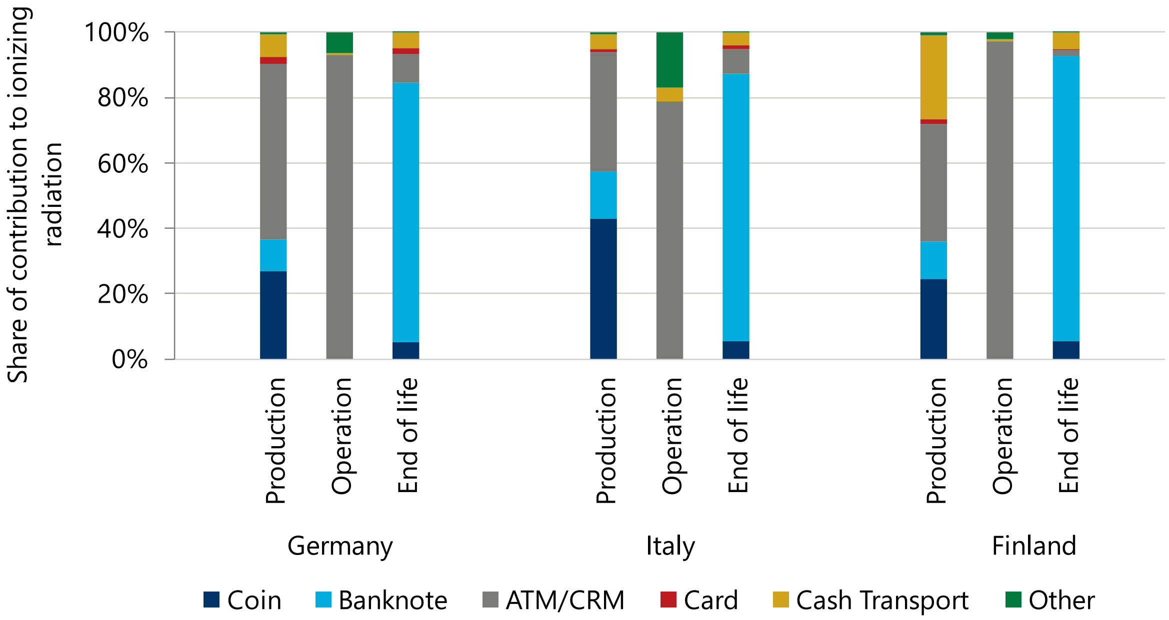
FIGURE 50: SHARE OF IONIZING RADIATION BY CASH SUBSYSTEMS



Source: Oxford Economics

The contribution of the digital subsystems to the impact on ionizing radiation in each phase is shown in Figure 51. In the production phase, the shares of the different subsystems in the three countries are similar to those in the GWP analysis. Important subsystems in the production phases in the three countries are the coin and ATM/CRM subsystems. In addition, the cash transport subsystem also significantly contributes to the impact on ionizing radiation. Our results suggest that the impact during the operation phase is mainly caused by the ATM/CRM subsystem. Compared to the GWP impact, the small and large CCMs and the data centres are responsible for a relatively larger impact on ionizing radiation. The impact in the end-of-life phase is dominated by the banknote subsystem which accounts for 80% of the impact in this phase in Germany, 82% in Italy, and 87% in Finland.

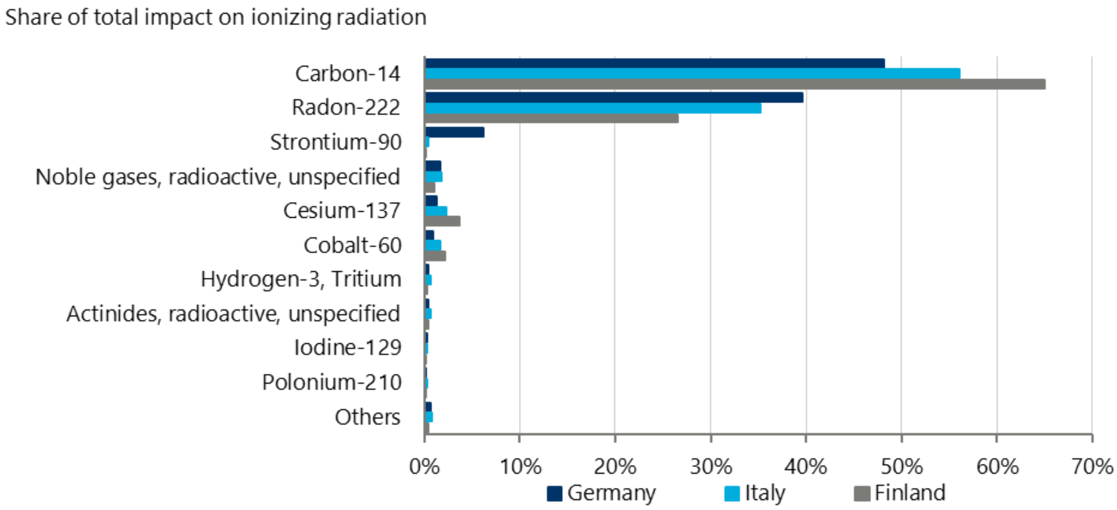
FIGURE 51: IONIZING RADIATION OF CASH POS PAYMENT BY PHASE AND SUBSYSTEM



Source: Oxford Economics

The main emissions for ionizing radiation of the cash POS payment system are displayed in Figure 52. As in the digital POS payment system case, carbon-14 and radon-222 are estimated to be the leading contributors to ionizing radiation. Especially in Finland, carbon-14 contributes a significantly higher share (and, therefore, radon-222 a lower share) to the total impact on ionizing radiation compared to Germany and Italy. Again, other isotopes, such as cesium-137 or cobalt-60, only contribute a minor share to the total impact.

FIGURE 52: MAIN EMISSIONS FOR IONIZING RADIATION IN THE CASH SYSTEM



Source: Oxford Economics

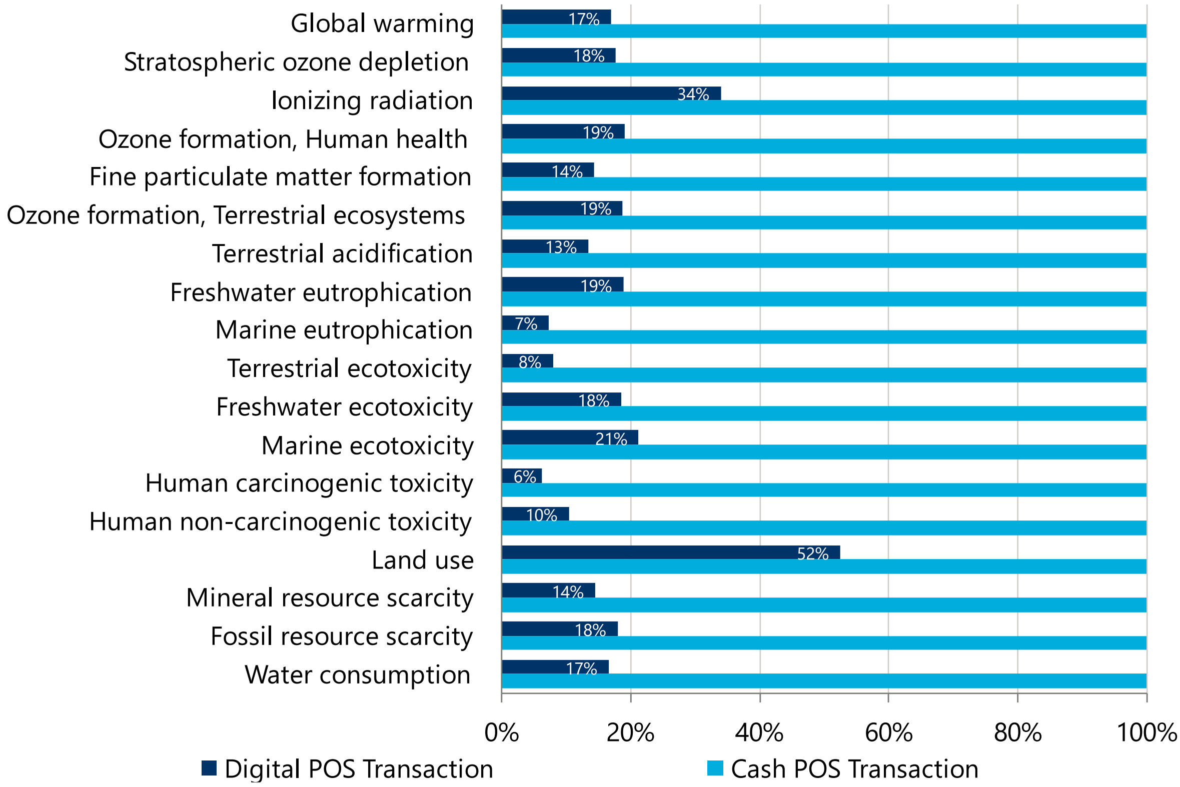
Table 69 in Appendix 3 shows the main processes regarding ionizing radiation for the cash POS payment system.

5.2 COMPARISON OF THE DIGITAL AND CASH PAYMENT SYSTEMS

5.2.1 All impact categories

In this chapter, we compare the environmental impact of an average digital and cash POS payment for all impact categories across the three countries. Figure 53 to Figure 55 show the impact of a digital POS payment as a percentage of the impact of a cash POS payment in each impact category for Germany, Italy, and Finland.

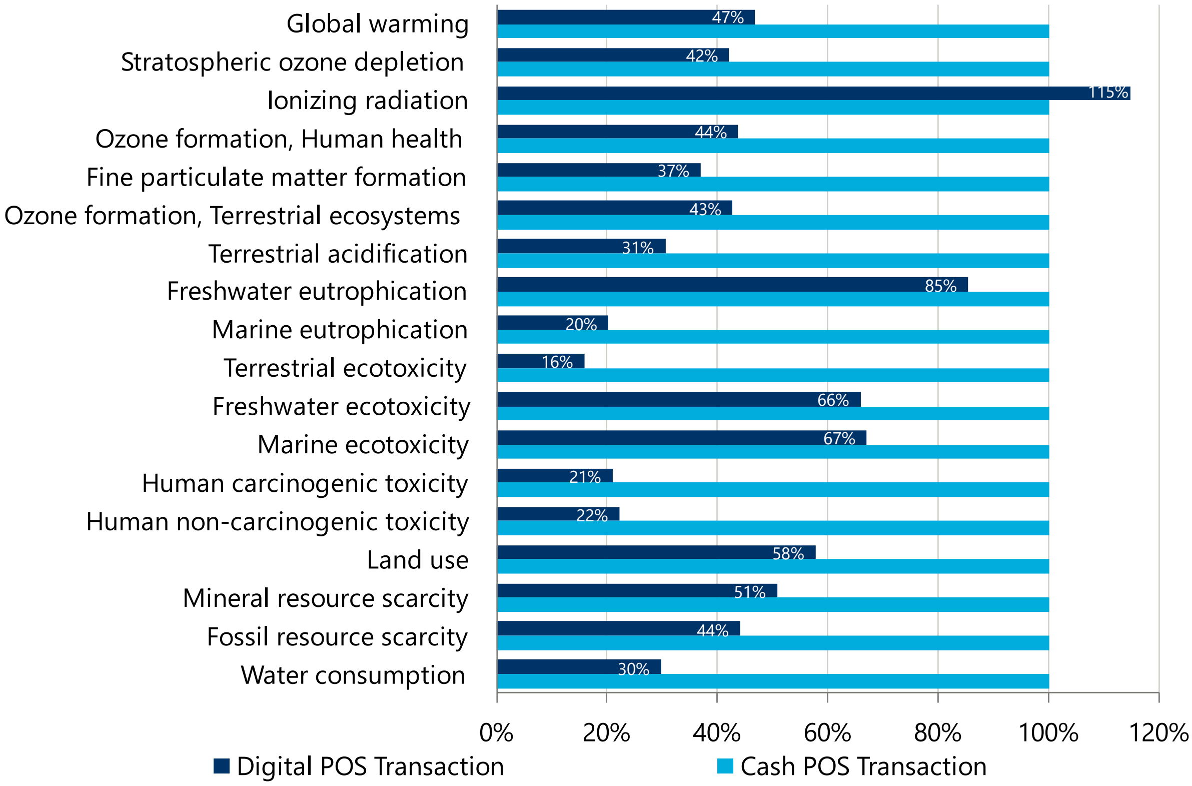
FIGURE 53: IMPACT COMPARISON OF A DIGITAL VS. A CASH POS TRANSACTION IN GERMANY



Note: The impact of a cash POS transaction is normalised to 100% in each impact category.

Source: Oxford Economics

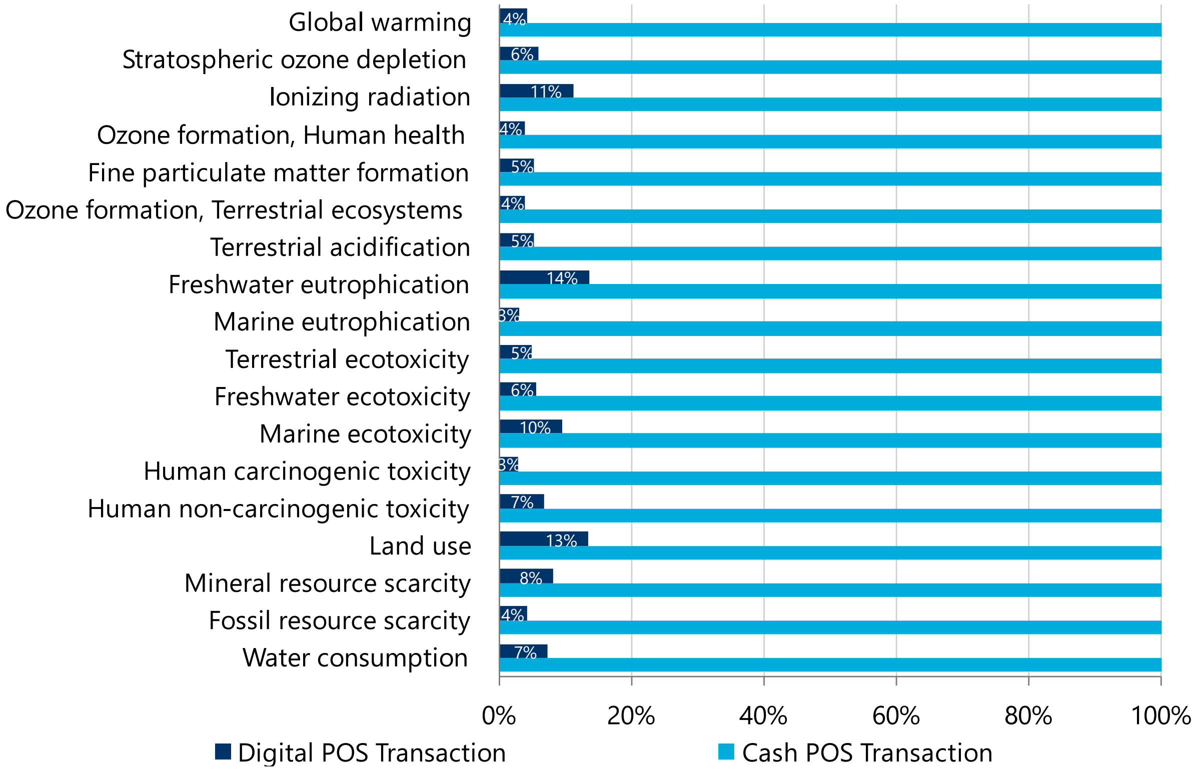
FIGURE 54: IMPACT COMPARISON OF A DIGITAL VS. A CASH POS TRANSACTION IN ITALY



Note: The impact of a cash POS transaction is normalised to 100% in each impact category.

Source: Oxford Economics

FIGURE 55: IMPACT COMPARISON OF A DIGITAL VS. A CASH POS TRANSACTION IN FINLAND



Note: The impact of a cash POS transaction is normalised to 100% in each impact category.

Source: Oxford Economics

The figures show that the impact of a digital POS payment is smaller than that of a cash POS payment in every impact category in all three countries except for ionizing radiation in Italy. Thus, our estimated results suggest that there is almost no trade-off between different impact categories. Ionizing radiation in the cash system in Italy is lower than in the other countries due to the local electricity mix that produces less ionizing radiation since it is not as reliant on nuclear energy. Additionally, ionizing radiation in the digital system is comparatively high in Italy due to the high number of terminals produced.

Overall, the difference between both payment systems is largest in Finland and smallest in Italy across all impact categories. Our results suggest that in Germany, the largest differences between a digital and a cash POS transaction occur in the impact categories human carcinogenic toxicity, marine eutrophication, terrestrial ecotoxicity, human non-carcinogenic toxicity, and terrestrial acidification. While human carcinogenic toxicity increases various types of cancer, marine eutrophication leads to damage to marine species, terrestrial ecotoxicity and acidification cause damage to terrestrial species, and non-carcinogenic toxicity may lead to increases in other diseases. In Italy, according to our results, the same impact categories show the largest differences in the impact of one cash vs. a digital transaction, although the ordering is different than in Germany. In Finland, the results differ slightly. Although the difference between digital and cash is largest in the categories of human carcinogenic toxicity and marine eutrophication here as well, the rest of the impact indicators deviate compared to the other two countries. Instead, fossil resource scarcity, ozone formation, terrestrial ecosystems as well as human health, and global warming show the largest differences in impact. While fossil resource scarcity may lead to rising oil/gas/coal energy costs, ozone formation, terrestrial ecosystems/human health damages terrestrial species/human health. Global warming leads to an increase in other diseases and malnutrition as well as damage to freshwater and terrestrial species.

The smallest differences between both payment systems occur in land use, ionising radiation, and marine ecotoxicity in Germany. In Italy, the impact of a digital POS payment is largest compared to a cash one in the categories of ionising radiation, freshwater eutrophication, marine ecotoxicity, and freshwater ecotoxicity. Lastly, in Finland, the relative impact of a digital POS payment is largest in the categories of freshwater eutrophication, land use, and ionizing radiation.

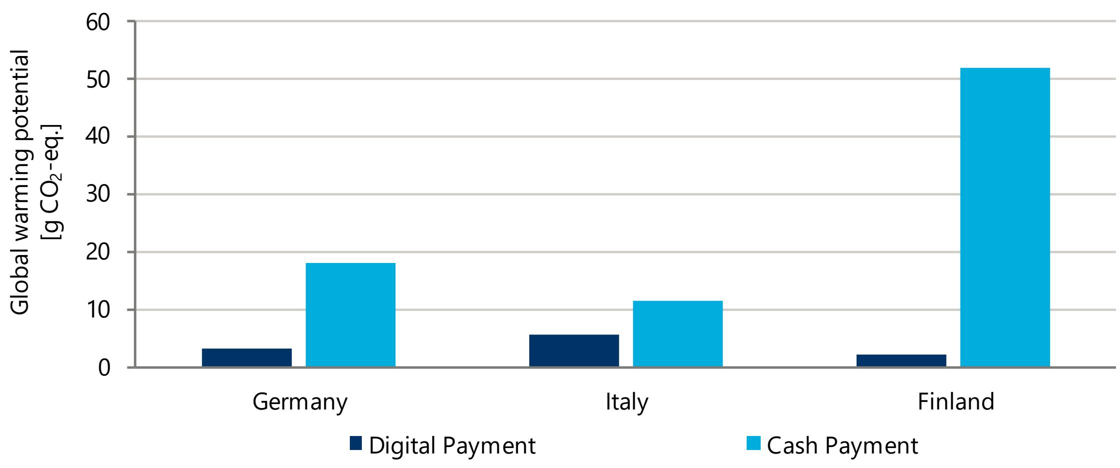
5.2.2 Detailed analysis for selected impact categories

In this chapter, we compare an average digital POS transaction to a cash one in detail for our three selected impact categories: GWP, mineral resource scarcity, and ionizing radiation.

Global Warming Potential

Figure 56 shows the GWP impact of one average digital POS payment compared to one average cash POS payment for Germany, Italy, and Finland.

FIGURE 56: GLOBAL WARMING POTENTIAL OF ONE DIGITAL VS. CASH POS TRANSACTION



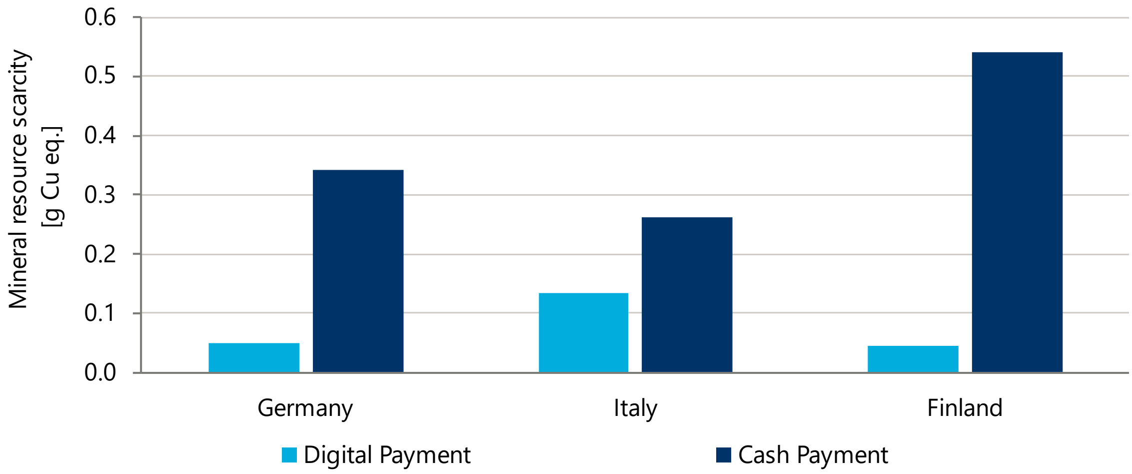
Source: Oxford Economics

Our results indicate that a cash POS payment leads to a GWP impact 5.9 times greater than a digital one in Germany, 2.1 times greater in Italy, and 23.6 times greater in Finland. As discussed in Chapter 5.1, the main reason for the large impact of a cash POS payment in Finland is the long travel distances within the country to reach the closest ATM for cash withdrawal. Furthermore, the low share of cash payments at POS in Finland (20%) results in assigning the cash systems' impacts (i.e., the required infrastructure) to a much lower number of transactions than in Italy and Germany. Compared to Finland and Germany, the relatively high GWP impact of digital payments in Italy is mainly caused by the high number of terminals per payment in Italy (see Chapter 5.1).

Mineral resource scarcity

The impact on mineral resource scarcity of one average digital POS payment compared to one average cash POS payment for Germany, Italy, and Finland is depicted in Figure 57.

FIGURE 57: MINERAL RESOURCE SCARCITY OF ONE DIGITAL VS. CASH POS TRANSACTION



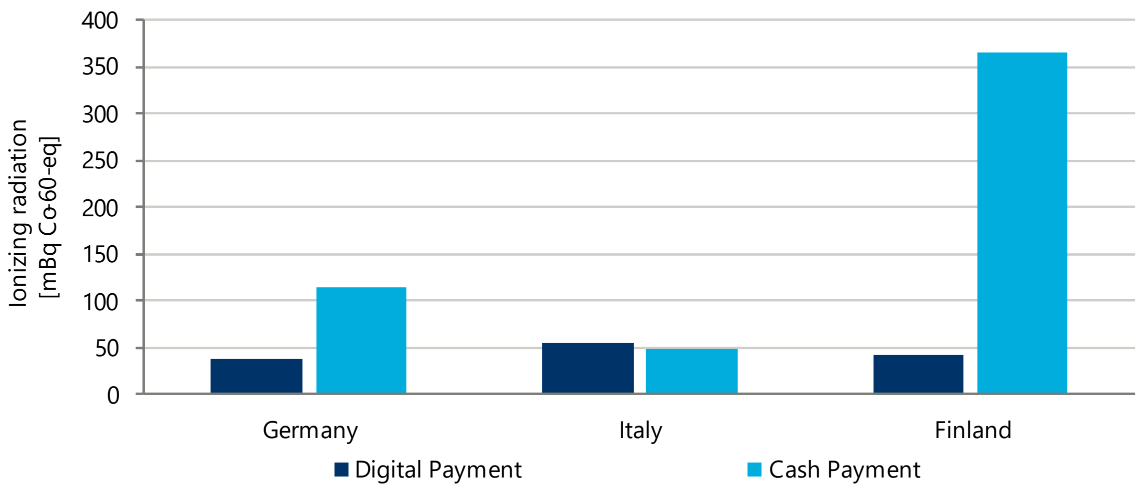
Source: Oxford Economics

Our results indicate that a cash POS payment leads to an impact on mineral resource scarcity 6.9 times greater than a digital one in Germany, 2.0 times greater in Italy, and 12.2 times greater in Finland.

Ionizing radiation

The impact on ionizing radiation of one average digital POS payment compared to one average cash POS payment for Germany, Italy, and Finland is depicted in Figure 58.

FIGURE 58: IONIZING RADIATION OF ONE DIGITAL VS. CASH POS TRANSACTION



Source: Oxford Economics

According to our results, a cash POS payment leads to an impact on ionizing radiation 3 times greater than a digital one in Germany, 0.9 times greater in Italy, and 9 times greater in Finland.

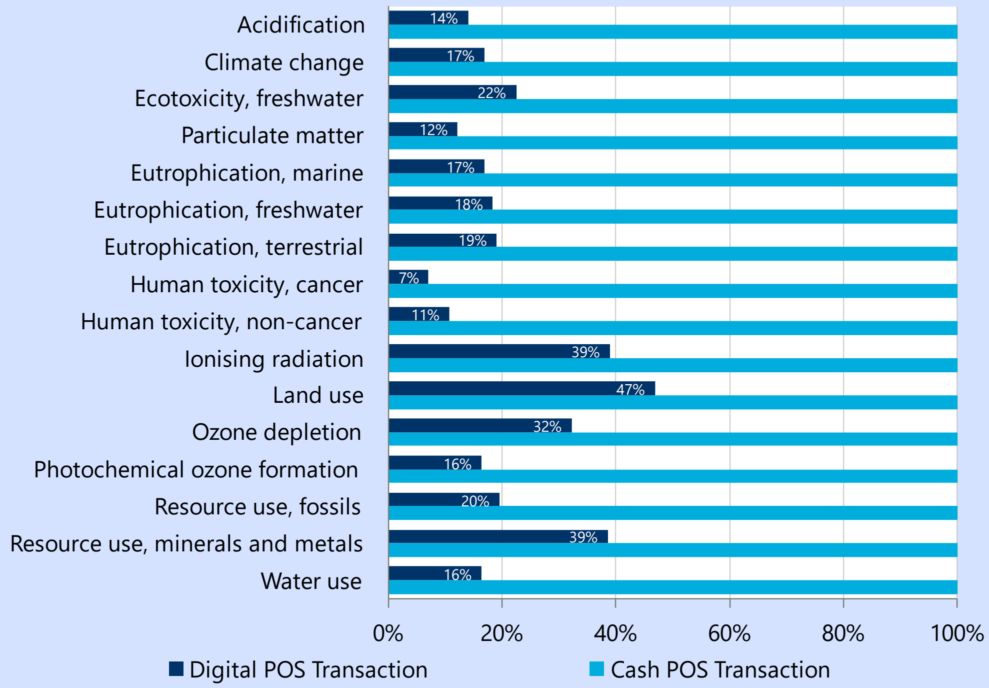
BOX 3: RESULTS OF LIFE CYCLE IMPACT ASSESSMENT USING THE ENVIRONMENTAL FOOTPRINT METHOD

This LCA study relies on the ReCiPe 2016 method to quantify the environmental impact of the digital and cash payment systems. This method was chosen to ensure that the results of this study can be compared to previous studies that have been conducted on these systems.[102] However, as the method was introduced many years ago, newer methods for environmental LCA have been introduced in the meantime. To ensure that our results are not overturned by using a newer method, this box shows the impact assessment of a cash and a digital POS transaction using a more up-to-date method.

One of these newer methods is the Environmental Footprint (EF) method which is the method adopted in the Environmental Footprint transition phase of the European Commission. As of writing this report, the current version of the EF method is 3.1.

The results of the EF 3.1 method are shown in Figure 59 to Figure 61 which depict the characterisation results in the different impact categories of one cash or digital POS transaction in the three countries. The system creating the highest impact is presented as 100% contribution. One can see that the results of the Environmental Footprint method are consistent with those of the ReCiPe 2016 method. In Germany and Finland, a digital POS transaction has a lower impact than a cash POS transaction in every category. In Italy, a digital POS transaction has a lower impact than a cash one in every category apart from "ionising radiation" and "resource use, minerals and metals".

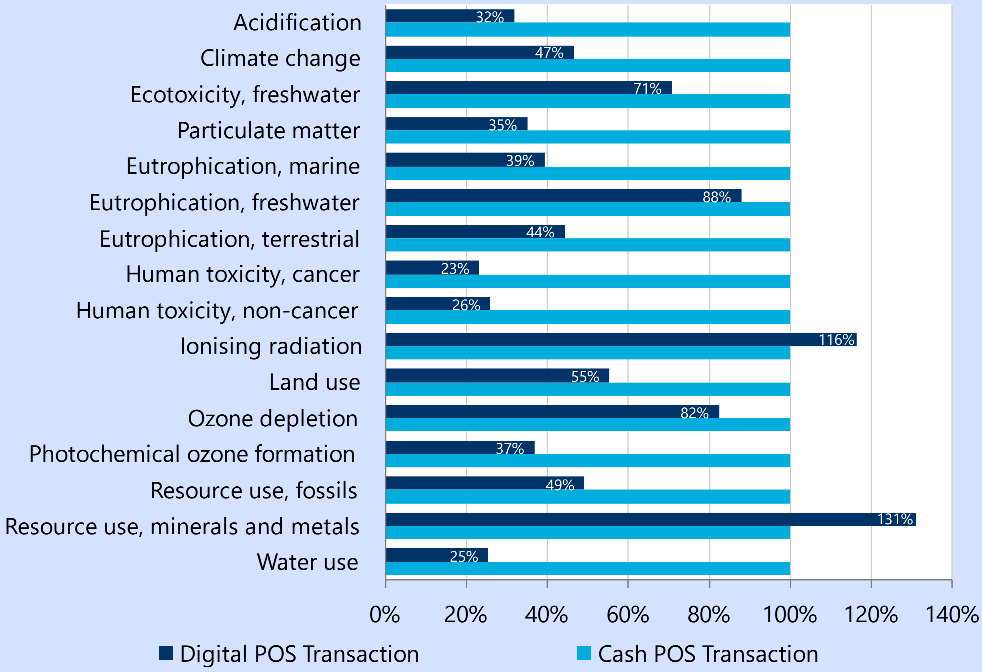
FIGURE 59: CHARACTERISATION RESULTS OF ONE CASH OR DIGITAL POS TRANSACTION IN GERMANY USING THE ENVIRONMENTAL FOOTPRINT 3.1 METHOD



Source: Oxford Economics

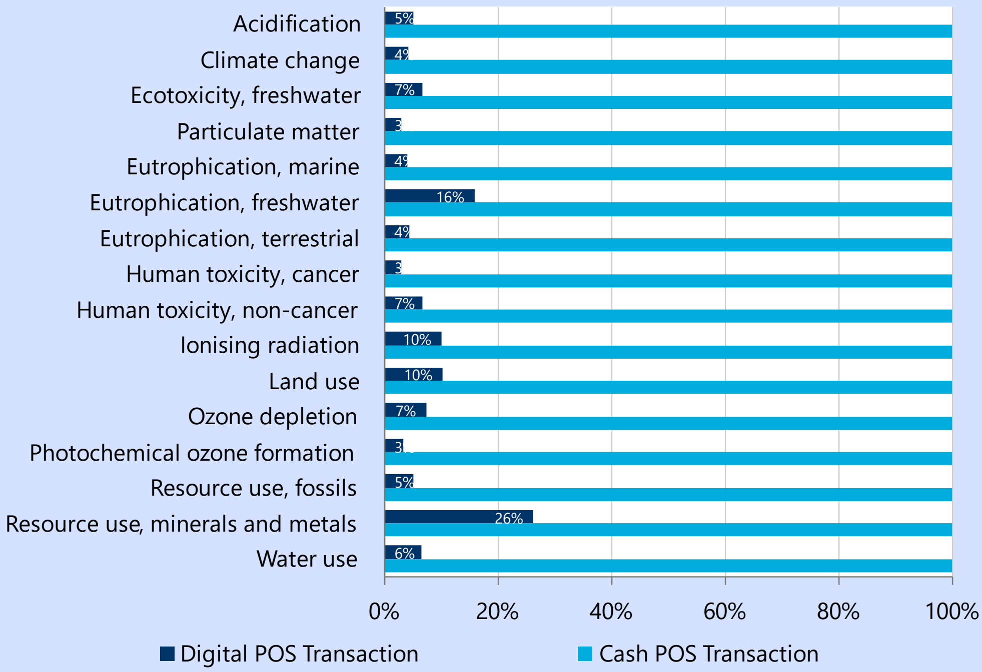
[102] See e.g. Hanegraaf et al. (2018) and Lindgreen et al. (2023).

FIGURE 60: CHARACTERISATION RESULTS OF ONE CASH OR DIGITAL POS TRANSACTION IN ITALY USING THE ENVIRONMENTAL FOOTPRINT 3.1 METHOD



Source: Oxford Economics

FIGURE 61: CHARACTERISATION RESULTS OF ONE CASH OR DIGITAL POS TRANSACTION IN FINLAND USING THE ENVIRONMENTAL FOOTPRINT 3.1 METHOD



Source: Oxford Economics

The absolute impact results using the EF 3.1 method are displayed in Table 24.

TABLE 24: ABSOLUTE RESULTS OF THE CHARACTERISATION RESULTS OF ONE CASH OR DIGITAL POS TRANSACTION USING THE ENVIRONMENTAL FOOTPRINT METHOD 3.1

Impact category	Unit	Cash in Germany	Digital in Germany	Cash in Italy	Digital in Italy	Cash in Finland	Digital in Finland
Acidification	mol H+ eq	1,24E-04	1,73E-05	1,02E-04	3,25E-05	2,57E-04	1,33E-05
Climate change	kg CO_2 eq	1,77E-02	2,99E-03	1,12E-02	5,24E-03	5,08E-02	2,15E-03
Ecotoxicity, freshwater	CTUe	1,79E-01	4,02E-02	1,35E-01	9,55E-02	4,58E-01	3,10E-02
Particulate matter	disease inc.	9,31E-10	1,13E-10	7,09E-10	2,48E-10	3,00E-09	8,67E-11
Eutrophication, marine	kg N eq	2,14E-05	3,63E-06	1,71E-05	6,73E-06	5,85E-05	2,38E-06
Eutrophication, freshwater	kg P eq	1,49E-06	2,74E-07	6,79E-07	5,96E-07	1,43E-06	2,27E-07
Eutrophication, terrestrial	mol N eq	2,09E-04	3,97E-05	1,60E-04	7,12E-05	6,11E-04	2,67E-05
Human toxicity, cancer	CTUh	3,20E-11	2,25E-12	2,12E-11	4,94E-12	6,37E-11	1,92E-12
Human toxicity, non-cancer	CTUh	9,09E-10	9,78E-11	7,70E-10	2,00E-10	1,25E-09	8,47E-11
Ionising radiation	kBq U-235 eq	5,20E-04	2,02E-04	2,53E-04	2,94E-04	2,18E-03	2,19E-04
Land use	Pt	1,40E-01	6,55E-02	1,11E-01	6,14E-02	3,21E-01	3,29E-02
Ozone depletion	kg CFC11 eq	3,63E-10	1,17E-10	2,63E-10	2,17E-10	1,12E-09	8,23E-11
Photochemical ozone formation	kg NMVOC eq	7,52E-05	1,23E-05	6,01E-05	2,21E-05	2,42E-04	8,24E-06
Resource use, fossils	MJ	2,36E-01	4,62E-02	1,50E-01	7,37E-02	7,04E-01	3,58E-02
Resource use, minerals and metals	kg Sb eq	9,00E-07	3,47E-07	7,65E-07	1,00E-06	1,21E-06	3,16E-07
Water use	m3 depriv.	5,02E-03	8,23E-04	5,33E-03	1,36E-03	8,37E-03	5,44E-04

Source: Oxford Economics

It is important to keep in mind however that these results are based on assumptions and estimation made during the inventory analysis. For example, one major factor for the environmental impact of the digital POS payment system across the three countries, in particular regarding the impact category "resource use, minerals and metals", is the use of gold. Gold is used in all kinds of electronics, but the amount used is typically small. As a result, changes in assumptions and estimation can lead to large changes in the amount of gold used in the digital POS payment system and its environmental impact.

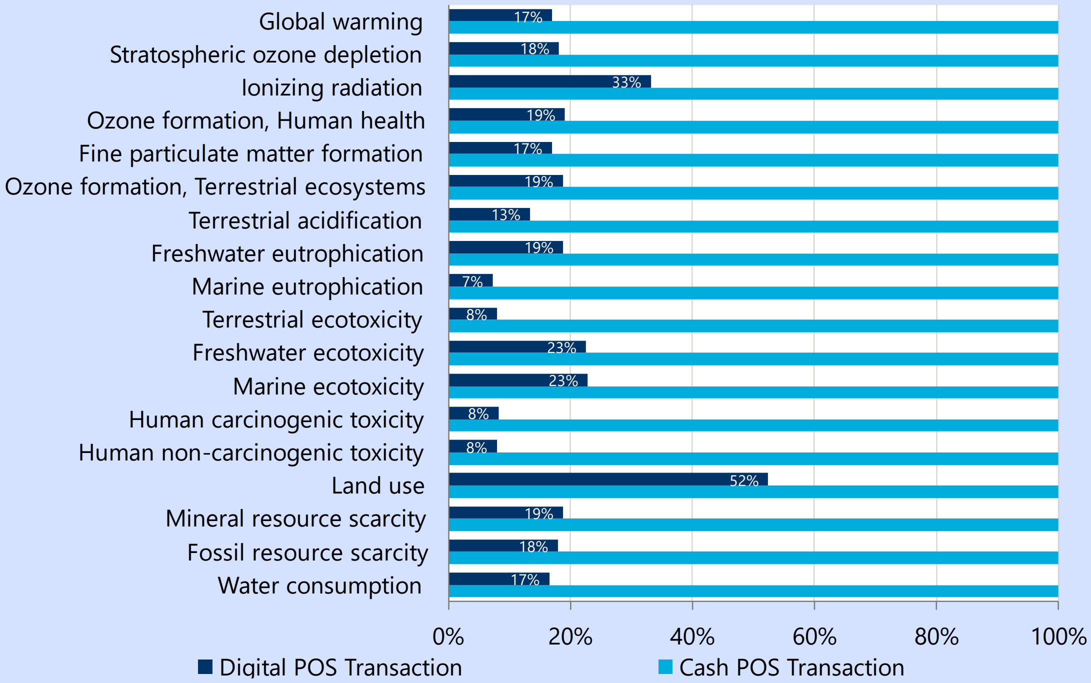
BOX 4: RESULTS OF LIFE CYCLE IMPACT ASSESSMENT USING DIFFERENT CULTURAL PERSPECTIVES OF THE RECIPE METHOD

As explained in chapter 3.5 there exist three different cultural perspectives regarding the ReCiPe method. These perspectives account for different sources of uncertainty and choices. Within our study we followed the hierarchical perspective. To check the robustness of our results, we have computed the baseline for the other two perspectives, namely the egalitarian and the individualist, as well which is presented in the following.

Individualist perspective

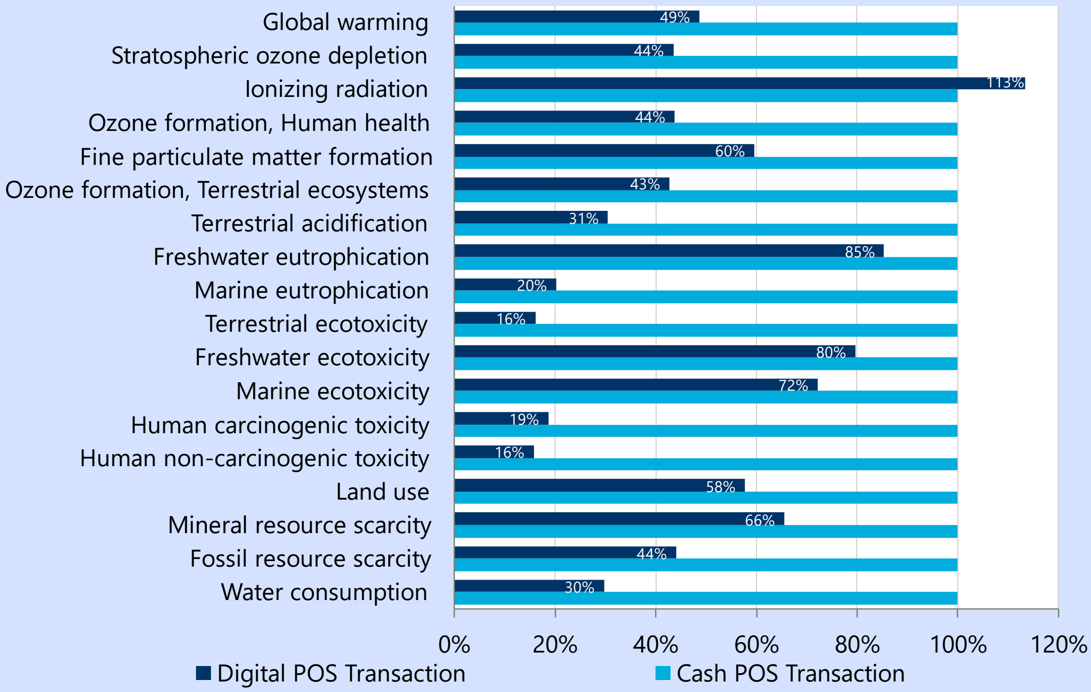
The results of the individualist perspective of the ReCiPe method are shown in Figure 62 to Figure 64, which depict the characterisation results in the different impact categories of one cash or digital POS transaction in the three countries. The system creating the highest impact is presented as 100% contribution. A digital POS transaction has a lower impact than a cash POS transaction in every category in Germany and Finland. In Italy, a digital POS transaction has a lower impact than a cash one in every category apart from "ionising radiation".

FIGURE 62: CHARACTERISATION RESULTS OF ONE CASH OR DIGITAL POS TRANSACTION IN GERMANY USING THE INDIVIDUALIST PERSPECTIVE OF THE RECIPE METHOD



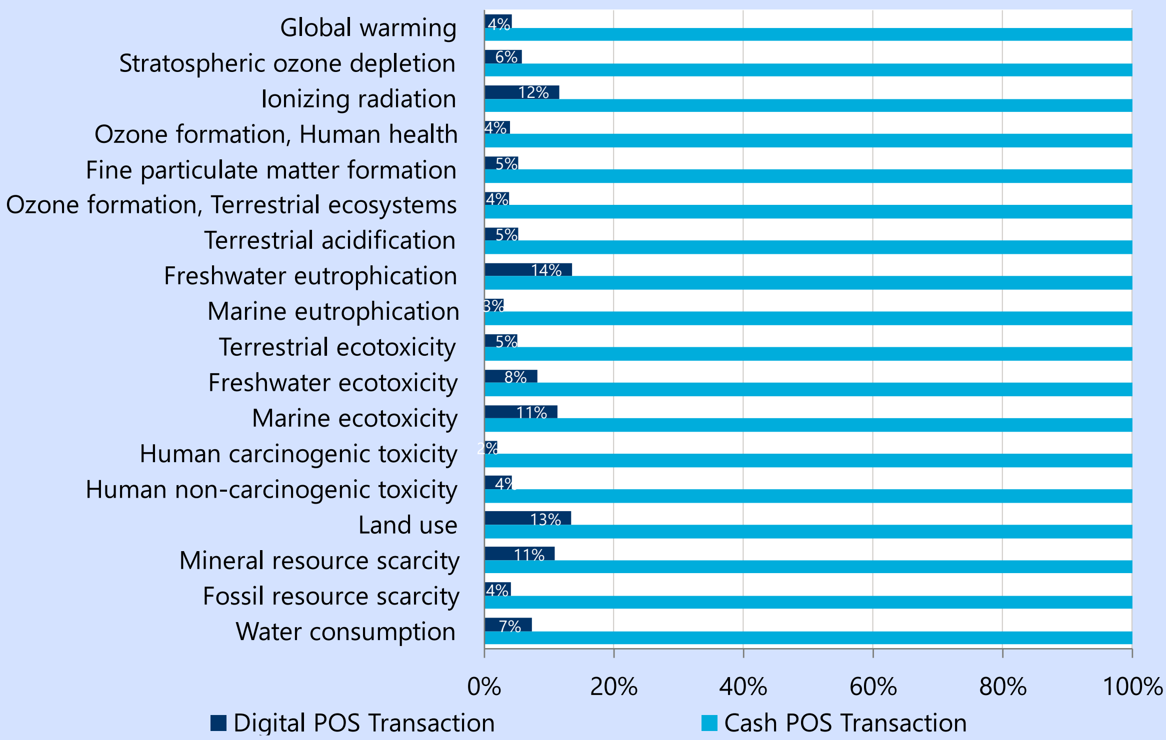
Source: Oxford Economics

FIGURE 63: CHARACTERISATION RESULTS OF ONE CASH OR DIGITAL POS TRANSACTION IN ITALY USING THE INDIVIDUALIST PERSPECTIVE OF THE RECIPE METHOD



Source: Oxford Economics

FIGURE 64: CHARACTERISATION RESULTS OF ONE CASH OR DIGITAL POS TRANSACTION IN FINLAND USING THE INDIVIDUALIST PERSPECTIVE OF THE RECIPE METHOD



Source: Oxford Economics

The absolute impact results using the individualist perspective of the ReCiPe method are displayed in Table 25.

TABLE 25: ABSOLUTE RESULTS OF THE CHARACTERISATION RESULTS OF ONE CASH OR DIGITAL POS TRANSACTION USING THE INDIVIDUALIST PERSPECTIVE OF THE RECIPE METHOD

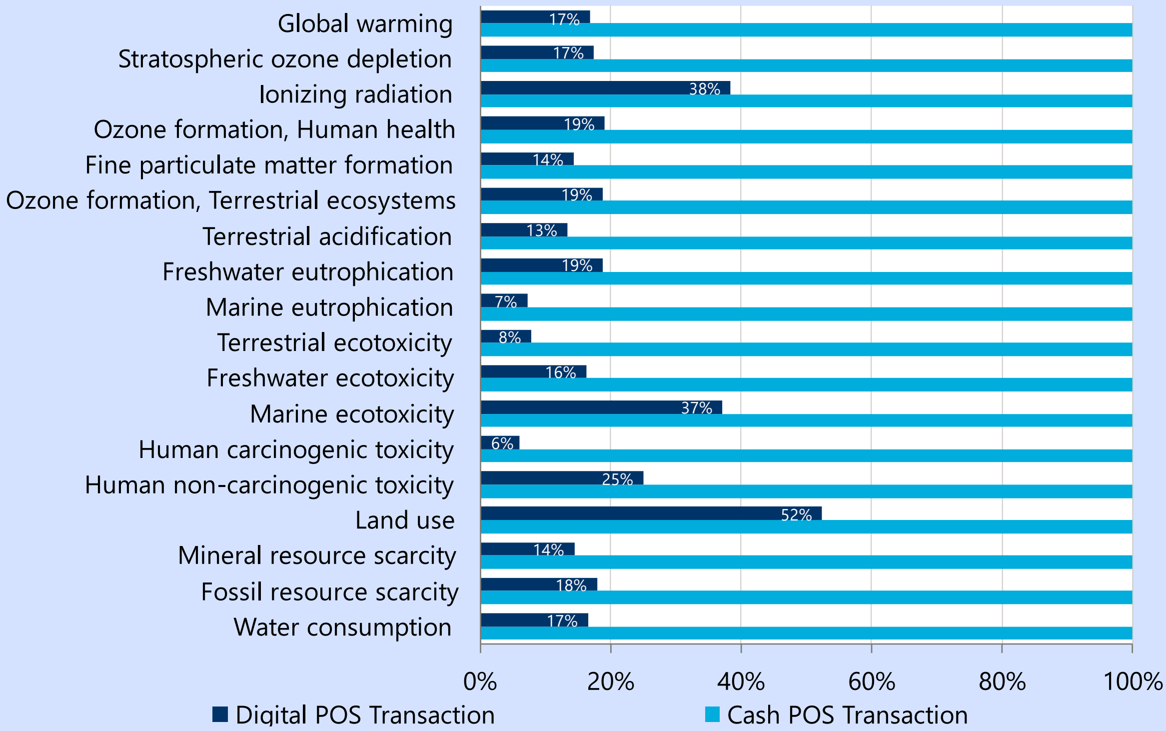
Impact category	Unit	Cash in Germany	Digital in Germany	Cash in Italy	Digital in Italy	Cash in Finland	Digital in Finland
Global warming	kg C02 eq	2.06E-02	3.50E-03	1.35E-02	6.56E-03	5.94E-02	2.52E-03
Stratospheric ozone depletion	kg CFC11 eq	5.42E-09	9.81E-10	3.56E-09	1.55E-09	1.27E-08	7.44E-10
Ionizing radiation	kBq Co-60 eq	8.37E-05	2.78E-05	3.48E-05	3.95E-05	2.51E-04	2.92E-05
Ozone formation, Human health	kg NOx eq	4.69E-05	8.96E-06	3.64E-05	1.59E-05	1.51E-04	5.91E-06
Fine particulate matter formation	kg PM2.5 eq	8.27E-06	1.40E-06	5.72E-06	3.41E-06	2.20E-05	1.15E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.96E-05	9.29E-06	3.87E-05	1.65E-05	1.61E-04	6.13E-06
Terrestrial acidification	kg SO2 eq	8.52E-05	1.14E-05	7.06E-05	2.16E-05	1.68E-04	8.90E-06
Freshwater eutrophication	kg P eq	1.71E-06	3.21E-07	8.02E-07	6.84E-07	1.85E-06	2.52E-07
Marine eutrophication	kg N eq	1.49E-06	1.08E-07	1.33E-06	2.70E-07	2.11E-06	6.37E-08
Terrestrial ecotoxicity	kg 1,4-DCB	1.65E-01	1.32E-02	1.52E-01	2.45E-02	2.36E-01	1.20E-02
Freshwater ecotoxicity	kg 1,4-DCB	4.38E-05	9.87E-06	3.29E-05	2.62E-05	1.03E-04	8.45E-06
Marine ecotoxicity	kg 1,4-DCB	5.57E-05	1.27E-05	4.69E-05	3.38E-05	9.99E-05	1.13E-05
Human carcinogenic toxicity	kg 1,4-DCB	1.09E-05	8.97E-07	9.10E-06	1.70E-06	3.59E-05	7.07E-07
Human non-carcinogenic toxicity	kg 1,4-DCB	1.34E-03	1.07E-04	1.21E-03	1.91E-04	2.21E-03	9.38E-05
Land use	m2a crop eq	1.08E-03	5.69E-04	8.86E-04	5.11E-04	2.06E-03	2.78E-04
Mineral resource scarcity	kg Cu eq	2.90E-04	5.45E-05	2.29E-04	1.50E-04	4.51E-04	4.94E-05
Fossil resource scarcity	kg oil eq	4.79E-03	8.57E-04	3.22E-03	1.42E-03	1.47E-02	6.12E-04
Water consumption	m3	1.86E-04	3.07E-05	1.64E-04	4.88E-05	3.08E-04	2.27E-05

Source: Oxford Economics

Egalitarian perspective

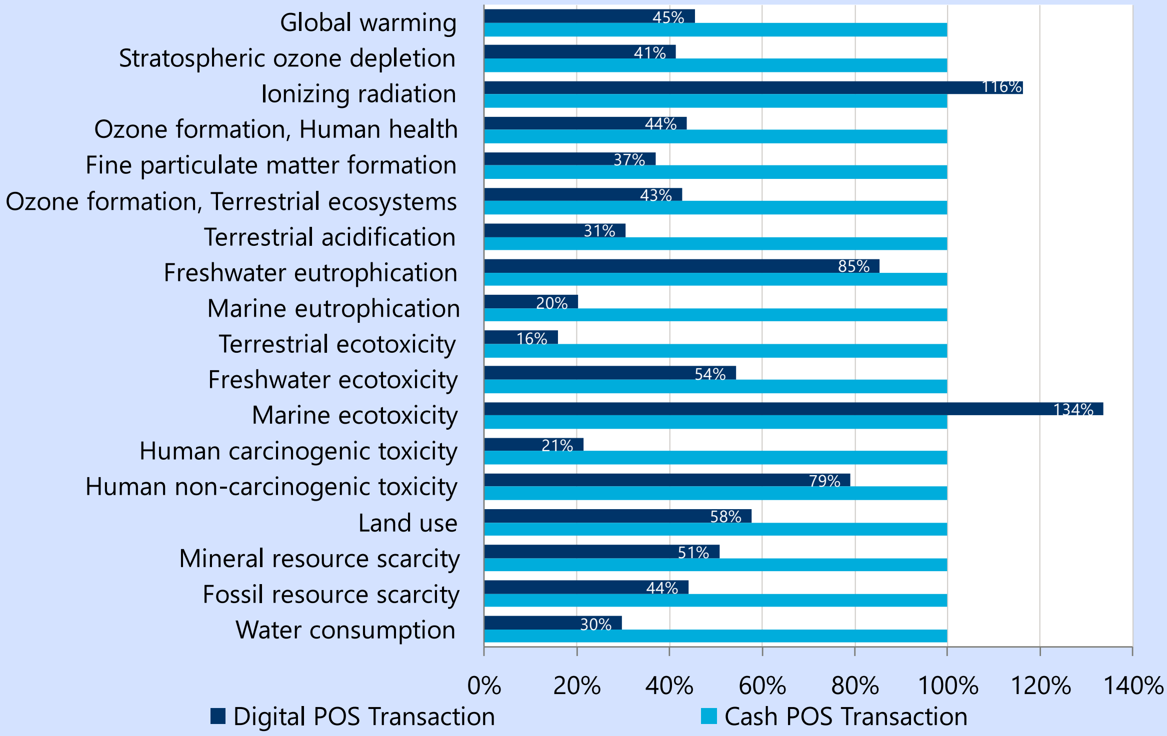
The results of the egalitarian perspective of the ReCiPe method are shown in Figure 65 to Figure 67. Similar to the individualist perspective method, a digital POS transaction has a lower impact than a cash POS transaction in every category in Germany and Finland. In Italy, a digital POS transaction has a lower impact than a cash one in every category apart from "ionising radiation" and "marine ecotoxicity".

FIGURE 65: CHARACTERISATION RESULTS OF ONE CASH OR DIGITAL POS TRANSACTION IN GERMANY USING THE EGALITARIAN PERSPECTIVE OF THE RECIPE METHOD



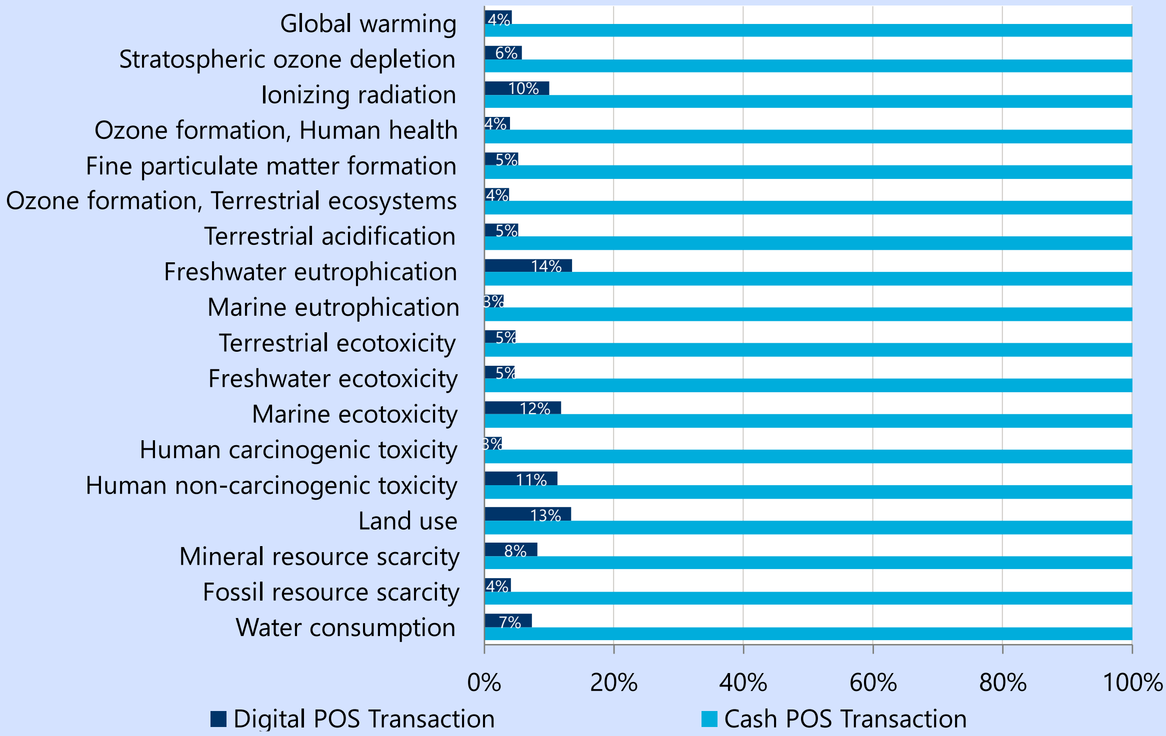
Source: Oxford Economics

FIGURE 66: CHARACTERISATION RESULTS OF ONE CASH OR DIGITAL POS TRANSACTION IN ITALY USING THE EGALITARIAN PERSPECTIVE OF THE RECIPE METHOD



Source: Oxford Economics

FIGURE 67: CHARACTERISATION RESULTS OF ONE CASH OR DIGITAL POS TRANSACTION IN FINLAND USING THE EGALITARIAN PERSPECTIVE OF THE RECIPE METHOD



Source: Oxford Economics

The absolute impact results using the egalitarian perspective of the ReCiPe method are displayed in Table 26.

TABLE 26: ABSOLUTE RESULTS OF THE CHARACTERISATION RESULTS OF ONE CASH OR DIGITAL POS TRANSACTION USING THE EGALITARIAN PERSPECTIVE OF THE RECIPE METHOD

Impact category	Unit	Cash in Germany	Digital in Germany	Cash in Italy	Digital in Italy	Cash in Finland	Digital in Finland
Global warming	kg C02 eq	1.63E-02	2.75E-03	1.02E-02	4.62E-03	4.66E-02	1.97E-03
Stratospheric ozone depletion	kg CFC11 eq	1.22E-08	2.13E-09	7.99E-09	3.31E-09	2.82E-08	1.64E-09
Ionizing radiation	kBq Co-60 eq	6.87E-04	2.64E-04	3.30E-04	3.84E-04	2.84E-03	2.86E-04
Ozone formation, Human health	kg NOx eq	4.69E-05	8.96E-06	3.64E-05	1.59E-05	1.51E-04	5.91E-06
Fine particulate matter formation	kg PM2.5 eq	3.25E-05	4.66E-06	2.59E-05	9.57E-06	7.05E-05	3.69E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.96E-05	9.29E-06	3.87E-05	1.65E-05	1.61E-04	6.13E-06
Terrestrial acidification	kg SO2 eq	8.52E-05	1.14E-05	7.06E-05	2.16E-05	1.68E-04	8.90E-06
Freshwater eutrophication	kg P eq	1.71E-06	3.21E-07	8.02E-07	6.84E-07	1.85E-06	2.52E-07
Marine eutrophication	kg N eq	1.49E-06	1.08E-07	1.33E-06	2.70E-07	2.11E-06	6.37E-08
Terrestrial ecotoxicity	kg 1,4-DCB	4.16E-01	3.28E-02	3.83E-01	6.09E-02	6.16E-01	2.97E-02
Freshwater ecotoxicity	kg 1,4-DCB	7.35E-05	1.20E-05	5.57E-05	3.03E-05	2.14E-04	1.01E-05
Marine ecotoxicity	kg 1,4-DCB	7.94E-01	2.95E-01	6.25E-01	8.35E-01	2.19E+00	2.59E-01
Human carcinogenic toxicity	kg 1,4-DCB	6.04E-02	3.61E-03	3.58E-02	7.68E-03	1.16E-01	3.11E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	1.20E+00	3.01E-01	1.01E+00	7.97E-01	2.37E+00	2.67E-01
Land use	m2a crop eq	1.08E-03	5.69E-04	8.86E-04	5.11E-04	2.06E-03	2.78E-04
Mineral resource scarcity	kg Cu eq	3.42E-04	4.93E-05	2.62E-04	1.33E-04	5.42E-04	4.45E-05
Fossil resource scarcity	kg oil eq	4.79E-03	8.57E-04	3.22E-03	1.42E-03	1.47E-02	6.12E-04
Water consumption	m3	1.86E-04	3.07E-05	1.64E-04	4.88E-05	3.08E-04	2.27E-05

Source: Oxford Economics

6. LIFE-CYCLE ASSESSMENT—INTERPRETATION

6.1 COMPARISON

Abstracting from individually perceived advantages and disadvantages of digital and cash payments, the results of our analysis indicate the following: The comparison of an average digital and cash POS transaction in Italy, Finland, and Germany suggests that a digital transaction at POS had a lower environmental impact than a cash transaction in 18 out of 18 impact categories in Germany and Finland, as well as 17 out of 18 impact categories in Italy in 2022. The only category where an average digital transaction at POS had a larger impact than an average cash transaction at POS was ionising radiation in Italy.

In general, the differences in the impact of both systems were smallest in Italy and largest in Finland. The largest environmental impact of an average digital POS transaction was estimated in Italy and the smallest in Finland. For cash the opposite is true: the largest impact of an average cash POS transaction was estimated in Finland, the smallest in Italy. Considering the digital system, the production phase was most relevant in the three countries across the majority of indicators followed by the operation phase. The high effects estimated for Italy are mainly driven by the terminal production that contributes much more to the environmental impact than in the other two countries. Concerning terminals, the assignment factor of one terminal to a digital POS transaction is much larger in Italy than in Germany and Finland because of the high number of terminals in Italy and their relatively short lifetime. While the average POS terminal in Italy is used for only 6,456 digital POS transactions, it is used for more than 28,870 in Germany and even 46,152 transactions in Finland. Thus, a much larger share of the terminal is allocated to the average digital POS transaction in Italy. The EoL phase only contributes small shares to the environmental impact in all countries across all impact categories.

In the cash system, the highest impact across all impact categories was estimated in Finland and the lowest in Italy. Here, the estimated impact is not as clearly distributed across the phases as in the digital system. In Germany and Italy, the production phase dominates across most impact categories although the impact of the production and the operation phase are much more equally distributed. The high impact estimated in Finland is mostly driven by the operation phase that is dominating here. The main driver in the operation phase is ATM/CRM usage, due to the long way travelled to ATMs/CRMs in Finland. Moreover, cash transport has a significant impact in Finland as well, again caused by the geographical population structure of the country. In the production phase, coin and ATM/CRM production are the most relevant inputs. Only in Finland, the cash transport production is even larger. Again, environmental impacts caused during the EoL phase are comparatively small across all countries and impact categories.

Lastly, considering ionising radiation in Italy—the only case in which an average cash POS transaction was estimated to have a smaller impact than an average digital POS transaction—both systems help to explain the result. The impact of an average digital POS transaction is much higher in Italy than in Germany and Finland and at the same time, the impact of a cash transaction in Italy is much lower.

The main driver behind the higher impact of the digital system is terminal production as mentioned before. The impact on ionising radiation in the cash system is lowest in Italy due to the operation phase. Here, the countries show differences in the number of ATMs/CRMs and thus, in the assignment factor that indicates how much of ATMs/CRMs operation phase can be allocated to an average cash POS transaction. Although the number of cash POS transactions is by far the highest in Italy, the country has only 56% of the ATMs/CRMs than Germany does, for instance. Thus, one ATM/CRM supports about 1.1 million cash POS transactions in Germany over the course of its lifetime and 2.6 million cash POS transactions in Italy (in Finland 1.4 million cash payments are supported). Thus, the impact of an ATM's energy usage is spread across more cash payments in Italy, reducing its impact compared to the other countries.

Based on these analyses it becomes clear that the impact of an average POS transaction—whether conducted digitally or with cash—is largely dependent on the utilisation of the existing system. Two components are crucial to determine the utilisation and the impact: the existing infrastructure and the total number of POS transactions. A particularly large impact may thus either be caused by a high impact of the overall infrastructure, a low number of POS transactions, or a combination of both. This has been discussed regarding the high number of POS terminals in Italy, for instance. To reduce the impact of an average POS transaction for either system, the impact of the overall infrastructure could be reduced, e.g., by increasing the expected lifespan and evaluating the actual need for aspects like ATMs/CRMs regularly, or by increasing the number of POS payments, if for example the infrastructure already exists or is desirable to build up for whatever reason. A reduction of the environmental impact of an average POS transaction is therefore reached when the utilisation of the existing infrastructure is maximized. However, these results only relate to the environmental impact of POS transactions. Other aspects concerning social or security issues, for instance, should be considered as well before deriving conclusions. Moreover, as has been illustrated by the study, many factors impact the outcome, as payment systems are complex. It is important to remember the context of this study that shapes the underlying assumptions, data, and methods, as well as the transferability to other contexts. The results were estimated for Germany, Italy, and Finland for the year 2022. Lastly, the analysis was based on several critical assumptions and data were partly uncertain. We therefore conducted several sensitivity checks as displayed in the next chapter. Concerning uncertainty, we also performed a Monte Carlo simulation (see Chapter 6.3). All limitations and assumptions made are also summarized in Chapter 6.4.

6.2 SENSITIVITY ANALYSIS

The results of the impact assessment in Chapter 5 are based on some uncertain assumptions regarding the functioning of the digital and cash payment process within the three countries. To analyse how sensitive the obtained environmental impact sizes are to a variation of these assumptions, we formulated 15 additional sensitivity checks to evaluate the robustness of our results. These checks were formulated based on two criteria. The first criterion is that assumptions made during the inventory analysis with a high degree of uncertainty were examined in a sensitivity check. For example, we consider the data on the way people travel to ATMs to withdraw money as uncertain. As a result, we have formulated a sensitivity check that removes this part of the system from the model (see Chapter 6.2.1). The second criterion is that we tended to focus on sensitivity checks that increase the impact of the digital system and/or decrease the impact of the cash system to examine whether the ordering of the cash and digital system can change, i.e., whether a sensitivity check can result in the cash system having a lower impact than the digital one.[103]

We show the overall results of our sensitivity checks in Table 27. The table shows the impact of a digital POS transaction relative to a cash one in each impact category for all sensitivity checks for each country. For example, a value of 50% means that a digital POS transaction has an impact half as large as a cash one in that sensitivity check.

Furthermore, we estimated a sensitivity check that combines different sensitivity checks in a way that results in a best-case for cash compared to a worst-case for a digital payment at POS (called "Worst case for digital POS payments vs. best case for cash POS payments"). The results are presented in section 6.2.16.

[103] Note that we already made conservative assumptions in the baseline model as outlined in Chapter 4.

TABLE 27: OVERVIEW OF THE RESULTS FROM THE SENSITIVITY ANALYSIS

Robustness Checks:

1: No way to ATM/CRM (impact on cash payment system)

2: Newer POS terminal model (impact on digital payment system)

3: No refurbishment of terminals (impact on digital payment system)

4: Worst EoL for refurbished terminals (impact on digital payment system)

5: Printing of two paper receipts (impact on digital payment system)

6: Higher energy use of digital data centres (impact on digital payment system)

7: Higher energy use for cash data centres (impact on cash payment system)

8: Lower energy use of digital data centres (impact on digital payment system)

9: Data centres local grid (digital only) (impact on digital payment system)

10: Data centres local grid (impact on cash and digital systems)

11: More small CCMs (impact on cash payment system)

12: No small CCMs (impact on cash payment system)

13: Recycled cards (impact on cash and digital payment system)

14: Double life of banknotes (impact on cash payment system)

15: No overhead during coin production (impact on cash payment system)

Note: The colouring of the cells illustrates the change of a sensitivity check relative to the baseline. A dark red colour means that the percentage increased a lot compared to the baseline, whereas a dark green colour means that the percentage increased only by a bit or even decreased relative to the baseline. For example, an average digital POS transaction has 16.9% of the impact on global warming as an average cash POS transaction in Germany. Sensitivity analysis 1 excluded the way to ATM/CRM decreasing the impact of an average cash POS transaction in Germany. As a result, the impact of a digital cash POS transaction is 26.3% as high as the impact of a cash transaction at POS in this analysis. Thus, the digital POS transaction has become relatively worse as indicated by the red colour.

The result for the combined scenario is not depicted in this table as it constitutes a combination of several other sensitivity checks. Its result can be found in section 6.2.16.

Relative impact of a digital POS payment compared to a cash one in Germany:

Impact Category	Base-line	Sensitivity Analysis														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Global warming	16.9%	26.3%	16.2%	17.4%	16.9%	17.4%	20.0%	/	16.9%	17.4%	17.4%	16.5%	16.9%	16.7%	17.1%	17.3%
Stratospheric ozone depletion	17.7%	23.6%	16.7%	18.1%	17.7%	18.7%	21.2%	/	17.7%	18.3%	18.3%	17.3%	17.7%	17.3%	19.1%	18.3%
Ionizing radiation	33.9%	37.0%	32.0%	34.4%	33.9%	35.1%	45.2%	/	33.9%	26.9%	27.0%	33.1%	33.9%	33.7%	34.5%	34.8%
Ozone formation, Human health	19.1%	31.1%	18.4%	19.6%	19.1%	19.6%	21.9%	/	19.1%	19.0%	19.0%	18.6%	19.1%	18.9%	19.4%	20.0%
Fine particulate matter formation	14.3%	17.9%	13.8%	14.8%	14.4%	14.8%	17.3%	/	14.3%	14.5%	14.5%	13.9%	14.3%	14.2%	14.5%	16.5%
Ozone formation, Terrestrial ecosystems	18.7%	30.8%	18.1%	19.3%	18.8%	19.3%	21.5%	/	18.7%	18.7%	18.7%	18.3%	18.8%	18.6%	19.0%	19.7%
Terrestrial acidification	13.4%	16.2%	13.5%	13.8%	13.4%	13.8%	16.2%	/	13.4%	13.5%	13.5%	13.1%	13.4%	13.3%	13.6%	15.8%
Freshwater eutrophication	18.8%	20.3%	16.2%	19.5%	18.8%	19.3%	22.7%	/	18.8%	21.6%	21.5%	17.7%	18.8%	18.7%	20.1%	19.7%
Marine eutrophication	7.3%	7.9%	7.5%	7.5%	7.3%	7.5%	7.8%	/	7.3%	7.3%	7.3%	7.0%	7.3%	7.3%	11.1%	7.3%
Terrestrial ecotoxicity	7.9%	8.6%	7.4%	8.1%	7.9%	7.9%	10.5%	/	7.9%	7.9%	7.9%	7.8%	7.9%	7.8%	7.9%	10.2%
Freshwater ecotoxicity	18.4%	26.2%	14.1%	19.4%	18.9%	18.7%	22.9%	/	18.4%	18.5%	18.5%	17.4%	18.4%	18.4%	19.4%	19.6%
Marine ecotoxicity	21.2%	25.4%	17.1%	22.3%	21.2%	21.3%	27.1%	/	21.1%	21.2%	21.2%	20.0%	21.2%	21.1%	21.3%	25.3%
Human carcinogenic toxicity	6.2%	7.3%	6.3%	6.5%	6.3%	6.4%	7.9%	/	6.2%	6.3%	6.3%	6.2%	6.2%	6.2%	6.3%	6.8%
Human non-carcinogenic toxicity	10.3%	11.1%	9.5%	10.7%	10.4%	10.5%	13.5%	/	10.3%	10.4%	10.4%	10.2%	10.4%	10.3%	10.4%	13.4%
Land use	52.4%	61.4%	51.9%	52.7%	52.4%	56.4%	54.8%	/	52.4%	51.6%	51.6%	51.7%	52.4%	52.4%	66.3%	54.1%

Impact Category	Base-line	Sensitivity Analysis														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mineral resource scarcity	14.4%	16.0%	13.0%	15.2%	14.4%	14.5%	18.5%	/	14.4%	14.5%	14.5%	14.0%	14.4%	14.4%	14.5%	17.2%
Fossil resource scarcity	17.9%	29.5%	17.3%	18.3%	17.9%	18.6%	21.1%	/	17.9%	17.9%	17.9%	17.5%	17.9%	17.4%	18.1%	18.3%
Water consumption	16.5%	18.2%	15.8%	16.9%	16.5%	17.5%	19.0%	/	16.5%	16.7%	16.7%	16.3%	16.5%	16.9%	21.3%	17.2%

Source: Oxford Economics

Relative impact of a digital POS payment compared to a cash one in Italy:

Impact Category	Base-line	Sensitivity Analysis														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Global warming	46.8%	81.5%	41.9%	47.5%	46.9%	49.2%	51.6%	46.8%	45.9%	47.1%	47.1%	46.5%	46.9%	46.6%	47.8%	48.5%
Stratospheric ozone depletion	42.1%	59.1%	35.1%	42.7%	42.2%	44.4%	47.4%	42.1%	41.1%	42.1%	42.1%	41.8%	42.2%	41.7%	47.4%	44.4%
Ionizing radiation	114.8%	135.2%	94.2%	115.9%	114.8%	120.5%	141.7%	114.1%	109.4%	90.8%	91.4%	113.4%	114.9%	114.5%	118.9%	122.0%
Ozone formation, Human health	43.8%	72.6%	39.6%	44.4%	43.8%	45.2%	47.4%	43.7%	43.0%	44.2%	44.2%	43.4%	43.8%	43.6%	44.6%	46.6%
Fine particulate matter formation	37.0%	45.7%	33.8%	37.5%	37.1%	38.0%	40.7%	36.9%	36.2%	37.5%	37.5%	36.7%	37.0%	36.8%	37.4%	44.3%
Ozone formation, Terrestrial ecosystems	42.8%	71.7%	39.0%	43.4%	42.8%	44.1%	46.3%	42.7%	42.1%	43.3%	43.2%	42.4%	42.8%	42.6%	43.6%	45.4%
Terrestrial acidification	30.5%	36.3%	31.1%	31.0%	30.5%	31.5%	33.9%	30.5%	29.9%	31.1%	31.1%	30.4%	30.5%	30.4%	31.0%	37.5%
Freshwater eutrophication	85.4%	96.8%	60.8%	86.8%	85.4%	87.7%	93.7%	85.2%	83.7%	83.3%	83.3%	83.0%	85.5%	85.2%	98.6%	94.7%
Marine eutrophication	20.3%	21.8%	21.5%	20.5%	20.3%	23.4%	20.8%	20.3%	20.2%	20.2%	20.2%	20.0%	20.3%	20.3%	33.4%	20.5%

Impact Category	Baseline	Sensitivity Analysis														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Terrestrial ecotoxicity	15.9%	17.0%	13.7%	16.1%	15.9%	16.0%	18.7%	15.9%	15.3%	15.9%	15.9%	15.8%	15.9%	15.9%	15.9%	21.1%
Freshwater ecotoxicity	65.9%	94.9%	39.0%	67.1%	66.5%	66.5%	72.1%	65.8%	64.6%	65.9%	65.9%	64.7%	65.9%	65.9%	70.9%	71.6%
Marine ecotoxicity	67.0%	78.8%	45.0%	68.2%	67.1%	67.2%	74.0%	66.9%	65.6%	67.0%	67.0%	66.0%	67.0%	66.9%	67.7%	83.1%
Human carcinogenic toxicity	21.0%	25.3%	21.3%	21.3%	21.0%	21.4%	23.7%	20.9%	20.4%	21.0%	21.0%	20.9%	21.0%	20.9%	21.1%	24.0%
Human non-carcinogenic toxicity	22.2%	23.6%	17.9%	22.5%	22.2%	22.6%	25.7%	22.2%	21.5%	22.2%	22.2%	22.1%	22.2%	22.2%	22.3%	29.8%
Land use	57.7%	66.7%	54.6%	58.0%	57.7%	67.5%	60.6%	57.7%	57.2%	56.9%	56.9%	57.5%	57.7%	57.7%	77.5%	60.1%
Mineral resource scarcity	50.8%	56.1%	42.0%	51.7%	50.8%	51.0%	56.0%	50.7%	49.7%	50.7%	50.7%	50.3%	50.8%	50.7%	50.9%	64.3%
Fossil resource scarcity	44.1%	79.2%	39.7%	44.7%	44.1%	46.1%	48.8%	44.0%	43.1%	44.5%	44.5%	43.7%	44.1%	43.6%	44.8%	45.4%
Water consumption	29.7%	32.3%	26.1%	30.1%	29.7%	32.0%	32.5%	29.7%	29.2%	32.2%	32.2%	29.6%	29.7%	30.0%	39.8%	31.2%

Source: Oxford Economics

Relative impact of a digital POS payment compared to a cash one in Finland:

Impact Category	Baseline	Sensitivity Analysis														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Global warming	4.2%	18.9%	4.1%	4.4%	4.2%	4.6%	5.3%	/	3.7%	4.0%	4.0%	4.2%	4.2%	4.2%	4.3%	4.3%
Stratospheric ozone depletion	5.8%	17.8%	5.6%	6.0%	5.8%	6.6%	7.3%	/	5.1%	6.0%	6.0%	5.8%	5.8%	5.8%	6.0%	5.9%
Ionizing radiation	11.2%	13.3%	10.8%	11.3%	11.2%	11.9%	14.7%	/	9.5%	16.8%	16.7%	11.1%	11.2%	11.1%	11.3%	11.3%
Ozone formation, Human health	3.9%	15.6%	3.8%	4.0%	3.9%	4.3%	4.8%	/	3.5%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	4.0%

Impact Category	Baseline	Sensitivity Analysis														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Fine particulate matter formation	5.2%	12.3%	5.1%	5.4%	5.3%	5.6%	6.6%	/	4.6%	5.4%	5.4%	5.2%	5.2%	5.2%	5.3%	5.6%
Ozone formation, Terrestrial ecosystems	3.8%	15.4%	3.7%	3.9%	3.8%	4.2%	4.7%	/	3.4%	3.7%	3.7%	3.8%	3.8%	3.8%	3.8%	3.9%
Terrestrial acidification	5.3%	11.7%	5.3%	5.5%	5.3%	5.7%	6.7%	/	4.6%	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%	5.7%
Freshwater eutrophication	13.6%	23.8%	12.1%	14.1%	13.6%	14.6%	17.2%	/	11.9%	12.8%	12.8%	13.0%	13.6%	13.6%	14.4%	14.2%
Marine eutrophication	3.0%	4.7%	3.1%	3.1%	3.0%	3.5%	3.4%	/	2.9%	3.0%	3.0%	3.0%	3.0%	3.0%	4.0%	3.0%
Terrestrial ecotoxicity	4.8%	7.4%	4.6%	4.9%	4.8%	4.9%	6.6%	/	4.0%	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%	5.7%
Freshwater ecotoxicity	5.7%	17.0%	4.7%	5.9%	5.8%	5.8%	7.3%	/	4.9%	5.6%	5.6%	5.6%	5.7%	5.7%	5.8%	5.8%
Marine ecotoxicity	9.5%	20.1%	8.2%	10.0%	9.6%	9.6%	12.5%	/	8.1%	9.5%	9.5%	9.3%	9.5%	9.5%	9.6%	10.4%
Human carcinogenic toxicity	2.9%	5.5%	2.9%	3.0%	2.9%	3.0%	3.8%	/	2.4%	2.8%	2.8%	2.9%	2.9%	2.9%	2.9%	3.0%
Human non-carcinogenic toxicity	6.7%	9.8%	6.3%	6.9%	6.7%	7.0%	9.0%	/	5.6%	6.7%	6.7%	6.7%	6.7%	6.7%	6.7%	8.0%
Land use	13.5%	25.8%	13.3%	13.6%	13.5%	17.7%	14.7%	/	12.9%	13.9%	13.9%	13.4%	13.5%	13.5%	15.1%	13.7%
Mineral resource scarcity	8.2%	13.4%	7.6%	8.6%	8.2%	8.3%	10.8%	/	7.0%	8.2%	8.2%	8.1%	8.2%	8.2%	8.2%	9.1%
Fossil resource scarcity	4.2%	20.2%	4.0%	4.3%	4.2%	4.6%	5.2%	/	3.7%	3.8%	3.8%	4.1%	4.2%	4.1%	4.2%	4.2%
Water consumption	7.4%	11.3%	7.1%	7.5%	7.4%	8.6%	8.8%	/	6.7%	8.8%	8.8%	7.3%	7.4%	7.4%	8.5%	7.5%

Source: Oxford Economics

One can see that in no sensitivity check a digital POS transaction has a larger impact than a cash one when it had a lower impact in the baseline. In other words, our sensitivity checks only resulted in a larger impact of a digital POS transaction compared to a cash one in the category ionizing radiation in Italy, as this was the only category-country combination where a digital POS transaction had a larger impact than a cash one in the baseline.

In the following, for each sensitivity check, we first specify and justify the modified assumption, and then discuss the impact results of that sensitivity check in more detail.

6.2.1 No Way to ATM/CRM (impact on cash payment system)

As noticed already, the way to reach the next ATM/CRM has a large impact on the impact categories. Especially in Finland, due to the long driving distances, this could influence the robustness of the results. Hence, we test the robustness of the results by assuming that no way to the ATM/CRM needs to be overcome at all.

TABLE 28: INVENTORY TABLE ADJUSTMENTS FOR NO WAY TO ATM/CRM

	Baseline Scenario	Sensitivity Check
Transport to reach the next ATM/CRM by car		
Germany	147,521,458.17 km	0 km
Italy	146,938,594.54 km	0 km
Finland	28,217,169.66 km	0 km
Transport to reach the next ATM/CRM by bicycle		
Germany	59,383,930.80 km	0 km
Italy	13,487,471.96 km	0 km
Finland	9,135,033.60 km	0 km
Transport to reach the next ATM/CRM by public transport (bus)		
Germany	29,632,700 km	0 km
Italy	37,016,514.87 km	0 km
Finland	5,860,800 km	0 km
Transport to reach the next ATM/CRM by motor scooter		
Germany	-	0 km
Italy	8,318,620.43 km	0 km
Finland	-	0 km

Source: Oxford Economics

The results for the sensitivity analysis on the impact of the digital payment system relative to the cash system are displayed in Figure 68. The impact of a cash POS transaction in the baseline case is normalised to 100% (i.e., the light blue bar). Additionally, the impact of a digital POS payment relative to a cash POS payment in the baseline case is displayed by the dark blue squares. For example, the dark blue square for global warming in Germany indicates that an average digital POS transaction has 16.9% of the impact on global warming as an average cash POS transaction. The grey bar represents the impact of the sensitivity check on the estimates for a cash POS payment. For example, an average cash POS transaction in Germany has 65% of the impact on global warming as an average cash POS transaction in the baseline case. The new impact, in the sensitivity check case, of a digital POS payment relative to a cash POS payment is displayed by green triangles. All categories in which the sensitivity check increased/decreased the relative impact of a digital POS payment compared to a cash payment are represented by green triangles higher/lower than the blue squares of the baseline estimation. If the sensitivity check did not influence the cash system, the grey bars remain at 100%. If the green triangles, i.e. the relative impact of a digital POS in the sensitivity check, change relative to the dark blue squares, i.e. the impact of a digital POS payment in the baseline case, without the cash payment being impacted, then this implies that assumptions in the digital payment system have been changed.[104] The interpretation of the bar charts in the following chapters (see chapter 6.2.1 to 6.2.16) follow the same interpretation. Hence, in this sensitivity check, the impact of the cash payment system should decrease relative to the baseline as travel distances to the next ATM/CRM are assumed to be 0 km and the digital payment system is not changed from baseline.

As expected, the results change significantly across most impact categories decreasing the impact of an average cash POS transaction relative to an average digital POS transaction. Considering, GWP, for instance, a digital POS transaction had an impact equal to 16.9% of a cash POS in Germany in the baseline (see dark blue square in global warming for Germany). Although this increased to 26.3% in the robustness check (see green triangle in global warming for Germany), an average digital POS transaction still had a much smaller impact than an average cash POS transaction on GWP. In Italy, this value increased from 46.8% to 81.5% and in Finland from 4.2% to 18.9% (see Table 27 and Figure 68). Thus, in all countries analysed, the impact of an average cash and digital POS transaction becomes more similar as the way to ATM/CRM is not considered. Yet, in all three countries, an average digital POS transaction remains less harmful concerning GWP.[105]

Further impact categories that were affected significantly are stratospheric ozone depletion, ozone formation (human health), ozone formation (terrestrial ecosystems), freshwater ecotoxicity, marine ecotoxicity, land use and fossil resource scarcity. Overall, the results for Finland are affected the most due to the long distances travelled.

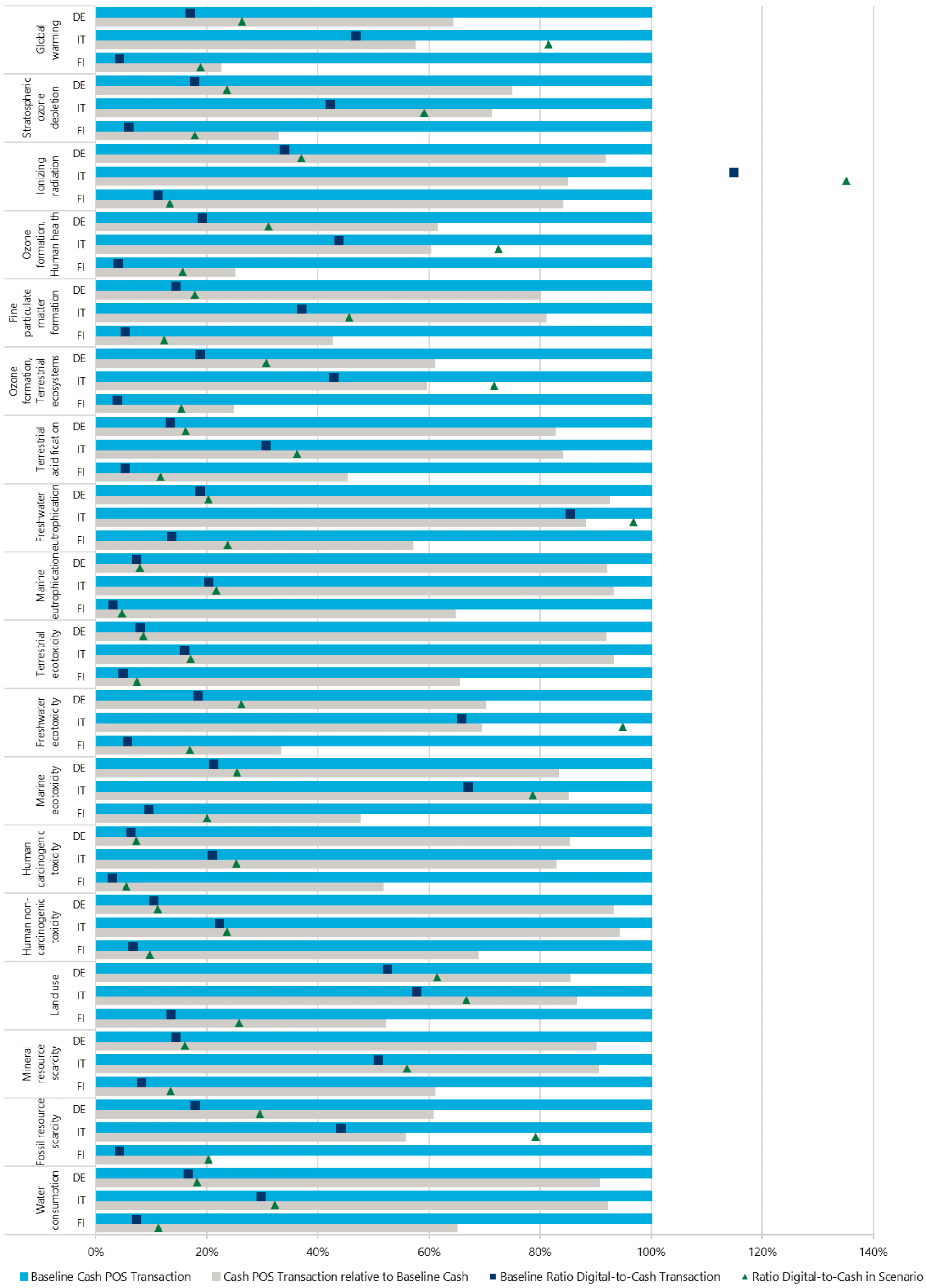
Although—considering all impact categories—this sensitivity check impacts the results the most among all robustness checks, digital POS payments remain the payment method with a smaller environmental impact in all countries. The only exception is ionising radiation in Italy, where the impact of a digital POS transaction exceeded that of an average cash transaction in the baseline already. This effect is even more pronounced if the way to ATM is not considered. As mentioned above, this result can be explained by two factors: The impact of an average digital POS transaction is much higher in Italy than in Germany and Finland and at the same time the impact of a cash transaction in Italy is much lower. The main driver behind the higher impact of the digital system is terminal production. The impact on ionising radiation of the cash system is lowest in Italy due to the operation phase. In detail, the number of ATMs is much smaller in Italy than in Germany, for instance.

[104] Three exceptions in which both payment systems were impacted exit, namely: data centres local grid (Chapter 6.2.10), recycled cards (Chapter 6.2.13), and the worst vs. best case scenario (Chapter 6.2.16).

[105] An important contributor to the environmental impact of a cash POS payment in this sensitivity check is the usage of copper in coins.

FIGURE 68: IMPACT OF NO WAY TO ATM/CRM ON THE CASH SYSTEM AND THE RELATIVE IMPACT OF THE DIGITAL SYSTEM

Note: All categories in which the sensitivity check decreased/increased the cash payment system, relative to the baseline cash payment estimates, are represented by grey bars lower/higher than 100%. If the sensitivity check did not influence the cash system, the grey bars remain at 100%. If the green triangles, i.e. the impact of a digital POS payment relative to a cash one in the sensitivity check, change relative to the dark blue squares, i.e. the impact of a digital POS payment relative to a cash one in the baseline case, without the cash payment being impacted, then this implies that assumptions in the digital payment system have been changed. Only in three cases estimates for both payment systems were impacted, namely: data centres local grid (Chapter 6.2.10), recycled cards (Chapter 6.2.13), and the worst vs. best case scenario (Chapter 6.2.16).



Source: Oxford Economics

6.2.2 Newer POS terminal model (impact on digital payment system)

In the baseline model, we used the same material inputs as reported by Lindgreen et. al (2017) because we were not able to gather data on the models of terminals currently in use in the three countries. However, newer terminals are significantly more energy-efficient and use less material. To take the effect of these newer terminals into account, we used information from a leading terminal producer on a current terminal. All input changes in the sensitivity check are displayed in Table 29. Only the environmental impact of digital payments is influenced by this change (see Figure 69).

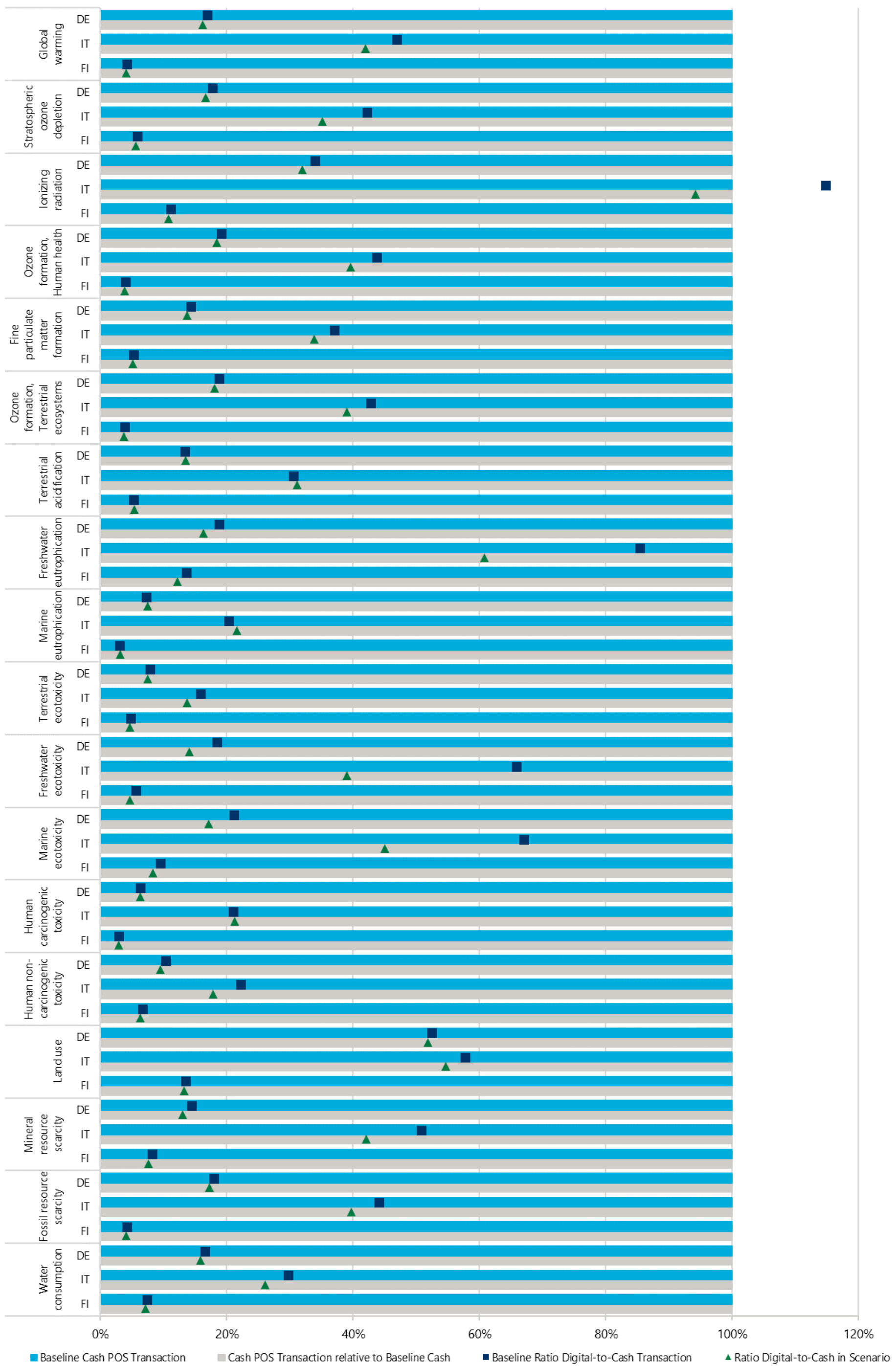
TABLE 29: INVENTORY TABLE ADJUSTMENTS FOR NEWER POS TERMINAL MODEL

Dataset	Amount		
	Germany	Italy	Finland
Power supply unit, for desktop computer {GLO}| market for power supply unit, for desktop computer | Cut-off, U	0.058503401 pieces		
Battery cell, Li-ion, NMC111 {GLO}| market for battery cell, Li-ion, NMC111 | Cut-off, U	47 g		
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	136 g		
Injection moulding, without electricity {GLO}| market for injection moulding | Cut-off, U	136 g		
Silicone product {RoW}| market for silicone product | Cut-off, U	8 g		
Injection moulding, without electricity {GLO}| market for injection moulding | Cut-off, U	8 g		
Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	0.004117647 pieces		
Electronic component, passive, unspecified {GLO}| market for electronic component, passive, unspecified | Cut-off, U	58 g		
Electricity, medium voltage {VN}| market for electricity, medium voltage | Cut-off, U	6.12244898 kWh		
Average distance from distribution centres to customers for one POS terminal in 2022	0.25 tkm	0.48 tkm	0.13 tkm
Maintenance—mainly postal swap	0.0897851 tkm	0.0001867 tkm	0.0000466 tkm
Energy use per terminal without printing per day	0.000241 kWh	0.000058 kWh	0.000299 kWh
Energy use per terminal Printing only per day	0.000699 kWh	0.000118 kWh	0.000609 kWh
Energy use per terminal for non-processing time	0.001780 kWh	0.001795 kWh	0.001776 kWh

Source: Oxford Economics

FIGURE 69: IMPACT OF NEWER POS TERMINAL MODELS ON THE CASH SYSTEM AND THE RELATIVE IMPACT OF THE DIGITAL SYSTEM

Note: All categories in which the sensitivity check decreased/increased the cash payment system, relative to the baseline cash payment estimates, are represented by grey bars lower/higher than 100%. If the sensitivity check did not influence the cash system, the grey bars remain at 100%. If the green triangles, i.e. the impact of a digital POS payment relative to a cash one in the sensitivity check, change relative to the dark blue squares, i.e. the impact of a digital POS payment relative to a cash one in the baseline case, without the cash payment being impacted, then this implies that assumptions in the digital payment system have been changed. Only in three cases estimates for both payment systems were impacted, namely: data centres local grid (Chapter 6.2.10), recycled cards (Chapter 6.2.13), and the worst vs. best case scenario (Chapter 6.2.16).



Source: Oxford Economics.

The results indicate that the environmental impact of an average digital transaction at POS decreases significantly for all countries and across most impact categories. The impact categories affected most by the robustness check are ionising radiation, freshwater eutrophication, freshwater ecotoxicity, and marine ecotoxicity. As terminal production plays a particularly important role in digital POS transactions in Italy, the country is affected most by the sensitivity analysis. Looking at ionising radiation in Italy, the result flipped such that a digital POS transaction has a lower estimated impact than a cash POS transaction across all impact categories in all countries.

6.2.3 No refurbishment of terminals (impact on digital payment system)

In the terminal subsystem, we assumed that some terminals are refurbished, which extends their average lifetime, but also adds a disposal scenario in Asia as an assumption. In the sensitivity check, we assume that all terminals are disposed of in their respective country, not allowing for any refurbishment and thus reducing the average life expectancy of a terminal to 5 years. A detailed presentation of the changes made for the sensitivity check is displayed in Table 30.

TABLE 30: INVENTORY TABLE NO REFURBISHMENT OF TERMINALS

	Baseline Scenario	Sensitivity Check
Average lifespan of a terminal (in years) including refurbishing rates		
Germany	5.57	5
Italy	5.11	5
Finland	5.7	5
Assignment factor for one payment terminal (production)		
Germany	3.46E-05	3.86E-05
Italy	1.57E-04	1.61E-04
Finland	2.17E-05	2.47E-05
Assignment factor for average distance from customer to warehouse for disposal/recycling for one POS terminal in 2022		
Germany	3.46E-05	3.86E-05
Italy	1.57E-04	1.61E-04
Finland	2.17E-05	2.47E-05
Assignment factor for average distance from warehouse to waste treatment		
Germany	2.94E-05	3.28E-05
Italy	1.43E-04	1.46E-04
Finland	1.51E-05	1.72E-05
Assignment factor for average distance from warehouse to recycling company for one POS terminal in 2022		
Germany	1.26E-06	1.40E-06
Italy	1.08E-05	1.10E-05
Finland	3.59E-06	4.10E-06
Assignment factor for average distance from warehouse to the port of Rotterdam		
Germany	3.94E-06	/

Italy	3.59E-06	/
Finland	3.01E-06	/
Assignment factor for average distance from the port of Rotterdam to the port of Malaysia		
Germany	3.94E-06	/
Italy	3.59E-06	/
Finland	/	/
Assignment factor for refurbished terminals as a whole		
Germany	3.94E-06	/
Italy	3.94E-06	/
Finland	3.94E-06	/

Source: Oxford Economics

The changes in the estimated impacts were minor and not significant across all impact categories and countries. Yet, the sensitivity check led to larger estimated impacts for a digital POS transaction. Nevertheless, compared to the baseline—no flips between the system occurred. A digital transaction had a lower environmental impact than a cash transaction in 18 out of 18 impact categories in Germany and Finland and 17 out of 18 in Italy. Here, ionising radiation remained the one impact category where we estimated a larger impact of a digital POS transaction.

6.2.4 Worst EoL for refurbished terminals (impact on digital payment system)

We further account for the possibility that, in the end-of-life phase, the refurbished terminals shipped to Asia are treated with the worst possible environmental impact due to the possibility that terminal components are being disposed of using open burning.

TABLE 31: INVENTORY TABLE ADJUSTMENTS FOR WORST EOL FOR REFURBISHED TERMINALS

	Baseline Scenario	Sensitivity Check
Germany	Used industrial electronic device {RoW}| market for used industrial electronic device | Cut-off, U: 345.798 g	Waste plastic, consumer electronics {GLO}| treatment of waste plastic, consumer electronics, open burning | Cut-off, U: 228.19 g Waste, electrical and electronic cables {RoW}| treatment of waste, electrical and electronic cables, open burning | Cut-off, U: 117.608g
Italy	Used industrial electronic device {RoW}| market for used industrial electronic device | Cut-off, U: 345.798 g	Waste plastic, consumer electronics {GLO}| treatment of waste plastic, consumer electronics, open burning | Cut-off, U: 228.19 g Waste, electrical and electronic cables {RoW}| treatment of waste, electrical and electronic cables, open burning | Cut-off, U: 117.608g
Finland	Used industrial electronic device {RoW}| market for used industrial electronic device | Cut-off, U: 345.798 g	Waste plastic, consumer electronics {GLO}| treatment of waste plastic, consumer electronics, open burning | Cut-off, U: 228.19 g Waste, electrical and electronic cables {RoW}| treatment of waste, electrical and electronic cables, open burning | Cut-off, U: 117.608g

Source: Oxford Economics

The assumption that terminals are treated with the worst possible environmental impact at their end-of-life does not noticeably affect the estimates for the environmental impact in all countries. If at all, the cash system becomes worse relative to the baseline. Thus, this more conservative sensitivity check does not change the main result on the comparison of cash and digital POS transactions in all three countries and all impact categories and no results are flipped.

6.2.5 Printing of two paper receipts (impact on digital payment system)

Our baseline estimation assumes that 1.54 paper receipts are printed per digital POS transaction in Germany and 1.08 paper receipts per transaction in Italy and Finland. However, these estimates were quite uncertain as data availability was limited. In this sensitivity check, we therefore account for the worst-case possibility that in all countries two receipts are printed in each digital POS transaction (i.e., merchant and customer receipts are always printed). The sensitivity check only influences the digital payment system (see Figure 70).

TABLE 32: INVENTORY TABLE ADJUSTMENTS FOR PRINTING OF TWO PAPER RECEIPTS

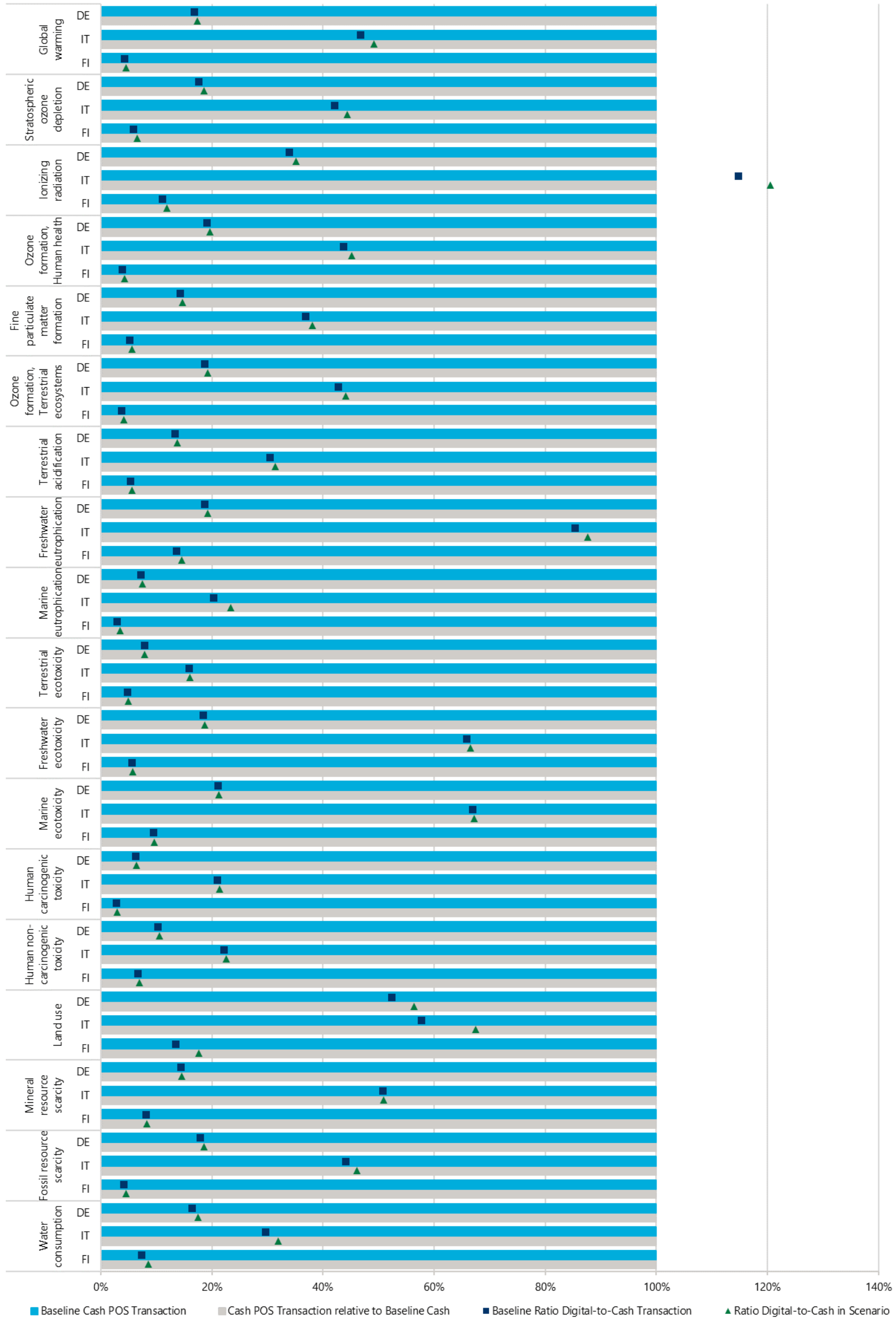
	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
Assignment Factor Operation	1.54	1.08	1.08		2.00	
Energy use per terminal Printing only per day	0.000578 kWh	0.000097 kWh	0.000504 kWh	0.000751 kWh	0.000180 kWh	0.000933 kWh
Energy use per terminal for non-processing time	0.004746 kWh	0.004788 kWh	0.004736 kWh	0.004743 kWh	0.004786 kWh	0.004729 kWh

Source: Oxford Economics

The results are displayed in Figure 70. The environmental impact of an average digital transaction at POS increases for all countries. **However, the only impact categories with a notable difference are land use in all three countries and ionising radiation in Italy.**

FIGURE 70: IMPACT OF PRINTING TWO PAPER RECEIPTS ON THE CASH SYSTEM AND THE RELATIVE IMPACT OF THE DIGITAL SYSTEM

Note: All categories in which the sensitivity check decreased/increased the cash payment system, relative to the baseline cash payment estimates, are represented by grey bars lower/higher than 100%. If the sensitivity check did not influence the cash system, the grey bars remain at 100%. If the green triangles, i.e. the impact of a digital POS payment relative to a cash one in the sensitivity check, change relative to the dark blue squares, i.e. the impact of a digital POS payment relative to a cash one in the baseline case, without the cash payment being impacted, then this implies that assumptions in the digital payment system have been changed. Only in three cases estimates for both payment systems were impacted, namely: data centres local grid (Chapter 6.2.10), recycled cards (Chapter 6.2.13), and the worst vs. best case scenario (Chapter 6.2.16).



Source: Oxford Economics

6.2.6 Higher energy use of digital data centres (impact on digital payment system)

In the baseline model for the digital transaction, we assumed that data centres' energy consumption for cooling and auxiliary equipment is included in the ESG reports in our analysis. To account for the possibility that energy consumption for cooling and auxiliary equipment was not included, we increased the overall energy usage by a factor of 1.75 based on Montevecchi, et al. (2020, p. 57). Again, only the digital payment system is influenced by this change in modelling assumptions (see Figure 71). Overall, as digital data centres now consume more energy, the impact of a digital POS transaction relative to a cash payment should increase compared to the baseline case.

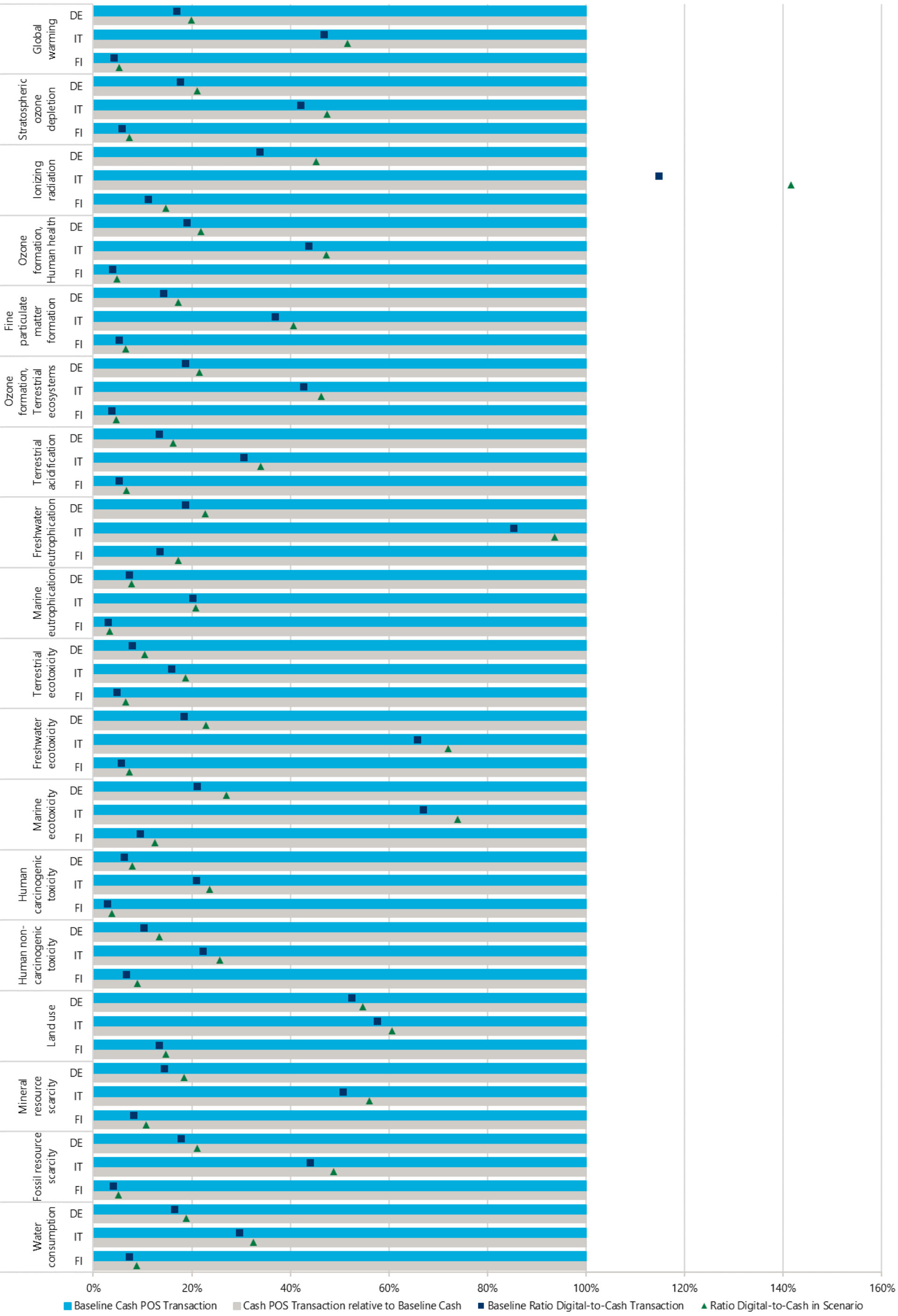
TABLE 33: INVENTORY TABLE ADJUSTMENTS FOR HIGHER ENERGY USE OF DIGITAL DATA CENTRES

	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
Assignment Factor Production	1.81E-11	2.05E-11	2.40E-11	3.04E-11	3.28E-11	3.62E-11
Assignment Factor Production – Material for Building	4.17E-12	4.72E-12	5.52E-12	6.99E-12	7.54E-12	8.33E-12
Assignment Factor Operation – Water consumption for cooling	0.00125	0.00142	0.00166	0.00210	0.00226	0.00250
Issuing Bank: Energy consumption	0.00046			0.00080		
Payment Service Provider: Energy consumption	0.00067			0.00117		
Assignment Factor End-of-life	1.814E-11	2.054E-11	2.399E-11	3.037E-11	3.277E-11	3.621E-11
Average energy consumption per POS transaction in kWh	0.00125	0.00141	0.00166	0.0021	0.0023	0.0025

Source: Oxford Economics

FIGURE 71: IMPACT OF HIGHER DIGITAL DATA CENTRE ENERGY USE ON THE CASH SYSTEM AND THE RELATIVE IMPACT OF THE DIGITAL SYSTEM

Note: All categories in which the sensitivity check decreased/increased the cash payment system, relative to the baseline cash payment estimates, are represented by grey bars lower/higher than 100%. If the sensitivity check did not influence the cash system, the grey bars remain at 100%. If the green triangles, i.e. the impact of a digital POS payment relative to a cash one in the sensitivity check, change relative to the dark blue squares, i.e. the impact of a digital POS payment relative to a cash one in the baseline case, without the cash payment being impacted, then this implies that assumptions in the digital payment system have been changed. Only in three cases estimates for both payment systems were impacted, namely: data centres local grid (Chapter 6.2.10), recycled cards (Chapter 6.2.13), and the worst vs. best case scenario (Chapter 6.2.16).



Source: Oxford Economics.

The sensitivity check indicates that changing the assumption on digital data centres' energy usage significantly alters the result for all countries. Since the impact of an average digital POS transaction is increased, the difference between both payment options is smaller compared to the baseline analysis. The difference is particularly pronounced concerning ionising radiation. Yet, no result is flipped, i.e. a digital POS payment has a smaller estimated impact in 18 out of 18 categories in Germany and Finland and 17 out of 18 in Italy with ionising radiation being the exception.

6.2.7 Higher energy use for cash data centres (impact on cash payment system)

For the calculation of the energy consumption for the back-end processing of an ATM/CRM in the baseline, we relied on an expert who suggested an energy consumption of about 25% of the one for processing a digital POS transaction. A bottom-up estimation for Italy yielded an average energy consumption of 0.56167 Wh per transaction, which is a share of 59% compared to a digital POS transaction in the baseline. To account for this uncertainty, we change the assumption on the possible energy consumption of processing a withdrawal or deposit at ATMs and CRMs.

TABLE 34: INVENTORY TABLE ADJUSTMENTS FOR HIGHER ENERGY USE OF CASH DATA CENTRES IN ITALY

	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
Assignment Factor Production	/	4.42E-13	/	/	7.01E-13	/
Assignment Factor Material for Building	/	1.02E-13	/	/	1.61E-13	/
Assignment Factor End-of-life	/	4.42E-13	/	/	7.01E-13	/
Operation – Water consumption for cooling in m^3	/	6.60E+02	/	/	1.05E+03	/
Operation – Energy Consumption back-end in kWh	/	366,883.81	/	/	581,566.94	/
Average energy consumption per ATM withdrawal in kWh	/	0.00035	/	/	0.00056	/

Source: Oxford Economics

The result for Italy suggests no significant increase in the estimated impact of an average cash transaction at POS. Therefore, the overall results remain the same as well.

6.2.8 Lower energy use of digital data centres (impact on digital payment system)

As explained in Chapter 4.1, there is some uncertainty around the actual energy consumed by data centres per digital transaction. In this sensitivity check, we account for the fact that the energy consumption could potentially overestimate the issuing banks' and PSPs' electricity consumption while underestimating the impact of the national card scheme. This reduces all countries' average electricity consumption per transaction to 1.249346 Wh per transaction.

TABLE 35: INVENTORY TABLE ADJUSTMENTS FOR LOWER ENERGY USE OF DIGITAL DATA CENTRES

	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
Assignment Factor Production	1.81E-11	2.05E-11	2.40E-11	1.81065E-11		
Assignment Factor Material for Building	4.17E-12	4.72E-12	5.52E-12	4.16449E-12		
Assignment Factor Operation – Water consumption for cooling	0.001251905	0.001417324	0.001655309	0.001249346		
Card Scheme: Energy consumption in kWh	0.000127023	0.000292441	0.000530426	0.000523437		
Issuing Bank: Energy consumption in kWh	0.00046			0.000163468		
Payment Service Provider: Energy consumption in kWh	0.00067			0.000562441		
Assignment Factor End-of-life	1.81436E-11	2.05409E-11	2.39900E-11	1.81065E-11		
Average energy consumption per POS transaction in kWh	0.00125	0.00141	0.00166	0.00125		

Source: Oxford Economics

The results for Germany remain rather unchanged. In Italy, the impact of a digital POS transaction is slightly decreased leading to a larger difference in the environmental impact of both options. In Finland, the results change the most due to the decreased impact of a digital POS payment. Here, the largest variation occurs for ionising radiation and freshwater eutrophication. Across all countries and impact categories, the overall results comparing a cash and digital POS transaction remain the same.

6.2.9 Data centres local grid (digital only) (impact on digital payment system)

Another assumption on the energy usage of the data centres made in the baseline estimate was that the data centres' electricity grid share corresponds to that of the installed capacity in Europe. However, the proximity of data centres is generally important and expert interviews revealed that the location of the PSPs' and the issuing bank's data centres is mostly in the country itself (except for cloud-based data centres). Therefore, we conducted a sensitivity check that uses country-specific grid factors for the PSP and the issuing bank[106].

[106] We did not consider a sensitivity check, where 100% green electricity is used for digital data centres as that would reduce the environmental impact of the digital system. Therefore, our baseline specification is the more conservative approach.

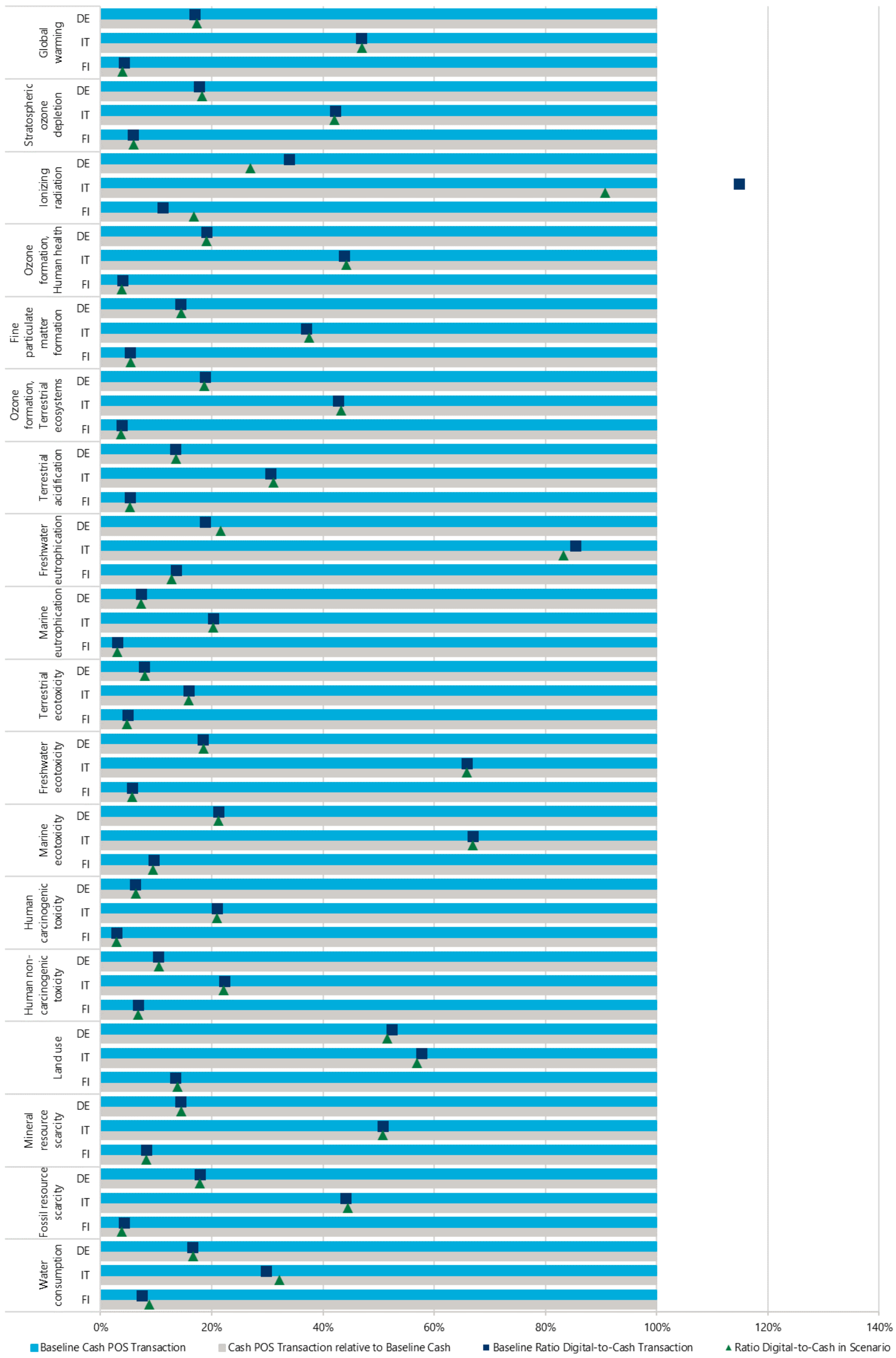
TABLE 36: INVENTORY TABLE ADJUSTMENTS FOR DATA CENTRES LOCAL GRID (DIGITAL ONLY)

	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
Issuing Bank: Energy Consumption	Data centre average electricity mix (see Table 9)			Electricity, low voltage {DE}| market for electricity, low voltage | Cut-off, U		
Payment Service Provider: Energy consumption	Data centre average electricity mix (see Table 9)			Electricity, low voltage {DE}| market for electricity, low voltage | Cut-off, U		

Source: Oxford Economics

FIGURE 72: IMPACT OF DIGITAL DATA CENTRE LOCAL GRID USE ON THE CASH SYSTEM AND THE RELATIVE IMPACT OF THE DIGITAL SYSTEM

Note: All categories in which the sensitivity check decreased/increased the cash payment system, relative to the baseline cash payment estimates, are represented by grey bars lower/higher than 100%. If the sensitivity check did not influence the cash system, the grey bars remain at 100%. If the green triangles, i.e. the impact of a digital POS payment relative to a cash one in the sensitivity check, change relative to the dark blue squares, i.e. the impact of a digital POS payment relative to a cash one in the baseline case, without the cash payment being impacted, then this implies that assumptions in the digital payment system have been changed. Only in three cases estimates for both payment systems were impacted, namely: data centres local grid (Chapter 6.2.10), recycled cards (Chapter 6.2.13), and the worst vs. best case scenario (Chapter 6.2.16).



Source: Oxford Economics

The results are displayed in Figure 72. **Overall, the results of this sensitivity check are more mixed.** In Germany, most impact categories are not noticeably affected. Regarding freshwater eutrophication, the impact of the digital POS payment increased leading to a smaller difference between the impact of a cash and a digital POS payment. Looking at ionising radiation and land use, the digital system improved, widening the difference. Generally, the same is true for Italy. Here, the digital POS payment was estimated to have a smaller impact concerning ionising radiation and freshwater eutrophication. The impact was increased however in the impact category of land use. In Finland, the estimated impacts on GWP, freshwater eutrophication, and fossil resource scarcity were reduced for the digital system compared to the baseline. The impact on water consumption and ionising radiation was increased, however. No results were flipped.

6.2.10 Data centres local grid (cash and digital) (impact on cash and digital payment systems)

In addition to the change in the grid factors of data centres utilised for digital transactions, we also change the assumption that the data centres of ATMs and CRMs are connected to the local grid. Hence, in this sensitivity check the assumptions for both, the digital and the cash payment system are changed.

TABLE 37: INVENTORY TABLE ADJUSTMENTS FOR DATA CENTRES LOCAL GRID (DIGITAL AND CASH)

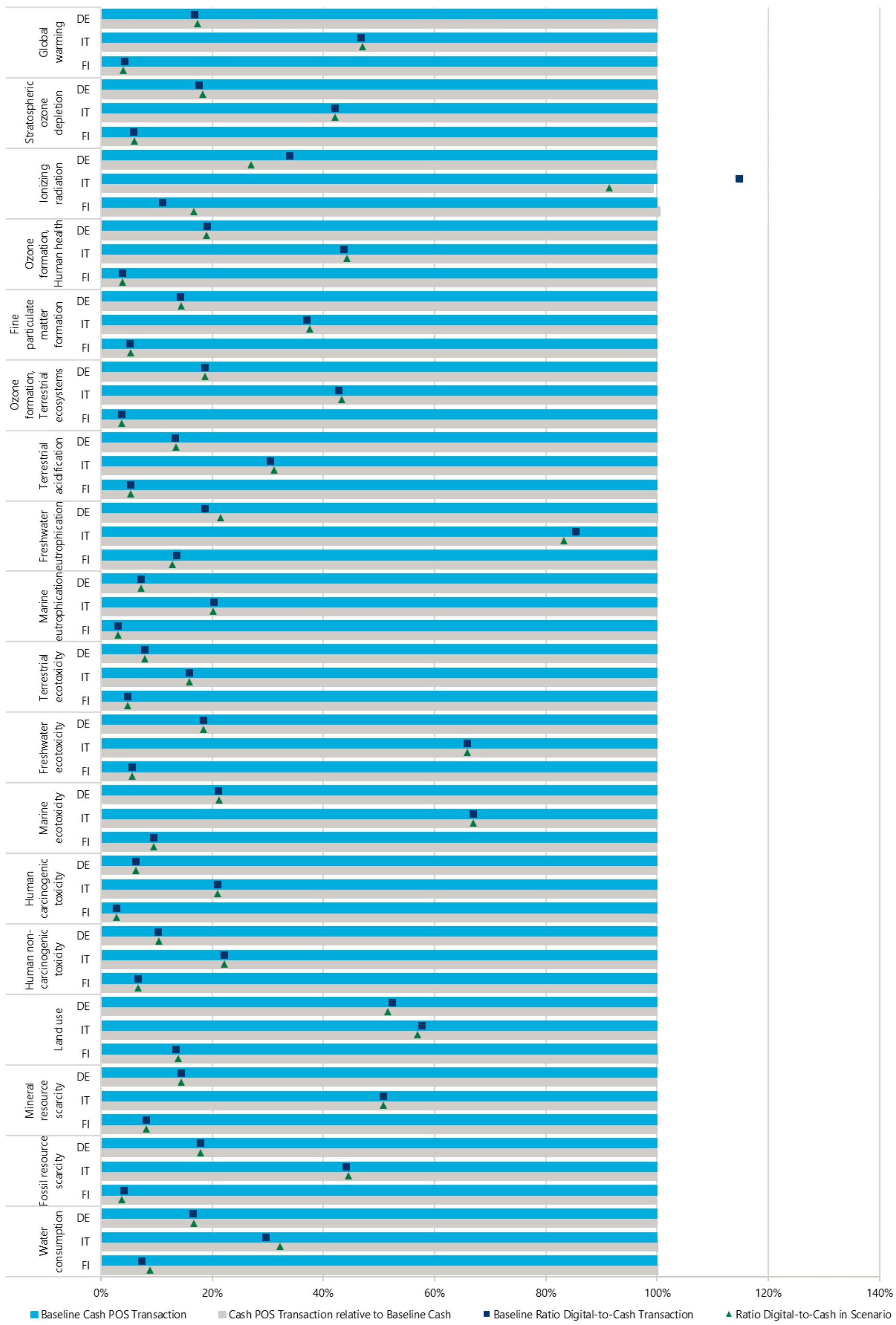
	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
Issuing Bank: Energy Consumption	Energy consumption back-end processing, grid factor data centre average electricity mix (see Table 9)			Energy consumption back-end processing, Electricity, low voltage {DE}| market for electricity, low voltage | Cut-off, U		
Payment Service Provider: Energy consumption	Energy consumption back-end processing, grid factor data centre average electricity mix (see Table 9)			Energy consumption back-end processing, Electricity, low voltage {DE}| market for electricity, low voltage | Cut-off, U		

Source: Oxford Economics

In this sensitivity check, the results for the digital POS transaction coincide with the estimates of the sensitivity check *"Data Centres Local Grid (Digital only)"*. For an average cash transaction at POS, the new assumption on the local grid usage of ATMs and CRMs does not change the obtained estimates at all for all three countries considerably (see Figure 73, importantly notice that in this sensitivity check the assumptions for both, the digital and the cash payment system, are changed and not just of the cash system as it may be indicated by the figure).

FIGURE 73: IMPACT OF CASH & DIGITAL DATA CENTRE LOCAL GRID USE ON THE CASH SYSTEM AND THE RELATIVE IMPACT OF THE DIGITAL SYSTEM

Note: All categories in which the sensitivity check decreased/increased the cash payment system, relative to the baseline cash payment estimates, are represented by grey bars lower/higher than 100%. If the sensitivity check did not influence the cash system, the grey bars remain at 100%. If the green triangles, i.e. the impact of a digital POS payment relative to a cash one in the sensitivity check, change relative to the dark blue squares, i.e. the impact of a digital POS payment relative to a cash one in the baseline case, without the cash payment being impacted, then this implies that assumptions in the digital payment system have been changed. Only in three cases estimates for both payment systems were impacted, namely: data centres local grid (Chapter 6.2.10), recycled cards (Chapter 6.2.13), and the worst vs. best case scenario (Chapter 6.2.16).



Source: Oxford Economics.

6.2.11 More small CCMs (impact on cash payment system)

The number of small CCMs in usage is hard to estimate and includes high uncertainties regarding their true number. In the baseline estimation, we modelled the number of CCMs by scaling the number of CCMs in use in Italy to Germany and Finland. To check the influence of this assumption, we additionally calculated the number of CCMs by using information from the ECB (2017) as described in inventory analysis (see Chapter 4, Subsystem 8). The change in method yielded a significantly higher number of small CCMs in all three countries.

TABLE 38: INVENTORY TABLE ADJUSTMENTS FOR MORE SMALL CCMS

	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
Assignment Factor	1.49E-08	1.48E-08	1.46E-08	1.73E-06	3.80E-07	1.33E-06

Source: Oxford Economics

The results only change slightly in this sensitivity check. Overall, the impact of the cash system is rather increased leading to a larger difference between the estimated impacts of a digital vs. a cash POS transaction. The impact categories affected the most were freshwater eutrophication, freshwater ecotoxicity, and marine ecotoxicity. No results were flipped.

6.2.12 No small CCMs (impact on cash payment system)

Moreover, we run the model without any small CCMs as an additional sensitivity check due to the number of small CCMs being difficult to estimate.

TABLE 39: INVENTORY TABLE ADJUSTMENTS FOR NO SMALL CCMS

	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
Assignment Factor	1.49E-08	1.48E-08	1.46E-08	/	/	/

Source: Oxford Economics

The estimated results remain the same and no relevant changes in the estimated impacts occur.

6.2.13 Recycled cards (impact on cash and digital payment system)

As another sensitivity check, we analysed whether assuming that cards are produced from recycled Polyethylene rather than virgin PVC as in the baseline significantly alters the obtained environmental impacts. Changing this assumption could influence both the digital payment system as well as the environmental impact of cash transactions, due to cards being used to withdraw money from ATMs.

TABLE 40: INVENTORY TABLE ADJUSTMENTS FOR RECYCLED CARDS

	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
Card Body Production – Input	Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U			Polyethylene, high density, granulate, recycled {RoW}| market for polyethylene, high density, granulate, recycled | Cut-off, U		

Source: Oxford Economics

Allowing cards to be produced from recycled material does not change the estimated impact for both systems significantly. If any changes are detected, the difference between the impacts of both payments increases, i.e., a digital POS transaction has an even smaller environmental impact than a cash POS transaction.

6.2.14 Longer lifetime of banknotes (impact on cash payment system)

The assumed lifetime of the average banknote was 3.03 years. Although these data are based on several publications, the second series of euro banknotes could have an extended lifetime since new materials should increase their robustness. Nevertheless, to estimate how a longer lifetime could impact the results, we performed a sensitivity check assuming an expected lifetime of 10 years.

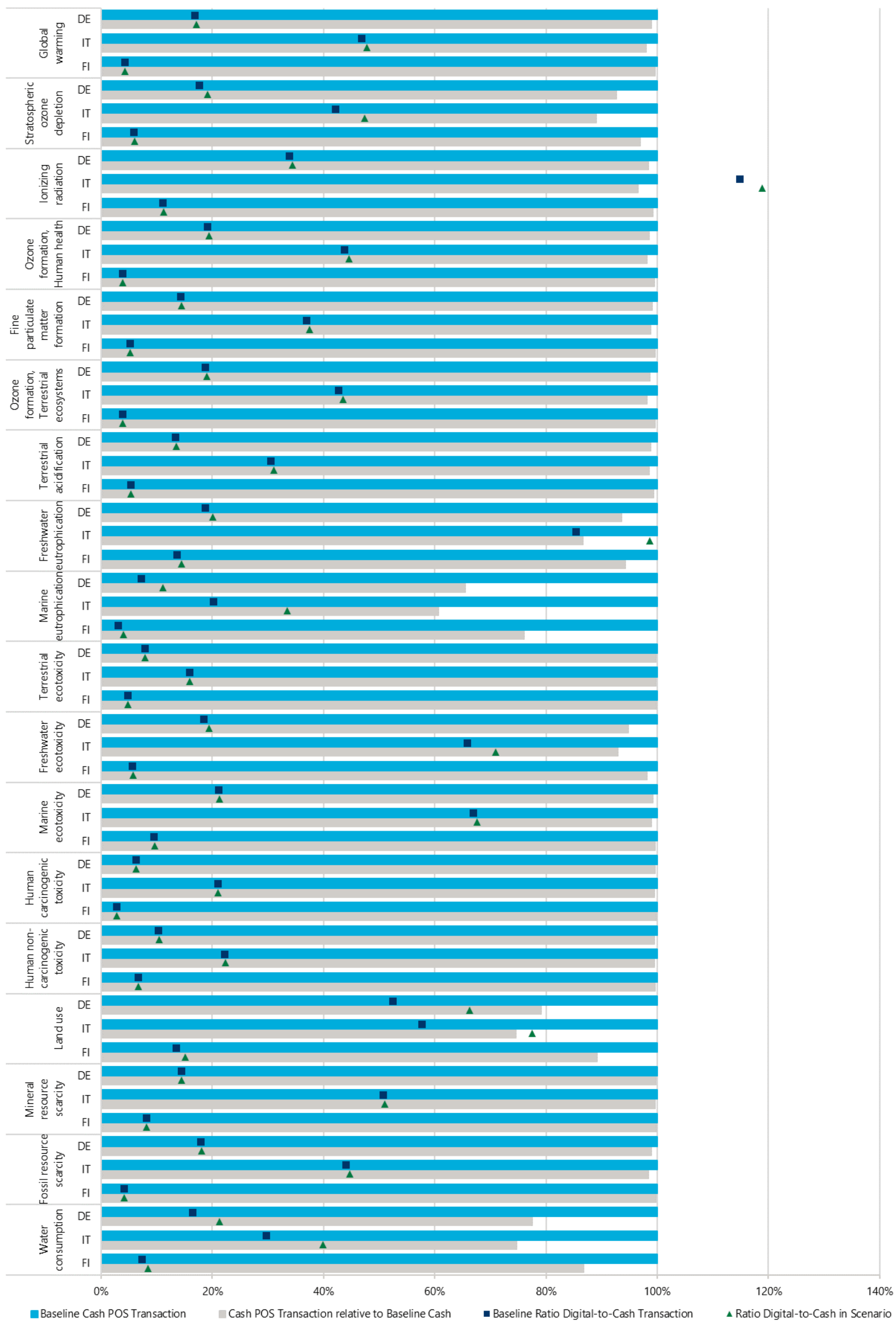
TABLE 41: INVENTORY TABLE ADJUSTMENTS FOR LONGER LIFETIME OF BANKNOTES

	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
Assignment Factor	0.041950	0.041780	0.041080	0.020975	0.020890	0.020540

Source: Oxford Economics

FIGURE 74: IMPACT OF A LONGER LIFETIME OF BANKNOTES ON THE CASH SYSTEM AND THE RELATIVE IMPACT OF THE DIGITAL SYSTEM

Note: All categories in which the sensitivity check decreased/increased the cash payment system, relative to the baseline cash payment estimates, are represented by grey bars lower/higher than 100%. If the sensitivity check did not influence the cash system, the grey bars remain at 100%. If the green triangles, i.e. the impact of a digital POS payment relative to a cash one in the sensitivity check, change relative to the dark blue squares, i.e. the impact of a digital POS payment relative to a cash one in the baseline case, without the cash payment being impacted, then this implies that assumptions in the digital payment system have been changed. Only in three cases estimates for both payment systems were impacted, namely: data centres local grid (Chapter 6.2.10), recycled cards (Chapter 6.2.13), and the worst vs. best case scenario (Chapter 6.2.16).



Source: Oxford Economics.

While some impact categories are not affected by the adjusted input data, others change noticeably. As Figure 74 indicates, the cash system improves leading to a more similar estimated impact of both payment options compared to the baseline estimated. The affected impact categories include marine eutrophication, land use, water consumption, and freshwater eutrophication. For Finland, the results change the least. Nevertheless, no flips were detected across all countries.

6.2.15 No overhead during coin production (impact on cash payment system)

Although the assumed data for overhead production rely on publications, we decided to perform a sensitivity check assuming no coin overhead production as it constitutes the more conservative assumption.

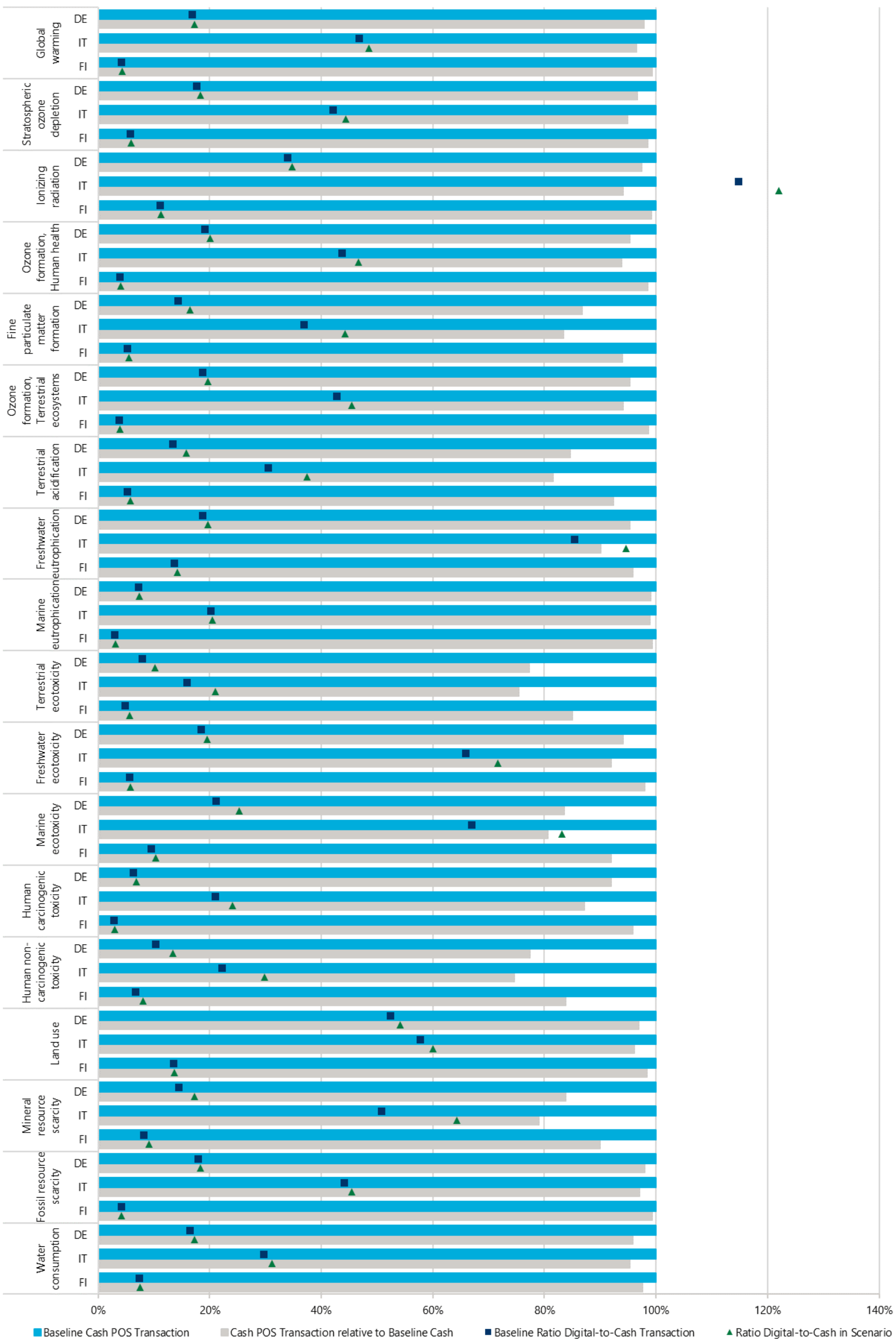
TABLE 42: INVENTORY TABLE ADJUSTMENTS FOR NO OVERHEAD DURING COIN PRODUCTION

	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
Assignment Factor – Inputs/Outputs & Energy	3.832E-02	3.817E-02	3.753E-02	2.683E-02	2.672E-02	2.627E-02

Source: Oxford Economics

FIGURE 75: IMPACT NO OVERHEAD DURING COIN PRODUCTION ON THE CASH SYSTEM AND THE RELATIVE IMPACT OF THE DIGITAL SYSTEM

Note: All categories in which the sensitivity check decreased/increased the cash payment system, relative to the baseline cash payment estimates, are represented by grey bars lower/higher than 100%. If the sensitivity check did not influence the cash system, the grey bars remain at 100%. If the green triangles, i.e. the impact of a digital POS payment relative to a cash one in the sensitivity check, change relative to the dark blue squares, i.e. the impact of a digital POS payment relative to a cash one in the baseline case, without the cash payment being impacted, then this implies that assumptions in the digital payment system have been changed. Only in three cases estimates for both payment systems were impacted, namely: data centres local grid (Chapter 6.2.10), recycled cards (Chapter 6.2.13), and the worst vs. best case scenario (Chapter 6.2.16)



Source: Oxford Economics.

Again, the results change mostly for Germany and Italy with only minor changes in the estimated effects for Finland. Further, and more generally, the results in Figure 75 indicate that the cash payment system improves leading to a more similar estimated impact of a cash and a digital POS transaction. The largest changes occurred for marine ecotoxicity, fossil resource scarcity, human non-carcinogenic toxicity, and freshwater eutrophication. Again, no results were flipped.

6.2.16 Worst case for digital POS payments vs. best case for cash POS payments

To account for the fact that some of the sensitivity checks presented could occur combined, we have performed a last sensitivity check presenting the best-case scenario for cash and the worst-case scenario for digital payments at POS. More specifically, this sensitivity check combines the following sensitivity checks:

- **No way to ATM/CRM**
- **No refurbishment of terminals**
- **Printing of two paper receipts**
- **Higher energy use of digital data centres**
- **No small CCMs**
- **Double life of banknotes**
- **No overhead during coin production**

The selection of these checks was based on the results depicted in Table 27. The sensitivity check "Worst EoL for refurbished terminals" was not included in this check even though it increases the environmental impact of the digital system as it is mutually exclusive with the sensitivity check "No refurbishment of terminals." We chose the latter for inclusion in this sensitivity check since it has a larger effect on the impact of the digital system (see Table 27). Further, the sensitivity check "Data centres local grid (digital only) improves the environmental impact of the digital system for some impact categories and worsens it for other categories. Thus, we have excluded this sensitivity check here as well.

The details on how we adjusted the estimation in each of these sensitivity checks are presented in the corresponding subchapters 6.2.1 to 6.2.15.

TABLE 43: INVENTORY TABLE ADJUSTMENTS FOR WORST CASE DIGITAL POS PAYMENTS VS. BEST CASE CASH POS PAYMENTS

	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
No way to ATM/CRM						
Transport to reach the next ATM/CRM by car	147,521,458.17 km	146,938,594.54 km	28,217,169.66 km	0km	0km	0km
Transport to reach the next ATM/CRM by bicycle	59,383,930.80 km	13,487,471.96 km	9,135,033.60 km	0km	0km	0km
Transport to reach the next ATM/CRM by public transport (bus)	29,632,700 km	37,016,514.87 km	5,860,800 km	0km	0km	0km

	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
Transport to reach the next ATM/CRM by motor scooter	/	8,318,620.43 km	/	0km	0km	0km
No refurbishment of terminals						
Average lifespan of a terminal (in years) including refurbishing rates	5.57	5.11	5.7	5	5	5
Assignment factor for one payment terminal (production)	3.46E-05	1.57E-04	2.17E-05	3.86E-05	1.61E-04	2.47E-05
Assignment factor for average distance from customer to warehouse for disposal/recycling for one POS terminal in 2022	3.46E-05	1.57E-04	2.17E-05	3.86E-05	1.61E-04	2.47E-05
Assignment factor for average distance from warehouse to waste treatment	2.94E-05	1.43E-04	1.51E-05	3.28E-05	1.46E-04	1.72E-05
Assignment factor for average distance from warehouse to recycling company for one POS terminal in 2022	1.26E-06	1.08E-05	3.59E-06	1.40E-06	1.10E-05	4.10E-06
Assignment factor for average distance from warehouse to the port of Rotterdam	3.94E-06	3.59E-06	3.01E-06	/	/	/
Assignment factor for average distance from the port of Rotterdam to the port of Malaysia	3.94E-06	3.59E-06	/	/	/	/
Assignment factor for refurbished terminals as a whole	3.94E-06	3.94E-06	3.94E-06	/	/	/
Printing of two paper receipts						
Assignment Factor Operation	1.54	1.08	1.08	2.00		
Energy use per terminal Printing only per day	0.000578 kWh	0.000097 kWh	0.000504 kWh	0.000751 kWh	0.000180 kWh	0.000933 kWh
Energy use per terminal for non-processing time	0.004746 kWh	0.004788 kWh	0.004736 kWh	0.004743 kWh	0.004786 kWh	0.004729 kWh
Higher energy use of digital data centres						
Assignment Factor Production	1.81E-11	2.05E-11	2.40E-11	3.04E-11	3.28E-11	3.62E-11

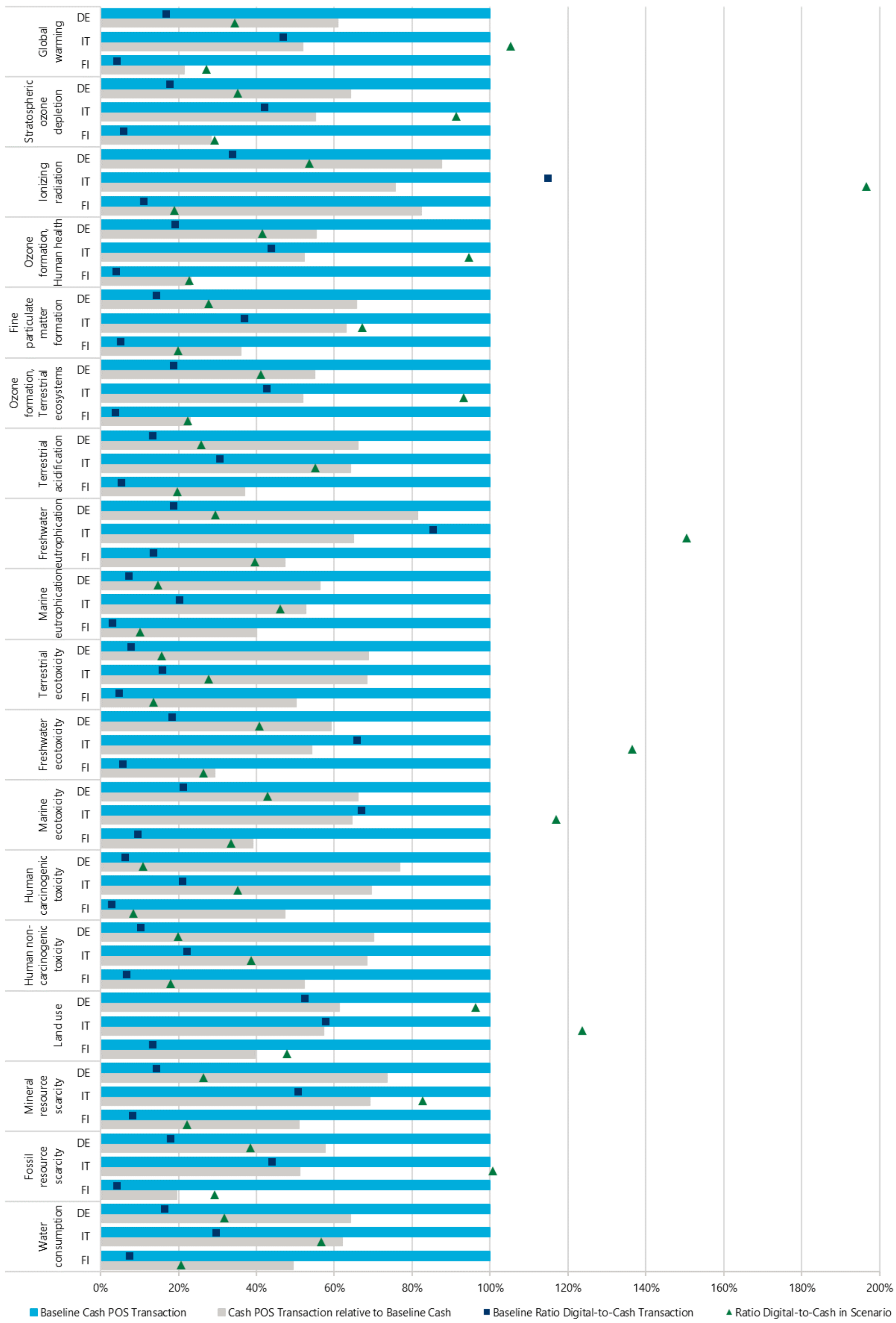
	Baseline Scenario			Sensitivity Check		
	Germany	Italy	Finland	Germany	Italy	Finland
Assignment Factor Production – Material for Building	4.17E-12	4.72E-12	5.52E-12	6.99E-12	7.54E-12	8.33E-12
Assignment Factor Operation – Water consumption for cooling	0.00125	0.00142	0.00166	0.00210	0.00226	0.00250
Issuing Bank: Energy consumption	0.00046			0.00080		
Payment Service Provider: Energy consumption	0.00067			0.00117		
Assignment Factor End-of-life	1.814E-11	2.054E-11	2.399E-11	3.037E-11	3.277E-11	3.621E-11
Average energy consumption per POS transaction in kWh	0.00125	0.00141	0.00166	0.0021	0.0023	0.0025
No small CCMs						
Assignment Factor	1.49E-08	1.48E-08	1.46E-08	/	/	/
Double life of banknotes						
Assignment Factor	0.041950	0.041780	0.041080	0.020975	0.020890	0.020540
No overhead during coin production						
Assignment Factor – Inputs/Outputs & Energy	3.832E-02	3.817E-02	3.753E-02	2.683E-02	2.672E-02	2.627E-02

Source: Oxford Economics

The results of the combined sensitivity checks are displayed in Figure 76. **For all impact categories and across all countries the results change noticeably. Hence, changing more than one assumption on the digital and cash payment system significantly alters the result.** Since, by the modelling of the sensitivity check, the impact of an average digital POS transaction is increased and the impact of an average cash POS transaction is decreased, the difference between both payment options decreases across all impact categories compared to the baseline analysis. However, overall, the results are mixed. While the sensitivity check indicates an improvement of a digital POS payment relative to a cash POS payment, leading to a more similar estimated impact of the two payment systems, the results across all impact categories for Germany and Finland do not flip. However, for Italy, comparing the "worst case" for digital POS payments with the "best case" scenario for cash POS payments flipped such that a cash POS transaction has a lower estimated impacted than a digital POS transaction for the impact categories of global warming, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, land use, and fossil resource scarcity.

FIGURE 76: IMPACT OF THE WORST-CASE DIGITAL SCENARIO VS. BEST-CASE CASH SCENARIO ON THE CASH SYSTEM AND THE RELATIVE IMPACT OF THE DIGITAL SYSTEM

Note: All categories in which the sensitivity check decreased/increased the cash payment system, relative to the baseline cash payment estimates, are represented by grey bars lower/higher than 100%. If the sensitivity check did not influence the cash system, the grey bars remain at 100%. If the green triangles, i.e. the impact of a digital POS payment relative to a cash one in the sensitivity check, change relative to the dark blue squares, i.e. the impact of a digital POS payment relative to a cash one in the baseline case, without the cash payment being impacted, then this implies that assumptions in the digital payment system have been changed. Only in three cases estimates for both payment systems were impacted, namely: data centres local grid (Chapter 6.2.10), recycled cards (Chapter 6.2.13), and the worst vs. best case scenario (Chapter 6.2.16)



Source: Oxford Economics.

6.2.17 Conclusion on sensitivity checks

Overall, all sensitivity checks indicate that digital POS payments tend to have a lower environmental impact compared to cash payments across all countries—some sensitivity checks show an enhancement in favour of digital payments in terms of environmental impact. The estimates especially of the "no way to ATM/CRM" sensitivity check indicate that changing assumptions regarding transport and travelling distances can significantly reduce the estimated environmental benefit of digital over cash payments. Nevertheless, digital payment remains the payment option with the lower estimated environmental impact. One exception is the impact category of ionizing radiation in Italy. Here, in the sensitivity checks, cash payments are equally detrimental to the environment as digital payments and sometimes even slightly less harmful, consistent with the baseline estimates.

If several sensitivity checks are combined into a best-case and worst-case scenario for cash and digital payments, respectively, then the estimated environmental benefit of digital over cash payments can turn, in this scenario for Italy, making cash the payment option with a lower estimated environmental impact across several categories. For Germany and Finland, however, digital payment remains the payment option with the lower estimated environmental impact across all categories. Nevertheless, as indicated by the results for Italy, it is possible that not considered combinations of assumptions on the payment systems exist such that the estimates indicate a lower environmental impact of cash POS payments relative to digital payments.

6.3 UNCERTAINTY ANALYSIS WITH MONTE-CARLO SIMULATION

Since the LCA analysis is based on many variables and the corresponding data have varying degrees of reliability, the influence of data uncertainty on the results must be assessed. To quantify this influence, we used Monte-Carlo simulations building on the pedigree matrix approach (PRé Sustainability, 2014) (see Chapter 3.7 and Appendix 2). More specifically, we ran three Monte Carlo simulations with 1,000 iterations per simulation per country. In the first simulation, we used the whole system including the cash and digital payment system and identified the share of the iterations in which an average cash payment at POS was worse than an average digital payment at POS regarding all the impact indicators studied. In other simulations, both systems were run separately. While the first simulation is best suited to analyse the uncertainty related to the comparison of both systems' impact, the other simulations are useful for studying the uncertainty of each subsystem in detail. In the following, we first present the Monte-Carlo results for all impact categories before looking in more detail at the three selected categories "global warming potential", "mineral resource scarcity", and "ionizing radiation."

To implement the pedigree matrix approach, we defined such a matrix for every dataset in our inventory analysis. A pedigree matrix consists of 5 categories, namely reliability, completeness, temporal correlation, geographical correlation, and further technological correlation. For each of these dimensions, several categories exist in ecoinvent, reflecting varying levels of data quality. For instance, concerning reliability, the categories provided from best to worst are verified data based on measurements (1), verified data partly based on assumptions or non-verified data based on measurements (2), non-verified data partly based on qualified estimates (3), qualified estimate (e.g., by industrial expert) (4), and non-qualified estimate (5).

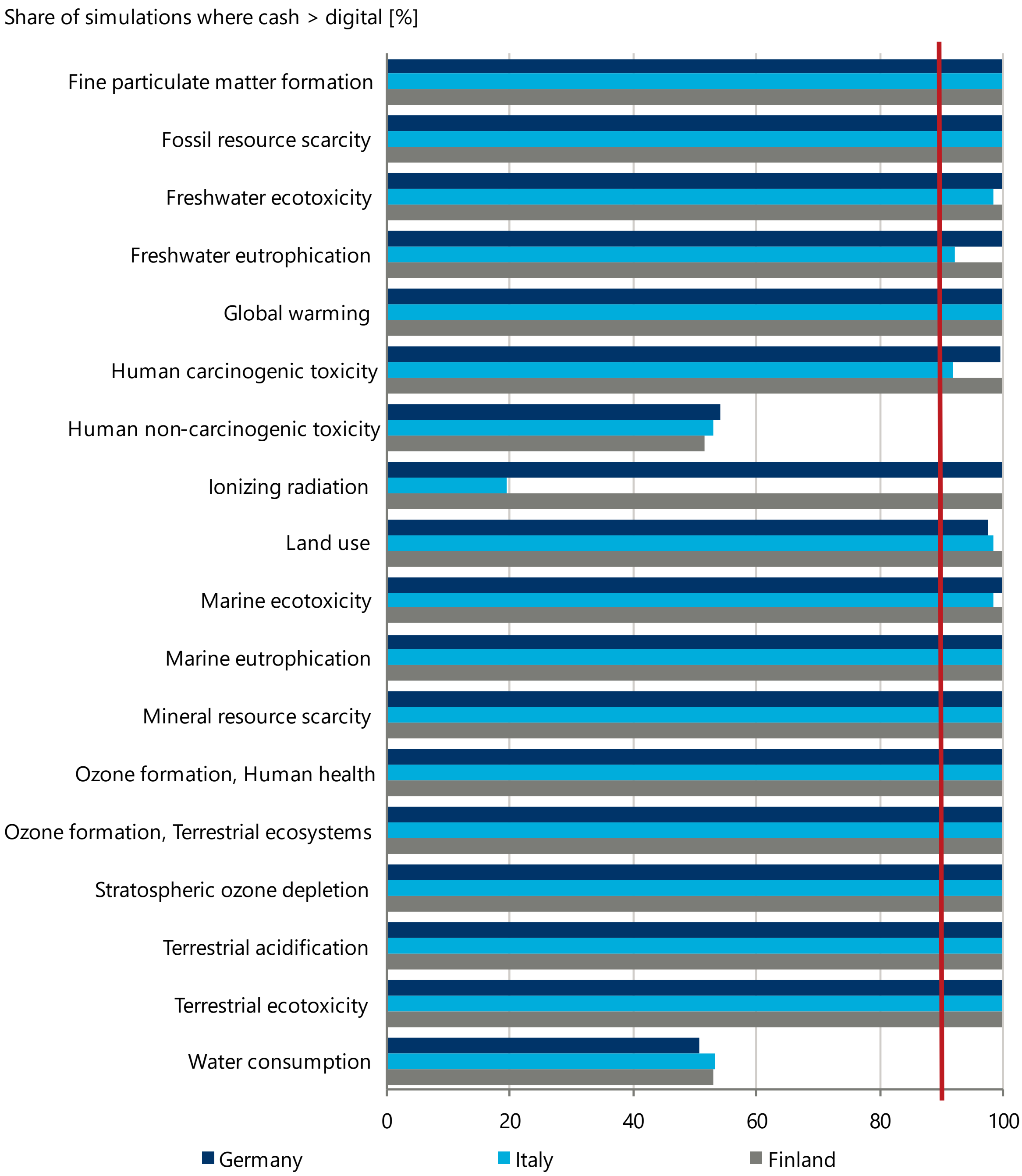
Although the predefined categories for each dimension help to increase comparability across LCA studies, it was sometimes challenging to select the right category for a specific variable. For instance, although data used to model the material inputs of a euro coin are more than three years old, it could be argued that it is valid to assume the best category concerning temporal correlation since euro coin inputs are normed and thus remain the same. To ensure the highest quality of our analysis, we chose to be conservative in the data quality assessment and picked the lower ranking category whenever categorisation was questionable. The pedigree matrices are displayed in Appendix 4.

6.3.1 All impact categories

The results of our Monte-Carlo simulations for all impact categories are shown in Figure 77. More detailed results can be found in Source: Oxford Economics

Appendix 6.

FIGURE 77: MONTE CARLO SIMULATION RESULTS FOR AN AVERAGE CASH AND DIGITAL POS PAYMENT ACROSS ALL IMPACT CATEGORIES



Source: Oxford Economics

For most impact categories, an average cash payment had a larger environmental impact than an average digital payment in 100% of the iterations. In other words, paying digitally at POS has a lower environmental impact than paying with cash with high certainty for most impact categories.[107] The impact categories can broadly be grouped into those where the results are still rather certain, i.e., the same outcome was estimated in at least 90% of the simulations, and those that are identified as rather uncertain (the same outcome was estimated in less than 90%). The results are displayed in Figure 77. All categories in which a digital POS payment had a lower impact than a cash POS payment with high certainty are represented by bars higher than the 90% vertical line in red. For ten impact categories,[108] 100% of the simulations confirmed that an average cash payment has a larger impact than an average digital payment across all countries.

In Germany, cash POS payments are more harmful than digital ones in 100% of simulations in 14 impact categories, including GWP, mineral resource scarcity, and ionizing radiation, for instance. For human carcinogenic toxicity—the impact category with the largest normalised effect—cash has a bigger impact than digital POS transactions in 99.5% of the iterations. Moreover, digital POS payments have a smaller effect than cash ones on land use in 97.5% of the iterations. Yet, for some impact categories, the results are rather uncertain. These are water consumption and human non-carcinogenic toxicity where cash had a higher impact in only 50.8% and 54.2% of the cases respectively.

In Italy, our results show that a cash POS payment has a larger impact than a digital one in 100% of the simulations in ten categories including GWP and mineral resource scarcity. Moreover, in five other impact categories, certainty was rather high, i.e., more than 90%. These include marine ecotoxicity (98.4%), freshwater ecotoxicity (98.4%), land use (98.4%), freshwater eutrophication (92.2%), and human carcinogenic toxicity (92%). Furthermore, in three categories the results are rather uncertain. As in Germany, this includes the categories human non-carcinogenic toxicity (53.1%) and water consumption (53.3%). The category ionizing radiation is a special case as our baseline results show that a digital POS payment has a larger impact than a cash one in this category in Italy. Our Monte-Carlo results indicate that in 19.5% of simulations, cash POS payments had a larger impact. This underlines the uncertainty of the baseline result of this impact category in Italy.

In Finland, the results of 16 categories have a high certainty. For two categories the estimated effects are rather uncertain, namely human non-carcinogenic toxicity (51.7%) and water consumption (53%).

Overall, it can be summarized that for most of the indicators, an average cash POS payment shows a larger impact than an average digital POS payment with high certainty. Whenever the difference in the estimated impact between both payment options is smaller, uncertainty tends to be higher. Thus, results for Finland are comparatively certain whereas they are the least certain for Italy, matching the differences in the impact of both systems across countries (see Chapter 5). The results for water consumption and human non-carcinogenic toxicity are rather uncertain across all countries.

[107] For detailed information on the mean, standard deviation, and the 95% confidence interval of each impact category see Table in Appendix 2.

[108] Namely, fine particulate matter formation, fossil resource scarcity, global warming, marine eutrophication, mineral resource scarcity, ozone formation, human health, ozone formation, terrestrial ecosystems, stratospheric ozone depletion, terrestrial acidification, and terrestrial ecotoxicity.

To better understand why the results for the category "human non-carcinogenic toxicity" are so uncertain, Table 44 shows the standard deviation of this category across the different simulation runs for each phase in the cash and digital systems.

TABLE 44: MONTE-CARLO SIMULATION RESULTS FOR HUMAN NON-CARCINOGENIC TOXICITY

	Standard deviation (in kg 1.4-DCB)		
	Germany	**Italy**	**Finland**
Cash system			
Production phase	6.80E-01	6.70E-01	6.68E-01
Operation phase	1.15E-01	8.65E-02	5.64E-01
End-of-life phase	6.23E-04	4.13E-04	1.37E-03
Digital system			
Production phase	7.56E-02	2.31E-01	6.21E-02
Operation phase	7.99E-03	6.72E-03	7.02E-03
End-of-life phase	6.34E-04	9.15E-04	2.71E-04

Source: Oxford Economics

One can see that within the cash production phase, the main uncertainty in terms of human non-carcinogenic toxicity arises from the production phase. This finding is driven mainly by the production of banknotes. In the digital payment system, the largest uncertainty also stems from the production phase, followed by the operation phase.

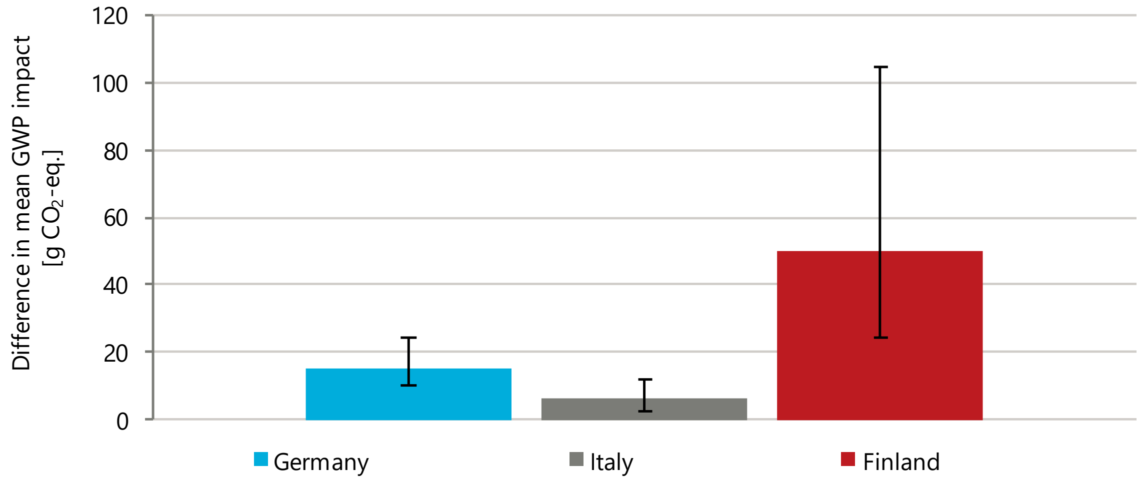
For more detailed information on the Monte-Carlo simulations, see Source: Oxford Economics

Appendix 6.

6.3.2 Global Warming

In this subchapter, we look more closely at the Monte-Carlo results for the GWP impact category. Figure 78 illustrates the average difference in the GWP impact between the cash and the digital POS payment system across all simulation runs as well as the 95% confidence intervals.

FIGURE 78: DIFFERENCE IN MEAN GWP IMPACT BETWEEN CASH AND DIGITAL POS TRANSACTIONS



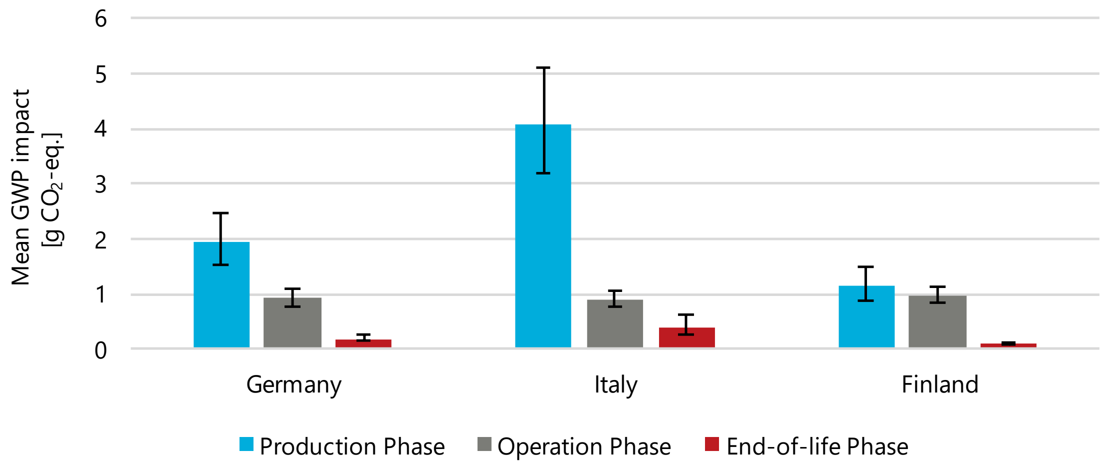
Note: Bars indicate 95% confidence intervals
Source: Oxford Economics

In our simulations, a cash POS transaction accounts on average for a GWP impact of 15 g CO_2 equivalents larger than a digital one in Germany, 6.1 g CO_2 equivalents in Italy, and 49.9 g CO_2 equivalents in Finland. In Germany, we estimated that the 95% confidence interval for the difference in GWP impact between a cash and a digital transaction is between 10.3 and 24.2 g CO_2 equivalents. In other words, after running 1,000 iterations we can say that a cash transaction emits between 10.3 and 24.2 g CO_2 equivalents more than an average digital transaction with a certainty of 95%. The 95% confidence interval for Italy is between 2.5 and 12 g CO_2 equivalents and for Finland between 24.5 and 105.1 g CO_2 equivalents. Furthermore, the difference in GWP impact between a cash and a digital POS transaction is likely larger in Finland than in Germany or Italy. For further information on the mean, standard deviation, and the 95% confidence interval, see Source: Oxford Economics

Appendix 6.

In addition, we have conducted a more in-depth analysis of each system. Considering the digital POS payment system, the standard deviation is the largest in the production phase in all countries (see Figure 79). Here—as well as in the end-of-life phase—the spread is largest in Italy, followed by Germany, and Finland. Regarding the ordering of the different phases, our results suggest that it is highly likely that the production phase is the most important, followed by the operation and then the end-of-life phase in Germany and Italy. However, in Finland the lower bound estimate of the production phase is smaller than the upper bound estimate of the operation phase, leading to some degree of uncertainty regarding the phase contributing most to the GWP impact of a digital POS transaction. However, the end-of-life phase contributes the least with high certainty.

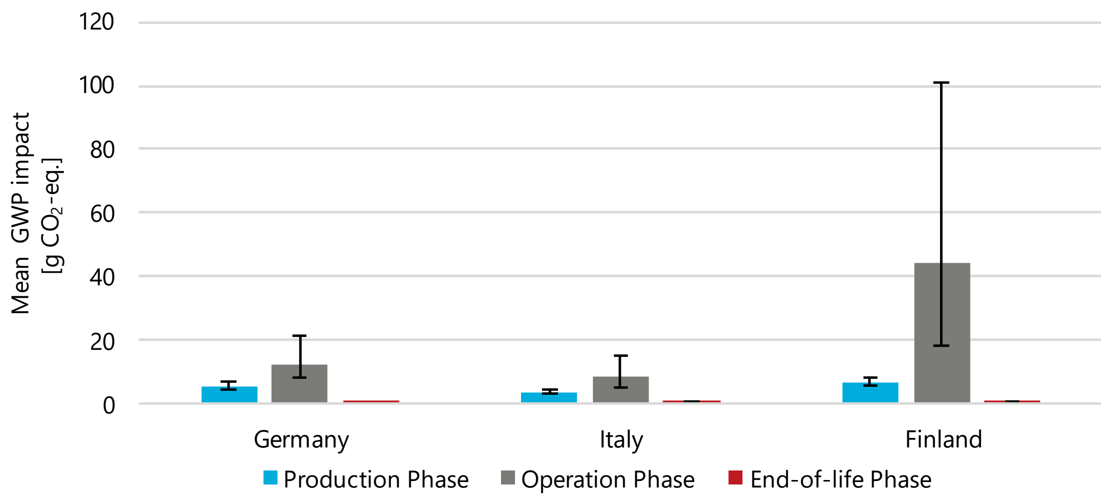
FIGURE 79: MEAN IMPACT OF A DIGITAL POS TRANSACTION ON GWP BY PHASE



Note: Bars indicate 95% confidence intervals
Source: Oxford Economics

Turning to the cash system, the standard deviation is largest in the operation phase in all countries, followed by the production and end-of-life phases (see Figure 80). In the production and operation phase, the spread is biggest in Finland and lowest in Italy. In the end-of-life phase, it is the largest in Italy and lowest in Germany. For all countries, the operation phase has the largest impact on GWP followed by the production and the operation phase with high certainty.

FIGURE 80: MEAN IMPACT OF A CASH POS TRANSACTION ON GWP BY PHASE

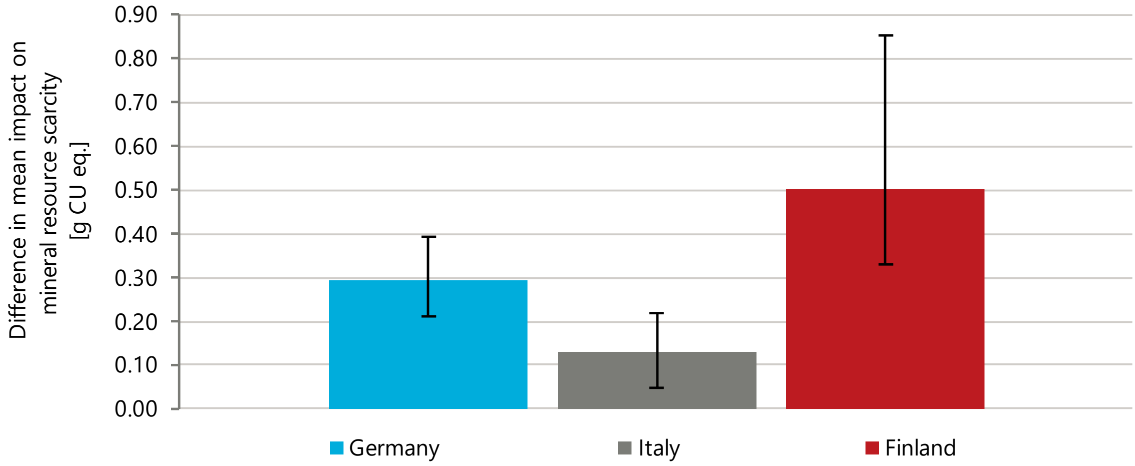


Note: Bars indicate 95% confidence intervals
Source: Oxford Economics

6.3.3 Mineral resource scarcity

Figure 81 illustrates the average difference in the impact on mineral resource scarcity between the cash and the digital POS payment system across all simulation runs as well as the 95% confidence intervals.

FIGURE 81: DIFFERENCE IN MEAN IMPACT ON MINERAL RESOURCE SCARCITY BETWEEN CASH AND DIGITAL POS TRANSACTIONS

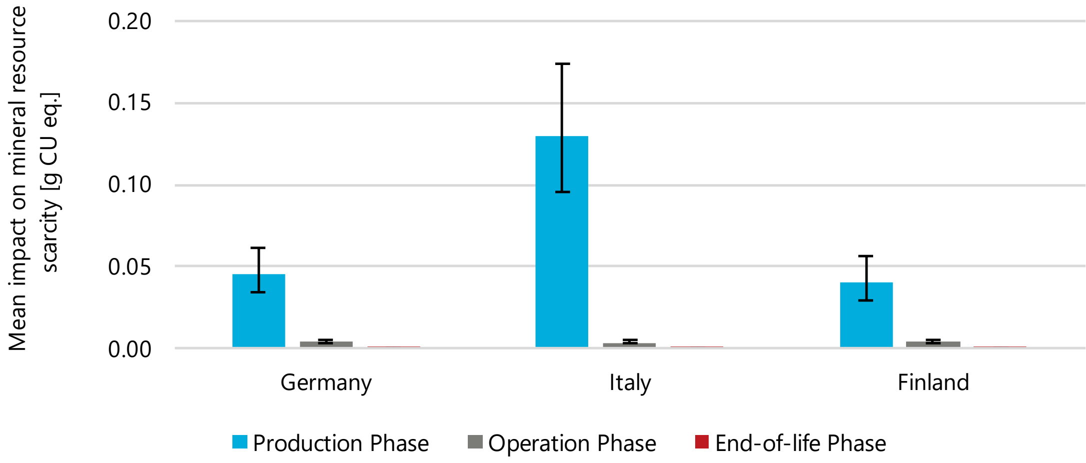


Note: Bars indicate 95% confidence intervals
Source: Oxford Economics

In our simulations, the impact on mineral resource scarcity is on average 0.3 g CU eq. larger for a cash POS transaction than a digital one in Germany, 0.1 g CU eq. larger in Italy, and 0.5 g CU eq. larger in Finland. In Germany, we estimate that the 95% confidence interval for the difference in impact between a cash and a digital POS transaction is between 0.21 and 0.39 g CU eq. The 95% confidence interval for Italy is between 0.05 and 0.22 g CU eq. and for Finland between 0.33 and 0.85 g CU eq. Thus, we can reject the possibility that a digital POS transaction has a larger impact on mineral resource scarcity than a cash one with high certainty in all countries. Comparing the results across the analysed countries, highest uncertainty is associated with the results for Italy and lowest for Finland. Additionally, there is some uncertainty about which country has the largest difference in impact between a cash and a digital POS transaction.

Looking at the digital POS payment system, the standard deviation is the largest in the production phase in all countries (see Figure 82). Furthermore, there is high certainty about the ordering of the different phases. In all three countries, the impact is largest in the production phase and smallest in the end-of-life phase with high certainty.

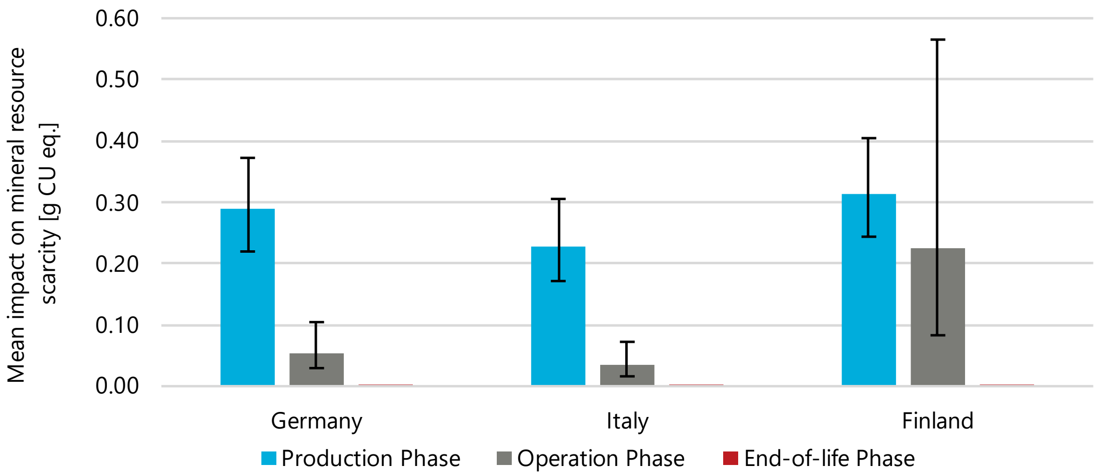
FIGURE 82: MEAN IMPACT OF A DIGITAL POS TRANSACTION ON MINERAL RESOURCE SCARCITY BY PHASE



Note: Bars indicate 95% confidence intervals
Source: Oxford Economics

The Monte-Carlo results of the cash POS payment system are shown in Figure 83. The standard deviation is largest in the production phase in Germany and Italy. In contrast, it is larger in the operation phase compared to the production phase in Finland. The high uncertainty in the production and operation phases means that we cannot say with high certainty which phase has the larger impact in any of the three countries. Our results suggest, however, that the end-of-life phase very likely has the smallest impact in Germany and Finland.

FIGURE 83: MEAN IMPACT OF A CASH POS TRANSACTION ON MINERAL RESOURCE SCARCITY BY PHASE

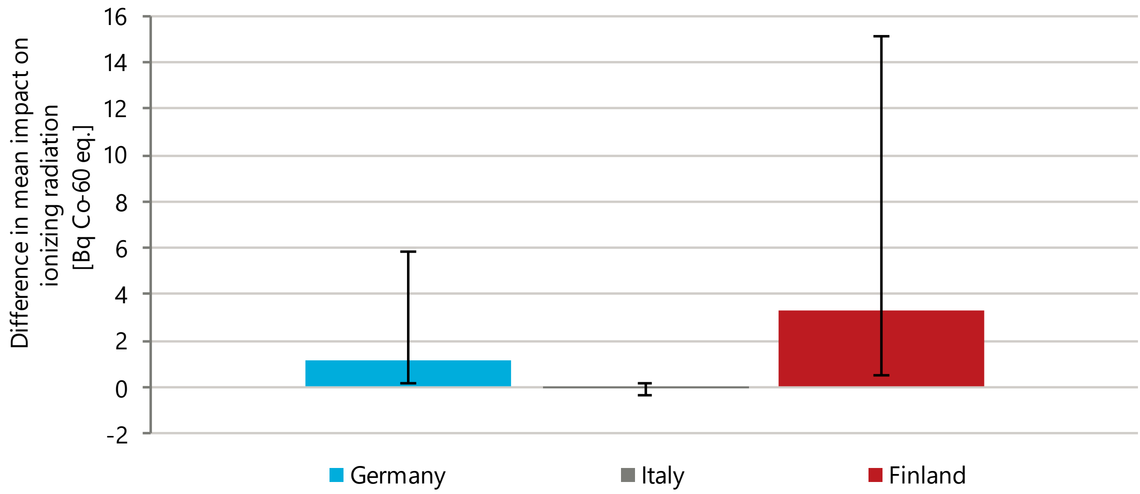


Note: Bars indicate 95% confidence intervals
Source: Oxford Economics

6.3.4 Ionizing radiation

Finally, Figure 84 depicts the average difference in the impact on ionizing radiation between the cash and the digital POS payment system across all simulation runs as well as the 95% confidence intervals.

FIGURE 84: DIFFERENCE IN MEAN IMPACT ON IONIZING RADIATION BETWEEN CASH AND DIGITAL POS TRANSACTIONS

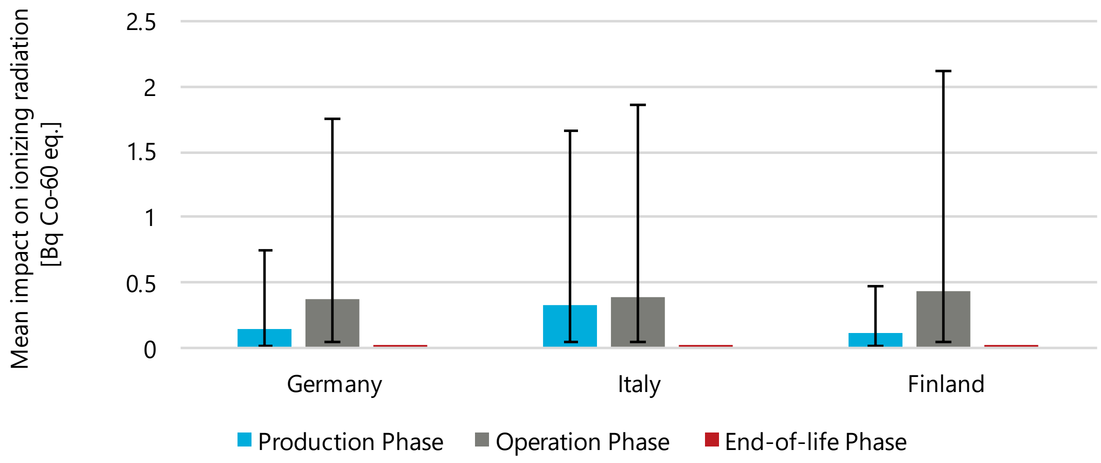


Note: Bars indicate 95% confidence intervals
Source: Oxford Economics

Our simulations suggest that the impact on ionizing radiation is on average 1.16 Bq Co-60 equivalents larger for a cash POS transaction than a digital one in Germany, 0.057 Bq Co-60 equivalents smaller in Italy, and 3.29 Bq Co-60 equivalents larger in Finland. In Germany, we estimate that the 95% confidence interval for the difference in impact between a cash and a digital POS transaction is between 0.12 and 5.81 Bq Co-60 equivalents. The 95% confidence interval for Italy is between -0.41 and 0.13 Bq Co-60 equivalents and for Finland between 0.45 and 15.2 Bq Co-60 equivalents. In particular, the result for Italy means that we cannot reject with high certainty the possibility that a cash POS transaction has a larger impact on ionizing radiation than a digital one. There is also uncertainty over the ordering between the three countries. For example, we cannot reject with high certainty the possibility that the difference in the impact between a cash and a digital POS transaction is larger in Germany compared to Finland.

The average impact and the 95% confidence intervals for each phase of a digital POS transaction are displayed in Figure 85. One can see that the standard deviation is largest in the operation phase in all three countries. There is also significant uncertainty about the ordering of the different phases: it is uncertain whether the production or the operation phase has a larger impact in all countries.

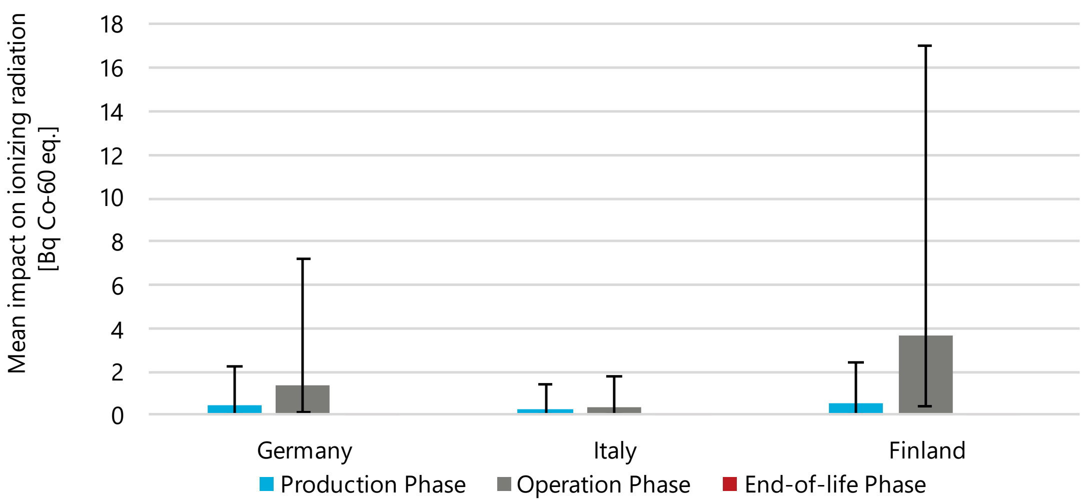
FIGURE 85: MEAN IMPACT OF A DIGITAL POS TRANSACTION ON IONIZING RADIATION BY PHASE



Note: Bars indicate 95% confidence intervals
Source: Oxford Economics

The simulation results for the cash POS payment system are shown in Figure 86. The standard deviation is the largest in the operation phase in all three countries. Our results also show that there is significant uncertainty about whether the impact on ionizing radiation is highest in the production or the operation phase in all countries.

FIGURE 86: MEAN IMPACT OF A CASH POS TRANSACTION ON IONIZING RADIATION BY PHASE



Note: Bars indicate 95% confidence intervals
Source: Oxford Economics

6.4 DATA QUALITY, LIMITATIONS, AND UNCERTAINTIES

Our results were robust to several sensitivity checks. Furthermore, the Monte Carlo Simulations showed that for most impact categories, digital POS transactions have a high probability of being more environmentally harmful than cash POS transactions. Nevertheless, the limitations and critical assumptions underlying the analysis should be kept in mind when interpreting the results and before drawing conclusions. Thus, in the chapter, the most critical assumptions are summarized, and data uncertainty is discussed. First, some general aspects are mentioned that affect the study overall. Second, a deep dive into the subsystems is displayed to provide transparency on all levels of detail.

General limitations

The analysis presented is extensive and complex. It is important to remember which questions can be answered by the study and which ones are out of scope.

First, the analysis only considers the environmental impacts that are associated with the average cash and digital payments made at a POS. Other important factors such as convenience of payment, security issues, and accessibility, for instance, were out of scope of this study. Yet, they are important to consider when comparing both systems.

Next, the analysis only holds for the year 2022 given the data points used and assumptions made in this study. Since the use of cash vs. digital means for payments at POS develop quite dynamically, the estimates would likely change noticeably if performed for another year. This is especially true, as the utilisation rate of the existing infrastructure is crucial for the estimated impact of an average cash or digital transaction at POS. Increasing payments, for instance, could thus reduce the average impact of one payment noticeably. Additionally, we did not consider any offsetting effects that could occur, if, for example, an increased use of digital payments would lead to an increase in payments at POS overall. Such scenarios are out of scope of this study but should be considered when drawing conclusions.

Furthermore, a central aspect is that the average cash and digital POS transactions in 2022 were analysed for Germany, Italy, and Finland. Thus, the results do not approximate the impact of the cash and the digital payment systems as a whole. This is important to note as the impact of the average POS payment depends on both, the impact of the overall system and the total number of POS payments. In other words, the environmental impact of an average POS transaction largely depends on the utilisation rate of the infrastructure. Given the dynamics in the use of different payment options, this is important to keep in mind. Additionally, this could constitute a trade-off, as little infrastructure may be good for the environmental impact of the average POS transaction, but could impact other dimensions of people’s lives negatively, if for example no ATM/CRM is available, or no terminals are present in shops.

Moreover, it is important to remember that the analysis was done for 2022 and three specific countries. As shown by the variance between the three countries analysed, impacts may vary widely between countries, depending on their infrastructure for both systems and payment method shares at POS. Both aspects may be influenced by culture, population tensity, digitalisation rate, regulation, and many other characteristics. Thus, the results cannot be used to make statements on the environmental impacts of average POS transactions in other countries or for other years and are only valid for the chosen geographic are in 2022. Please note, however, that for many data point no data were available for 2022. Thus, older data have been used whenever necessary introducing a further source of uncertainty.

Another point to highlight once again is that only POS transactions were considered. All other payments, such as online purchases or P2P payments, were out of the scope of the study. This is especially important as many digital payments are not conducted at POS and it could be argued that increased digital payments go hand in hand with increased online purchases. However, estimating these impacts and analysing potential substitution effects are not part of this study. Here, only POS transactions were analysed, and the results only hold given everything else remains constant.

Furthermore, it should be noted that since a market activity was studied instead of a product, many stakeholders were involved and gaining primary data was tough. Yet, as some data referred to normalised inputs, for example for coins and banknotes, secondary data should not be of less quality. For other subsystems, the combination of different literature and use of secondary data was more problematic. For example, to approximate the material inputs for ATMs/CRMs in Germany correctly, it would be necessary to have data on the distribution of providers and models used and gather information on the material inputs, production processes etc. for all the different models to build an average ATM/CRM for each country. Yet as this was not feasible, we aimed to identify the market-leading companies or models and approximate them. Again, often secondary data with a possibly lower reliability from the literature or public company reports were used.

Concerning the main data sources, we heavily relied on the payment statistics (ECB, 2022b) and the SPACE report (ECB, 2022a) to estimate the number of cash and digital POS payments that were used in all subsystems and are decisive for the results. We typically estimated the impact for a whole system, i.e., the material inputs for one ATM, and divided it by the number of cash or digital POS payments. Other numbers would impact every subsystem and change the results drastically. However, as both statistics stem from reliable sources and there were no better options to the best of our knowledge, we deem the data quite reliable. Still, feedback from several stakeholders has revealed that the numbers published might underestimate the number of digital payments in Germany. Furthermore, some data inconsistencies have been spotted in the Italian numbers of the Payment statistics, which could not be resolved by asking the respective authorities.

In general, packaging and transport data were often approximated, and software inputs were never considered. If in question, we mostly opted for the conservative option, rather overestimating the impact of an average digital payment system than underestimating it and vice versa for the average cash payment system.

Subsystems 1 and 9 - Cards

In terms of data uncertainties in the digital payment system, we could use some updated data and verify the effect of newer trends in the sensitivity checks. Regarding subsystems 1 and 9, i.e., payment cards, data availability was comparatively good. Both systems were modelled identically with varying assignment factors. Since the assignment factors used for the digital systems were identical to the ones used in the cash system or larger, the overall inventory had larger effects on the digital system. Material inputs were taken from a well-published study that nevertheless was published in 2017. Some uncertainty was associated with the production location of the chip and card body. This is important since for many impact categories, transport (by aircraft) had the largest effect, such as for GWP and fine particulate matter, for instance. However, by using leading companies and their main production facilities, we consider our assumptions regarding the production location as largely valid. Moreover, as transport distances based on these assumptions are quite large, they constitute conservative assumptions. Therefore, the impact of the digital system is likely not to be underestimated. A clear limitation of our modelling of the subsystem is that any software inputs were not taken into account as in all other subsystems as well. This is especially important since no virtual payment cards were considered. Instead, the impact of all physical cards was estimated and then assigned to an average digital payment at POS. Further critical assumptions that should be kept in mind include the lifespan of cards at 3.5 years and their disposal via domestic waste. Since more and more companies are implementing card recycling schemes (Reuters, 2023), the impacts could be overestimated here. Regarding the lifespan, a shorter lifetime would increase the comparative impact of the digital system whereas a larger lifespan would decrease it.

Subsystem 2 – Payment terminals

Considering subsystem 2 on payment terminals, most data were taken from the same well-published study (Lindgreen, et al., 2017) and confirmed by industry experts. Since the data used represent a rather old terminal model, we have additionally included a sensitivity check modelling a more modern version. However, since we assume that quite a few of the old models are still being used, we stuck with the older model for the baseline analysis. As the older system is less efficient, using it in the baseline analysis constitutes the more conservative assumption, leaning towards overestimating the impact of the digital system. Moreover, there was some uncertainty regarding the end-of-life of terminals, especially regarding the shares of refurbished and recycled terminals. Data were received from a PSP, constituting a rather valid source. However, as the shares assumed influence average lifetime and thus most of the assignment factors used, variations in these assumptions could have large impacts. Therefore, we have also run a sensitivity check assuming no refurbishment of terminals and assuming the worsts-case scenario for refurbished terminals' EoL as it is not clear how the refurbished terminals—that are assumed to be exported to Asia—are disposed of. However, as mentioned before, all sensitivity checks confirmed the overall result of the analysis. The assumptions made on the use of paper receipts are important as well since paper receipts contribute the largest shares to the impact in the operation and EoL phase of terminals. As discussed, the true range for the number of receipts printed lies between 1 and 2 in Germany and between 0 and 2 in Italy and Finland. The approach presented—using average numbers of customers printing receipts voluntarily to estimate the overall average numbers—appears the most suitable to us. However, it should be kept in mind that if more paper receipts were printed, the impact of the digital system would be higher whereas it would be lower if fewer paper receipts were printed. A sensitivity check assuming that 2 paper receipts are printed in each country controls for the worst-case scenario. Again, the overall results hold, but the impact of the digital system is significantly increased. Further critical assumptions that should be kept in mind when interpreting the results are that terminals are never turned off and use electricity 24 hours per day, 7 days a week and the impact of payment terminals is completely assigned to digital POS transactions. Again, these assumptions constitute a rather conservative approach, leaning towards overestimating the impact of the digital system. Finally, it should be noted that software inputs were not considered in this subsystem either.

Subsystems 3 and 11 – Data centres

Data centres constitute two subsystems—3 and 11—that are based on several critical assumptions and impact the cash and digital system. It should be noted that the digital system is impacted more, as more inputs of an average data centre are assigned to the digital system than the cash system. Unfortunately, data availability on the material inputs of data centres is quite low. Thus, we used the data available and combined this information with the knowledge gained through the expert interviews. Since the largest impact was measured during the operation phase, the underlying data and assumptions are particularly important. The inputs here are mostly internet usage and electricity usage with the latter one being particularly hard to estimate. Although this has been considered in the Monte-Carlo uncertainty analysis, we decided to run several sensitivity checks using different methods to estimate electricity usage, accounting for the high degree of uncertainty regarding the data used in the baseline analysis. These include testing for higher and lower energy usage and using the national grid. For the sensitivity check testing for higher energy usage, we tried to calculate the energy consumption by looking at the energy use of data centres used for processing transactions in each country, assuming a certain share of the energy used by the whole data centre for processing POS transactions only, and divided this by the actual processed POS transactions in that data centre. A drawback of this approach is that the outcome highly depends on the expert guess on the usage share of energy for POS transaction processing and excludes energy consumed by cloud data centres, which are used more frequently. As displayed in Chapter 6.2, the sensitivity check impacted the overall estimated environmental impacts notably. Yet, the overall result comparing the average POS payment in both systems was not flipped. It should be noted that in the baseline we assumed all data centres to be in Europe, while in sensitivity checks we assumed them to be located in the specific country of analysis. Thus, results could differ if data centres were located outside of Europe, using a worse grid emissions factor, for instance. The industry experts we interviewed argued that data centres used are highly likely located in Europe due to regulations on data security. Moreover, for all cases, we assumed the national grid emission factor although some experts argued that data centres produce and use more renewable energies. Using the national emission grid factor constituted the more conservative assumption from our point of view. Lastly, data centre construction activities, packaging of external IT equipment, and transport associated with maintenance were not included in the analysis due to a lack of data.

Subsystem 4 - Smartphones

Subsystem 4 —smartphones—were assumed to be connected to a physical card in all cases. In other words, if a digital POS transaction is conducted, we assigned the impact of the smartphone on top of the other subsystems, reflecting the share of smartphone payments used and the share of smartphones that can be assigned to a POS payment activity. Unfortunately, due to a lack of data, it was not possible to differentiate more between different digital payment methods, i.e., only physical card, smartphone and virtual card, smartphone without card, etc. However, covering virtual cards or no cards at all would reduce the overall impact of the system. Hence, our approaches are rather conservative, increasing confidence in the overall results. For the inputs, an ecoinvent dataset was used, so data validity was quite high. However, the data used (a smartphone from the year 2014) were quite old and it is not clear whether newer models have a smaller or larger environmental impact. Some uncertainty is also associated with transport data. Once again, we have used a rather conservative estimate available in the literature. For the energy usage and assignment factor no data were available, so we developed a method to approximate it using a sample of three. There is some uncertainty regarding these data as well. We did not consider any app installation or updates in this section due to a lack of data. The need for internet access varies between providers of mobile payment solutions. Apple Pay does not require internet access, while Google Pay and Samsung Pay require regular access to the internet from time to time to load new tokens (Lowry, 2022). Due to a lack of more specific data, we have thus omitted impacts caused by internet access though the smartphone. Nevertheless, the internet used by the data centre processing the transaction is still included in the corresponding subsystem 4. Moreover, digital POS payments conducted by other devices such as smartwatches were not taken into account. It should be noted that although there is some uncertainty regarding this subsystem, its overall effect on the environmental impact of digital POS payments is currently quite low since it is rarely used for digital payments. However, this might change in the future.

Subsystem 5 - Banknotes

Concerning this subsystem, most inputs were retrieved from a well-published study (Hanegraaf, Jonker, Mandley, & Miedema, Life cycle assessment of cash payments, 2018). Although data are more than five years old and from the Netherlands, we consider the inputs quite robust, as they are standardized inputs for euro notes that are used in all the analysed countries as well. Critical assumptions made concern the number of banknotes that can be attributed to cash POS payments. Since produced banknotes are used for several purposes, e.g., value storage, we did not assign all banknotes produced to the average cash POS transaction. Instead, we assigned only 33% of total banknotes in circulation to the cash payments reflecting 21% of the value of banknotes in circulation which is in line with the literature (Zamora-Pérez, 2021). Although this approach could be debated, we considered it the most conservative assumption. Additionally, the assignment of banknotes in circulation to the countries of relevance was challenging and associated with a notable level of uncertainty. Although the assumed average lifetime of about three years is confirmed by several sources, these data may mostly reflect data for the first series. Assuming that a large part of the banknotes used for transactions stems from the second series, which is supposed to be more robust, we checked the results for a longer lifetime of banknotes as well. Again, the overall impacts were confirmed. Some uncertainty was associated with the transport distances during the production and EoL phases. However, these impacts were minor. Lastly, we did not include any storage facilities for banknotes, such as safes.

Subsystem 6 – Coins

Like the subsystem on banknotes, inputs to euro coins are normed. Hence, we considered these data to be relatively robust. However, identifying the right share of coins used for transactions and assigning them to the countries where they are in circulation was difficult. According to the literature, only 36% of the coins produced end up being used for transactions (Deutsche Bundesbank, 2015). We only considered a fraction of the coins produced. Moreover, we made some assumptions on overhead production in the baseline, as this was mentioned in the literature. However, since the assumptions increased the environmental impact of coins, we also included a sensitivity check not considering the overhead production. The overall results remained the same. We did not consider coin storage in the analysis. Moreover, we assumed that, although nationally produced coins are used for transactions across Europe independent of the place of production (especially due to their long lifetime), national coin sides do not cause any differences in the material inputs, and that 100% of the coin materials are recycled at the end of their lifetime. Especially the latter assumption may be questionable. Yet, it constitutes the most conservative assumption.

Subsystem 7 – Cash-in-transit

For cash-in-transit companies, data were retrieved from the literature and desk research. The input considered here is the cash-in-transit truck that transports cash. Since these vehicles are specifically designed to be secure and are typically solely used for cash transports, we modelled them instead of using an existing dataset for a more standardized vehicle. While we are rather confident regarding these inputs, we also estimated the number of trucks and the distance they typically drive to transport cash. We received these data for Germany and Italy from separate sources with very different distances. Furthermore, we got information on the lifetime of the trucks in the specific countries. Using these numbers, we were able to estimate the km driven per year on average, which is 30,000 km per year on average for Germany and 133,334 km for Italy. These differences between Italy and Germany are due to the different country-specific lifetime of a truck in the sense of the overall years and the overall km driven per truck, which we received from primary sources. For Finland, we did not receive any data. To be the most conservative, we assumed that trucks drive as much in Finland as they do in Germany. Since Finland is less densely populated, trucks likely drive more in Finland in reality, thus leading to a larger impact of the cash POS payment system. Data validity appears to be rather low concerning these aspects. We did not include any other aspects, such as buildings for the cash-in-transit companies.

Subsystem 8 – Cash counting machines

This subsystem was divided into small and large cash counting machines. For both systems, we approximated the inputs, but consider the approximations to be quite uncertain. Although we had information on the overall weight of the machines, the information on the composition was not very robust. This was taken into account in the Monte-Carlo uncertainty analysis. To allocate the impact of small and large cash counting machines, we needed to approximate the total number of machines and the number of banknotes counted. For the large machines, the overall number in the euro area was stated and we assumed that the machines were distributed across the countries according to their cash POS payments share or their share of banknotes in circulation. We further assumed that the large machines count all banknotes in circulation and thus only attributed a share of the machines to the cash payment system, corresponding to the share of banknotes used for transactions. For the small cash counting machines, we received an amount from Italy and approximated the amounts for Germany and Finland based on that using the total number of banknotes in circulation in each of these countries. Again, we assumed that all banknotes are counted, but only those are considered that are used for transactions. Although this assumption may be debatable, it is the more conservative approach. To account for the uncertainties regarding the total number of small CCMs, we also performed two sensitivity checks. We did not consider the building for the cash counting machines, any storage facilities, and software inputs. Coin counting was not considered either.

Subsystem 10 – ATMs/CRMs

For the subsystems on ATMS/CRMs, one crucial simplifying assumption was that the material inputs and EoL processes are identical for ATMs/CRMs. For electricity usage, we estimated a weighted average reflecting data for both and their relative usage shares. Since the inputs were largely taken from a well-published study (Hanegraaf, Jonker, Mandley, & Miedema, Life cycle assessment of cash payments, 2018) and many inputs are likely to have remained the same, we consider these comparatively valid. A large factor in these systems' environmental impact was the way customers travelled to ATMs. To estimate this, we gathered average distance information and identified data on typical means of transport. Unfortunately, it was not possible to get data on the average distance travelled which could differ from the average distance to ATMs if people use ATMs/CRMs more and less often depending on the distance. We consider this especially important for Finland due to the population structure of the country. Thus, there is some uncertainty associated with the average distance used in the analysis. Moreover, only for Germany, we found data on the share of these travels to ATMs/CRMs solely for that reason and not connected to any other activity. We have assumed that these shares are similar in the other two countries. The estimation should be rather robust, since by taking only those ways into account that are only travelled for that reason and correcting for an average vehicle load factor, we have rather underestimated the way to ATM/CRM attributable to cash payments. We again included a sensitivity check not taking the way to ATM/CRM into account. Other options such as withdrawing cash in shops or at the bank counter were not considered. However, as we based all ATM/CRM calculations on actual numbers of ATMs/CRMs and withdrawals/deposits, this should not result in a distortion of the environmental impact.[109] We therefore implicitly assume a way of 0 km to withdraw cash in a shop or at the bank counter. We further assumed that no ATMs/CRMs are recycled, as stated by one of the interviewed industry experts. Again, we did not consider any software inputs in this subsystem.

Summary – main limitations

Due to the scope and complexity of the analysis we summarise the main data limitations in this subchapter. They either limit the explanatory power of the analysis, concern significant data quality issues, have a meaningful impact on the results, or a combination of these.

- The analysis only considers the environmental impact of a cash vs. a digital payment at POS in the three countries analysed in 2022. Other factors, such as convenience of payment, security, or accessibility were not considered in this study. Moreover, since the average cash and digital payments were studied, country specifics and the year analysed are crucial since both the existing infrastructure of both systems and the number of payments determine the estimated effect. The results should therefore not be extrapolated to other countries or years.
- The number of cash and digital payments made at POS are crucial for all subsystems. Although the source used is deemed reliable, any changes here would change the estimated impacts significantly.
- The number of coins and banknotes used for transactions were estimated using a number of assumptions. This includes estimating the number of coins and banknotes per country and estimating what share of coins and banknotes are used for transactions instead of value storage or hoarding, for instance. If the number of coins and banknotes used for transactions was actually smaller, the estimated impact of an average cash transaction at POS would be lower (and vice

[109] Instead, the value of a cash withdrawal/deposit is biased using our approach. Yet, as these data are not used in our analysis, the estimation of the environmal impact is not affected.

versa). If the overestimation is large enough, digital POS payments could potentially have a larger environmental impact than cash payments.

- The way travelled to ATM/CRM to withdraw or deposit cash was estimated based on several assumptions. Due to a lack of data, the average distance to ATM/CRM was used as a proxy for the average distance travelled to ATM/CRM. However, people living in rural areas might go to the ATM/CRM less often reducing the average distance travelled to ATM/CRM. This is important because the way to ATM/CRM significantly impacted the estimated environmental impact of a cash transaction, especially in Finland. If the way travelled to ATM/CRM is actually lower than assumed, the estimated impact of an average cash payment at POS would reduce. Note however that we computed a sensitivity check in which the way to ATM/CRM is entirely excluded from the model. Thus, this assumption alone cannot turn around the baseline result that digital POS payments have a smaller environmental impact than cash payments.
- Data availability was also limited considering the energy use of data centres. Again, since this impacted the estimated results notably, any changes here could significantly alter the estimated results. Note that we have included a sensitivity check which models a higher energy usage for digital data centres (see Chapter 6.2.6).

6.5 COMPLETENESS CHECK

All data are provided in the life-cycle inventory, Chapter 4, and summarized in the respective inventory tables that can be found in the same chapter. The system boundaries are described in Chapter 3. Data were collected for all processes inside the system boundaries. All processes with a significant contribution to the results contributing to the goal and scope of the study are included. Limitations and critical assumptions are displayed and discussed in Chapters 3.2.5 and 6.4.

For the background data, the ecoinvent database 3.9.1 was used. Since it is a commonly used and recognized database compliant with ISO 14040 and 14044 (Vilabrille Paz, Ciroth, Mitra, Birnbach, & Wunsch, 2022), the background data completeness requirement is fulfilled.

6.6 CONSISTENCY CHECK

The assumptions made, methods applied, and data used are in line with the goal and scope of the study. Discussions and explanations to evaluate consistency can be found in the following chapters:

- The payment methods at POS analysed are commonly used in the three countries of relevance and are thus representative of the market activity.
- All lifecycle stages are included for both systems. The system boundaries are therefore identical as far as both systems can be compared (see Chapter 3).
- The data collected have the same level of detail. All information is provided in the inventory (Chapter 4).
- For both payment systems, the LCIA results were assessed equally in Chapter 5. While all impact categories are displayed and all results can be found in the appendix, the analysis in the text focuses on three impact categories in more detail. Such categories included global warming potential and mineral resource scarcity due to their relevance. Lastly, we decided to include the results for ionizing radiation in more detail in the text as the difference in the impact of both systems was smallest here.

- The best available data were selected for all modelling inputs. We used primary data whenever possible or primary sources to confirm secondary data. In most cases, secondary data with lower liability were used. Overviews of the key primary sources are displayed in Table 2 and Table 3. The key secondary sources used are displayed in Table 1. All details on the sources used are also described in the inventory tables in Chapter 4.
- Concerning the geographical location of foreground data, we tried to be as specific as possible. To account for uncertainties or varying/larger geographic regions, we performed the Monte-Carlo uncertainty analysis (see Chapter 6.3). The same holds for background data.
- To assign the impacts, we first subdivided the multifunctional process of paying at POS into several subsystems. We then determined a physical causality for the assignment. Within the subsystems, we mostly calculated the impact of a physical unit, e.g., one ATM or one average coin, and assigned it to one average POS transaction.

7. CONCLUSIONS AND RECOMMENDATIONS

In our study we have performed a comparative LCA comparing an average payment at POS paid cash vs. digitally. The functional unit underlying the analysis therefore was one average POS transaction. We have studied three countries, namely Germany, Italy, and Finland. The year of analysis was 2022. For the digital system we considered cards, payment terminals, data centres, and smartphones. For the cash system we considered banknotes, coins, cash-in-transit, cash counting machines, cards, ATMs/CRMs, and data centres.

Our study indicates that digital POS payments could have a smaller environmental impact than cash POS payments. Across most impact categories, including global warming and mineral resource scarcity, paying digitally at POS is estimated to be more environmentally favourable than cash payments in Germany, Italy, and Finland. The only exception is ionising radiation in Italy where an average cash payment is estimated to have a smaller impact than an average digital payment at POS. For most impact categories the estimated impact of a digital payment at POS was largest in Italy and smallest in Finland. The main driver here is the production phase followed by the operation phase. Terminal production is especially important in Italy due to the number of terminals used. This is a large driver of the bigger impact of a digital POS transaction in Italy compared to the other two countries. Considering cash, the smallest impact was estimated in Italy and the largest in Finland. Again, production and operation phase are most important here. While the ATM/CRM subsystem has a large impact here overall, it is particularly pronounced in Finland. This is mainly due to the long estimated way travelled to ATM/CRM. However, there is considerable uncertainty associated with these data. Nevertheless, the long distances travelled in Finland are an important factor also for cash transport, for instance.

Overall, the environmental impact of both payment systems is rather small. For example, considering a country's total CO_2 emissions, the climate change impact of the entire digital payments system ranges from only about 0.0023 to 0.0082% and of the cash payments system from 0.024 to 0.041%. Also, the payment systems' impact on people's average environmental footprint is rather small: Putting emissions into perspective, the GWP of an average digital POS transaction in all countries is comparable to just one average Google search request (consisting of 2x searches and 3x page views) with about 3.85 g CO_2 equivalents (Butterworth, 2023). Additionally, in Germany and Italy, the GWP of an average cash POS transaction corresponds to the average carbon emission emitted by one person within just one minute (which can be approximately estimated at 15.22 and 10.84 g CO_2 equivalents in Germany and Italy, respectively (own calculation based on Our World in Data (2023a)). Finally, for Finland's cash system, where the highest GWP was estimated at 51.8 g CO_2 equivalents, this corresponds to streaming Netflix for 60 minutes in Europe, which is estimated to emit around 55 g CO_2 equivalents by Netflix (Carbon Trust, 2021).

It is important to remember precisely what has been studied and what the limitations of the analysis presented are. The LCA refers to an average cash and digital POS transaction that were studied. Thus, two elements crucially influence the estimated results: The impact of the existing infrastructure (i.e., number of ATMs/CRMs, number of terminals, etc.) and the number of cash or digital POS payments.

Combining both yields the impact of the average cash or digital POS transaction. Thus, one key factor of the estimated impact is the utilisation rate of the infrastructure. A large share of "underused" products such as ATMs, terminals or cash trucks can increase the impact of an average payment in both systems significantly. Therefore, it is important to balance the needs of the cash and digital payment systems to enhance the subsystem's overall impact or utilisation. Here it is also important to note that the environmental impact of a payment system is not the only aspect that needs to be considered by policymakers. Other aspects like convenience of payment, data security and accessibility may impact a consumer's preference for one or the other payment method. For example, while some people may prefer digital payments as they consider them more convenient, others may appreciate the high degree of data security associated with cash payments. The top three advantages of digital payments—according to a survey across the euro area commissioned by the ECB (2022a)—are that consumers do not have to carry a lot of cash with them (62%), that the payment process is conducted faster (40%), and that it is considered to be easier (30%). Comparing the technological factors between cash and digital payments, cash payments are not dependent on functioning software at the POS and users of cash do not need any technological knowledge or literacy, which is, however, the case for digital payments. Thus, cash might be more convenient for some users (NTT Data, 2024). Moreover, the top three reasons for preferring cash are that consumers are more aware of their spending (40%), that it is anonymous and protects privacy better (40%), and that it is immediately settled (32%) (ECB, 2022a).

Because of the importance of these country specifics, it is also crucial to remember that the estimated impact hold for Germany, Italy, and Finland for 2022. Changes in the infrastructure of both systems and the number of payments made at POS in each system will impact the results significantly. Lastly, behavioural changes were not considered. Thus, if increased digital payments at POS would go hand in hand with an overall increase in the number of payments made at POS the benefits to the environment might be offset or even more. Prior research has shown that digital payment options, such as debit cards, can increase consumers' willingness-to-pay (see e.g., Runnemark, Hedman & Xiao (2015)) and consumption of non-food items and durable goods, especially for previously cash-dependent households (Agrawal, Ghosh, Li, & Ruan, 2022). Such rebound effects caused by digital payment options can decrease the estimated environmental benefit of digital relative to cash payments. Hence, when trying to mitigate the environmental impact of local payment systems, policymakers need to take these possible rebound effects into account.

Within our study we defined system boundaries for all life-cycle stages, processes, and flows in the product system. Generally, all life cycle stages from "cradle to grave" are included and we tried to model the systems as detailed and holistic as possible. Nevertheless, some parts were excluded in our study due to restrictions to data availability or minor relative influence. These exclusions included cash register equipment, software, cash storages, rooms for cash centres, coin counting machines, data centre on-site facility construction, and partially packaging or material inputs contributing less than 1% in terms of mass to the inputs in the data centre subsystem. Furthermore, we did not model cash advances in shops or at POS, digital payments via digital cards or PayPal, POS apps on smartphones and their internet connection.

In addition, we faced limitations regarding the availability of data. As a result, we had to make many assumptions during our inventory analysis. When interpreting our findings, it is important that one keeps in mind the uncertainty of our data. While our results appear rather robust considering our sensitivity checks and our uncertainty Monte-Carlo analysis, there remains uncertainty about our results. Therefore, future research into the topic is needed to validate them.

To improve the environmental impact of both payment systems, different stakeholders should be involved. First, the industries themselves can work to improve life expectancy of products, materials used, and energy efficiency, for instance. We identified that this holds particularly true for cards, ATMs/CRMs, terminals, data centres, and cash transport.

Moreover, administrators and policymakers should aim to optimise the utilisation rate of both systems considering other aspects mentioned before, such as accessibility, security, etc. as well. Since the impact of cash payments is mostly determined by the ATM/CRM subsystem in all countries, stakeholders could carefully consider how many ATMs/CRMs are needed. Moreover, one solution would be to decrease the number of ATMs/CRMs in use while increasing the possibility and incentives of using cash advances in shop. Especially in countries with a low cash payment rate such as Finland, this would probably reduce the environmental impact of the whole system considerably. To reduce the impact of the average digital payment, utilisation of terminals and cards should be optimised. Furthermore, other options including digital payment through (non)-digital QR-code-stickers by retailers in combination with smartphone payments (as, e.g., increasingly implemented in the Swiss Payments system), could reduce the average number of terminals and cards required. Regulatory aspects can further help to reduce the impact of both systems. The requirement to print at least one receipt on paper in Germany hinders the improvement of the system, for instance. Lastly, providing green energy can help to improve the impact of several systems.

Overall, the digital transformation of the payment system is not an easy task and needs the support of all stakeholders. Research could support the decision-making by running scenarios on possible measures to quantify the impact of these measures and rank their contribution to reducing a country's payment system's environmental impact. Balancing the transformation and the environmental impact of the POS payment system along the way remains a specific challenge. Further research into that topic could be beneficial.

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APPENDIX 1: OVERVIEW OF RECIPE 2016 IMPACT CATEGORIES

TABLE 45: DESCRIPTION OF THE MIDPOINT IMPACT CATEGORIES

Midpoint Impact Category	Characterisation Factor	Unit	Importance
Climate Change	Global Warming Potential	kg CO_2 eq. to air	Increased atmospheric concentration of GHG will increase radiative forcing capacity, leading to an increase in the global mean temperature. This can cause diseases and malnutrition. Further, it can cause damage to freshwater and terrestrial species.
Ozone Depletion	Ozone depletion potential	kg CFC -11 eq. to air	Emissions of ozone-depleting substances destroy ozone molecules, thereby decreasing ozone levels. This can cause an increase in various types of cancer as well as in other diseases due to the increased UVB radiation.
Ionising Radiation	Ionising radiation potential	kBq Co-60 eq. to air	Burning coal and nuclear fuel cycles (e.g., mining, waste disposal) generate emissions of radionuclides which can affect human health (causing various types of cancer as well as other diseases)
Fine Particulate Matter Formation	Particulate matter formation potential	kg PM2.5 eq. to air	Air pollution through fine particular matter (e.g., NOx, NH3) that causes aerosols in the atmosphere can lead to an increase in respiratory disease.
Ozone Formation: Human Health	Photochemical oxidant formation: humans	kg Nox eq. to air	Ground-level ozone formation is hazardous to human health as it can cause an increase in respiratory disease.

Midpoint Impact Category	Characterisation Factor	Unit	Importance
Ozone Formation: Terrestrial Ecosystem	Photochemical oxidant formation: ecosystems	kg NOx eq. to air	Next to its impact on human health, ground-level ozone formation can negatively impact terrestrial species through its negative impact on vegetation.
Terrestrial Acidification	Terrestrial acidification potential	kg SO2 eq. to air	The deposition of nutrients such as sulphates or nitrates changes the acidity levels in the soil. This change in the soil's chemical properties will cause damage to terrestrial species occurrence.
Freshwater Eutrophication	Freshwater eutrophication potential	kg P eq. to freshwater	Nutrient emissions into freshwater bodies lead to an increased nutrient uptake of autotrophic and heterotrophic species. This will lead to a relative loss of species, damaging the freshwater ecosystem.
Marine Eutrophication	Marine eutrophication potential	kg P eq. to marine water	The process of raising nutrient levels in marine systems due to runoff and leaching of plant nutrients and soil can cause damage to marine species through, e.g., the disappearance of demersal marine species.
Human Carcinogenic Toxicity	Human toxicity potential	kg 1,4-DCB eq. to urban air	The emission of chemicals increases the chemical concentration in the environment. This higher exposure leads to a higher chemical intake by humans, causing an increase in various types of cancer.
Human Non-Carcinogenic Toxicity	Human toxicity potential	kg 1,4-DCB eq. to urban air	The emission of chemicals increases the chemical concentration in the environment. This higher exposure leads to a higher chemical intake by humans, causing an increase in various types of diseases.
Terrestrial Ecotoxicity	Terrestrial ecotoxicity potential	kg 1,4-DCB eq. to industrial soil	The emission of chemicals increases the chemical concentration in the terrestrial environment. Species' higher exposure to the chemicals and their potential

Midpoint Impact Category	Characterisation Factor	Unit	Importance
			disappearance causes damage to the terrestrial ecosystem.
Freshwater Ecotoxicity	Freshwater ecotoxicity potential	kg 1,4-DCB eq. to freshwater	The emission of chemicals increases the chemical concentration in freshwater. Species' higher exposure to the chemicals and their potential disappearance causes damage to the freshwater ecosystem.
Marine Ecotoxicity	Marine ecotoxicity potential	kg 1,4-DCB eq. to marine water	The emission of chemicals increases the chemical concentration in the marine environment. Marine species' higher exposure to the chemicals and their potential disappearance causes damage to the marine ecosystem.
Land Use	Agricultural land occupation potential	m^2 x year (yr) annual cropland eq.	Changes in the land cover or land use itself (e.g., agricultural activities) cause damage to terrestrial species through a reduction of their habitat.
Water Use	Water consumption potential	m^3 water eq. consumed	Includes the usage of water in a way such that the consumed water is afterwards not available to humans nor the ecosystem (e.g., evaporated, incorporated in products). This can cause an increase in malnutrition as well as the disappearance of several freshwater and terrestrial species.
Mineral Resource Scarcity	Surplus ore potential	kg Cu eq.	The extraction of mineral resources decreases the ore grade, increasing the amount of ore produced per kg of mineral resource extracted. The increased extraction will lead to reduced resource availability.
Fossil Resource Scarcity	Fossil fuel potential	kg oil eq.	Increased fossil fuel extraction can cause reduced resource availability.

Source: Oxford Economics based on Huijbregts et al. (2017) and Huijbregts et al. (2016)

APPENDIX 2: DETAILED IMPACT ASSESSMENT RESULTS

TABLE 46: CHARACTERISATION RESULTS FOR THE PRODUCTION PHASE OF THE CASH SYSTEM IN GERMANY

Impact category	Unit	Total	Fictional coin	Fictional banknote	ATM/CRM	Cash Transport	Cash Counting	Data Centre Cash	Card Cash
Global warming	kg CO2 eq	5.54E-03	1.35E-03	3.47E-04	3.06E-03	5.79E-04	6.37E-06	1.71E-05	1.79E-04
Stratospheric ozone depletion	kg CFC11 eq	3.00E-09	9.18E-10	1.02E-09	8.08E-10	1.83E-10	2.61E-12	8.35E-12	5.51E-11
Ionizing radiation	kBq Co-60 eq	3.57E-05	9.64E-06	3.37E-06	1.92E-05	2.48E-06	4.37E-08	1.30E-07	8.06E-07
Ozone formation, Human health	kg NOx eq	1.84E-05	7.55E-06	1.15E-06	7.43E-06	1.53E-06	1.86E-08	6.23E-08	6.65E-07
Fine particulate matter formation	kg PM2.5 eq	2.14E-05	1.44E-05	5.98E-07	4.98E-06	1.14E-06	1.27E-08	5.41E-08	2.01E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.93E-05	7.77E-06	1.20E-06	7.95E-06	1.64E-06	1.93E-08	6.43E-08	6.92E-07
Terrestrial acidification	kg SO2 eq	5.80E-05	4.38E-05	1.97E-06	9.28E-06	2.24E-06	2.67E-08	1.29E-07	5.74E-07
Freshwater eutrophication	kg P eq	8.75E-07	2.68E-07	2.18E-07	3.28E-07	4.37E-08	1.40E-09	3.36E-09	1.23E-08
Marine eutrophication	kg N eq	1.32E-06	5.22E-08	1.03E-06	2.16E-07	1.09E-08	6.78E-10	4.17E-10	1.03E-08
Terrestrial ecotoxicity	kg 1,4-DCB	3.19E-01	2.94E-01	1.87E-03	1.78E-02	3.56E-03	4.34E-05	5.90E-04	1.20E-03
Freshwater ecotoxicity	kg 1,4-DCB	3.20E-05	1.15E-05	6.04E-06	1.16E-05	2.47E-06	5.08E-08	1.65E-07	2.01E-07
Marine ecotoxicity	kg 1,4-DCB	1.88E-04	1.43E-04	4.27E-06	3.31E-05	5.52E-06	2.24E-07	1.03E-06	8.71E-07
Human carcinogenic toxicity	kg 1,4-DCB	7.19E-04	2.47E-04	5.03E-06	3.99E-04	6.55E-05	1.53E-07	9.29E-07	1.69E-06
Human non-carcinogenic toxicity	kg 1,4-DCB	1.85E-02	1.68E-02	1.95E-04	1.15E-03	2.75E-04	4.75E-06	4.05E-05	8.26E-05
Land use	m2a crop eq	7.79E-04	1.33E-04	4.53E-04	1.09E-04	1.36E-05	2.28E-07	7.71E-07	6.88E-05
Mineral resource scarcity	kg Cu eq	2.87E-04	1.85E-04	1.74E-06	8.40E-05	1.44E-05	1.72E-07	9.12E-07	6.58E-07
Fossil resource scarcity	kg oil eq	1.36E-03	3.27E-04	8.87E-05	7.35E-04	1.45E-04	1.73E-06	4.26E-06	5.64E-05
Water consumption	m3	1.30E-04	2.55E-05	8.29E-05	1.62E-05	3.62E-06	4.23E-08	1.46E-07	1.24E-06

TABLE 47: CHARACTERISATION RESULTS FOR THE OPERATION PHASE OF THE CASH SYSTEM IN GERMANY

Impact category	Unit	Total	Cash Transport	ATM/CRM	Cash Counting	Data Centre Cash
Global warming	kg CO2 eq	1.24E-02	4.61E-04	1.18E-02	2.13E-05	1.24E-04
Stratospheric ozone depletion	kg CFC11 eq	4.81E-09	1.08E-10	4.63E-09	1.12E-11	5.88E-11
Ionizing radiation	kBq Co-60 eq	7.73E-05	5.14E-07	7.19E-05	2.92E-07	4.60E-06
Ozone formation, Human health	kg NOx eq	2.78E-05	2.31E-06	2.52E-05	2.46E-08	2.30E-07
Fine particulate matter formation	kg PM2.5 eq	1.10E-05	5.07E-07	1.03E-05	1.43E-08	1.77E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.95E-05	2.42E-06	2.68E-05	2.53E-08	2.38E-07
Terrestrial acidification	kg SO2 eq	2.68E-05	1.15E-06	2.52E-05	4.07E-08	4.51E-07
Freshwater eutrophication	kg P eq	8.29E-07	3.12E-09	8.11E-07	3.16E-09	1.21E-08
Marine eutrophication	kg N eq	1.67E-07	1.06E-08	1.55E-07	9.94E-11	8.42E-10
Terrestrial ecotoxicity	kg 1,4-DCB	6.76E-02	7.78E-03	5.89E-02	1.08E-04	7.85E-04
Freshwater ecotoxicity	kg 1,4-DCB	2.45E-05	1.34E-06	2.30E-05	1.50E-08	1.66E-07
Marine ecotoxicity	kg 1,4-DCB	7.06E-05	6.03E-06	6.37E-05	6.62E-08	7.47E-07
Human carcinogenic toxicity	kg 1,4-DCB	2.00E-04	2.68E-06	1.95E-04	1.97E-07	1.36E-06
Human non-carcinogenic toxicity	kg 1,4-DCB	3.67E-03	1.34E-04	3.46E-03	8.24E-06	6.23E-05
Land use	m2a crop eq	3.05E-04	2.37E-05	2.76E-04	4.60E-07	4.42E-06
Mineral resource scarcity	kg Cu eq	5.49E-05	5.22E-07	5.36E-05	7.09E-08	7.11E-07
Fossil resource scarcity	kg oil eq	3.41E-03	1.49E-04	3.22E-03	5.22E-06	3.39E-05
Water consumption	m3	5.49E-05	8.45E-07	5.19E-05	1.54E-07	1.94E-06

Source: Oxford Economics

TABLE 48: CHARACTERISATION RESULTS FOR THE END-OF-LIFE PHASE OF THE CASH SYSTEM IN GERMANY

Impact category	Unit	Total	Fictional coin	ATM/CRM	Fictional Banknote	Cash Transport	Cash Counting	Data Centre Cash	Card Cash
Global warming	kg CO2 eq	1.65E-04	3.13E-06	5.51E-05	5.28E-05	2.64E-05	5.66E-07	1.64E-07	2.66E-05
Stratospheric ozone depletion	kg CFC11 eq	2.28E-10	4.63E-12	2.55E-11	1.65E-10	1.23E-11	8.95E-14	1.10E-13	2.04E-11
Ionizing radiation	kBq Co-60 eq	3.85E-07	2.01E-08	3.35E-08	3.06E-07	1.82E-08	2.32E-11	3.05E-11	7.09E-09
Ozone formation, Human health	kg NOx eq	7.06E-07	1.18E-08	4.76E-07	1.78E-07	1.94E-08	1.27E-10	7.36E-11	2.09E-08
Fine particulate matter formation	kg PM2.5 eq	1.60E-07	2.80E-09	1.06E-07	3.48E-08	1.07E-08	2.39E-11	2.08E-11	5.28E-09
Ozone formation, Terrestrial ecosystems	kg NOx eq	7.23E-07	1.22E-08	4.88E-07	1.81E-07	1.99E-08	1.29E-10	7.50E-11	2.13E-08
Terrestrial acidification	kg SO2 eq	3.43E-07	6.93E-09	2.05E-07	1.03E-07	1.53E-08	6.21E-11	6.12E-11	1.29E-08
Freshwater eutrophication	kg P eq	5.47E-09	3.02E-10	4.66E-10	4.02E-09	2.19E-10	3.05E-12	7.54E-13	4.59E-10
Marine eutrophication	kg N eq	4.59E-09	7.54E-11	1.34E-09	2.65E-09	2.47E-10	7.36E-13	6.75E-13	2.82E-10
Terrestrial ecotoxicity	kg 1,4-DCB	2.81E-04	2.66E-05	1.12E-04	6.38E-05	4.87E-05	3.53E-07	8.25E-08	2.95E-05
Freshwater ecotoxicity	kg 1,4-DCB	2.10E-06	5.75E-09	6.22E-07	7.13E-08	1.36E-06	2.41E-09	8.29E-09	3.59E-08
Marine ecotoxicity	kg 1,4-DCB	3.01E-06	2.17E-08	9.20E-07	1.26E-07	1.86E-06	3.51E-09	1.13E-08	6.72E-08
Human carcinogenic toxicity	kg 1,4-DCB	2.50E-06	3.97E-08	5.32E-07	1.51E-06	1.69E-07	1.97E-09	6.55E-10	2.42E-07
Human non-carcinogenic toxicity	kg 1,4-DCB	4.39E-05	1.27E-06	7.66E-06	1.91E-05	1.05E-05	4.11E-08	5.78E-08	5.32E-06
Land use	m2a crop eq	1.27E-06	1.01E-07	4.37E-07	5.25E-07	1.20E-07	2.21E-10	1.29E-09	8.72E-08
Mineral resource scarcity	kg Cu eq	1.93E-07	5.44E-09	8.34E-08	7.03E-08	1.62E-08	6.09E-11	1.03E-10	1.72E-08
Fossil resource scarcity	kg oil eq	2.43E-05	8.41E-07	1.33E-05	8.51E-06	9.02E-07	3.32E-09	2.40E-09	7.43E-07
Water consumption	m3	9.53E-07	1.54E-08	9.38E-08	3.17E-07	4.29E-08	1.41E-10	2.36E-10	4.83E-07

Source: Oxford Economics

TABLE 49: CHARACTERISATION RESULTS FOR THE PRODUCTION PHASE OF THE DIGITAL SYSTEM IN GERMANY

Impact category	Unit	Total	Card Digital	Terminal	Smartphone	Data Centre Digital
Global warming	kg CO2 eq	0.001946743	0.000920319	0.000674262	6.30E-08	0.000352099
Stratospheric ozone depletion	kg CFC11 eq	7.35E-10	2.84E-10	2.79E-10	2.84E-14	1.72E-10
Ionizing radiation	kBq Co-60 eq	1.16E-05	4.15E-06	4.83E-06	5.06E-10	2.67E-06
Ozone formation, Human health	kg NOx eq	6.97E-06	3.42E-06	2.26E-06	1.49E-10	1.28E-06
Fine particulate matter formation	kg PM2.5 eq	3.58E-06	1.03E-06	1.43E-06	1.19E-10	1.11E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	7.23E-06	3.56E-06	2.35E-06	1.55E-10	1.32E-06
Terrestrial acidification	kg SO2 eq	8.68E-06	2.95E-06	3.07E-06	2.17E-10	2.66E-06
Freshwater eutrophication	kg P eq	2.41E-07	6.33E-08	1.09E-07	1.26E-11	6.91E-08
Marine eutrophication	kg N eq	8.82E-08	5.29E-08	2.67E-08	3.47E-12	8.58E-09
Terrestrial ecotoxicity	kg 1,4-DCB	2.57E-02	6.19E-03	7.41E-03	3.04E-07	0.012142515
Freshwater ecotoxicity	kg 1,4-DCB	9.21E-06	1.03E-06	4.77E-06	2.20E-10	3.40E-06
Marine ecotoxicity	kg 1,4-DCB	5.11E-05	4.48E-06	2.54E-05	5.59E-10	2.12E-05
Human carcinogenic toxicity	kg 1,4-DCB	4.58E-05	8.71E-06	1.79E-05	9.31E-10	1.91E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	1.86E-03	4.25E-04	6.05E-04	3.17E-08	0.000832586
Land use	m2a crop eq	3.96E-04	3.54E-04	2.61E-05	1.19E-09	1.59E-05
Mineral resource scarcity	kg Cu eq	4.55E-05	3.38E-06	2.33E-05	4.34E-10	1.88E-05
Fossil resource scarcity	kg oil eq	0.000561625	2.90E-04	0.0001838	1.58E-08	8.76E-05
Water consumption	m3	1.54E-05	6.39E-06	6.06E-06	3.65E-10	3.00E-06

Source: Oxford Economics

TABLE 50: CHARACTERISATION RESULTS FOR THE OPERATION PHASE OF THE DIGITAL SYSTEM IN GERMANY

Impact category	Unit	Total	Data Centre Digital	Smartphone	Terminal
Global warming	kg CO2 eq	9.19E-04	0.000537967	8.61E-06	0.000371949
Stratospheric ozone depletion	kg CFC11 eq	4.53E-10	2.75E-10	4.51E-12	1.74E-10
Ionizing radiation	kBq Co-60 eq	2.67E-05	1.92E-05	1.18E-07	7.40E-06
Ozone formation, Human health	kg NOx eq	1.78E-06	8.17E-07	9.92E-09	9.49E-07
Fine particulate matter formation	kg PM2.5 eq	1.02E-06	4.40E-07	5.75E-09	5.74E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.85E-06	8.50E-07	1.02E-08	9.89E-07
Terrestrial acidification	kg SO2 eq	2.60E-06	1.21E-06	1.64E-08	1.37E-06
Freshwater eutrophication	kg P eq	7.56E-08	3.79E-08	1.28E-09	3.65E-08
Marine eutrophication	kg N eq	1.50E-08	3.00E-09	4.01E-11	1.20E-08
Terrestrial ecotoxicity	kg 1,4-DCB	0.004463976	0.003113269	4.36E-05	0.001307089
Freshwater ecotoxicity	kg 1,4-DCB	1.02E-06	4.63E-07	6.06E-09	5.50E-07
Marine ecotoxicity	kg 1,4-DCB	3.41E-06	2.07E-06	2.67E-08	1.31E-06
Human carcinogenic toxicity	kg 1,4-DCB	9.32E-06	4.98E-06	7.96E-08	4.26E-06
Human non-carcinogenic toxicity	kg 1,4-DCB	0.000379905	0.000230676	3.32E-06	0.000145904
Land use	m2a crop eq	0.000171648	2.44E-05	1.86E-07	0.000147056
Mineral resource scarcity	kg Cu eq	3.73E-06	2.26E-06	2.86E-08	1.44E-06
Fossil resource scarcity	kg oil eq	0.000288811	0.000156654	2.11E-06	0.000130049
Water consumption	m3	1.25E-05	5.00E-06	6.22E-08	7.40E-06

Source: Oxford Economics

TABLE 51: CHARACTERISATION RESULTS FOR THE END-OF-LIFE PHASE OF THE DIGITAL SYSTEM IN GERMANY

Impact category	Unit	Total	Card Digital	Data Centre Digital	Smartphone	Terminal
Global warming	kg CO2 eq	0.000190042	1.37E-04	3.38E-06	2.67E-10	5.01E-05
Stratospheric ozone depletion	kg CFC11 eq	2.35E-10	1.05E-10	2.25E-12	2.02E-16	1.28E-10
Ionizing radiation	kBq Co-60 eq	5.98E-08	3.64E-08	6.27E-10	6.25E-13	2.27E-08
Ozone formation, Human health	kg NOx eq	2.12E-07	1.08E-07	1.51E-09	3.79E-13	1.03E-07
Fine particulate matter formation	kg PM2.5 eq	6.35E-08	2.71E-08	4.27E-10	2.28E-13	3.59E-08
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.16E-07	1.09E-07	1.54E-09	3.87E-13	1.05E-07
Terrestrial acidification	kg SO2 eq	1.27E-07	6.64E-08	1.26E-09	4.81E-13	5.93E-08
Freshwater eutrophication	kg P eq	4.12E-09	2.36E-09	1.55E-11	6.03E-15	1.74E-09
Marine eutrophication	kg N eq	5.16E-09	1.45E-09	1.39E-11	3.51E-15	3.70E-09
Terrestrial ecotoxicity	kg 1,4-DCB	0.000269035	1.52E-04	1.70E-06	1.11E-09	0.000115635
Freshwater ecotoxicity	kg 1,4-DCB	5.72E-07	1.85E-07	1.71E-07	8.93E-12	2.17E-07
Marine ecotoxicity	kg 1,4-DCB	9.37E-07	3.45E-07	2.32E-07	1.27E-11	3.60E-07
Human carcinogenic toxicity	kg 1,4-DCB	2.48E-06	1.24E-06	1.35E-08	5.56E-12	1.22E-06
Human non-carcinogenic toxicity	kg 1,4-DCB	5.81E-05	2.74E-05	1.19E-06	1.15E-10	2.96E-05
Land use	m2a crop eq	8.39E-07	4.48E-07	2.66E-08	2.60E-12	3.64E-07
Mineral resource scarcity	kg Cu eq	1.49E-07	8.83E-08	2.12E-09	4.45E-13	5.85E-08
Fossil resource scarcity	kg oil eq	7.01E-06	3.82E-06	4.93E-08	2.35E-11	3.14E-06
Water consumption	m3	2.76E-06	2.48E-06	4.85E-09	1.63E-12	2.71E-07

Source: Oxford Economics

TABLE 52: CHARACTERISATION RESULTS FOR THE PRODUCTION PHASE OF THE CASH SYSTEM IN ITALY

Impact category	Unit	Total	Fictional coin	Fictional banknote	ATM/CRM	Cash Transport	Cash Counting	Data Centre Cash	Card Cash
Global warming	kg CO2 eq	0.003278243	0.001329715	0.000347588	0.001295275	0.000237708	6.13E-06	8.58E-06	5.33E-05
Stratospheric ozone depletion	kg CFC11 eq	2.36E-09	9.10E-10	1.01E-09	3.41E-10	7.51E-11	2.52E-12	4.18E-12	1.61E-11
Ionizing radiation	kBq Co-60 eq	2.20E-05	9.46E-06	3.14E-06	8.07E-06	1.02E-06	4.20E-08	6.49E-08	2.03E-07
Ozone formation, Human health	kg NOx eq	1.27E-05	7.46E-06	1.19E-06	3.17E-06	6.29E-07	1.79E-08	3.12E-08	2.02E-07
Fine particulate matter formation	kg PM2.5 eq	1.76E-05	1.43E-05	6.10E-07	2.10E-06	4.66E-07	1.22E-08	2.71E-08	6.17E-08
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.32E-05	7.67E-06	1.25E-06	3.39E-06	6.74E-07	1.85E-08	3.22E-08	2.11E-07
Terrestrial acidification	kg SO2 eq	5.07E-05	4.36E-05	2.00E-06	3.92E-06	9.18E-07	2.58E-08	6.48E-08	1.76E-07
Freshwater eutrophication	kg P eq	6.39E-07	2.65E-07	2.13E-07	1.38E-07	1.79E-08	1.36E-09	1.68E-09	2.99E-09
Marine eutrophication	kg N eq	1.17E-06	5.17E-08	1.02E-06	9.07E-08	4.49E-09	6.66E-10	2.09E-10	3.10E-09
Terrestrial ecotoxicity	kg 1,4-DCB	0.30415437	0.29237884	0.001968827	0.007642461	0.001463593	4.24E-05	0.000295807	0.000362453
Freshwater ecotoxicity	kg 1,4-DCB	2.36E-05	1.14E-05	6.03E-06	4.90E-06	1.01E-06	4.88E-08	8.29E-08	6.04E-08
Marine ecotoxicity	kg 1,4-DCB	0.00016433	0.000142705	4.33E-06	1.40E-05	2.27E-06	2.15E-07	5.17E-07	2.62E-07
Human carcinogenic toxicity	kg 1,4-DCB	0.000446446	0.000246243	5.00E-06	0.000167236	2.69E-05	1.47E-07	4.66E-07	5.03E-07
Human non-carcinogenic toxicity	kg 1,4-DCB	0.017535634	0.016693794	0.000194286	0.000485455	0.000112705	4.60E-06	2.03E-05	2.45E-05
Land use	m2a crop eq	0.000656545	0.000131882	0.00045125	4.64E-05	5.60E-06	2.20E-07	3.86E-07	2.08E-05
Mineral resource scarcity	kg Cu eq	0.000227793	0.00018412	1.74E-06	3.52E-05	5.90E-06	1.66E-07	4.57E-07	1.97E-07
Fossil resource scarcity	kg oil eq	0.000804993	0.000321433	9.09E-05	0.000312091	5.96E-05	1.66E-06	2.13E-06	1.71E-05
Water consumption	m3	0.000117214	2.55E-05	8.28E-05	6.83E-06	1.48E-06	4.05E-08	7.30E-08	4.17E-07

Source: Oxford Economics

TABLE 53: CHARACTERISATION RESULTS FOR THE OPERATION PHASE OF THE CASH SYSTEM IN ITALY

Impact category	Unit	Total	Cash Transport	ATM/CRM	Cash Counting	Data Centre Cash
Global warming	kg CO2 eq	0.008045577	0.000971374	0.006943024	1.86E-05	1.13E-04
Stratospheric ozone depletion	kg CFC11 eq	2.74E-09	2.27E-10	2.45E-09	9.04E-12	5.30E-11
Ionizing radiation	kBq Co-60 eq	2.57E-05	1.08E-06	2.03E-05	1.37E-07	4.20E-06
Ozone formation, Human health	kg NOx eq	2.33E-05	4.86E-06	1.82E-05	3.20E-08	2.14E-07
Fine particulate matter formation	kg PM2.5 eq	8.17E-06	1.07E-06	6.91E-06	1.82E-08	1.69E-07
Ozone formation,	kg NOx eq	2.50E-05	5.09E-06	1.97E-05	3.46E-08	2.21E-07
Terrestrial ecosystems	kg NOx eq	2.50E-05	5.09E-06	1.97E-05	3.46E-08	2.21E-07
Terrestrial acidification	kg SO2 eq	1.97E-05	2.41E-06	1.68E-05	5.27E-08	4.28E-07
Freshwater eutrophication	kg P eq	1.59E-07	6.56E-09	1.41E-07	4.29E-10	1.14E-08
Marine eutrophication	kg N eq	1.28E-07	2.23E-08	1.05E-07	8.00E-11	7.82E-10
Terrestrial ecotoxicity	kg 1,4-DCB	0.052165697	0.016370352	0.034972909	0.00010083	0.000721605
Freshwater ecotoxicity	kg 1,4-DCB	1.82E-05	2.82E-06	1.53E-05	1.32E-08	1.57E-07
Marine ecotoxicity	kg 1,4-DCB	5.45E-05	1.27E-05	4.10E-05	6.11E-08	7.08E-07
Human carcinogenic toxicity	kg 1,4-DCB	0.000128298	5.64E-06	0.000121235	1.62E-07	1.26E-06
Human non-carcinogenic toxicity	kg 1,4-DCB	0.002172626	0.000282609	0.001825704	6.68E-06	5.76E-05
Land use	m2a crop eq	0.000228404	4.99E-05	0.000174068	5.08E-07	3.89E-06
Mineral resource scarcity	kg Cu eq	3.46E-05	1.10E-06	3.28E-05	6.54E-08	6.67E-07
Fossil resource scarcity	kg oil eq	0.002399974	0.000314225	0.002049448	5.70E-06	3.06E-05
Water consumption	m3	4.64E-05	1.78E-06	4.25E-05	3.12E-07	1.85E-06

Source: Oxford Economics

TABLE 54: CHARACTERISATION RESULTS FOR THE END-OF-LIFE PHASE OF THE CASH SYSTEM IN ITALY

Impact category	Unit	Total	Fictional coin	ATM/CRM	Fictional Banknote	Cash Transport	Cash Counting	Data Centre End Cash	Card Cash
Global warming	kg CO2 eq	0.000190027	8.15E-06	2.35E-05	0.000131338	1.08E-05	3.11E-07	8.24E-08	1.58E-05
Stratospheric ozone depletion	kg CFC11 eq	1.66E-10	2.71E-12	1.00E-11	1.45E-10	5.06E-12	5.20E-14	5.49E-14	3.30E-12
Ionizing radiation	kBq Co-60 eq	1.86E-07	1.01E-08	1.41E-08	1.52E-07	7.45E-09	2.46E-11	1.53E-11	1.87E-09
Ozone formation, Human health	kg NOx eq	4.01E-07	9.69E-09	1.99E-07	1.79E-07	7.96E-09	8.90E-11	3.69E-11	4.62E-09
Fine particulate matter formation	kg PM2.5 eq	9.80E-08	2.86E-09	4.45E-08	4.22E-08	4.37E-09	2.19E-11	1.04E-11	4.04E-09
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.12E-07	1.02E-08	2.04E-07	1.84E-07	8.16E-09	9.11E-11	3.76E-11	4.74E-09
Terrestrial acidification	kg SO2 eq	2.19E-07	6.82E-09	8.58E-08	1.17E-07	6.29E-09	4.87E-11	3.07E-11	3.35E-09
Freshwater eutrophication	kg P eq	2.67E-09	1.53E-10	1.70E-10	2.03E-09	8.97E-11	2.08E-12	3.78E-13	2.31E-10
Marine eutrophication	kg N eq	3.00E-08	1.51E-09	5.99E-10	2.46E-08	1.01E-10	1.11E-11	3.38E-13	3.22E-09
Terrestrial ecotoxicity	kg 1,4-DCB	0.000158328	2.06E-05	4.70E-05	6.43E-05	2.00E-05	2.25E-07	4.13E-08	6.18E-06
Freshwater ecotoxicity	kg 1,4-DCB	9.04E-07	4.58E-09	2.61E-07	6.97E-08	5.56E-07	2.14E-09	4.15E-09	6.22E-09
Marine ecotoxicity	kg 1,4-DCB	1.32E-06	1.73E-08	3.86E-07	1.28E-07	7.64E-07	3.04E-09	5.65E-09	1.23E-08
Human carcinogenic toxicity	kg 1,4-DCB	1.79E-06	2.99E-08	2.23E-07	1.39E-06	6.93E-08	1.09E-09	3.28E-10	7.79E-08
Human non-carcinogenic toxicity	kg 1,4-DCB	2.38E-05	7.86E-07	3.09E-06	1.47E-05	4.30E-06	2.66E-08	2.90E-08	8.43E-07
Land use	m2a crop eq	9.35E-07	8.94E-08	1.88E-07	5.81E-07	4.93E-08	3.06E-10	6.48E-10	2.63E-08
Mineral resource scarcity	kg Cu eq	1.11E-07	4.16E-09	3.46E-08	6.25E-08	6.65E-09	4.18E-11	5.16E-11	2.97E-09
Fossil resource scarcity	kg oil eq	1.60E-05	7.69E-07	5.60E-06	9.05E-06	3.70E-07	3.23E-09	1.20E-09	1.93E-07
Water consumption	m3	5.91E-07	2.43E-08	4.16E-08	4.40E-07	1.76E-08	1.18E-10	1.18E-10	6.74E-08

Source: Oxford Economics

TABLE 55: CHARACTERISATION RESULTS FOR THE PRODUCTION PHASE OF THE DIGITAL SYSTEM IN ITALY

Impact category	Unit	Total	Card Digital	Terminal	Smartphone	Data Centre Digital
Global warming	kg CO2 eq	0.004093658	0.000618734	0.003076227	7.57E-08	0.000398621
Stratospheric ozone depletion	kg CFC11 eq	1.65E-09	1.87E-10	1.27E-09	3.41E-14	1.94E-10
Ionizing radiation	kBq Co-60 eq	2.74E-05	2.36E-06	2.20E-05	6.07E-10	3.02E-06
Ozone formation, Human health	kg NOx eq	1.42E-05	2.35E-06	1.03E-05	1.80E-10	1.45E-06
Fine particulate matter formation	kg PM2.5 eq	8.49E-06	7.16E-07	6.51E-06	1.43E-10	1.26E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.47E-05	2.45E-06	1.07E-05	1.87E-10	1.50E-06
Terrestrial acidification	kg SO2 eq	1.90E-05	2.05E-06	1.40E-05	2.61E-10	3.01E-06
Freshwater eutrophication	kg P eq	6.08E-07	3.48E-08	4.95E-07	1.51E-11	7.82E-08
Marine eutrophication	kg N eq	1.68E-07	3.60E-08	1.22E-07	4.17E-12	9.72E-09
Terrestrial ecotoxicity	kg 1,4-DCB	0.051816639	0.004211468	0.033857909	3.65E-07	0.013746897
Freshwater ecotoxicity	kg 1,4-DCB	2.63E-05	7.02E-07	2.17E-05	2.64E-10	3.85E-06
Marine ecotoxicity	kg 1,4-DCB	0.000142665	3.05E-06	0.000115573	6.71E-10	2.40E-05
Human carcinogenic toxicity	kg 1,4-DCB	0.000109164	5.84E-06	8.17E-05	1.12E-09	2.16E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	0.003977705	0.000284821	0.002750251	3.81E-08	0.000942595
Land use	m2a crop eq	0.000379092	0.00024137	0.000119765	1.43E-09	1.80E-05
Mineral resource scarcity	kg Cu eq	0.000129457	2.29E-06	0.000105914	5.21E-10	2.13E-05
Fossil resource scarcity	kg oil eq	0.0011375	0.000199175	0.00083909	1.90E-08	9.92E-05
Water consumption	m3	3.58E-05	4.84E-06	2.76E-05	4.38E-10	3.39E-06

Source: Oxford Economics

TABLE 56: CHARACTERISATION RESULTS FOR THE OPERATION PHASE OF THE DIGITAL SYSTEM IN ITALY

Impact category	Unit	Total	Card Digital	Terminal	Smartphone	Data Centre Digital
Global warming	kg CO2 eq	4.09E-03	6.19E-04	3.08E-03	7.57E-08	3.99E-04
Stratospheric ozone depletion	kg CFC11 eq	1.65E-09	1.87E-10	1.27E-09	3.41E-14	1.94E-10
Ionizing radiation	kBq Co-60 eq	2.74E-05	2.36E-06	2.20E-05	6.07E-10	3.02E-06
Ozone formation, Human health	kg NOx eq	1.42E-05	2.35E-06	1.03E-05	1.80E-10	1.45E-06
Fine particulate matter formation	kg PM2.5 eq	8.49E-06	7.16E-07	6.51E-06	1.43E-10	1.26E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.47E-05	2.45E-06	1.07E-05	1.87E-10	1.50E-06
Terrestrial acidification	kg SO2 eq	1.90E-05	2.05E-06	1.40E-05	2.61E-10	3.01E-06
Freshwater eutrophication	kg P eq	6.08E-07	3.48E-08	4.95E-07	1.51E-11	7.82E-08
Marine eutrophication	kg N eq	1.68E-07	3.60E-08	1.22E-07	4.17E-12	9.72E-09
Terrestrial ecotoxicity	kg 1,4-DCB	5.18E-02	4.21E-03	3.39E-02	3.65E-07	1.37E-02
Freshwater ecotoxicity	kg 1,4-DCB	2.63E-05	7.02E-07	2.17E-05	2.64E-10	3.85E-06
Marine ecotoxicity	kg 1,4-DCB	1.43E-04	3.05E-06	1.16E-04	6.71E-10	2.40E-05
Human carcinogenic toxicity	kg 1,4-DCB	1.09E-04	5.84E-06	8.17E-05	1.12E-09	2.16E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	3.98E-03	2.85E-04	2.75E-03	3.81E-08	9.43E-04
Land use	m2a crop eq	3.79E-04	2.41E-04	1.20E-04	1.43E-09	1.80E-05
Mineral resource scarcity	kg Cu eq	1.29E-04	2.29E-06	1.06E-04	5.21E-10	2.13E-05
Fossil resource scarcity	kg oil eq	1.14E-03	1.99E-04	8.39E-04	1.90E-08	9.92E-05
Water consumption	m3	3.58E-05	4.84E-06	2.76E-05	4.38E-10	3.39E-06

Source: Oxford Economics

TABLE 57: CHARACTERISATION RESULTS FOR THE END-OF-LIFE PHASE OF THE DIGITAL SYSTEM IN ITALY

Impact category	Unit	Total	Card Digital	Data Centre Digital	Smartphone	Terminal
Global warming	kg CO2 eq	0.000406937	0.000184083	3.83E-06	5.06E-10	0.000219025
Stratospheric ozone depletion	kg CFC11 eq	1.22E-10	3.84E-11	2.55E-12	1.98E-16	8.15E-11
Ionizing radiation	kBq Co-60 eq	9.17E-08	2.17E-08	7.10E-10	7.60E-13	6.93E-08
Ozone formation, Human health	kg NOx eq	1.62E-07	5.37E-08	1.71E-09	4.38E-13	1.07E-07
Fine particulate matter formation	kg PM2.5 eq	1.45E-07	4.70E-08	4.84E-10	2.81E-13	9.75E-08
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.66E-07	5.51E-08	1.75E-09	4.48E-13	1.09E-07
Terrestrial acidification	kg SO2 eq	1.28E-07	3.89E-08	1.43E-09	5.82E-13	8.78E-08
Freshwater eutrophication	kg P eq	6.00E-09	2.68E-09	1.76E-11	9.20E-15	3.30E-09
Marine eutrophication	kg N eq	9.04E-08	3.75E-08	1.57E-11	6.17E-14	5.29E-08
Terrestrial ecotoxicity	kg 1,4-DCB	0.000232667	7.19E-05	1.92E-06	1.25E-09	0.000158887
Freshwater ecotoxicity	kg 1,4-DCB	9.15E-07	7.23E-08	1.93E-07	1.07E-11	6.50E-07
Marine ecotoxicity	kg 1,4-DCB	1.38E-06	1.43E-07	2.63E-07	1.51E-11	9.74E-07
Human carcinogenic toxicity	kg 1,4-DCB	2.81E-06	9.05E-07	1.53E-08	6.42E-12	1.89E-06
Human non-carcinogenic toxicity	kg 1,4-DCB	3.40E-05	9.79E-06	1.35E-06	1.29E-10	2.29E-05
Land use	m2a crop eq	9.43E-07	3.06E-07	3.01E-08	3.24E-12	6.07E-07
Mineral resource scarcity	kg Cu eq	1.13E-07	3.46E-08	2.40E-09	5.17E-13	7.63E-08
Fossil resource scarcity	kg oil eq	6.90E-06	2.24E-06	5.58E-08	2.86E-11	4.60E-06
Water consumption	m3	1.76E-06	7.83E-07	5.49E-09	1.86E-12	9.71E-07

Source: Oxford Economics

TABLE 58: CHARACTERISATION RESULTS FOR THE PRODUCTION PHASE OF THE CASH SYSTEM IN FINLAND

Impact category	Unit	Total	Fictional coin	Fictional banknote	ATM/CRM	Cash Transport	Cash Counting	Data Centre Cash	Card Cash
Global warming	kg CO2 eq	6.65E-03	1.30E-03	3.50E-04	2.39E-03	2.51E-03	2.09E-05	2.50E-05	5.21E-05
Stratospheric ozone depletion	kg CFC11 eq	3.36E-09	8.95E-10	1.00E-09	6.31E-10	7.93E-10	8.20E-12	1.22E-11	1.74E-11
Ionizing radiation	kBq Co-60 eq	4.17E-05	1.03E-05	4.78E-06	1.50E-05	1.08E-05	1.47E-07	1.90E-07	5.98E-07
Ozone formation, Human health	kg NOx eq	2.14E-05	7.32E-06	1.27E-06	5.84E-06	6.63E-06	6.09E-08	9.11E-08	2.00E-07
Fine particulate matter formation	kg PM2.5 eq	2.37E-05	1.41E-05	6.24E-07	3.89E-06	4.92E-06	3.98E-08	7.92E-08	6.35E-08
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.26E-05	7.53E-06	1.32E-06	6.25E-06	7.10E-06	6.30E-08	9.40E-08	2.09E-07
Terrestrial acidification	kg SO2 eq	6.23E-05	4.29E-05	2.00E-06	7.25E-06	9.68E-06	8.09E-08	1.89E-07	1.77E-07
Freshwater eutrophication	kg P eq	9.27E-07	2.60E-07	2.10E-07	2.55E-07	1.89E-07	3.89E-09	4.91E-09	3.22E-09
Marine eutrophication	kg N eq	1.28E-06	5.08E-08	1.01E-06	1.68E-07	4.74E-08	1.19E-09	6.10E-10	3.27E-09
Terrestrial ecotoxicity	kg 1,4-DCB	3.20E-01	2.87E-01	2.24E-03	1.40E-02	1.54E-02	9.59E-05	8.63E-04	3.79E-04
Freshwater ecotoxicity	kg 1,4-DCB	3.74E-05	1.12E-05	5.98E-06	9.06E-06	1.07E-05	1.71E-07	2.42E-07	6.26E-08
Marine ecotoxicity	kg 1,4-DCB	1.97E-04	1.40E-04	4.49E-06	2.59E-05	2.39E-05	7.60E-07	1.51E-06	2.71E-07
Human carcinogenic toxicity	kg 1,4-DCB	8.43E-04	2.42E-04	5.01E-06	3.10E-04	2.83E-04	5.09E-07	1.36E-06	5.24E-07
Human non-carcinogenic toxicity	kg 1,4-DCB	1.88E-02	1.64E-02	1.97E-04	8.98E-04	1.19E-03	1.36E-05	5.92E-05	2.58E-05
Land use	m2a crop eq	7.45E-04	1.30E-04	4.46E-04	8.57E-05	5.91E-05	7.32E-07	1.13E-06	2.24E-05
Mineral resource scarcity	kg Cu eq	3.13E-04	1.81E-04	1.74E-06	6.54E-05	6.23E-05	5.89E-07	1.33E-06	2.10E-07
Fossil resource scarcity	kg oil eq	1.64E-03	3.14E-04	9.12E-05	5.76E-04	6.29E-04	5.74E-06	6.23E-06	1.67E-05
Water consumption	m3	1.36E-04	2.51E-05	8.15E-05	1.27E-05	1.57E-05	1.57E-07	2.13E-07	4.48E-07

Source: Oxford Economics

TABLE 59: CHARACTERISATION RESULTS FOR THE OPERATION PHASE OF THE CASH SYSTEM IN FINLAND

Impact category	Unit	Total	Cash Transport	ATM/CRM	Cash Counting	Data Centre Cash
Global warming	kg CO2 eq	0.044925097	0.002064235	0.042715626	1.11E-05	1.34E-04
Stratospheric ozone depletion	kg CFC11 eq	1.51E-08	4.82E-10	1.45E-08	1.01E-11	6.42E-11
Ionizing radiation	kBq Co-60 eq	0.000321791	2.30E-06	0.00031307	1.46E-06	4.96E-06
Ozone formation, Human health	kg NOx eq	0.00012879	1.03E-05	0.000118187	2.09E-08	2.45E-07
Fine particulate matter formation	kg PM2.5 eq	4.66E-05	2.27E-06	4.42E-05	1.73E-08	1.84E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.000137558	1.08E-05	0.00012647	2.18E-08	2.53E-07
Terrestrial acidification	kg SO2 eq	0.000105289	5.12E-06	9.97E-05	3.59E-08	4.71E-07
Freshwater eutrophication	kg P eq	9.25E-07	1.39E-08	8.98E-07	5.10E-10	1.28E-08
Marine eutrophication	kg N eq	8.21E-07	4.73E-08	7.73E-07	9.45E-11	8.98E-10
Terrestrial ecotoxicity	kg 1,4-DCB	0.25219365	0.034788116	0.2164743	8.70E-05	0.000844215
Freshwater ecotoxicity	kg 1,4-DCB	0.000118692	5.99E-06	0.000112514	1.24E-08	1.74E-07
Marine ecotoxicity	kg 1,4-DCB	0.000313958	2.70E-05	0.000286134	4.91E-08	7.82E-07
Human carcinogenic toxicity	kg 1,4-DCB	0.000890279	1.20E-05	0.000876709	1.35E-07	1.46E-06
Human non-carcinogenic toxicity	kg 1,4-DCB	0.011491092	0.000600563	0.01081707	6.89E-06	6.66E-05
Land use	m2a crop eq	0.001315815	0.000106123	0.001203626	1.15E-06	4.91E-06
Mineral resource scarcity	kg Cu eq	0.000228805	2.33E-06	0.000225656	6.50E-08	7.51E-07
Fossil resource scarcity	kg oil eq	0.013072188	0.00066775	0.012364761	2.71E-06	3.70E-05
Water consumption	m3	0.000171161	3.78E-06	0.000165037	3.21E-07	2.02E-06

Source: Oxford Economics

TABLE 60: CHARACTERISATION RESULTS FOR THE END-OF-LIFE PHASE OF THE CASH SYSTEM IN FINLAND

Impact category	Unit	Total	Fictional coin	ATM/CRM	Fictional Banknote	Cash Transport	Cash Counting	Data Centre Cash	Card Cash
Global warming	kg CO2 eq	2.19E-04	1.91E-06	4.30E-05	4.84E-05	1.14E-04	1.98E-06	2.40E-07	9.40E-06
Stratospheric ozone depletion	kg CFC11 eq	2.42E-10	4.04E-12	1.97E-11	1.58E-10	5.34E-11	3.06E-13	1.60E-13	6.32E-12
Ionizing radiation	kBq Co-60 eq	1.50E-06	8.17E-08	2.62E-08	1.31E-06	7.86E-08	6.80E-11	4.46E-11	2.36E-09
Ozone formation, Human health	kg NOx eq	6.39E-07	6.29E-09	3.71E-07	1.70E-07	8.40E-08	4.75E-10	1.08E-10	6.97E-09
Fine particulate matter formation	kg PM2.5 eq	1.71E-07	1.88E-09	8.27E-08	3.77E-08	4.62E-08	8.81E-11	3.04E-11	1.99E-09
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.54E-07	6.47E-09	3.80E-07	1.73E-07	8.61E-08	4.83E-10	1.10E-10	7.11E-09
Terrestrial acidification	kg SO2 eq	3.32E-07	4.11E-09	1.60E-07	9.70E-08	6.63E-08	2.28E-10	8.96E-11	4.32E-09
Freshwater eutrophication	kg P eq	2.99E-09	1.28E-10	3.59E-10	1.38E-09	9.46E-10	1.13E-11	1.10E-12	1.58E-10
Marine eutrophication	kg N eq	7.24E-09	1.79E-10	1.05E-09	4.53E-09	1.07E-09	8.36E-12	9.87E-13	3.94E-10
Terrestrial ecotoxicity	kg 1,4-DCB	3.85E-04	9.45E-06	8.84E-05	6.41E-05	2.11E-04	1.25E-06	1.21E-07	1.06E-05
Freshwater ecotoxicity	kg 1,4-DCB	6.45E-06	2.64E-09	4.84E-07	6.78E-08	5.87E-06	4.15E-09	1.21E-08	1.14E-08
Marine ecotoxicity	kg 1,4-DCB	8.95E-06	8.25E-09	7.17E-07	1.22E-07	8.06E-06	6.49E-09	1.65E-08	2.19E-08
Human carcinogenic toxicity	kg 1,4-DCB	2.69E-06	3.03E-08	4.15E-07	1.43E-06	7.32E-07	6.68E-09	9.58E-10	7.89E-08
Human non-carcinogenic toxicity	kg 1,4-DCB	7.20E-05	8.96E-07	5.97E-06	1.78E-05	4.54E-05	1.22E-07	8.45E-08	1.67E-06
Land use	m2a crop eq	2.16E-06	8.93E-08	3.45E-07	1.17E-06	5.21E-07	7.22E-10	1.89E-09	3.22E-08
Mineral resource scarcity	kg Cu eq	2.17E-07	4.41E-09	6.51E-08	7.11E-08	7.02E-08	2.23E-10	1.51E-10	5.53E-09
Fossil resource scarcity	kg oil eq	2.07E-05	3.45E-07	1.04E-05	5.78E-06	3.90E-06	1.35E-08	3.50E-09	2.63E-07
Water consumption	m3	8.95E-07	2.30E-08	7.36E-08	4.63E-07	1.86E-07	5.80E-10	3.45E-10	1.48E-07

Source: Oxford Economics

TABLE 61: CHARACTERISATION RESULTS FOR THE PRODUCTION PHASE OF THE DIGITAL SYSTEM IN FINLAND

Impact category	Unit	Total	Card Digital	Terminal	Smartphone	Data Centre Digital
Global warming	kg CO2 eq	1.13E-03	2.42E-04	4.24E-04	8.44E-08	4.66E-04
Stratospheric ozone depletion	kg CFC11 eq	4.83E-10	8.10E-11	1.75E-10	3.83E-14	2.27E-10
Ionizing radiation	kBq Co-60 eq	9.33E-06	2.78E-06	3.03E-06	6.83E-10	3.52E-06
Ozone formation, Human health	kg NOx eq	4.05E-06	9.32E-07	1.43E-06	1.99E-10	1.69E-06
Fine particulate matter formation	kg PM2.5 eq	2.67E-06	2.95E-07	8.98E-07	1.60E-10	1.47E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.20E-06	9.70E-07	1.48E-06	2.06E-10	1.75E-06
Terrestrial acidification	kg SO2 eq	6.27E-06	8.24E-07	1.92E-06	2.92E-10	3.52E-06
Freshwater eutrophication	kg P eq	1.75E-07	1.50E-08	6.82E-08	1.70E-11	9.13E-08
Marine eutrophication	kg N eq	4.34E-08	1.52E-08	1.68E-08	4.67E-12	1.13E-08
Terrestrial ecotoxicity	kg 1,4-DCB	2.25E-02	1.76E-03	4.66E-03	4.10E-07	1.61E-02
Freshwater ecotoxicity	kg 1,4-DCB	7.78E-06	2.91E-07	2.99E-06	2.96E-10	4.50E-06
Marine ecotoxicity	kg 1,4-DCB	4.53E-05	1.26E-06	1.59E-05	7.54E-10	2.81E-05
Human carcinogenic toxicity	kg 1,4-DCB	3.90E-05	2.44E-06	1.13E-05	1.25E-09	2.53E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	1.60E-03	1.20E-04	3.79E-04	4.27E-08	1.10E-03
Land use	m2a crop eq	1.42E-04	1.04E-04	1.65E-05	1.60E-09	2.10E-05
Mineral resource scarcity	kg Cu eq	4.04E-05	9.75E-07	1.46E-05	5.86E-10	2.48E-05
Fossil resource scarcity	kg oil eq	3.09E-04	7.75E-05	1.16E-04	2.11E-08	1.16E-04
Water consumption	m3	9.84E-06	2.08E-06	3.80E-06	4.92E-10	3.96E-06

Source: Oxford Economics

TABLE 62: CHARACTERISATION RESULTS FOR THE OPERATION PHASE OF THE DIGITAL SYSTEM IN FINLAND

Impact category	Unit	Total	Data Centre Digital	Smartphone	Terminal
Global warming	kg CO2 eq	9.76E-04	6.87E-04	6.19E-06	2.83E-04
Stratospheric ozone depletion	kg CFC11 eq	4.90E-10	3.52E-10	5.66E-12	1.32E-10
Ionizing radiation	kBq Co-60 eq	3.14E-05	2.45E-05	8.15E-07	6.05E-06
Ozone formation, Human health	kg NOx eq	1.75E-06	1.03E-06	1.17E-08	7.08E-07
Fine particulate matter formation	kg PM2.5 eq	9.91E-07	5.43E-07	9.69E-09	4.38E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.83E-06	1.08E-06	1.22E-08	7.37E-07
Terrestrial acidification	kg SO2 eq	2.57E-06	1.51E-06	2.01E-08	1.05E-06
Freshwater eutrophication	kg P eq	7.57E-08	4.76E-08	2.85E-10	2.79E-08
Marine eutrophication	kg N eq	1.24E-08	3.80E-09	5.28E-11	8.56E-09
Terrestrial ecotoxicity	kg 1,4-DCB	5.07E-03	3.96E-03	4.86E-05	1.06E-03
Freshwater ecotoxicity	kg 1,4-DCB	1.00E-06	5.76E-07	6.93E-09	4.18E-07
Marine ecotoxicity	kg 1,4-DCB	3.67E-06	2.58E-06	2.74E-08	1.06E-06
Human carcinogenic toxicity	kg 1,4-DCB	9.63E-06	6.31E-06	7.55E-08	3.24E-06
Human non-carcinogenic toxicity	kg 1,4-DCB	4.10E-04	2.92E-04	3.85E-06	1.14E-04
Land use	m2a crop eq	1.36E-04	3.15E-05	6.44E-07	1.04E-04
Mineral resource scarcity	kg Cu eq	4.02E-06	2.84E-06	3.63E-08	1.15E-06
Fossil resource scarcity	kg oil eq	2.99E-04	2.01E-04	1.51E-06	9.71E-05
Water consumption	m3	1.19E-05	6.19E-06	1.80E-07	5.58E-06

Source: Oxford Economics

TABLE 63: CHARACTERISATION RESULTS FOR THE END-OF-LIFE PHASE OF THE DIGITAL SYSTEM IN FINLAND

Impact category	Unit	Total	Card Digital	Data Centre Digital	Smartphone	Terminal
Global warming	kg CO2 eq	8.76E-05	4.37E-05	4.47E-06	3.81E-10	3.94E-05
Stratospheric ozone depletion	kg CFC11 eq	1.17E-10	2.94E-11	2.98E-12	2.68E-16	8.43E-11
Ionizing radiation	kBq Co-60 eq	2.65E-08	1.10E-08	8.29E-10	8.47E-13	1.47E-08
Ozone formation, Human health	kg NOx eq	1.05E-07	3.24E-08	2.00E-09	5.16E-13	7.10E-08
Fine particulate matter formation	kg PM2.5 eq	3.39E-08	9.25E-09	5.65E-10	3.10E-13	2.41E-08
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.07E-07	3.31E-08	2.04E-09	5.28E-13	7.23E-08
Terrestrial acidification	kg SO2 eq	6.31E-08	2.01E-08	1.67E-09	6.54E-13	4.13E-08
Freshwater eutrophication	kg P eq	2.02E-09	7.34E-10	2.05E-11	8.36E-15	1.27E-09
Marine eutrophication	kg N eq	7.97E-09	1.83E-09	1.84E-11	1.06E-14	6.12E-09
Terrestrial ecotoxicity	kg 1,4-DCB	0.000127232	4.93E-05	2.24E-06	1.52E-09	7.57E-05
Freshwater ecotoxicity	kg 1,4-DCB	4.08E-07	5.29E-08	2.25E-07	1.21E-11	1.30E-07
Marine ecotoxicity	kg 1,4-DCB	6.28E-07	1.02E-07	3.07E-07	1.71E-11	2.19E-07
Human carcinogenic toxicity	kg 1,4-DCB	1.18E-06	3.67E-07	1.78E-08	7.50E-12	7.95E-07
Human non-carcinogenic toxicity	kg 1,4-DCB	2.89E-05	7.76E-06	1.57E-06	1.55E-10	1.95E-05
Land use	m2a crop eq	4.32E-07	1.50E-07	3.52E-08	3.59E-12	2.47E-07
Mineral resource scarcity	kg Cu eq	6.69E-08	2.57E-08	2.80E-09	6.02E-13	3.84E-08
Fossil resource scarcity	kg oil eq	3.42E-06	1.22E-06	6.51E-08	3.23E-11	2.13E-06
Water consumption	m3	8.67E-07	6.90E-07	6.41E-09	2.20E-12	1.70E-07

Source: Oxford Economics

APPENDIX 3: MAIN EMITTING PROCESSES FOR IMPACT CATEGORIES

TABLE 64: MAIN EMITTING PROCESSES FOR GWP IN THE DIGITAL SYSTEM ACROSS COUNTRIES

Process	Share of total
Germany	
Transport, freight, aircraft, long haul {GLO}| transport, freight, aircraft, belly-freight, long haul | Cut-off, U	7.5%
Transport, freight, aircraft, long haul {GLO}| transport, freight, aircraft, dedicated freight, long haul | Cut-off, U	6.2%
Electricity, high voltage {DE}| electricity production, lignite | Cut-off, U	5.5%
Natural gas, vented {GLO}| natural gas venting from petroleum/natural gas production | Cut-off, U	4.0%
Electricity, high voltage {GB}| electricity production, natural gas, conventional power plant | Cut-off, U	3.5%
Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	2.4%
Waste polystyrene {RoW}| treatment of waste polystyrene, municipal incineration | Cut-off, U	2.3%
Polystyrene, general purpose {RoW}| polystyrene production, general purpose | Cut-off, U	2.2%
Electricity, high voltage {DE}| electricity production, hard coal | Cut-off, U	1.7%
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U	1.5%
Italy	
Transport, freight, aircraft, long haul {GLO}| transport, freight, aircraft, belly-freight, long haul | Cut-off, U	5.2%
Transport, freight, aircraft, long haul {GLO}| transport, freight, aircraft, dedicated freight, long haul | Cut-off, U	4.3%
Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	3.7%
Natural gas, vented {GLO}| natural gas venting from petroleum/natural gas production | Cut-off, U	3.6%
Waste paperboard {RoW}| treatment of waste paperboard, sanitary landfill | Cut-off, U	3.0%
Electricity, high voltage {DE}| electricity production, lignite | Cut-off, U	2.5%
Electricity, high voltage {GB}| electricity production, natural gas, conventional power plant | Cut-off, U	2.3%
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	1.9%
Waste graphical paper {RoW}| treatment of waste graphical paper, sanitary landfill | Cut-off, U	1.8%
Electricity, high voltage {CN-NM}| electricity production, hard coal | Cut-off, U	1.8%
Finland	
Electricity, high voltage {GB}| electricity production, natural gas, conventional power plant | Cut-off, U	6.0%
Electricity, high voltage {DE}| electricity production, lignite | Cut-off, U	6.0%
Natural gas, vented {GLO}| natural gas venting from petroleum/natural gas production | Cut-off, U	3.5%
Transport, freight, aircraft, long haul {GLO}| transport, freight, aircraft, belly-freight, long haul | Cut-off, U	3.3%
Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	2.8%
Transport, freight, aircraft, long haul {GLO}| transport, freight, aircraft, dedicated freight, long haul | Cut-off, U	2.7%
Electricity, high voltage {DE}| electricity production, hard coal | Cut-off, U	1.9%
Electricity, high voltage {NL}| electricity production, hard coal | Cut-off, U	1.9%
Electricity, high voltage {IR}| electricity production, natural gas, conventional power plant | Cut-off, U	1.5%
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	1.5%

Source: Oxford Economics

TABLE 65:MAIN EMITTING PROCESSES FOR GWP IN THE CASH SYSTEM ACROSS COUNTRIES

Process	Share of total
Germany	
Electricity, high voltage {DE}| electricity production, lignite | Cut-off, U	12.5%
Natural gas, vented {GLO}| natural gas venting from petroleum/natural gas production | Cut-off, U	4.9%
Pig iron {RoW}| pig iron production | Cut-off, U	4.0%
Electricity, high voltage {DE}| electricity production, hard coal | Cut-off, U	4.0%
Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	2.2%
Transport, passenger car, medium size, diesel, EURO 3 {RoW}| transport, passenger car, medium size, diesel, EURO 3 | Cut-off, U	2.1%
Transport, passenger car, medium size, diesel, EURO 5 {RoW}| transport, passenger car, medium size, diesel, EURO 5 | Cut-off, U	1.9%
Transport, passenger car, medium size, diesel, EURO 4 {RoW}| transport, passenger car, medium size, diesel, EURO 4 | Cut-off, U	1.7%
Electricity, high voltage {DE}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U	1.7%
Transport, passenger car, medium size, petrol, EURO 3 {RoW}| transport, passenger car, medium size, petrol, EURO 3 | Cut-off, U	1.6%
Italy	
Natural gas, vented {GLO}| natural gas venting from petroleum/natural gas production | Cut-off, U	6.8%
Pig iron {RoW}| pig iron production | Cut-off, U	3.3%
Transport, passenger car, medium size, diesel, EURO 3 {RoW}| transport, passenger car, medium size, diesel, EURO 3 | Cut-off, U	2.5%
Electricity, high voltage {IT}| electricity production, hard coal | Cut-off, U	2.2%
Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	2.2%
Electricity, high voltage {IT}| electricity production, natural gas, combined cycle power plant | Cut-off, U	2.1%
Transport, regular bus {CH}| transport, regular bus | Cut-off, U	2.1%
Electricity, high voltage {IT}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, U	2.1%
Transport, passenger car, medium size, diesel, EURO 4 {RoW}| transport, passenger car, medium size, diesel, EURO 4 | Cut-off, U	2.0%
Transport, passenger car, medium size, petrol, EURO 3 {RoW}| transport, passenger car, medium size, petrol, EURO 3 | Cut-off, U	1.9%
Finland	
Natural gas, vented {GLO}| natural gas venting from petroleum/natural gas production | Cut-off, U	7.3%
Transport, passenger car, medium size, diesel, EURO 3 {RoW}| transport, passenger car, medium size, diesel, EURO 3 | Cut-off, U	4.6%
Transport, passenger car, medium size, diesel, EURO 4 {RoW}| transport, passenger car, medium size, diesel, EURO 4 | Cut-off, U	3.7%
Transport, passenger car, medium size, petrol, EURO 3 {RoW}| transport, passenger car, medium size, petrol, EURO 3 | Cut-off, U	3.5%
Transport, regular bus {CH}| transport, regular bus | Cut-off, U	3.3%
Transport, passenger car, small size, petrol, EURO 3 {RoW}| transport, passenger car, small size, petrol, EURO 3 | Cut-off, U	3.2%
Transport, passenger car, medium size, diesel, EURO 5 {RoW}| transport, passenger car, medium size, diesel, EURO 5 | Cut-off, U	2.8%
Pig iron {RoW}| pig iron production | Cut-off, U	2.7%
Transport, passenger car, medium size, petrol, EURO 4 {RoW}| transport, passenger car, medium size, petrol, EURO 4 | Cut-off, U	2.2%
Transport, passenger car, small size, petrol, EURO 4 {RoW}| transport, passenger car, small size, petrol, EURO 4 | Cut-off, U	2.1%

Source: Oxford Economics

TABLE 66: MAIN EMITTING PROCESSES FOR MINERAL RESOURCE SCARCITY IN THE DIGITAL SYSTEM ACROSS COUNTRIES

Process	Share of total
Germany	
Gold, unrefined {RoW}| gold mine operation and gold production, unrefined | Cut-off, U	17.1%
Gold {RoW}| silver-gold mine operation with refinery | Cut-off, U	11.3%
Tantalum concentrate, 30% Ta2O5 {RoW}| tantalum mine operation and beneficiation | Cut-off, U	4.8%
Tantalum concentrate, 30% Ta2O5 {CD}| tantalum mine operation and beneficiation | Cut-off, U	4.7%
Copper concentrate, sulfide ore {RoW}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	4.0%
Copper concentrate, sulfide ore {GLO}| molybdenite mine operation | Cut-off, U	3.9%
Silver {RoW}| silver-gold mine operation with refinery | Cut-off, U	3.5%
Cobalt hydroxide {GLO}| cobalt production | Cut-off, U	3.4%
Copper, cathode {GLO}| copper production, cathode, solvent extraction and electrowinning process | Cut-off, U	3.4%
Gold {AU}| gold production | Cut-off, U	3.1%
Italy	
Gold, unrefined {RoW}| gold mine operation and gold production, unrefined | Cut-off, U	19.6%
Gold {RoW}| silver-gold mine operation with refinery | Cut-off, U	13.0%
Cobalt hydroxide {GLO}| cobalt production | Cut-off, U	5.8%
Tantalum concentrate, 30% Ta2O5 {RoW}| tantalum mine operation and beneficiation | Cut-off, U	5.4%
Tantalum concentrate, 30% Ta2O5 {CD}| tantalum mine operation and beneficiation | Cut-off, U	5.3%
Silver {RoW}| silver-gold mine operation with refinery | Cut-off, U	3.8%
Gold {AU}| gold production | Cut-off, U	3.5%
Gold {RoW}| gold-silver mine operation with refinery | Cut-off, U	3.5%
Tin concentrate {RoW}| tin mine operation | Cut-off, U	3.3%
Gold {US}| gold production | Cut-off, U	2.8%
Finland	
Gold, unrefined {RoW}| gold mine operation and gold production, unrefined | Cut-off, U	17.1%
Gold {RoW}| silver-gold mine operation with refinery | Cut-off, U	11.3%
Tantalum concentrate, 30% Ta2O5 {RoW}| tantalum mine operation and beneficiation | Cut-off, U	4.9%
Tantalum concentrate, 30% Ta2O5 {CD}| tantalum mine operation and beneficiation | Cut-off, U	4.8%
Copper concentrate, sulfide ore {RoW}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	4.3%
Copper concentrate, sulfide ore {GLO}| molybdenite mine operation | Cut-off, U	4.1%
Silver {RoW}| silver-gold mine operation with refinery | Cut-off, U	3.6%
Copper, cathode {GLO}| copper production, cathode, solvent extraction and electrowinning process | Cut-off, U	3.6%
Copper concentrate, sulfide ore {CL}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	3.2%
Gold {AU}| gold production | Cut-off, U	3.1%

Source: Oxford Economics

TABLE 67: MAIN EMITTING PROCESSES FOR MINERAL RESOURCE SCARCITY IN THE CASH SYSTEM ACROSS COUNTRIES

Process	Share of total
Germany	
Iron ore, crude ore, 46% Fe {GLO}| iron ore mine operation, 46% Fe | Cut-off, U	18.9%
Ferronickel {GLO}| ferronickel production | Cut-off, U	11.4%
Copper concentrate, sulfide ore {RoW}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	7.7%
Copper concentrate, sulfide ore {GLO}| molybdenite mine operation | Cut-off, U	7.4%
Copper, cathode {GLO}| copper production, cathode, solvent extraction and electrowinning process | Cut-off, U	6.6%
Copper concentrate, sulfide ore {CL}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	5.8%
Copper concentrate, sulfide ore {CN}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	4.8%
Nickel, class 1 {GLO}| cobalt production | Cut-off, U	4.1%
Iron ore, crude ore, 63% Fe {IN}| iron ore mine operation, 63% Fe | Cut-off, U	3.0%
Copper concentrate, sulfide ore {US}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	2.0%
Italy	
Iron ore, crude ore, 46% Fe {GLO}| iron ore mine operation, 46% Fe | Cut-off, U	13.0%
Copper concentrate, sulfide ore {RoW}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	9.4%
Ferronickel {GLO}| ferronickel production | Cut-off, U	9.1%
Copper concentrate, sulfide ore {GLO}| molybdenite mine operation | Cut-off, U	9.0%
Copper, cathode {GLO}| copper production, cathode, solvent extraction and electrowinning process | Cut-off, U	8.1%
Copper concentrate, sulfide ore {CL}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	7.1%
Copper concentrate, sulfide ore {CN}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	5.9%
Nickel, class 1 {GLO}| cobalt production | Cut-off, U	5.3%
Nickel concentrate, 16% Ni {CA-QC}| nickel mine operation and benefication to nickel concentrate, 16% Ni | Cut-off, U	2.4%
Copper concentrate, sulfide ore {US}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	2.4%
Finland	
Iron ore, crude ore, 46% Fe {GLO}| iron ore mine operation, 46% Fe | Cut-off, U	22.99%
Ferronickel {GLO}| ferronickel production | Cut-off, U	13.94%
Copper concentrate, sulfide ore {RoW}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	5.36%
Copper concentrate, sulfide ore {GLO}| molybdenite mine operation | Cut-off, U	5.17%
Copper, cathode {GLO}| copper production, cathode, solvent extraction and electrowinning process | Cut-off, U	4.61%
Copper concentrate, sulfide ore {CL}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	4.06%
Bauxite {GLO}| bauxite mine operation | Cut-off, U	3.76%
Iron ore, crude ore, 63% Fe {IN}| iron ore mine operation, 63% Fe | Cut-off, U	3.62%
Platinum group metal concentrate {ZA}| platinum group metal, mine and concentration operations | Cut-off, U	3.48%
Copper concentrate, sulfide ore {CN}| copper mine operation and beneficiation, sulfide ore | Cut-off, U	3.36%

Source: Oxford Economics

TABLE 68: MAIN EMITTING PROCESSES FOR IONIZING RADIATION IN THE DIGITAL SYSTEM ACROSS COUNTRIES

Process	Share of total
Germany	
Spent nuclear fuel {RoW}| treatment of spent nuclear fuel, reprocessing | Cut-off, U	23.3%
Electricity, high voltage {GB}| electricity production, nuclear, boiling water reactor | Cut-off, U	15.1%
Uranium ore, as U {RNA}| uranium mine operation, underground | Cut-off, U	14.6%
Uranium ore, as U {RoW}| uranium mine operation, underground | Cut-off, U	13.8%
Low level radioactive waste {CH}| treatment of low level radioactive waste, plasma torch incineration | Cut-off, U	9.6%
Uranium, in yellowcake {RoW}| uranium production, in yellowcake | Cut-off, U	3.7%
Electricity, high voltage {SE}| electricity production, nuclear, boiling water reactor | Cut-off, U	2.5%
Uranium, in yellowcake {RNA}| uranium production, in yellowcake | Cut-off, U	1.6%
Electricity, high voltage {DE}| electricity production, nuclear, boiling water reactor | Cut-off, U	1.4%
Electricity, high voltage {CH}| electricity production, nuclear, boiling water reactor | Cut-off, U	1.1%
Italy	
Spent nuclear fuel {RoW}| treatment of spent nuclear fuel, reprocessing | Cut-off, U	24.7%
Uranium ore, as U {RNA}| uranium mine operation, underground | Cut-off, U	13.8%
Uranium ore, as U {RoW}| uranium mine operation, underground | Cut-off, U	13.1%
Electricity, high voltage {GB}| electricity production, nuclear, boiling water reactor | Cut-off, U	12.1%
Low level radioactive waste {CH}| treatment of low level radioactive waste, plasma torch incineration | Cut-off, U	9.1%
Uranium, in yellowcake {RoW}| uranium production, in yellowcake | Cut-off, U	3.6%
Electricity, high voltage {SE}| electricity production, nuclear, boiling water reactor | Cut-off, U	2.1%
Electricity, high voltage {SERC}| electricity production, nuclear, boiling water reactor | Cut-off, U	1.6%
Uranium, in yellowcake {RNA}| uranium production, in yellowcake | Cut-off, U	1.5%
Electricity, high voltage {RFC}| electricity production, nuclear, boiling water reactor | Cut-off, U	1.4%
Finland	
Spent nuclear fuel {RoW}| treatment of spent nuclear fuel, reprocessing | Cut-off, U	21.7%
Electricity, high voltage {GB}| electricity production, nuclear, boiling water reactor | Cut-off, U	17.6%
Uranium ore, as U {RNA}| uranium mine operation, underground | Cut-off, U	14.0%
Uranium ore, as U {RoW}| uranium mine operation, underground | Cut-off, U	13.3%
Low level radioactive waste {CH}| treatment of low level radioactive waste, plasma torch incineration | Cut-off, U	9.4%
Uranium, in yellowcake {RoW}| uranium production, in yellowcake | Cut-off, U	3.6%
Electricity, high voltage {FI}| electricity production, nuclear, boiling water reactor | Cut-off, U	3.1%
Electricity, high voltage {SE}| electricity production, nuclear, boiling water reactor | Cut-off, U	2.6%
Uranium, in yellowcake {RNA}| uranium production, in yellowcake | Cut-off, U	1.6%
Electricity, high voltage {CH}| electricity production, nuclear, boiling water reactor | Cut-off, U	1.1%

Source: Oxford Economics

TABLE 69: MAIN EMITTING PROCESSES FOR IONIZING RADIATION IN THE CASH SYSTEM ACROSS COUNTRIES

Process	Share of total
Germany	
Spent nuclear fuel {RoW}| treatment of spent nuclear fuel, reprocessing | Cut-off, U	27.4%
Uranium ore, as U {RNA}| uranium mine operation, underground | Cut-off, U	16.5%
Uranium ore, as U {RoW}| uranium mine operation, underground | Cut-off, U	15.6%
Low level radioactive waste {CH}| treatment of low level radioactive waste, plasma torch incineration | Cut-off, U	10.7%
Electricity, high voltage {DE}| electricity production, nuclear, boiling water reactor | Cut-off, U	6.3%
Uranium, in yellowcake {RoW}| uranium production, in yellowcake | Cut-off, U	4.2%
Electricity, high voltage {SE}| electricity production, nuclear, boiling water reactor | Cut-off, U	2.2%
Electricity, high voltage {GB}| electricity production, nuclear, boiling water reactor | Cut-off, U	1.9%
Uranium, in yellowcake {RNA}| uranium production, in yellowcake | Cut-off, U	1.8%
Electricity, high voltage {CH}| electricity production, nuclear, boiling water reactor | Cut-off, U	1.1%
Italy	
Spent nuclear fuel {RoW}| treatment of spent nuclear fuel, reprocessing | Cut-off, U	27.7%
Uranium ore, as U {RNA}| uranium mine operation, underground | Cut-off, U	14.6%
Uranium ore, as U {RoW}| uranium mine operation, underground | Cut-off, U	13.8%
Low level radioactive waste {CH}| treatment of low level radioactive waste, plasma torch incineration | Cut-off, U	9.3%
Electricity, high voltage {CH}| electricity production, nuclear, boiling water reactor | Cut-off, U	4.7%
Uranium, in yellowcake {RoW}| uranium production, in yellowcake | Cut-off, U	3.7%
Electricity, high voltage {GB}| electricity production, nuclear, boiling water reactor | Cut-off, U	2.8%
Electricity, high voltage {SE}| electricity production, nuclear, boiling water reactor | Cut-off, U	2.6%
Uranium, in yellowcake {RNA}| uranium production, in yellowcake | Cut-off, U	1.6%
Electricity, high voltage {SERC}| electricity production, nuclear, boiling water reactor | Cut-off, U	1.3%
Finland	
Electricity, high voltage {FI}| electricity production, nuclear, boiling water reactor | Cut-off, U	26.2%
Spent nuclear fuel {RoW}| treatment of spent nuclear fuel, reprocessing | Cut-off, U	17.0%
Uranium ore, as U {RNA}| uranium mine operation, underground | Cut-off, U	11.0%
Uranium ore, as U {RoW}| uranium mine operation, underground | Cut-off, U	10.4%
Electricity, high voltage {SE}| electricity production, nuclear, boiling water reactor | Cut-off, U	8.9%
Low level radioactive waste {CH}| treatment of low level radioactive waste, plasma torch incineration | Cut-off, U	8.1%
Uranium, in yellowcake {RoW}| uranium production, in yellowcake | Cut-off, U	2.8%
Electricity, high voltage {FI}| electricity production, nuclear, pressure water reactor | Cut-off, U	2.7%
Electricity, high voltage {RU}| electricity production, nuclear, boiling water reactor | Cut-off, U	1.8%
Uranium, in yellowcake {RNA}| uranium production, in yellowcake | Cut-off, U	1.2%

Source: Oxford Economics

APPENDIX 4: DETAILED CHARACTERISATION RESULTS FOR EACH SENSITIVITY ANALYSIS

TABLE 70: NO WAY TO ATM/CRM (IMPACT ON CASH PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg $C0_2$ eq	3.06E-03	5.39E-03	2.20E-03	1.16E-02	6.61E-03	1.16E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.42E-09	2.22E-09	1.09E-09	6.02E-09	3.75E-09	6.13E-09
Ionizing radiation	kBq Co-60 eq	3.85E-05	5.50E-05	4.07E-05	1.04E-04	4.07E-05	3.07E-04
Ozone formation, Human health	kg NO_x eq	8.96E-06	1.59E-05	5.91E-06	2.88E-05	2.20E-05	3.78E-05
Fine particulate matter formation	kg PM2.5 eq	4.66E-06	9.57E-06	3.69E-06	2.60E-05	2.10E-05	3.00E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.29E-06	1.65E-05	6.13E-06	3.02E-05	2.31E-05	3.98E-05
Terrestrial acidification	kg SO2 eq	1.14E-05	2.16E-05	8.90E-06	7.04E-05	5.94E-05	7.59E-05
Freshwater eutrophication	kg P eq	3.21E-07	6.84E-07	2.52E-07	1.58E-06	7.07E-07	1.06E-06
Marine eutrophication	kg N eq	1.08E-07	2.70E-07	6.37E-08	1.37E-06	1.24E-06	1.36E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.05E-02	5.66E-02	2.77E-02	3.55E-01	3.33E-01	3.75E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.08E-05	2.81E-05	9.19E-06	4.12E-05	2.96E-05	5.41E-05
Marine ecotoxicity	kg 1,4-DCB	5.55E-05	1.47E-04	4.96E-05	2.18E-04	1.87E-04	2.47E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.76E-05	1.21E-04	4.98E-05	7.85E-04	4.78E-04	8.97E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	2.30E-03	4.39E-03	2.04E-03	2.07E-02	1.86E-02	2.09E-02
Land use	m2a crop eq	5.69E-04	5.11E-04	2.78E-04	9.26E-04	7.67E-04	1.08E-03
Mineral resource scarcity	kg Cu eq	4.93E-05	1.33E-04	4.45E-05	3.08E-04	2.38E-04	3.31E-04
Fossil resource scarcity	kg oil eq	8.57E-04	1.42E-03	6.12E-04	2.91E-03	1.79E-03	3.02E-03
Water consumption	m3	3.07E-05	4.88E-05	2.27E-05	1.68E-04	1.51E-04	2.00E-04

Source: Oxford Economics

TABLE 71: NEWER POS TERMINAL MODEL (IMPACT ON DIGITAL PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg CO_2 eq	2.93E-03	4.83E-03	2.12E-03	1.81E-02	1.15E-02	5.18E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.34E-09	1.85E-09	1.04E-09	8.04E-09	5.27E-09	1.87E-08
Ionizing radiation	kBq Co-60 eq	3.63E-05	4.51E-05	3.94E-05	1.13E-04	4.79E-05	3.65E-04
Ozone formation, Human health	kg NO_x eq	8.63E-06	1.44E-05	5.70E-06	4.69E-05	3.64E-05	1.51E-04
Fine particulate matter formation	kg PM2.5 eq	4.48E-06	8.75E-06	3.58E-06	3.25E-05	2.59E-05	7.05E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	8.97E-06	1.51E-05	5.92E-06	4.96E-05	3.87E-05	1.61E-04
Terrestrial acidification	kg SO2 eq	1.15E-05	2.20E-05	8.96E-06	8.52E-05	7.06E-05	1.68E-04
Freshwater eutrophication	kg P eq	2.78E-07	4.88E-07	2.25E-07	1.71E-06	8.02E-07	1.85E-06
Marine eutrophication	kg N eq	1.12E-07	2.87E-07	6.61E-08	1.49E-06	1.33E-06	2.11E-06
Terrestrial ecotoxicity	kg 1,4-DCB	2.88E-02	4.90E-02	2.66E-02	3.87E-01	3.56E-01	5.73E-01
Freshwater ecotoxicity	kg 1,4-DCB	8.28E-06	1.67E-05	7.61E-06	5.86E-05	4.27E-05	1.63E-04
Marine ecotoxicity	kg 1,4-DCB	4.48E-05	9.91E-05	4.29E-05	2.62E-04	2.20E-04	5.20E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.80E-05	1.23E-04	5.00E-05	9.21E-04	5.77E-04	1.74E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.11E-03	3.53E-03	1.92E-03	2.22E-02	1.97E-02	3.04E-02
Land use	m2a crop eq	5.63E-04	4.84E-04	2.74E-04	1.08E-03	8.86E-04	2.06E-03
Mineral resource scarcity	kg Cu eq	4.43E-05	1.10E-04	4.13E-05	3.42E-04	2.62E-04	5.42E-04
Fossil resource scarcity	kg oil eq	8.27E-04	1.28E-03	5.92E-04	4.79E-03	3.22E-03	1.47E-02
Water consumption	m3	2.94E-05	4.29E-05	2.18E-05	1.86E-04	1.64E-04	3.08E-04

Source: Oxford Economics

TABLE 72: NO REFURBISHMENT OF TERMINALS (IMPACT ON DIGITAL PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg $C0_2$ eq	3.14E-03	5.47E-03	2.26E-03	1.81E-02	1.15E-02	5.18E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.46E-09	2.25E-09	1.12E-09	8.04E-09	5.27E-09	1.87E-08
Ionizing radiation	kBq Co-60 eq	3.90E-05	5.55E-05	4.12E-05	1.13E-04	4.79E-05	3.65E-04
Ozone formation, Human health	kg NO_x eq	9.21E-06	1.62E-05	6.11E-06	4.69E-05	3.64E-05	1.51E-04
Fine particulate matter formation	kg PM2.5 eq	4.82E-06	9.72E-06	3.82E-06	3.25E-05	2.59E-05	7.05E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.56E-06	1.68E-05	6.33E-06	4.96E-05	3.87E-05	1.61E-04
Terrestrial acidification	kg SO2 eq	1.17E-05	2.19E-05	9.17E-06	8.52E-05	7.06E-05	1.68E-04
Freshwater eutrophication	kg P eq	3.34E-07	6.96E-07	2.62E-07	1.71E-06	8.02E-07	1.85E-06
Marine eutrophication	kg N eq	1.12E-07	2.73E-07	6.63E-08	1.49E-06	1.33E-06	2.11E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.13E-02	5.74E-02	2.83E-02	3.87E-01	3.56E-01	5.73E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.13E-05	2.87E-05	9.62E-06	5.86E-05	4.27E-05	1.63E-04
Marine ecotoxicity	kg 1,4-DCB	5.84E-05	1.50E-04	5.18E-05	2.62E-04	2.20E-04	5.20E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.97E-05	1.23E-04	5.14E-05	9.21E-04	5.77E-04	1.74E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.37E-03	4.45E-03	2.09E-03	2.22E-02	1.97E-02	3.04E-02
Land use	m2a crop eq	5.72E-04	5.14E-04	2.80E-04	1.08E-03	8.86E-04	2.06E-03
Mineral resource scarcity	kg Cu eq	5.20E-05	1.36E-04	4.65E-05	3.42E-04	2.62E-04	5.42E-04
Fossil resource scarcity	kg oil eq	8.78E-04	1.44E-03	6.28E-04	4.79E-03	3.22E-03	1.47E-02
Water consumption	m3	3.14E-05	4.95E-05	2.32E-05	1.86E-04	1.64E-04	3.08E-04

Source: Oxford Economics

TABLE 73: WORST EOL FOR REFURBISHED TERMINALS (IMPACT ON DIGITAL PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg $C0_2$ eq	3.15E-03	5.66E-03	2.39E-03	1.81E-02	1.15E-02	5.18E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.50E-09	2.34E-09	1.24E-09	8.04E-09	5.27E-09	1.87E-08
Ionizing radiation	kBq Co-60 eq	3.98E-05	5.77E-05	4.35E-05	1.13E-04	4.79E-05	3.65E-04
Ozone formation, Human health	kg NO_x eq	9.22E-06	1.65E-05	6.44E-06	4.69E-05	3.64E-05	1.51E-04
Fine particulate matter formation	kg PM2.5 eq	4.80E-06	9.85E-06	3.97E-06	3.25E-05	2.59E-05	7.05E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.57E-06	1.71E-05	6.68E-06	4.96E-05	3.87E-05	1.61E-04
Terrestrial acidification	kg SO2 eq	1.17E-05	2.22E-05	9.56E-06	8.52E-05	7.06E-05	1.68E-04
Freshwater eutrophication	kg P eq	3.30E-07	7.03E-07	2.70E-07	1.71E-06	8.02E-07	1.85E-06
Marine eutrophication	kg N eq	1.12E-07	3.12E-07	7.45E-08	1.49E-06	1.33E-06	2.11E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.07E-02	5.71E-02	2.82E-02	3.87E-01	3.56E-01	5.73E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.09E-05	2.84E-05	9.48E-06	5.86E-05	4.27E-05	1.63E-04
Marine ecotoxicity	kg 1,4-DCB	5.57E-05	1.48E-04	5.01E-05	2.62E-04	2.20E-04	5.20E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.88E-05	1.23E-04	5.23E-05	9.21E-04	5.77E-04	1.74E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.34E-03	4.46E-03	2.12E-03	2.22E-02	1.97E-02	3.04E-02
Land use	m2a crop eq	6.12E-04	5.98E-04	3.64E-04	1.08E-03	8.86E-04	2.06E-03
Mineral resource scarcity	kg Cu eq	4.96E-05	1.34E-04	4.51E-05	3.42E-04	2.62E-04	5.42E-04
Fossil resource scarcity	kg oil eq	8.91E-04	1.49E-03	6.78E-04	4.79E-03	3.22E-03	1.47E-02
Water consumption	m3	3.25E-05	5.25E-05	2.63E-05	1.86E-04	1.64E-04	3.08E-04

Source: Oxford Economics

TABLE 74: PRINTING OF TWO PAPER RECEIPTS (IMPACT ON DIGITAL PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg CO_2 eq	3.15E-03	5.66E-03	2.39E-03	1.81E-02	1.15E-02	5.18E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.50E-09	2.34E-09	1.24E-09	8.04E-09	5.27E-09	1.87E-08
Ionizing radiation	kBq Co-60 eq	3.98E-05	5.77E-05	4.35E-05	1.13E-04	4.79E-05	3.65E-04
Ozone formation, Human health	kg NO_x eq	9.22E-06	1.65E-05	6.44E-06	4.69E-05	3.64E-05	1.51E-04
Fine particulate matter formation	kg PM2.5 eq	4.80E-06	9.85E-06	3.97E-06	3.25E-05	2.59E-05	7.05E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.57E-06	1.71E-05	6.68E-06	4.96E-05	3.87E-05	1.61E-04
Terrestrial acidification	kg SO2 eq	1.17E-05	2.22E-05	9.56E-06	8.52E-05	7.06E-05	1.68E-04
Freshwater eutrophication	kg P eq	3.30E-07	7.03E-07	2.70E-07	1.71E-06	8.02E-07	1.85E-06
Marine eutrophication	kg N eq	1.12E-07	3.12E-07	7.45E-08	1.49E-06	1.33E-06	2.11E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.07E-02	5.71E-02	2.82E-02	3.87E-01	3.56E-01	5.73E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.09E-05	2.84E-05	9.48E-06	5.86E-05	4.27E-05	1.63E-04
Marine ecotoxicity	kg 1,4-DCB	5.57E-05	1.48E-04	5.01E-05	2.62E-04	2.20E-04	5.20E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.88E-05	1.23E-04	5.23E-05	9.21E-04	5.77E-04	1.74E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.34E-03	4.46E-03	2.12E-03	2.22E-02	1.97E-02	3.04E-02
Land use	m2a crop eq	6.12E-04	5.98E-04	3.64E-04	1.08E-03	8.86E-04	2.06E-03
Mineral resource scarcity	kg Cu eq	4.96E-05	1.34E-04	4.51E-05	3.42E-04	2.62E-04	5.42E-04
Fossil resource scarcity	kg oil eq	8.91E-04	1.49E-03	6.78E-04	4.79E-03	3.22E-03	1.47E-02
Water consumption	m3	3.25E-05	5.25E-05	2.63E-05	1.86E-04	1.64E-04	3.08E-04

Source: Oxford Economics

TABLE 75: HIGHER ENERGY USE OF DIGITAL DATA CENTRES (IMPACT ON DIGITAL PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg $C0_2$ eq	3.61E-03	5.94E-03	2.75E-03	1.81E-02	1.15E-02	5.18E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.70E-09	2.50E-09	1.37E-09	8.04E-09	5.27E-09	1.87E-08
Ionizing radiation	kBq Co-60 eq	5.13E-05	6.78E-05	5.36E-05	1.13E-04	4.79E-05	3.65E-04
Ozone formation, Human health	kg NO_x eq	1.03E-05	1.73E-05	7.23E-06	4.69E-05	3.64E-05	1.51E-04
Fine particulate matter formation	kg PM2.5 eq	5.63E-06	1.05E-05	4.66E-06	3.25E-05	2.59E-05	7.05E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	1.07E-05	1.79E-05	7.49E-06	4.96E-05	3.87E-05	1.61E-04
Terrestrial acidification	kg SO2 eq	1.38E-05	2.40E-05	1.13E-05	8.52E-05	7.06E-05	1.68E-04
Freshwater eutrophication	kg P eq	3.88E-07	7.51E-07	3.19E-07	1.71E-06	8.02E-07	1.85E-06
Marine eutrophication	kg N eq	1.16E-07	2.78E-07	7.12E-08	1.49E-06	1.33E-06	2.11E-06
Terrestrial ecotoxicity	kg 1,4-DCB	4.04E-02	6.66E-02	3.76E-02	3.87E-01	3.56E-01	5.73E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.34E-05	3.08E-05	1.18E-05	5.86E-05	4.27E-05	1.63E-04
Marine ecotoxicity	kg 1,4-DCB	7.10E-05	1.63E-04	6.51E-05	2.62E-04	2.20E-04	5.20E-04
Human carcinogenic toxicity	kg 1,4-DCB	7.32E-05	1.37E-04	6.54E-05	9.21E-04	5.77E-04	1.74E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.99E-03	5.08E-03	2.73E-03	2.22E-02	1.97E-02	3.04E-02
Land use	m2a crop eq	5.94E-04	5.37E-04	3.03E-04	1.08E-03	8.86E-04	2.06E-03
Mineral resource scarcity	kg Cu eq	6.32E-05	1.47E-04	5.83E-05	3.42E-04	2.62E-04	5.42E-04
Fossil resource scarcity	kg oil eq	1.01E-03	1.57E-03	7.63E-04	4.79E-03	3.22E-03	1.47E-02
Water consumption	m3	3.52E-05	5.33E-05	2.72E-05	1.86E-04	1.64E-04	3.08E-04

Source: Oxford Economics

TABLE 76: HIGHER ENERGY USE FOR CASH DATA CENTRES (IMPACT ON CASH PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg $C0_2$ eq	3.01E-03	5.39E-03	2.09E-03	2.04E-02	1.15E-02	8.44E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.40E-09	2.22E-09	1.05E-09	8.73E-09	5.28E-09	2.91E-08
Ionizing radiation	kBq Co-60 eq	3.63E-05	5.50E-05	3.81E-05	1.15E-04	4.81E-05	4.03E-04
Ozone formation, Human health	kg NO_x eq	8.92E-06	1.59E-05	5.73E-06	5.36E-05	3.65E-05	2.33E-04
Fine particulate matter formation	kg PM2.5 eq	4.58E-06	9.57E-06	3.53E-06	3.41E-05	2.59E-05	1.00E-04
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.26E-06	1.65E-05	5.95E-06	5.67E-05	3.87E-05	2.49E-04
Terrestrial acidification	kg SO2 eq	1.11E-05	2.16E-05	8.47E-06	8.84E-05	7.07E-05	2.35E-04
Freshwater eutrophication	kg P eq	3.11E-07	6.84E-07	2.39E-07	1.71E-06	8.03E-07	2.45E-06
Marine eutrophication	kg N eq	1.09E-07	2.70E-07	6.33E-08	1.54E-06	1.33E-06	2.73E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.02E-02	5.66E-02	2.73E-02	3.94E-01	3.57E-01	7.47E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.08E-05	2.81E-05	9.10E-06	6.41E-05	4.28E-05	2.48E-04
Marine ecotoxicity	kg 1,4-DCB	5.52E-05	1.47E-04	4.91E-05	2.76E-04	2.20E-04	7.47E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.72E-05	1.21E-04	4.89E-05	9.47E-04	5.77E-04	2.33E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.27E-03	4.39E-03	2.00E-03	2.22E-02	1.97E-02	3.75E-02
Land use	m2a crop eq	5.69E-04	5.11E-04	2.75E-04	1.13E-03	8.86E-04	2.82E-03
Mineral resource scarcity	kg Cu eq	4.91E-05	1.33E-04	4.41E-05	3.44E-04	2.63E-04	6.90E-04
Fossil resource scarcity	kg oil eq	8.48E-04	1.42E-03	5.84E-04	5.50E-03	3.22E-03	2.43E-02
Water consumption	m3	3.09E-05	4.88E-05	2.24E-05	1.91E-04	1.64E-04	3.89E-04

Source: Oxford Economics

TABLE 77: LOWER ENERGY USE OF DIGITAL DATA CENTRES (IMPACT ON DIGITAL PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg $C0_2$ eq	3.05E-03	5.28E-03	1.93E-03	1.81E-02	1.15E-02	5.18E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.42E-09	2.17E-09	9.56E-10	8.04E-09	5.27E-09	1.87E-08
Ionizing radiation	kBq Co-60 eq	3.84E-05	5.24E-05	3.46E-05	1.13E-04	4.79E-05	3.65E-04
Ozone formation, Human health	kg NO_x eq	8.95E-06	1.57E-05	5.28E-06	4.69E-05	3.64E-05	1.51E-04
Fine particulate matter formation	kg PM2.5 eq	4.66E-06	9.37E-06	3.22E-06	3.25E-05	2.59E-05	7.05E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.29E-06	1.63E-05	5.47E-06	4.96E-05	3.87E-05	1.61E-04
Terrestrial acidification	kg SO2 eq	1.14E-05	2.11E-05	7.75E-06	8.52E-05	7.06E-05	1.68E-04
Freshwater eutrophication	kg P eq	3.21E-07	6.71E-07	2.20E-07	1.71E-06	8.02E-07	1.85E-06
Marine eutrophication	kg N eq	1.08E-07	2.69E-07	6.02E-08	1.49E-06	1.33E-06	2.11E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.04E-02	5.46E-02	2.29E-02	3.87E-01	3.56E-01	5.73E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.08E-05	2.76E-05	7.92E-06	5.86E-05	4.27E-05	1.63E-04
Marine ecotoxicity	kg 1,4-DCB	5.54E-05	1.44E-04	4.21E-05	2.62E-04	2.20E-04	5.20E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.75E-05	1.18E-04	4.22E-05	9.21E-04	5.77E-04	1.74E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.30E-03	4.25E-03	1.71E-03	2.22E-02	1.97E-02	3.04E-02
Land use	m2a crop eq	5.68E-04	5.06E-04	2.66E-04	1.08E-03	8.86E-04	2.06E-03
Mineral resource scarcity	kg Cu eq	4.93E-05	1.30E-04	3.78E-05	3.42E-04	2.62E-04	5.42E-04
Fossil resource scarcity	kg oil eq	8.57E-04	1.39E-03	5.39E-04	4.79E-03	3.22E-03	1.47E-02
Water consumption	m3	3.07E-05	4.79E-05	2.05E-05	1.86E-04	1.64E-04	3.08E-04

Source: Oxford Economics

TABLE 78: DATA CENTRES LOCAL GRID (DIGITAL ONLY) (IMPACT ON DIGITAL PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg $C0_2$ eq	3.14E-03	5.42E-03	2.05E-03	1.81E-02	1.15E-02	5.18E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.47E-09	2.22E-09	1.12E-09	8.04E-09	5.27E-09	1.87E-08
Ionizing radiation	kBq Co-60 eq	3.06E-05	4.35E-05	6.12E-05	1.13E-04	4.79E-05	3.65E-04
Ozone formation, Human health	kg NO_x eq	8.93E-06	1.61E-05	5.81E-06	4.69E-05	3.64E-05	1.51E-04
Fine particulate matter formation	kg PM2.5 eq	4.71E-06	9.71E-06	3.82E-06	3.25E-05	2.59E-05	7.05E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.26E-06	1.67E-05	6.03E-06	4.96E-05	3.87E-05	1.61E-04
Terrestrial acidification	kg SO2 eq	1.15E-05	2.20E-05	8.95E-06	8.52E-05	7.06E-05	1.68E-04
Freshwater eutrophication	kg P eq	3.69E-07	6.67E-07	2.38E-07	1.71E-06	8.02E-07	1.85E-06
Marine eutrophication	kg N eq	1.08E-07	2.70E-07	6.38E-08	1.49E-06	1.33E-06	2.11E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.07E-02	5.67E-02	2.74E-02	3.87E-01	3.56E-01	5.73E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.08E-05	2.81E-05	9.17E-06	5.86E-05	4.27E-05	1.63E-04
Marine ecotoxicity	kg 1,4-DCB	5.56E-05	1.47E-04	4.93E-05	2.62E-04	2.20E-04	5.20E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.85E-05	1.21E-04	4.93E-05	9.21E-04	5.77E-04	1.74E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.32E-03	4.37E-03	2.03E-03	2.22E-02	1.97E-02	3.04E-02
Land use	m2a crop eq	5.60E-04	5.04E-04	2.86E-04	1.08E-03	8.86E-04	2.06E-03
Mineral resource scarcity	kg Cu eq	4.94E-05	1.33E-04	4.44E-05	3.42E-04	2.62E-04	5.42E-04
Fossil resource scarcity	kg oil eq	8.58E-04	1.43E-03	5.54E-04	4.79E-03	3.22E-03	1.47E-02
Water consumption	m3	3.10E-05	5.29E-05	2.71E-05	1.86E-04	1.64E-04	3.08E-04

Source: Oxford Economics

TABLE 79: DATA CENTRES LOCAL GRID (CASH AND DIGITAL) (IMPACT ON CASH AND DIGITAL PAYMENT SYSTEMS)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg $C0_2$ eq	3.14E-03	5.42E-03	2.05E-03	1.81E-02	1.15E-02	5.18E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.47E-09	2.22E-09	1.12E-09	8.04E-09	5.27E-09	1.87E-08
Ionizing radiation	kBq Co-60 eq	3.06E-05	4.35E-05	6.12E-05	1.13E-04	4.76E-05	3.67E-04
Ozone formation, Human health	kg NO_x eq	8.93E-06	1.61E-05	5.81E-06	4.69E-05	3.64E-05	1.51E-04
Fine particulate matter formation	kg PM2.5 eq	4.71E-06	9.71E-06	3.82E-06	3.25E-05	2.59E-05	7.05E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.26E-06	1.67E-05	6.03E-06	4.96E-05	3.87E-05	1.61E-04
Terrestrial acidification	kg SO2 eq	1.15E-05	2.20E-05	8.95E-06	8.52E-05	7.06E-05	1.68E-04
Freshwater eutrophication	kg P eq	3.69E-07	6.67E-07	2.38E-07	1.71E-06	8.01E-07	1.85E-06
Marine eutrophication	kg N eq	1.08E-07	2.70E-07	6.38E-08	1.49E-06	1.33E-06	2.11E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.07E-02	5.67E-02	2.74E-02	3.87E-01	3.56E-01	5.73E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.08E-05	2.81E-05	9.17E-06	5.86E-05	4.27E-05	1.63E-04
Marine ecotoxicity	kg 1,4-DCB	5.56E-05	1.47E-04	4.93E-05	2.62E-04	2.20E-04	5.20E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.85E-05	1.21E-04	4.93E-05	9.21E-04	5.77E-04	1.74E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.32E-03	4.37E-03	2.03E-03	2.22E-02	1.97E-02	3.04E-02
Land use	m2a crop eq	5.60E-04	5.04E-04	2.86E-04	1.08E-03	8.86E-04	2.06E-03
Mineral resource scarcity	kg Cu eq	4.94E-05	1.33E-04	4.44E-05	3.42E-04	2.62E-04	5.42E-04
Fossil resource scarcity	kg oil eq	8.58E-04	1.43E-03	5.54E-04	4.79E-03	3.22E-03	1.47E-02
Water consumption	m3	3.10E-05	5.29E-05	2.71E-05	1.86E-04	1.64E-04	3.08E-04

Source: Oxford Economics

TABLE 80: MORE SMALL CCMS (IMPACT ON CASH PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg $C0_2$ eq	3.06E-03	5.39E-03	2.20E-03	1.85E-02	1.16E-02	5.21E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.42E-09	2.22E-09	1.09E-09	8.22E-09	5.31E-09	1.88E-08
Ionizing radiation	kBq Co-60 eq	3.85E-05	5.50E-05	4.07E-05	1.16E-04	4.85E-05	3.67E-04
Ozone formation, Human health	kg NO_x eq	8.96E-06	1.59E-05	5.91E-06	4.82E-05	3.67E-05	1.52E-04
Fine particulate matter formation	kg PM2.5 eq	4.66E-06	9.57E-06	3.69E-06	3.34E-05	2.61E-05	7.12E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.29E-06	1.65E-05	6.13E-06	5.09E-05	3.90E-05	1.62E-04
Terrestrial acidification	kg SO2 eq	1.14E-05	2.16E-05	8.90E-06	8.71E-05	7.10E-05	1.69E-04
Freshwater eutrophication	kg P eq	3.21E-07	6.84E-07	2.52E-07	1.82E-06	8.25E-07	1.94E-06
Marine eutrophication	kg N eq	1.08E-07	2.70E-07	6.37E-08	1.56E-06	1.35E-06	2.16E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.05E-02	5.66E-02	2.77E-02	3.91E-01	3.57E-01	5.76E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.08E-05	2.81E-05	9.19E-06	6.22E-05	4.35E-05	1.65E-04
Marine ecotoxicity	kg 1,4-DCB	5.55E-05	1.47E-04	4.96E-05	2.77E-04	2.23E-04	5.32E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.76E-05	1.21E-04	4.98E-05	9.32E-04	5.79E-04	1.74E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.30E-03	4.39E-03	2.04E-03	2.26E-02	1.98E-02	3.06E-02
Land use	m2a crop eq	5.69E-04	5.11E-04	2.78E-04	1.10E-03	8.89E-04	2.07E-03
Mineral resource scarcity	kg Cu eq	4.93E-05	1.33E-04	4.45E-05	3.53E-04	2.65E-04	5.50E-04
Fossil resource scarcity	kg oil eq	8.57E-04	1.42E-03	6.12E-04	4.90E-03	3.25E-03	1.48E-02
Water consumption	m3	3.07E-05	4.88E-05	2.27E-05	1.88E-04	1.65E-04	3.10E-04

Source: Oxford Economics

TABLE 81: NO SMALL CCMS (IMPACT ON CASH PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg $C0_2$ eq	3.06E-03	5.39E-03	2.20E-03	1.81E-02	1.15E-02	5.18E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.42E-09	2.22E-09	1.09E-09	8.03E-09	5.27E-09	1.87E-08
Ionizing radiation	kBq Co-60 eq	3.85E-05	5.50E-05	4.07E-05	1.13E-04	4.78E-05	3.65E-04
Ozone formation, Human health	kg NO_x eq	8.96E-06	1.59E-05	5.91E-06	4.69E-05	3.64E-05	1.51E-04
Fine particulate matter formation	kg PM2.5 eq	4.66E-06	9.57E-06	3.69E-06	3.25E-05	2.59E-05	7.05E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.29E-06	1.65E-05	6.13E-06	4.96E-05	3.87E-05	1.61E-04
Terrestrial acidification	kg SO2 eq	1.14E-05	2.16E-05	8.90E-06	8.52E-05	7.06E-05	1.68E-04
Freshwater eutrophication	kg P eq	3.21E-07	6.84E-07	2.52E-07	1.71E-06	8.01E-07	1.85E-06
Marine eutrophication	kg N eq	1.08E-07	2.70E-07	6.37E-08	1.49E-06	1.33E-06	2.11E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.05E-02	5.66E-02	2.77E-02	3.87E-01	3.56E-01	5.73E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.08E-05	2.81E-05	9.19E-06	5.86E-05	4.27E-05	1.63E-04
Marine ecotoxicity	kg 1,4-DCB	5.55E-05	1.47E-04	4.96E-05	2.62E-04	2.20E-04	5.20E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.76E-05	1.21E-04	4.98E-05	9.21E-04	5.76E-04	1.74E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.30E-03	4.39E-03	2.04E-03	2.22E-02	1.97E-02	3.04E-02
Land use	m2a crop eq	5.69E-04	5.11E-04	2.78E-04	1.08E-03	8.86E-04	2.06E-03
Mineral resource scarcity	kg Cu eq	4.93E-05	1.33E-04	4.45E-05	3.42E-04	2.62E-04	5.41E-04
Fossil resource scarcity	kg oil eq	8.57E-04	1.42E-03	6.12E-04	4.79E-03	3.22E-03	1.47E-02
Water consumption	m3	3.07E-05	4.88E-05	2.27E-05	1.86E-04	1.64E-04	3.08E-04

Source: Oxford Economics

TABLE 82: RECYCLED CARDS (IMPACT ON CASH AND DIGITAL PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg $C0_2$ eq	3.02E-03	5.37E-03	2.18E-03	1.81E-02	1.15E-02	5.18E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.39E-09	2.20E-09	1.08E-09	8.03E-09	5.27E-09	1.87E-08
Ionizing radiation	kBq Co-60 eq	3.82E-05	5.48E-05	4.07E-05	1.13E-04	4.79E-05	3.65E-04
Ozone formation, Human health	kg NO_x eq	8.88E-06	1.59E-05	5.89E-06	4.69E-05	3.64E-05	1.51E-04
Fine particulate matter formation	kg PM2.5 eq	4.62E-06	9.54E-06	3.68E-06	3.25E-05	2.59E-05	7.05E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.22E-06	1.65E-05	6.11E-06	4.96E-05	3.87E-05	1.61E-04
Terrestrial acidification	kg SO2 eq	1.13E-05	2.15E-05	8.87E-06	8.52E-05	7.06E-05	1.68E-04
Freshwater eutrophication	kg P eq	3.19E-07	6.83E-07	2.52E-07	1.71E-06	8.01E-07	1.85E-06
Marine eutrophication	kg N eq	1.08E-07	2.70E-07	6.38E-08	1.49E-06	1.33E-06	2.11E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.03E-02	5.65E-02	2.76E-02	3.87E-01	3.56E-01	5.73E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.08E-05	2.81E-05	9.19E-06	5.86E-05	4.27E-05	1.63E-04
Marine ecotoxicity	kg 1,4-DCB	5.54E-05	1.47E-04	4.95E-05	2.62E-04	2.20E-04	5.20E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.72E-05	1.21E-04	4.97E-05	9.21E-04	5.77E-04	1.74E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.29E-03	4.38E-03	2.04E-03	2.22E-02	1.97E-02	3.04E-02
Land use	m2a crop eq	5.68E-04	5.11E-04	2.78E-04	1.08E-03	8.86E-04	2.06E-03
Mineral resource scarcity	kg Cu eq	4.92E-05	1.33E-04	4.44E-05	3.42E-04	2.62E-04	5.42E-04
Fossil resource scarcity	kg oil eq	8.34E-04	1.40E-03	6.05E-04	4.78E-03	3.22E-03	1.47E-02
Water consumption	m3	3.13E-05	4.93E-05	2.28E-05	1.86E-04	1.64E-04	3.08E-04

Source: Oxford Economics

TABLE 83: LONGER LIFETIME OF BANKNOTES (IMPACT ON CASH PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg $C0_2$ eq	3.06E-03	5.39E-03	2.20E-03	1.79E-02	1.13E-02	5.16E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.42E-09	2.22E-09	1.09E-09	7.44E-09	4.69E-09	1.81E-08
Ionizing radiation	kBq Co-60 eq	3.85E-05	5.50E-05	4.07E-05	1.12E-04	4.62E-05	3.62E-04
Ozone formation, Human health	kg NO_x eq	8.96E-06	1.59E-05	5.91E-06	4.62E-05	3.58E-05	1.50E-04
Fine particulate matter formation	kg PM2.5 eq	4.66E-06	9.57E-06	3.69E-06	3.22E-05	2.56E-05	7.02E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.29E-06	1.65E-05	6.13E-06	4.89E-05	3.80E-05	1.60E-04
Terrestrial acidification	kg SO2 eq	1.14E-05	2.16E-05	8.90E-06	8.41E-05	6.96E-05	1.67E-04
Freshwater eutrophication	kg P eq	3.21E-07	6.84E-07	2.52E-07	1.60E-06	6.94E-07	1.75E-06
Marine eutrophication	kg N eq	1.08E-07	2.70E-07	6.37E-08	9.75E-07	8.09E-07	1.60E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.05E-02	5.66E-02	2.77E-02	3.86E-01	3.55E-01	5.72E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.08E-05	2.81E-05	9.19E-06	5.56E-05	3.97E-05	1.60E-04
Marine ecotoxicity	kg 1,4-DCB	5.55E-05	1.47E-04	4.96E-05	2.60E-04	2.18E-04	5.18E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.76E-05	1.21E-04	4.98E-05	9.18E-04	5.73E-04	1.73E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.30E-03	4.39E-03	2.04E-03	2.21E-02	1.96E-02	3.03E-02
Land use	m2a crop eq	5.69E-04	5.11E-04	2.78E-04	8.58E-04	6.60E-04	1.84E-03
Mineral resource scarcity	kg Cu eq	4.93E-05	1.33E-04	4.45E-05	3.41E-04	2.62E-04	5.41E-04
Fossil resource scarcity	kg oil eq	8.57E-04	1.42E-03	6.12E-04	4.74E-03	3.17E-03	1.47E-02
Water consumption	m3	3.07E-05	4.88E-05	2.27E-05	1.44E-04	1.23E-04	2.67E-04

Source: Oxford Economics

TABLE 84: NO OVERHEAD DURING COIN PRODUCTION (IMPACT ON CASH PAYMENT SYSTEM)

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg $C0_2$ eq	3.06E-03	5.39E-03	2.20E-03	1.77E-02	1.11E-02	5.14E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.42E-09	2.22E-09	1.09E-09	7.76E-09	5.00E-09	1.84E-08
Ionizing radiation	kBq Co-60 eq	3.85E-05	5.50E-05	4.07E-05	1.11E-04	4.51E-05	3.62E-04
Ozone formation, Human health	kg NO_x eq	8.96E-06	1.59E-05	5.91E-06	4.47E-05	3.42E-05	1.49E-04
Fine particulate matter formation	kg PM2.5 eq	4.66E-06	9.57E-06	3.69E-06	2.82E-05	2.16E-05	6.63E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.29E-06	1.65E-05	6.13E-06	4.73E-05	3.64E-05	1.59E-04
Terrestrial acidification	kg SO2 eq	1.14E-05	2.16E-05	8.90E-06	7.21E-05	5.76E-05	1.55E-04
Freshwater eutrophication	kg P eq	3.21E-07	6.84E-07	2.52E-07	1.63E-06	7.23E-07	1.78E-06
Marine eutrophication	kg N eq	1.08E-07	2.70E-07	6.37E-08	1.47E-06	1.32E-06	2.09E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.05E-02	5.66E-02	2.77E-02	2.99E-01	2.69E-01	4.87E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.08E-05	2.81E-05	9.19E-06	5.52E-05	3.93E-05	1.59E-04
Marine ecotoxicity	kg 1,4-DCB	5.55E-05	1.47E-04	4.96E-05	2.19E-04	1.77E-04	4.78E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.76E-05	1.21E-04	4.98E-05	8.47E-04	5.03E-04	1.66E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.30E-03	4.39E-03	2.04E-03	1.72E-02	1.47E-02	2.54E-02
Land use	m2a crop eq	5.69E-04	5.11E-04	2.78E-04	1.05E-03	8.52E-04	2.03E-03
Mineral resource scarcity	kg Cu eq	4.93E-05	1.33E-04	4.45E-05	2.86E-04	2.07E-04	4.87E-04
Fossil resource scarcity	kg oil eq	8.57E-04	1.42E-03	6.12E-04	4.69E-03	3.12E-03	1.46E-02
Water consumption	m3	3.07E-05	4.88E-05	2.27E-05	1.78E-04	1.57E-04	3.00E-04

Source: Oxford Economics

TABLE 85: WORST CASE FOR DIGITAL POS PAYMENTS VS. BEST CASE FOR CASH POS PAYMENTS

Impact category	Unit	Germany digital	Italy digital	Finland digital	Germany cash	Italy cash	Finland cash
Global Warming	kg CO_2 eq	3.78E-03	6.29E-03	3.01E-03	1.10E-02	5.97E-03	1.11E-02
Stratospheric ozone depletion	kg CFC_{11} eg	1.81E-09	2.65E-09	1.55E-09	5.15E-09	2.90E-09	5.28E-09
Ionizing radiation	kBq Co-60 eq	5.32E-05	7.11E-05	5.68E-05	9.93E-05	3.62E-05	3.01E-04
Ozone formation, Human health	kg NO_x eq	1.08E-05	1.80E-05	7.95E-06	2.59E-05	1.90E-05	3.49E-05
Fine particulate matter formation	kg PM2.5 eq	5.93E-06	1.10E-05	5.06E-06	2.14E-05	1.63E-05	2.54E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	1.12E-05	1.87E-05	8.24E-06	2.72E-05	2.00E-05	3.68E-05
Terrestrial acidification	kg SO2 eq	1.45E-05	2.49E-05	1.22E-05	5.62E-05	4.53E-05	6.20E-05
Freshwater eutrophication	kg P eq	4.09E-07	7.81E-07	3.47E-07	1.39E-06	5.19E-07	8.75E-07
Marine eutrophication	kg N eq	1.23E-07	3.23E-07	8.45E-08	8.39E-07	7.02E-07	8.41E-07
Terrestrial ecotoxicity	kg 1,4-DCB	4.15E-02	6.79E-02	3.88E-02	2.66E-01	2.44E-01	2.88E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.41E-05	3.16E-05	1.26E-05	3.47E-05	2.31E-05	4.77E-05
Marine ecotoxicity	kg 1,4-DCB	7.42E-05	1.66E-04	6.79E-05	1.73E-04	1.42E-04	2.03E-04
Human carcinogenic toxicity	kg 1,4-DCB	7.66E-05	1.41E-04	6.96E-05	7.08E-04	4.01E-04	8.21E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	3.10E-03	5.21E-03	2.86E-03	1.56E-02	1.35E-02	1.59E-02
Land use	m2a crop eq	6.40E-04	6.26E-04	3.92E-04	6.65E-04	5.07E-04	8.19E-04
Mineral resource scarcity	kg Cu eq	6.62E-05	1.50E-04	6.10E-05	2.51E-04	1.81E-04	2.75E-04
Fossil resource scarcity	kg oil eq	1.06E-03	1.66E-03	8.46E-04	2.76E-03	1.64E-03	2.88E-03
Water consumption	m3	3.77E-05	5.77E-05	3.14E-05	1.19E-04	1.02E-04	1.52E-04

Source: Oxford Economics

APPENDIX 5: PEDIGREE MATRICES

Interpretation of the Pedigree Matrices

In this appendix, pedigree matrices used in the uncertainty analysis are reported. For the analysis, the reliability, completeness, temporal correlation, geographical correlation, further technological correlation was assessed on a scale from 1 (higher quality) to 5 (lower quality). For each indicator, the following scores based on Ciroth et al. (2016), were used:

- Reliability:
- verified data based on measurements (1),
- verified data partly based on assumptions or non-verified data based on measurements (2),
- non-verified data partly based on qualified estimates (3),
- qualified estimates, e.g., by industrial experts (4),
- non-qualified estimates (5)
- Completeness:
- representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations (1),
- representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations (2),
- representative data from only some sites, <50%, relevant for the market considered or >50% of sites but from shorter periods (3),
- representative data from only one site relevant for the market considered or some sites but from shorter periods (4),
- representativeness unknown or data from a small number of sites and from shorter periods (5)
- Temporal correlation:
- less than 3 years of difference to the time period of the dataset (1),
- less than 6 years of difference to the time period of the dataset (2),
- less than 10 years of difference to the time period of the dataset (3),
- less than 15 years of difference to the time period of the dataset (4),
- age of data unknown or more than 15 years of difference to the time period of the dataset (5)
- Geographical correlation:
- data from area under study (1),
- average data from larger area in which the area under study is included (2),

- data from area with similar production conditions (3),
- data from area with slightly similar production conditions (4),
- data from unknown or distinctly different area (5)
- Further technological correlation:
- data from enterprises, processes, and materials under study (1),
- data from processes and materials under study but from different enterprises (2),
- data from processes and materials under study but from different technology (3),
- data on related processes or materials (4),
- data on related processes on laboratory scale or from different technology (5)

TABLE 86: PEDIGREE MATRIX OF THE CARDS SUBSYSTEM (DIGITAL AND CASH)

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Production																
Card body production	Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	3	2	2	2
	Injection moulding {GLO}| market for injection moulding | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3
	Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	3	2	2	2
	Injection moulding {GLO}| market for injection moulding | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3
	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	3	2	2	2
	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3
Chip production	Nickel, class 1 {GLO}| market for nickel, class 1 | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	2	2	2	2
	Metal working, average for metal product manufacturing {GLO}| market for metal working, average for metal product manufacturing | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	2	3	3	3
	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	2	2	2	2
	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	2	3	3	3
	Gold {GLO}| market for gold | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	3	2	2	2
	Metal working, average for metal product manufacturing {GLO}| market for metal working,	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
	average for metal product manufacturing | Cut-off, U															
	Glass fibre reinforced plastic	2	2	2	2	2	2	2	2	2	3	3	3	2	2	2
	Injection moulding {GLO}| market for injection moulding | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3
	Epoxy resin, liquid {RoW}| market for epoxy resin, liquid | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	3	2	2	2
	Injection moulding {GLO}| market for injection moulding | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3
	Silicon, electronics grade {GLO}| market for silicon, electronics grade | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	3	2	2	2
	Injection moulding {GLO}| market for injection moulding | Cut-off, U	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3
Chip (Malaysia) to Card Body Production (Singapore)	Transport, freight, lorry, unspecified {RoW}| market for transport, freight, lorry, unspecified | Cut-off, U	4	4	4	3	3	3	1	1	1	2	2	2	3	3	3
Card Body & Chip (Singapore) to Personalisation facility/logistic hub (Frankfurt) in the respective country	Transport, freight, aircraft, long haul {GLO}| market for transport, freight, aircraft, long haul | Cut-off, U	4	4	4	3	3	3	1	1	1	2	2	2	3	3	3
From logistic hub to warehouse	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	4	4	4	3	3	3	1	1	1	2	2	2	3	3	3
From warehouse to customer	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	4	4	4	3	3	3	1	1	1	2	2	2	3	3	3
Energy usage for personalisation of 1 card	Electricity, low voltage {DE}| market for electricity, low voltage | Cut-off, U	4	4	4	3	3	3	1	1	1	4	1	4	1	1	1

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Packaging from chip production to card assembly	Tubular particleboard {RoW}| market for tubular particleboard | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Packaging from production location (Singapore) to country of relevance	Tubular particleboard {RoW}| market for tubular particleboard | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Packaging from production location to country of relevance	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Packaging to the customer (two envelopes for PIN and Card)	Kraft paper {RER}| market for kraft paper | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
	Polystyrene, general purpose {GLO}| market for polystyrene, general purpose | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Assignment Factors	Cash	2	2	2	2	2	2	1	1	1	1	1	1	3	3	3
	Digital	2	2	2	2	2	2	1	1	1	1	3	1	3	3	3

End-of-life																
Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U	Waste polyvinylchloride {DE}| market for waste polyvinylchloride | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U	Waste polyvinylchloride {DE}| market for waste polyvinylchloride | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	Scrap copper {Europe without Switzerland} | market for scrap copper | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Nickel, class 1 {GLO}| market for nickel, class 1 | Cut-off, U	Scrap steel {Europe without Switzerland} | market for scrap steel | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	Scrap copper {Europe without Switzerland} | market for scrap copper | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Gold {GLO}| market for gold | Cut-off, U	Scrap steel {Europe without Switzerland} | market for scrap steel | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Glass fibre reinforced plastic	Waste glass {DE}| market for waste glass | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Epoxy resin, liquid {RoW}| market for epoxy resin, liquid | Cut-off, U	Waste plastic, mixture {DE}| market for waste plastic, mixture | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3

Silicon, electronics grade {GLO}| market for silicon, electronics grade | Cut-off, U	Waste plastic, mixture {DE}| market for waste plastic, mixture | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Tubular particleboard {RoW}| market for tubular particleboard | Cut-off, U	Waste wood, untreated {DE}| market for waste wood, untreated | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Corrugated board box {RER}| market for corrugated board box | Cut-off, U	Waste paperboard {DE}| market for waste paperboard | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	Waste plastic, mixture {DE}| market for waste plastic, mixture | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Kraft paper {RER}| market for kraft paper | Cut-off, U	Waste paperboard {DE}| market for waste paperboard | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Polystyrene, general purpose {GLO}| market for polystyrene, general purpose | Cut-off, U	Waste polystyrene {DE}| market for waste polystyrene | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Assignment Factors	Cash	2	2	2	2	2	2	1	1	1	1	1	1	3	3	3
	Digital	2	2	2	2	2	2	1	1	1	1	3	1	3	3	3

Source: Oxford Economics

TABLE 87: PEDIGREE MATRIX OF THE TERMINALS SUBSYSTEM

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Production																
Production of POS terminal	Power supply for desktop computer - 1 unit per terminal, GLO	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2
	Battery cell, Li-ion, NMC111 {GLO}| market for battery cell, Li-ion, NMC111 | Cut-off, U	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2
	Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2
	Injection moulding {GLO}| market for injection moulding | Cut-off, U	2	2	2	3	3	3	3	3	3	2	2	2	3	3	3
	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2
	Injection moulding {GLO}| market for injection moulding | Cut-off, U	2	2	2	3	3	3	3	3	3	2	2	2	3	3	3
	Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for glass fibre reinforced plastic, polyamide, injection moulded | Cut-off, U	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2
	Silicone product {RER}| market for silicone product | Cut-off, U	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2
	Injection moulding {GLO}| market for injection moulding | Cut-off, U	2	2	2	3	3	3	3	3	3	2	2	2	3	3	3
	Market for display, liquid crystal, 17 inches, GLO	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2
	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2
	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	2	2	2	3	3	3	3	3	3	2	2	2	3	3	3
	Printed wiring board, mounted mainboard, desktop computer, Pb free {GLO}| market for printed wiring board, mounted mainboard, desktop computer, Pb free | Cut-off, U	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2
	Integrated circuit, logic type {GLO}| market for integrated circuit, logic type | Cut-off, U	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
	Integrated circuit, memory type {GLO}| market for integrated circuit, memory type | Cut-off, U	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2
	Electricity, medium voltage {GLO}| market group for electricity, medium voltage | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Heat, district, or industrial, natural gas {GLO}| market group for heat, district or industrial, natural gas | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Heat, district or industrial, other than natural gas {GLO}| market group for heat, district or industrial, other than natural gas | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
Distance from Production (Vietnam) to Freight Airport in Luxembourg	Transport, freight, aircraft, long haul {GLO}| market for transport, freight, aircraft, long haul | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
Distance from Production (Vietnam) to the port of Marseille	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
Distance from Airport/Port to Warehouses (primary and secondary)	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
Average distance from distribution centres to customers for one POS terminal in 2022	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
Distance from Airport/Port to Warehouses (primary and secondary)	Market for transport, freight, sea, ferry, GLO			4			3			1			1			3
Producer packaging of POS terminal	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
PSP packaging of POS terminal	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
Assignment Factors		1	1	1	1	1	1	1	1	1	1	1	1	3	3	3
Operation																
Production of printing paper	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	3	3	3	3	4	4	2	2	2	4	4	4	3	3	3
	Injection moulding {GLO}| market for injection moulding | Cut-off, U	3	3	3	3	4	4	2	2	2	4	4	4	3	3	3
	Paper, wood containing, lightweight coated {RER}| market for paper, wood containing, lightweight coated | Cut-off, U	3	3	3	3	4	4	2	2	2	4	4	4	3	3	3
	Bisphenol A, powder {GLO}| market for bisphenol A, powder | Cut-off, U	3	3	3	3	4	4	2	2	2	4	4	4	3	3	3
	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	3	3	3	4	4	4	2	2	2	4	4	4	3	3	3
Maintenance - mainly postal swap	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	5	5	5	5	5	5	1	1	1	1	1	1	3	3	3
Energy use per terminal without printing per day	Electricity, low voltage {DE/IT/FI} | market for electricity, low voltage | Cut-off, U	2	2	2	3	3	3	2	2	2	4	4	4	2	2	2
Energy use per terminal Printing only per day	Electricity, low voltage {DE/IT/FI} | market for electricity, low voltage | Cut-off, U	2	2	2	3	3	3	2	2	2	4	4	4	2	2	2
Energy use per terminal for non-processing time	Electricity, low voltage {DE/IT/FI} | market for electricity, low voltage | Cut-off, U	2	2	2	3	3	3	2	2	2	4	4	4	2	2	2
Transmission of data via the internet	Internet access, work, 0.2 Mbit/s {CH}, with RER electricity | internet access, work, 0.2 Mbit/s | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Assignment Factors		3	3	3	5	5	5	2	2	2	2	2	2	3	3	3

End-of-life																
Power supply for desktop computer - 1 unit per terminal, GLO	Used industrial electronic device {CH}| treatment of used industrial electronic device, manual dismantling | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Battery cell, Li-ion, NMC111 {GLO}| market for battery cell, Li-ion, NMC111 | Cut-off, U	Used Li-ion battery, without transport {GLO}| market for used Li-ion battery | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	Waste plastic, mixture, without transport {DE/IT/FI} | market for waste plastic, mixture | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	Waste polypropylene, without transport {DE/IT/FI} | market for waste polypropylene | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for glass fibre reinforced plastic, polyamide, injection moulded | Cut-off, U	Waste plastic, mixture, without transport {DE/IT/FI} | market for waste plastic, mixture | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Silicone product {RER}| market for silicone product | Cut-off, U	Waste plastic, mixture, without transport {DE/IT/FI} | market for waste plastic, mixture | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Market for display, liquid crystal, 17 inches, GLO	Used liquid crystal display {CH}| treatment of used liquid crystal display, manual dismantling | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	Scrap copper {Europe without Switzerland} | treatment of scrap copper, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Printed wiring board, mounted mainboard, desktop computer, Pb free {GLO}| market for printed wiring board, mounted mainboard,	Electronics scrap from control units {RER}| treatment of electronics scrap from control units | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3

desktop computer, Pb free | Cut-off, U																
Integrated circuit, logic type {GLO}| market for integrated circuit, logic type | Cut-off, U	Electronics scrap from control units {RER}| treatment of electronics scrap from control units | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Integrated circuit, memory type {GLO}| market for integrated circuit, memory type | Cut-off, U	Electronics scrap from control units {RER}| treatment of electronics scrap from control units | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Assignment Factors		4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
Refurbished terminals as a whole	Used industrial electronic device {RoW}| market for used industrial electronic device | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Assignment Factors		4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	Waste polyvinylchloride {Europe without Switzerland} | market group for waste polyvinylchloride | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Corrugated board box {RER}| market for corrugated board box | Cut-off, U	Waste paperboard {Europe without Switzerland} | market group for waste paperboard | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Assignment Factors		1	1	1	1	1	1	1	1	1	1	1	1	3	3	3
Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	Waste graphical paper {DE/IT/FI} | market for waste graphical paper | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Paper, wood containing, lightweight coated {RER}| market for paper, wood containing, lightweight coated | Cut-off, U	Waste graphical paper {DE/IT/FI} | market for waste graphical paper | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3

Bisphenol A, powder {GLO}| market for bisphenol A, powder | Cut-off, U	Waste graphical paper {DE/IT/FI} | market for waste graphical paper | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	Waste plastic, mixture {DE/IT/FI} | market for waste plastic, mixture | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Assignment Factors		3	3	3	5	5	5	2	2	2	2	2	2	3	3	3
Average distance from customer to the warehouse for disposal/recycling for one POS terminal in 2022	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
Average distance from the warehouse to waste treatment	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
Average distance from warehouse to recycling company for one POS terminal in 2022	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
Average distance from the warehouse to the port of Rotterdam	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	4	4		3	3		1	1		1	1		3	3	
Average distance from the port of Rotterdam to the port of Malaysia	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3

Source: Oxford Economics

TABLE 88: PEDIGREE MATRIX OF THE SMARTPHONE SUBSYSTEM

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Production																
	Consumer electronics, mobile device, smartphone, without waste treatment {GLO}| market for consumer electronics, mobile device, smartphone | Cut-off, U	2	2	2	4	4	4	3	3	3	5	5	5	1	1	1
Transport production to the country of relevance via plane (Beijing to Frankfurt)	Transport, freight, aircraft, long haul {GLO}| market for transport, freight, aircraft, long haul | Cut-off, U	2	2	2	4	4	4	1	1	1	2	2	2	3	3	3
	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	2	2	2	4	4	4	1	1	1	2	2	2	3	3	3
Transport National transport to the customer	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	2	2	2	4	4	4	1	1	1	2	2	2	3	3	3
Packaging	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Assignment Factors		5	5	5	4	4	4	1	1	1	1	3	3	3	3	3
Operation																
Average electricity usage for payment	Electricity, low voltage {DE/IT/FI} | market for electricity, low voltage | Cut-off, U	5	5	5	4	4	4	1	1	1	1	3	3	2	2	2
Assignment Factors		5	5	5	4	4	4	1	1	1	1	1	1	4	4	4

End-of-life																
Consumer electronics, mobile device, smartphone, without waste treatment {GLO}| market for consumer electronics, mobile device, smartphone | Cut-off, U	Used cable {GLO}| market for used cable | Cut-off, U	5	5	5	3	3	3	1	1	1	2	2	2	2	2	2
Consumer electronics, mobile device, smartphone, without waste treatment {GLO}| market for consumer electronics, mobile device, smartphone | Cut-off, U	Used smartphone {GLO}| market for used smartphone | Cut-off, U	5	5	5	3	3	3	1	1	1	2	2	2	2	2	2
Corrugated board box {RER}| market for corrugated board box | Cut-off, U	Waste paperboard {DE/IT/FI} | market for waste paperboard | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	Waste polyethylene {DE/IT/FI} | market for waste polyethylene | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Assignment Factors		5	5	5	4	4	4	1	1	1	1	3	3	3	3	3

Source: Oxford Economics

TABLE 89: PEDIGREE MATRIX OF THE BANKNOTES SUBSYSTEM

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Production																
Cotton production	Fibre, cotton {GLO}| market for fibre, cotton | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Fibre, cotton, organic {GLO}| market for fibre, cotton, organic | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Fibre, cotton {RoW}| fibre production, cotton, ginning | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Polyethylene terephthalate, granulate, amorphous {GLO}| market for polyethylene terephthalate, granulate, amorphous | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
Foil production	Polyester-complexed starch biopolymer {GLO}| market for polyester-complexed starch biopolymer | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Aluminium, primary, ingot {RoW}| market for aluminium, primary, ingot | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Polyester resin, unsaturated {RER}| market for polyester resin, unsaturated | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Extrusion, plastic film, without electricity {RER}| extrusion, plastic film | Cut-off, U	5	5	5	4	4	4	3	3	3	3	3	3	3	3	3
	Metal working, average for aluminium product manufacturing, without electricity {RER}| metal working, average for aluminium product manufacturing | Cut-off, U	5	5	5	4	4	4	3	3	3	3	3	3	3	3	3
Thread production	Aluminium, primary, ingot {RoW}| market for aluminium, primary, ingot | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Polyester-complexed starch biopolymer {GLO}| market for polyester-complexed starch biopolymer | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Extrusion, plastic film, without electricity {RER}| extrusion, plastic film | Cut-off, U	5	5	5	4	4	4	3	3	3	3	3	3	3	3	3
	Metal working, average for aluminium product manufacturing, without electricity {RER}| metal working, average for aluminium product manufacturing | Cut-off, U	5	5	5	4	4	4	3	3	3	3	3	3	3	3	3

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Paper Production	Sulfate pulp, bleached {RoW}| market for sulfate pulp, bleached | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Chemi-thermomechanical pulp {GLO}| market for chemi-thermomechanical pulp | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Paper, newsprint {RER}| market for paper, newsprint | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Polyethylene terephthalate, granulate, amorphous {GLO}| market for polyethylene terephthalate, granulate, amorphous | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Paper, newsprint {RER}| market for paper, newsprint | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
Ink production	Printing ink, offset, without solvent, in 47.5% solution state {RoW}| market for printing ink, offset, without solvent, in 47.5% solution state | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
Banknote printing	Acetone, liquid {RoW}| market for acetone, liquid | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Waste newspaper {GLO}| market for waste newspaper | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Polyethylene terephthalate, granulate, amorphous {GLO}| market for polyethylene terephthalate, granulate, amorphous | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Polyethylene, low density, granulate {GLO}| market for polyethylene, low density, granulate | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Corrugated board box {RER}| corrugated board box production | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Waste paperboard, sorted {GLO}| market for waste paperboard, sorted | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Nickel, class 1 {GLO}| market for nickel, class 1 | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Polyethylene terephthalate, granulate, amorphous {GLO}| market for polyethylene terephthalate, granulate, amorphous | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Printed paper, without paper, toner, electricity {Europe without Switzerland} | operation, printer, laser, colour, per kg printed paper | Cut-off, U	5	5	5	4	4	4	3	3	3	3	3	3	3	3	3

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Packaging	Kraft paper {RER}| market for kraft paper | Cut-off, U	5	5	5	4	4	4	1	1	1	3	3	3	3	3	3
	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	5	5	5	4	4	4	1	1	1	3	3	3	3	3	3
	EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, U	5	5	5	4	4	4	1	1	1	3	3	3	3	3	3
Cotton production: Fairtrade cotton transport (production to paper mill)	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	2	2	2	4	4	4	3	2	2	3	1	1	3	3	3
Cotton production: Europe, port to paper mill	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	2	2	2	4	4	4	1	1	1	1	1	1	3	3	3
Paper production (paper mill to printing works)	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	5	5	5	4	4	4	1	1	1	1	1	1	3	3	3
Banknote production (printing works to central bank HQ)	Transport, freight, lorry, unspecified, WITHOUT LORRY {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	5	5	5	4	4	4	1	1	1	1	1	1	3	3	3
	Transport, freight, sea, ferry {GLO}| market for transport, freight, sea, ferry | Cut-off, U		5	5		4	4		1	1		1	1		3	3
Cotton production	Electricity, medium voltage {GLO}| market group for electricity, medium voltage | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
Foil production	Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Heat, district, or industrial, natural gas {RER}| market group for heat, district, or industrial, natural gas | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
Thread production	Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
	Heat, district, or industrial, natural gas {RER}| market group for heat, district, or industrial, natural gas | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
Paper production	Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
Banknote printing	Electricity, medium voltage {DE/IT/FI} | market for electricity, medium voltage | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Assignment Factor		3	3	3	2	2	2	1	1	1	1	3	3	3	3	3
End-of-life																
Cotton production: Fibre Cotton (GLO)	Waste textile, soiled {CH}| treatment of waste textile, soiled, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Cotton production: Fibre cotton, organic	Waste textile, soiled {CH}| treatment of waste textile, soiled, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Cotton production: Fibre cotton (RoW)	Waste textile, soiled {CH}| treatment of waste textile, soiled, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Cotton production	Waste polyethylene terephthalate {CH}| treatment of waste polyethylene terephthalate, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Foil production: Polyester-complexed starch bipolymer	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Foil production: Polyester resin	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Foil production:	Scrap aluminium {Europe without Switzerland} | treatment of scrap aluminium, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Printing ink	Waste paint {Europe without Switzerland} | treatment of waste paint, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Paper production: Sulfate pulp	Waste graphical paper {CH}| treatment of waste graphical paper, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Paper production: Chemi-thermomechanical pulp	Waste graphical paper {CH}| treatment of waste graphical paper, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Paper production: Paper newsprint	Waste graphical paper {CH}| treatment of waste graphical paper, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Paper production:	Waste polyethylene terephthalate {CH}| treatment of waste polyethylene terephthalate, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Paper production: Corrugated board box	Waste paperboard {CH}| treatment of waste paperboard, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Paper production: Paper newsprint	Waste graphical paper {CH}| treatment of waste graphical paper, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Thread production:	Scrap aluminium {Europe without Switzerland} | treatment of scrap aluminium, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	2	4	4	3	3	3
Thread production: Polyester-complexed starch biopolymer	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Banknote printing: Acetone, liquid	Municipal solid waste {DE}| treatment of municipal solid waste, incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	1	1	1	3	3	3
Banknote printing: Waste newspaper	Waste graphical paper {CH}| treatment of waste graphical paper, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Banknote printing: Polyethylene terephthalate, granulate, amorphous	Waste polyethylene terephthalate {CH}| treatment of waste polyethylene terephthalate, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Banknote printing: Polyethylene, low density, granulate	Waste polyethylene {CH}| treatment of waste polyethylene, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Banknote printing: Corrugated board box	Waste paperboard {CH}| treatment of waste paperboard, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Banknote printing: Waste paperboard, sorted	Waste paperboard {CH}| treatment of waste paperboard, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Banknote printing: Nickel, 99.5%	Scrap aluminium {CH}| treatment of scrap aluminium, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Banknote printing: Polyethylene terephthalate, granulate, amorphous	Waste polyethylene terephthalate {CH}| treatment of waste polyethylene terephthalate, municipal incineration | Cut-off, U	5	5	5	4	4	4	1	1	1	4	4	4	3	3	3
Kraft paper {RER}| market for kraft paper | Cut-off, U	Waste paperboard {DE}| market for waste paperboard | Cut-off, U	5	5	5	4	4	4	1	1	1	1	1	1	3	3	3
Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	Waste polyethylene {DE}| market for waste polyethylene | Cut-off, U	5	5	5	4	4	4	1	1	1	1	1	1	3	3	3

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, U	Waste wood, untreated {DE}| market for waste wood, untreated | Cut-off, U	5	5	5	4	4	4	1	1	1	1	1	1	3	3	3
Transport: Centre for analysis to waste incinerator	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	2	2	2	1	1	1	1	1	1	1	1	1	3	3	3
Shredding, granulating, and compacting of banknotes	Heat, district or industrial, natural gas {Europe without Switzerland} | heat production, natural gas, at boiler modulating >100kW | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
Shredding, granulating, and compacting of banknotes	Polyethylene terephthalate, granulate, amorphous {GLO}| market for polyethylene terephthalate, granulate, amorphous | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
Shredding, granulating, and compacting of banknotes	Electricity, medium voltage {DE}| market for electricity, medium voltage | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2
Assignment Factor		3	3	3	2	2	2	1	1	1	1	3	3	3	3	3

Source: Oxford Economics

TABLE 90: PEDIGREE MATRIX OF THE COINS SUBSYSTEM

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Production																
Fictional coin blank production	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	2	2	2	1	1	1	2	2	2	3	3	3	2	2	2
	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	2	2	2	1	1	1	2	2	2	3	3	3	2	2	2
	Aluminium, primary, liquid {GLO}| market for aluminium, primary, liquid | Cut-off, U	2	2	2	1	1	1	2	2	2	3	3	3	2	2	2
	Zinc {GLO}| market for zinc | Cut-off, U	2	2	2	1	1	1	2	2	2	3	3	3	2	2	2

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
	Tin {GLO}| market for tin | Cut-off, U	2	2	2	1	1	1	2	2	2	3	3	3	2	2	2
	Nickel, class 1 {GLO}| market for nickel, class 1 | Cut-off, U	2	2	2	1	1	1	2	2	2	3	3	3	2	2	2
	Metal working, average for metal product manufacturing {GLO}| market for metal working, average for metal product manufacturing | Cut-off, U	5	5	5	1	1	1	1	1	1	3	3	3	3	3	3
	Metal working, average for metal product manufacturing, without energy {RER}| metal working, average for metal product manufacturing | Cut-off, U	5	5	5	1	1	1	1	1	1	3	3	3	3	3	3
Assignment Factor for one transaction		3	3	3	2	1	1	1	1	1	1	4	4	3	3	3
Coin Blanks to Coin Mint	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	3	3	3	2	2	2	1	1	1	1	1	1	3	3	3
Coin Mint to HQ	Transport, freight, lorry, unspecified, WITHOUT LORRY {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	3	3	3	2	2	2	1	1	1	1	1	1	3	3	3
Packaging of coins	Kraft paper {RER}| market for kraft paper | Cut-off, U	5	5	5	2	2	2	1	1	1	2	2	2	3	3	3
	EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, U	5	5	5	2	2	2	1	1	1	2	2	2	3	3	3
Fictional Coin production	Electricity, medium voltage {DE/IT/FI} | market for electricity, medium voltage | Cut-off, U	2	2	2	1	1	1	2	2	2	1	1	1	2	2	2
Assignment Factor for one transaction without overhead		3	3	3	2	1	1	1	1	1	1	4	4	3	3	3
End-of-life																
Kraft paper {RER}| market for kraft paper | Cut-off, U	Waste paperboard {DE/IT/FI}| market for waste paperboard | Cut-off, U	5	5	5	4	4	4	1	1	1	1	1	1	3	3	3
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, U	Waste wood, untreated {DE/IT/FI}| market for waste wood, untreated | Cut-off, U	5	5	5	4	4	4	1	1	1	1	1	1	3	3	3
Transport: HQ to melting centre	Transport, freight, lorry, unspecified, WITHOUT LORRY {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	5	5	5	2	2	2	1	1	1	1	1	1	3	3	3

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Coin melting	Electricity, medium voltage {DE/IT/FI} | market for electricity, medium voltage | Cut-off, U	2	2	2	1	1	1	3	3	3	3	3	3	2	2	2

Source: Oxford Economics

TABLE 91: PEDIGREE MATRIX OF THE CASH-IN-TRANSIT SUBSYSTEM

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Production																
Cash Truck	Reinforcing steel {GLO}| market for reinforcing steel | Cut-off, U	2	2	2	4	4	4	2	2	2	3	3	3	2	2	2
	Passenger car, diesel, without waste treatment {GLO}| passenger car production, diesel | Cut-off, U	2	2	2	4	4	4	2	2	2	3	3	3	2	2	2
	Metal working, average for steel product manufacturing {GLO}| market for metal working, average for steel product manufacturing | Cut-off, U	2	2	2	4	4	4	2	2	2	3	3	3	3	3	3
Transport of cash truck to customer	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	1	1	1	4	4	4	1	1	1	1	1	1	3	3	3
Assignment Factor		4	4	1	2	2	1	1	1	1	1	1	4	3	3	3
Operation																
BN&Coins: Cash Handling for Circulation by Cash in Transit Companies	Transport, freight, lorry, unspecified, WITHOUT LORRY {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	5	5	5	2	3	4	1	1	1	4	1	4	3	3	3
Assignment Factor		4	4	1	2	2	1	1	1	1	1	1	4	3	3	3

End-of-life																
Reinforcing steel {GLO}| market for reinforcing steel | Cut-off, U	Scrap steel {Europe without Switzerland} | market for scrap steel | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Passenger car, diesel, without waste treatment {GLO}| passenger car production, diesel | Cut-off, U	Passenger car, diesel, only waste treatment {GLO}| passenger car production, diesel | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Assignment Factor		4	4	1	2	2	1	1	1	1	1	1	4	3	3	3

Source: Oxford Economics

TABLE 92: PEDIGREE MATRIX OF THE CASH COUNTING MACHINES (SMALL) SUBSYSTEM

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Production																
Material Input for 1 small Cash Counting Machine	Polystyrene, high impact {GLO}| market for polystyrene, high impact | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Injection moulding {GLO}| market for injection moulding | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Steel, unalloyed {GLO}| market for steel, unalloyed | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Metal working, average for steel product manufacturing {GLO}| market for metal working, average for steel product manufacturing | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
	Integrated circuit, logic type {GLO}| market for integrated circuit, logic type | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Assembly of liquid crystal display, auxiliaries, and energy use {GLO}| assembly of liquid crystal display, auxiliaries, and energy use | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Power adapter, for laptop {GLO}| market for power adapter, for laptop | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Keyboard {GLO}| market for keyboard | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
Packaging for 1 small CCM	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	3	3	3
	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	3	3	3
Transport from production to customer	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	1	1	1	4	4	4	1	1	1	1	1	1	3	3	3
Assignment Factor		5	5	5	3	3	3	1	1	1	4	1	4	3	3	3
Operation																
	Electricity, low voltage {DE/IT/FI} | market for electricity, low voltage | Cut-off, U	2	2	2	4	4	4	2	2	2	4	4	4	2	2	2
Assignment Factor		5	5	5	3	3	3	1	1	1	4	1	4	3	3	3
End-of-life																
Polystyrene, high impact {GLO}| market for polystyrene, high impact | Cut-off, U	Waste polystyrene {DE/IT/FI} | market for waste polystyrene | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Steel, unalloyed {GLO}| market for steel, unalloyed | Cut-off, U	Scrap steel {Europe without Switzerland} | market for scrap steel | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	Scrap copper {Europe without Switzerland} | market for scrap copper | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Integrated circuit, logic type {GLO}| market for integrated circuit, logic type | Cut-off, U	Waste electric and electronic equipment {GLO}| market for waste electric and electronic equipment | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	Used liquid crystal display {GLO}| market for used liquid crystal display | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Power adapter, for laptop {GLO}| market for power adapter, for laptop | Cut-off, U	Waste electric and electronic equipment {GLO}| market for waste electric and electronic equipment | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Keyboard {GLO}| market for keyboard | Cut-off, U	Waste electric and electronic equipment {GLO}| market for waste electric and electronic equipment | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Corrugated board box {RER}| market for corrugated board box | Cut-off, U	Waste paperboard {DE/IT/FI} | market for waste paperboard | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	Waste polyethylene {DE/IT/FI} | market for waste polyethylene | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Assignment Factor		5	5	5	3	3	3	1	1	1	4	1	4	3	3	3

Source: Oxford Economics

TABLE 93: PEDIGREE MATRIX OF THE CASH COUNTING MACHINES (LARGE) SUBSYSTEM

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Production																
Material Input for 1 large Cash Counting Machine	Polystyrene, high impact {GLO}| market for polystyrene, high impact | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Injection moulding {GLO}| market for injection moulding | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Steel, unalloyed {GLO}| market for steel, unalloyed | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Metal working, average for steel product manufacturing {GLO}| market for metal working, average for steel product manufacturing | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Integrated circuit, logic type {GLO}| market for integrated circuit, logic type | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Assembly of liquid crystal display, auxiliaries, and energy use {GLO}| assembly of liquid crystal display, auxiliaries and energy use | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Power adapter, for laptop {GLO}| market for power adapter, for laptop | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
	Keyboard {GLO}| market for keyboard | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	4	4	4
Packaging for 1 small CCM	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	3	3	3
	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	5	5	5	5	5	5	1	1	1	2	2	2	3	3	3
Transport from production to customer	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	1	1	1	4	4	4	1	1	1	1	1	1	3	3	3

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Assignment Factors		5	5	5	2	2	2	1	1	1	1	1	1	3	3	3
Operation																
	Electricity, low voltage {DE}| market for electricity, low voltage | Cut-off, U	2	2	2	4	4	4	2	2	2	4	4	4	2	2	2
Assignment Factors		5	5	5	2	2	2	1	1	1	1	1	1	3	3	3
End-of-life																
Market for polystyrene, high impact, GLO	Waste polystyrene {DE/IT/FI} | market for waste polystyrene | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Market for steel, unalloyed, GLO	Scrap steel {Europe without Switzerland} | market for scrap steel | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	Scrap copper {Europe without Switzerland} | market for scrap copper | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Integrated circuit production, logic type, GLO	Waste electric and electronic equipment {GLO}| market for waste electric and electronic equipment | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	Used liquid crystal display {GLO}| market for used liquid crystal display | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Power adapter, for laptop {GLO}| market for power adapter, for laptop | Cut-off, U	Waste electric and electronic equipment {GLO}| market for waste electric and electronic equipment | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Market for keyboard, GLO	Waste electric and electronic equipment {GLO}| market for waste electric and electronic equipment | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Corrugated board box {RER}| market for corrugated board box | Cut-off, U	Waste paperboard {DE/IT/FI} | market for waste paperboard | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	Waste polyethylene {DE/IT/FI} | market for waste polyethylene | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Assignment Factors		5	5	5	2	2	2	1	1	1	1	1	1	3	3	3

Source: Oxford Economics

TABLE 94: PEDIGREE MATRIX OF THE ATM/CRM SUBSYSTEM

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Production																
Production of CRM/ATM	Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	2	2	2	3	3	3	1	1	1	1	1	1	2	2	2
	Assembly of liquid crystal display, auxiliaries, and energy use {GLO}| market for assembly of liquid crystal display, auxiliaries and energy use | Cut-off, U	5	5	5	3	3	3	1	1	1	1	1	1	3	3	3
	Computer, desktop, without screen {GLO}| market for computer, desktop, without screen | Cut-off, U	2	2	2	3	3	3	1	1	1	1	1	1	2	2	2
	Reinforcing steel {GLO}| market for reinforcing steel | Cut-off, U	2	2	2	3	3	3	1	1	1	1	1	1	2	2	2
	Metal working, average for steel product manufacturing {RER}| metal working, average for steel product manufacturing | Cut-off, U	5	5	5	3	3	3	1	1	1	1	1	1	3	3	3
	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	2	2	2	3	3	3	1	1	1	1	1	1	2	2	2
	Injection moulding {RER}| market for injection moulding | Cut-off, U	5	5	5	3	3	3	1	1	1	1	1	1	3	3	3

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
Packaging of CRM/ATM	Kraft paper {RER}| market for kraft paper | Cut-off, U	5	5	5	5	5	5	1	1	1	1	1	1	3	3	3
	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	5	5	5	5	5	5	1	1	1	1	1	1	3	3	3
	EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, U	5	5	5	5	5	5	1	1	1	1	1	1	3	3	3
Transport production facility to customer	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	3	3	3
Assignment Factor		1	1	1	1	1	1	1	1	1	1	1	1	3	3	3
Operation																
Way to ATM/CRM using passenger car	Transport, passenger car {RER}| market for transport, passenger car | Cut-off, U	1	1	1	4	4	4	1	1	1	1	4	4	3	3	3
Way to ATM/CRM using bike	Transport, passenger, bicycle {CH}| transport, regular bus | Cut-off, U	1	1	1	4	4	4	1	1	1	1	4	4	3	3	3
Way to ATM/CRM using public transport	Transport, regular bus {CH}| transport, regular bus | Cut-off, U	1	1	1	4	4	4	1	1	1	1	4	4	3	3	3
Way to ATM/CRM using motorcycle	Transport, passenger, motor scooter {CH}| transport, passenger, motor scooter | Cut-off, U	1	1	1	4	4	4	1	1	1	1	4	4	3	3	3
Transport for servicing one ATM/CRM for a year	Transport, passenger car, EURO 5 {RER}| market for transport, passenger car, EURO 5 | Cut-off, U	4	4	4	3	3	3	1	1	1	4	1	4	3	3	3
ATM: Energy consumption	Electricity, low voltage {DE/IT/FI} | market for electricity, low voltage | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	1	1	1
CRM: Energy consumption	Electricity, low voltage {DE/IT/FI} | market for electricity, low voltage | Cut-off, U	4	4	4	3	3	3	1	1	1	1	1	1	1	1	1
Assignment Factor		1	1	1	1	1	1	1	1	1	1	1	1	3	3	3
End-of-life																
Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	Used liquid crystal display {GLO}| market for used liquid crystal display | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Computer, desktop, without screen {GLO}| market for computer,	Used industrial electronic device {CH}| market for used industrial electronic device | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3

Subsystem	Dataset	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation		
		DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI	DE	IT	FI
desktop, without screen | Cut-off, U																
Reinforcing steel {GLO}| market for reinforcing steel | Cut-off, U	Waste reinforcement steel {CH}| market for waste reinforcement steel | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	Waste polypropylene {Europe without Switzerland} | market group for waste polypropylene | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Kraft paper {RER}| market for kraft paper | Cut-off, U	Waste paperboard {Europe without Switzerland} | market group for waste paperboard | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Polyvinylchloride, suspension polymerised {GLO}| market for polyvinylchloride, suspension polymerised | Cut-off, U	Waste polyvinylchloride {Europe without Switzerland} | market group for waste polyvinylchloride | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, U	Waste wood, untreated {DE/IT/FI} | market for waste wood, untreated | Cut-off, U	5	5	5	4	4	4	1	1	1	2	2	2	3	3	3
Assignment Factor		1	1	1	1	1	1	1	1	1	1	1	1	3	3	3

Source: Oxford Economics

APPENDIX 6: DETAILED RESULTS OF UNCERTAINTY ANALYSIS

TABLE 95: RESULTS OF OVERALL MONTE CARLO SIMULATION—DIFFERENCE BETWEEN CASH AND DIGITAL

Impact category	Unit	Mean	Median	Standard Deviation	2.5%	97.5%	Percent of times Cash > Digital
Germany							
Fine particulate matter formation	kg PM2.5 eq	2.80E-05	2.74E-05	4.54E-06	2.07E-05	3.82E-05	100
Fossil resource scarcity	kg oil eq	3.92E-03	3.68E-03	1.11E-03	2.49E-03	6.70E-03	100
Freshwater ecotoxicity	kg 1,4-DCB	4.08E-03	3.96E-03	9.49E-04	2.58E-03	6.18E-03	100
Freshwater eutrophication	kg P eq	1.22E-05	1.10E-05	5.17E-06	6.33E-06	2.60E-05	100
Global warming	kg CO2 eq	1.50E-02	1.43E-02	3.58E-03	1.03E-02	2.42E-02	100
Human carcinogenic toxicity	kg 1,4-DCB	3.59E-03	3.34E-03	1.95E-03	7.14E-04	7.68E-03	99.5
Human non-carcinogenic toxicity	kg 1,4-DCB	7.79E-02	7.02E-02	6.76E-01	-1.24E+00	1.44E+00	54.2
Ionizing radiation	kBq Co-60 eq	1.16E-03	6.05E-04	1.93E-03	1.20E-04	5.81E-03	100
Land use	m2a crop eq	5.11E-04	5.16E-04	2.51E-04	-1.19E-07	9.88E-04	97.5
Marine ecotoxicity	kg 1,4-DCB	5.24E-03	5.09E-03	1.20E-03	3.34E-03	7.94E-03	100
Marine eutrophication	kg N eq	1.96E-06	1.95E-06	2.32E-07	1.55E-06	2.47E-06	100
Mineral resource scarcity	kg Cu eq	2.94E-04	2.90E-04	4.69E-05	2.11E-04	3.93E-04	100
Ozone formation, Human health	kg NOx eq	3.81E-05	3.64E-05	9.24E-06	2.49E-05	6.07E-05	100
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.04E-05	3.86E-05	1.00E-05	2.60E-05	6.54E-05	100
Stratospheric ozone depletion	kg CFC11 eq	6.93E-09	6.73E-09	1.35E-09	4.89E-09	1.02E-08	100
Terrestrial acidification	kg SO2 eq	7.42E-05	7.25E-05	1.17E-05	5.44E-05	9.99E-05	100
Terrestrial ecotoxicity	kg 1,4-DCB	3.57E-01	3.19E-01	1.62E-01	1.75E-01	7.77E-01	100
Water consumption	m3	-2.79E-04	1.58E-04	9.67E-03	-2.20E-02	1.80E-02	50.8

Impact category	Unit	Mean	Median	Standard Deviation	2.5%	97.5%	Percent of times Cash > Digital
Italy							
Fine particulate matter formation	kg PM2.5 eq	1.64E-05	1.60E-05	3.89E-06	9.93E-06	2.46E-05	100
Fossil resource scarcity	kg oil eq	1.79E-03	1.64E-03	8.09E-04	7.01E-04	3.75E-03	100
Freshwater ecotoxicity	kg 1,4-DCB	1.79E-03	1.72E-03	8.71E-04	2.88E-04	3.71E-03	98.4
Freshwater eutrophication	kg P eq	1.83E-06	1.79E-06	1.39E-06	-8.33E-07	4.80E-06	92.2
Global warming	kg CO2 eq	6.09E-03	5.62E-03	2.60E-03	2.52E-03	1.20E-02	100
Human carcinogenic toxicity	kg 1,4-DCB	1.58E-03	1.54E-03	1.12E-03	-5.24E-04	3.86E-03	92
Human non-carcinogenic toxicity	kg 1,4-DCB	3.92E-02	4.66E-02	6.62E-01	-1.34E+00	1.44E+00	53.1
Ionizing radiation	kBq Co-60 eq	-5.69E-05	-2.74E-05	1.42E-04	-4.07E-04	1.25E-04	19.5
Land use	m2a crop eq	3.77E-04	3.76E-04	1.66E-04	3.38E-05	7.04E-04	98.4
Marine ecotoxicity	kg 1,4-DCB	2.26E-03	2.14E-03	1.10E-03	2.96E-04	4.63E-03	98.4
Marine eutrophication	kg N eq	1.07E-06	1.06E-06	2.05E-07	7.13E-07	1.54E-06	100
Mineral resource scarcity	kg Cu eq	1.28E-04	1.26E-04	4.20E-05	4.67E-05	2.20E-04	100
Ozone formation, Human health	kg NOx eq	2.04E-05	1.95E-05	6.89E-06	9.56E-06	3.57E-05	100
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.20E-05	2.10E-05	7.39E-06	1.04E-05	3.87E-05	100
Stratospheric ozone depletion	kg CFC11 eq	3.35E-09	3.19E-09	9.93E-10	1.91E-09	5.61E-09	100
Terrestrial acidification	kg SO2 eq	4.94E-05	4.85E-05	1.07E-05	3.14E-05	7.28E-05	100
Terrestrial ecotoxicity	kg 1,4-DCB	3.02E-01	2.71E-01	1.46E-01	1.41E-01	6.57E-01	100
Water consumption	m3	6.74E-05	4.72E-04	6.19E-03	-1.37E-02	1.12E-02	53.3
Finland							
Fine particulate matter formation	kg PM2.5 eq	6.76E-05	6.23E-05	2.19E-05	4.14E-05	1.23E-04	100
Fossil resource scarcity	kg oil eq	1.41E-02	1.25E-02	6.57E-03	6.65E-03	3.10E-02	100
Freshwater ecotoxicity	kg 1,4-DCB	6.81E-03	6.34E-03	2.06E-03	4.02E-03	1.17E-02	100
Freshwater eutrophication	kg P eq	1.32E-05	1.20E-05	5.15E-06	6.81E-06	2.60E-05	100
Global warming	kg CO2 eq	4.99E-02	4.45E-02	2.19E-02	2.45E-02	1.05E-01	100
Human carcinogenic toxicity	kg 1,4-DCB	6.59E-03	5.96E-03	3.21E-03	2.14E-03	1.49E-02	100

Impact category	Unit	Mean	Median	Standard Deviation	2.5%	97.5%	Percent of times Cash > Digital
Human non-carcinogenic toxicity	kg 1,4-DCB	5.76E-02	5.59E-02	1.03E+00	-1.99E+00	2.14E+00	51.7
Ionizing radiation	kBq Co-60 eq	3.29E-03	1.89E-03	4.24E-03	4.54E-04	1.52E-02	100
Land use	m2a crop eq	1.79E-03	1.67E-03	6.06E-04	1.01E-03	3.37E-03	100
Marine ecotoxicity	kg 1,4-DCB	8.76E-03	8.17E-03	2.62E-03	5.25E-03	1.51E-02	100
Marine eutrophication	kg N eq	2.80E-06	2.63E-06	7.68E-07	1.88E-06	4.55E-06	100
Mineral resource scarcity	kg Cu eq	5.02E-04	4.73E-04	1.36E-04	3.30E-04	8.52E-04	100
Ozone formation, Human health	kg NOx eq	1.45E-04	1.33E-04	5.42E-05	7.91E-05	2.80E-04	100
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.55E-04	1.42E-04	5.84E-05	8.41E-05	2.99E-04	100
Stratospheric ozone depletion	kg CFC11 eq	1.80E-08	1.62E-08	7.31E-09	9.59E-09	3.62E-08	100
Terrestrial acidification	kg SO2 eq	1.60E-04	1.49E-04	4.95E-05	1.01E-04	2.83E-04	100
Terrestrial ecotoxicity	kg 1,4-DCB	5.45E-01	5.06E-01	1.89E-01	2.92E-01	1.01E+00	100
Water consumption	m3	3.80E-04	2.38E-03	2.64E-02	-5.91E-02	4.69E-02	53

Source: Oxford Economics

TABLE 96: RESULTS OF SEPARATE MONTE CARLO SIMULATIONS OF ALL IMPACT CATEGORIES

Impact category	Unit	Mean	Median	Standard Deviation	2.5%	97.5%	Mean	Median	Standard Deviation	2.5%	97.5%
		Cash system					Digital system				
Germany											
Fossil resource scarcity	kg oil eq	4.74E-03	4.51E-03	1.10E-03	3.28E-03	7.31E-03	8.60E-04	8.49E-04	9.76E-05	7.01E-04	1.07E-03
Mineral resource scarcity	kg Cu eq	3.40E-04	3.36E-04	4.51E-05	2.63E-04	4.46E-04	4.95E-05	4.90E-05	6.68E-06	3.84E-05	6.42E-05
Marine eutrophication	kg N eq	2.15E-06	2.14E-06	2.26E-07	1.73E-06	2.64E-06	2.11E-07	2.08E-07	2.77E-08	1.65E-07	2.73E-07
Marine ecotoxicity	kg 1,4-DCB	6.42E-03	6.24E-03	1.31E-03	4.43E-03	9.13E-03	1.22E-03	1.21E-03	1.81E-04	9.16E-04	1.65E-03
Land use	m2a crop eq	1.07E-03	1.05E-03	2.48E-04	6.36E-04	1.62E-03	5.77E-04	5.61E-04	3.83E-04	-1.00E-04	1.34E-03
Terrestrial acidification	kg SO2 eq	8.51E-05	8.33E-05	1.19E-05	6.64E-05	1.13E-04	1.14E-05	1.14E-05	1.01E-06	9.56E-06	1.35E-05
Terrestrial ecotoxicity	kg 1,4-DCB	3.88E-01	3.51E-01	1.61E-01	1.95E-01	8.28E-01	3.12E-02	2.83E-02	1.29E-02	1.74E-02	6.20E-02
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.93E-05	4.78E-05	9.26E-06	3.62E-05	7.12E-05	9.30E-06	9.18E-06	1.25E-06	7.35E-06	1.21E-05
Freshwater eutrophication	kg P eq	1.49E-05	1.36E-05	5.63E-06	8.02E-06	2.83E-05	2.54E-06	2.38E-06	8.07E-07	1.58E-06	4.51E-06
Freshwater ecotoxicity	kg 1,4-DCB	4.99E-03	4.84E-03	1.02E-03	3.45E-03	7.21E-03	9.44E-04	9.33E-04	1.40E-04	7.08E-04	1.26E-03
Water consumption	m3	4.12E-04	1.14E-03	1.02E-02	-2.19E-02	1.91E-02	1.53E-05	2.03E-05	1.62E-03	-3.49E-03	3.10E-03
Global warming	kg CO2 eq	1.79E-02	1.72E-02	3.43E-03	1.34E-02	2.62E-02	3.05E-03	3.03E-03	2.78E-04	2.59E-03	3.69E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	3.73E-02	1.62E-02	7.26E-01	-1.45E+00	1.55E+00	1.30E-02	1.25E-02	8.49E-02	-1.69E-01	1.84E-01
Human carcinogenic toxicity	kg 1,4-DCB	3.73E-03	3.44E-03	2.18E-03	8.48E-04	8.16E-03	2.51E-04	2.35E-04	1.51E-04	8.57E-06	5.89E-04
Ionizing radiation	kBq Co-60 eq	1.65E-03	9.24E-04	2.21E-03	2.02E-04	8.67E-03	4.85E-04	2.69E-04	7.22E-04	5.78E-05	2.11E-03
Stratospheric ozone depletion	kg CFC11 eq	8.28E-09	8.08E-09	1.30E-09	6.22E-09	1.14E-08	1.41E-09	1.37E-09	2.38E-10	1.09E-09	1.96E-09
Ozone formation, Human health	kg NOx eq	4.67E-05	4.53E-05	8.60E-06	3.45E-05	6.72E-05	8.96E-06	8.84E-06	1.21E-06	7.07E-06	1.17E-05

Impact category	Unit	Mean	Median	Standard Deviation	2.5%	97.5%	Mean	Median	Standard Deviation	2.5%	97.5%
Fine particulate matter formation	kg PM2.5 eq	3.25E-05	3.18E-05	4.48E-06	2.58E-05	4.30E-05	4.69E-06	4.66E-06	4.38E-07	3.89E-06	5.60E-06
Italy											
Fossil resource scarcity	kg oil eq	3.19E-03	3.07E-03	7.80E-04	2.11E-03	5.04E-03	1.43E-03	1.42E-03	1.84E-04	1.12E-03	1.83E-03
Mineral resource scarcity	kg Cu eq	2.63E-04	2.60E-04	3.89E-05	2.00E-04	3.60E-04	1.34E-04	1.32E-04	2.09E-05	9.84E-05	1.81E-04
Marine eutrophication	kg N eq	1.56E-06	1.54E-06	2.05E-07	1.22E-06	2.01E-06	4.94E-07	4.87E-07	6.23E-08	3.90E-07	6.37E-07
Marine ecotoxicity	kg 1,4-DCB	5.14E-03	5.02E-03	1.08E-03	3.45E-03	7.61E-03	2.90E-03	2.85E-03	5.15E-04	2.07E-03	3.98E-03
Land use	m2a crop eq	8.82E-04	8.77E-04	2.16E-04	4.59E-04	1.33E-03	5.15E-04	4.92E-04	2.78E-04	3.59E-05	1.12E-03
Terrestrial acidification	kg SO2 eq	7.09E-05	7.01E-05	1.05E-05	5.38E-05	9.53E-05	2.17E-05	2.15E-05	2.30E-06	1.78E-05	2.70E-05
Terrestrial ecotoxicity	kg 1,4-DCB	3.63E-01	3.29E-01	1.49E-01	1.86E-01	7.98E-01	5.80E-02	5.26E-02	2.33E-02	3.23E-02	1.17E-01
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.84E-05	3.76E-05	7.07E-06	2.80E-05	5.53E-05	1.66E-05	1.66E-05	2.09E-06	1.29E-05	2.14E-05
Freshwater eutrophication	kg P eq	6.88E-06	6.53E-06	1.63E-06	4.46E-06	1.09E-05	5.08E-06	4.90E-06	1.32E-06	3.24E-06	8.18E-06
Freshwater ecotoxicity	kg 1,4-DCB	3.99E-03	3.90E-03	8.60E-04	2.65E-03	6.00E-03	2.22E-03	2.19E-03	3.97E-04	1.58E-03	3.09E-03
Water consumption	m3	-4.97E-06	6.81E-04	8.02E-03	-1.82E-02	1.55E-02	-1.04E-05	1.30E-04	3.10E-03	-6.37E-03	5.75E-03
Global warming	kg CO2 eq	1.14E-02	1.10E-02	2.46E-03	8.03E-03	1.73E-02	5.41E-03	5.38E-03	5.48E-04	4.42E-03	6.59E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	3.88E-02	4.89E-02	6.56E-01	-1.25E+00	1.32E+00	3.24E-02	3.28E-02	2.39E-01	-4.63E-01	5.04E-01
Human carcinogenic toxicity	kg 1,4-DCB	2.12E-03	2.01E-03	1.27E-03	-2.22E-05	4.83E-03	5.23E-04	5.00E-04	3.54E-04	-1.22E-04	1.30E-03
Ionizing radiation	kBq Co-60 eq	6.84E-04	3.66E-04	1.01E-03	7.96E-05	3.28E-03	6.62E-04	3.75E-04	9.74E-04	8.30E-05	2.71E-03
Stratospheric ozone depletion	kg CFC11 eq	5.52E-09	5.40E-09	9.34E-10	4.09E-09	7.84E-09	2.23E-09	2.20E-09	2.93E-10	1.74E-09	2.88E-09
Ozone formation, Human health	kg NOx eq	3.62E-05	3.55E-05	6.57E-06	2.64E-05	5.20E-05	1.60E-05	1.59E-05	2.03E-06	1.24E-05	2.05E-05

Impact category	Unit	Mean	Median	Standard Deviation	2.5%	97.5%	Mean	Median	Standard Deviation	2.5%	97.5%
Fine particulate matter formation	kg PM2.5 eq	2.60E-05	2.57E-05	3.83E-06	1.98E-05	3.54E-05	9.64E-06	9.56E-06	1.11E-06	7.76E-06	1.22E-05
Finland											
Fossil resource scarcity	kg oil eq	1.51E-02	1.35E-02	6.83E-03	6.84E-03	3.16E-02	6.12E-04	6.07E-04	6.28E-05	5.05E-04	7.50E-04
Mineral resource scarcity	kg Cu eq	5.48E-04	5.22E-04	1.34E-04	3.66E-04	9.06E-04	4.46E-05	4.36E-05	6.50E-06	3.44E-05	5.94E-05
Marine eutrophication	kg N eq	2.97E-06	2.80E-06	7.53E-07	2.02E-06	4.83E-06	1.43E-07	1.42E-07	1.58E-08	1.16E-07	1.79E-07
Marine ecotoxicity	kg 1,4-DCB	9.79E-03	9.39E-03	2.67E-03	6.22E-03	1.71E-02	1.02E-03	9.99E-04	1.68E-04	7.50E-04	1.42E-03
Land use	m2a crop eq	2.07E-03	1.96E-03	6.46E-04	1.18E-03	3.62E-03	2.86E-04	2.80E-04	1.50E-04	-1.85E-06	6.01E-04
Terrestrial acidification	kg SO2 eq	1.71E-04	1.61E-04	4.96E-05	1.05E-04	2.96E-04	8.93E-06	8.87E-06	7.99E-07	7.48E-06	1.06E-05
Terrestrial ecotoxicity	kg 1,4-DCB	5.88E-01	5.38E-01	2.30E-01	3.07E-01	1.12E+00	2.76E-02	2.46E-02	1.09E-02	1.49E-02	5.67E-02
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.64E-04	1.52E-04	5.95E-05	8.86E-05	3.17E-04	6.16E-06	6.08E-06	6.39E-07	5.12E-06	7.58E-06
Freshwater eutrophication	kg P eq	1.52E-05	1.40E-05	5.56E-06	8.41E-06	3.00E-05	1.98E-06	1.87E-06	5.34E-07	1.23E-06	3.30E-06
Freshwater ecotoxicity	kg 1,4-DCB	7.60E-03	7.29E-03	2.09E-03	4.80E-03	1.32E-02	7.84E-04	7.65E-04	1.29E-04	5.76E-04	1.09E-03
Water consumption	m3	-1.61E-03	3.30E-04	2.82E-02	-6.28E-02	4.92E-02	-1.68E-05	1.05E-04	1.60E-03	-3.47E-03	2.77E-03
Global warming	kg CO2 eq	5.29E-02	4.83E-02	2.15E-02	2.58E-02	1.07E-01	2.20E-03	2.19E-03	1.68E-04	1.92E-03	2.59E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	1.01E-01	1.14E-01	1.03E+00	-2.06E+00	2.03E+00	1.37E-02	1.50E-02	7.12E-02	-1.32E-01	1.55E-01
Human carcinogenic toxicity	kg 1,4-DCB	7.13E-03	6.37E-03	3.79E-03	2.40E-03	1.65E-02	2.24E-04	2.10E-04	1.42E-04	1.35E-05	5.33E-04
Ionizing radiation	kBq Co-60 eq	4.03E-03	2.18E-03	5.88E-03	5.25E-04	1.95E-02	5.04E-04	2.93E-04	7.03E-04	6.39E-05	2.38E-03
Stratospheric ozone depletion	kg CFC11 eq	1.93E-08	1.78E-08	6.95E-09	1.02E-08	3.75E-08	1.10E-09	1.06E-09	1.90E-10	8.72E-10	1.53E-09
Ozone formation, Human health	kg NOx eq	1.54E-04	1.42E-04	5.49E-05	8.34E-05	2.96E-04	5.94E-06	5.87E-06	6.22E-07	4.92E-06	7.31E-06

Impact category	Unit	Mean	Median	Standard Deviation	2.5%	97.5%	Mean	Median	Standard Deviation	2.5%	97.5%
Fine particulate matter formation	kg PM2.5 eq	7.22E-05	6.75E-05	2.19E-05	4.31E-05	1.28E-04	3.71E-06	3.67E-06	3.51E-07	3.08E-06	4.47E-06

Source: Oxford Economics

APPENDIX 7: CRITICAL REVIEW

2024

Critical Review Statement:

The environmental impact of digital over cash payments in Europe: White paper report for the European Digital Payments Industry Alliance

Niels Jungbluth (Chair, ESU-services Ltd., CH)
Susanne Jorre (TÜV Rheinland Energy & Environment GmbH, DE)
Erik Roos Lindgreen (Roos Sustainability Research, NL)

European Digital Payments Industry Alliance

Schaffhausen, 12. April 2024

Imprint

Title	Critical Review: The environmental impact of digital over cash payments in Europe: White paper report for the European Digital Payments Industry Alliance
Authors	Niels Jungbluth, Susanne Jorre, Erik Roos Lindgreen Dr. Niels Jungbluth: ESU-services Ltd., fair consulting in sustainability Vorstadt 10, CH-8200 Schaffhausen www.esu-services.ch, jungbluth@esu-services.ch Susanne Jorre, TÜV Rheinland Energy & Environment GmbH, Susanne.Jorre@de.tuv.com Erik Roos Lindgreen Research & advice | Roos Sustainability Research | Admiraal de Ruijterweg 352H, 1055NA, Amsterdam | +31615257214 | erik@roossustainabilityresearch.com
Commissioner	European Digital Payments Industry Alliance
Publications	This critical review statement is only valid for the full report (including a short summary) as it was provided for final review (see Tab. 1.1). It is not valid for any stand-alone abstracts or summaries made by the commissioner, the authors, or other parties. This critical review statement should be published together fully with the LCA report. Each reference to this review statement is only allowed if the same publication also shows the full review statement without alterations or directly makes it available via a weblink. The reviewers keep the right to provide the full report including this critical review statement to each party asking about this review because of statements or claims made regarding the study reviewed.
Version	12.04.24 16:02 https://esuservices-my.sharepoint.com/personal/jungbluth_esu-services_ch/Documents/ESU-intern/720 CriticalReview/2023 Oxfordeconomics/review/Panel-Critical Review-statement-ISO14040-cLCA-POS-payments-v240412.docx

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1 Background and Objectives

The study "The environmental impact of digital over cash payments in Europe: White paper report for the European Digital Payments Industry Alliance" shall be carried out according to the standards ISO 14040/44/71. In this context, the customer has launched an external critical review according to the standard for this work. This critical review shall turn around points defined by the standard ISO (objectives and scope, analysis of the inventory, the evaluation of the impacts and the interpretation).

This is a public study which does allow comparative assertions. Therefore, a review panel is recommended according to ISO standard. Three different reviewers have been chosen by the commissioner and Niels Jungbluth was appointed as the Panel Chair to coordinate the review panel. Key characteristics for this review are summarized in the following Tab. 1.1.

Tab. 1.1 Key characteristics of the critical review

Title	The environmental impact of digital over cash payments in Europe: White paper report for the European Digital Payments Industry Alliance
Commissioner	European Digital Payments Industry Alliance
Main author	Dr. Yann Girard, (ygirard@oxfordeconomics.com) Johanna Neuhoff (jneuhoff@oxfordeconomics.com) Dr. Jan Sun, Hannah Zick, Sven von Wangenheim Oxford Economics Ltd., Continental Europe, C/O Mindspace, Friedrichstraße 68, 10117 Berlin, Germany Tel (direct): +49 (0) 30 166 368 101 | Mobile: +49 (0) 172 441 5514 www.oxfordeconomics.com
Products and variants investigated	Digital and Cash Payments in Germany, Finland, and Italy at point-of-sale
Scope	Cradle-to-grave
Functional unit	One payment with digital or cash at the point of sale
Scenarios	Several scenarios Payments in different countries (FI, DE, IT)
Standard to be applied	ISO 14040/44 (International Organization for Standardization (ISO) 2006a, b)
Product category rules	n.a.
Comparative study	Yes
Publication foreseen	Yes
Size of documentation provided for review	337 pages final LCA report with an executive summary
Software for background calculations	SimaPro 2023
Background database	Ecoinvent v3.9.1, Cut-off (ecoinvent Centre 2023)
Foreground data	Several stages of both systems with data from questionnaires and literature
LCI data for review	Fully documented in report and/or LCA software model
Life cycle impact assessment	ReCiPe 2016 (Huijbregts et al. 2017)
Stages of the review	One stage for the full documentation.
Meetings in person	None
Reviewer	Critical review panel: Dr. Niels Jungbluth, ESU-services Ltd., CH (Chair) Susanne Jorre, TÜV Rheinland Energy & Environment GmbH, DE (Methodology expert) Erik Roos Lindgreen, Roos Sustainability Research, NL (Technical expert)

2 Standards and review criteria

The critical review was carried out according to the International Standards ISO 14040/44 (International Organization for Standardization (ISO) 2006a, b) according to the following five aspects outlined in the standard. It is assessed whether

- *"the methods used to carry out the LCA are consistent with this International Standard,*
- *the methods used to carry out the LCA are scientifically and technically valid,*
- *the data used are appropriate and reasonable in relation to the goal of the study,*
- *the interpretations reflect the limitations identified and the goal of the study, and*
- *the study report is transparent and consistent."*

The International Organization for Standardization (ISO) (2006a:6.3) states the following concerning the procedure for the review of a comparative study planned for publication:

"A critical review may be carried out as a review by interested parties. In such a case, an external independent expert should be selected by the original study commissioner to act as chairperson of a review panel of at least three members. Based on the goal and scope of the study, the chairperson should select other independent qualified reviewers. This panel may include other interested parties affected by the conclusions drawn from the LCA, such as government agencies, non-governmental groups, competitors and affected industries."

3 Review process

The task of the reviewer is to review the documentation provided according to Tab. 1.1 including the four phases, namely

- Goal and scope definition,
- Inventory analysis,
- Impact assessment, and
- Interpretation

The goal of the study as such is not reviewed as this lies in the responsibility of the commissioner. However, it was reviewed whether the goal is stated explicitly and transparently. The definition of the scope is part of the critical review including the definition of the functional unit, the system definition and its boundaries, the allocation approaches, and the impact category indicators chosen.

The authors of the study provide access to the data necessary for an informed critical review. This holds also true for data provided by third parties and for confidential data. The review of the inventory analysis includes the inventory raw data (input data), the modelling approaches and selected inventory results.

The review of the impact assessment should include the impact and characterization factors applied, the impact indicator results and, eventually, the normalized results.

Within the interpretation phase, the consistency of the modelling, the data used, and the conclusions is reviewed and checked whether it is in line with the goal and scope definition. Data quality aspects, significance, and sensitivity analyses as well as completeness checks are subject to the critical review too.

The following interactions shown in Tab. 3.1 between the commissioner, the practitioner, and the review panel took place.

Tab. 3.1 Procedure of the critical review and interactions between the commissioner, the practitioner, and the review panel

Interaction	Date
Provision of 1st full draft report and LCI documentation, answer to feedback	1.12.2023
Submission of review feedback	18.12.2023
Telephone conference with authors to discuss open questions	11.1.2024
Provision of 3rd full draft report and LCI documentation and answers to review comments	12.1.2024
Submission of review feedback	17.1.2024
Provision of 3rd full draft report and LCI documentation and answers to review comments	7.2.2024
Submission of review feedback	29.2.2024
Discussion in Telco	7.3.2024
Provision of 4th full draft report and LCI documentation and answers to review comments	20.3.2024
Provision of draft critical review statement	9.4.2024
Final documentation	11.4.2024
Provision of final critical review statement	12.4.2024

The process of the review can be summarized as follows:

- The reviewers have identified some key issues, which are sufficiently addressed in the final report. Upon reviewer's request revisions were made concerning documentation in the report, LCI models, software, and description of results. There was no direct contact between the reviewers and the commissioner of the study.
- The final study report and the LCI model in Excel include almost all reviewer comments given in the earlier stages of the review process.
- The present definitive version of the review report considers the revisions made by the authors after submitting the feedback on the pre-final report.
- The goal of the study lies in the responsibility of the commissioner. It was reviewed whether the goal is stated explicitly and transparently.
- The definition of the scope was part of the critical review, the definition of the functional unit, the system definition and its boundaries and the allocation approaches. The review of the inventory analysis included the modelling in SimaPro.
- The review of the impact assessment includes only the impact indicator results, but no normalized results or weighted results.
- Within the interpretation phase, the consistency of the modelling, was reviewed and checked whether they are in line with the goal and scope definition.
- It was not in the responsibility of the reviewers to check the report for formatting, layout, grammar, and spelling issues.
- This critical review statement is only valid for the full documentation as it was provided for last stage of the review (see Tab. 1.1). It is not valid for any abstracts or summaries made by the commissioner, the authors, or other parties.

4 Critical review report according to ISO 14044

4.1 Consistency of the methods with the ISO standards

The functional unit and reference flow are considered appropriate for the goal and scope of this study.

The functional unit and reference flow were discussed among the reviewers and with the authors in view of the goal and scope of this study.

A simplification or choice on showing only single indicators has not been made in the report. The review statement is only valid for showing all indicators as provided in the study, but not for an extract of these results. Any choice on single indicators needs further justification which is not made in the report.

4.2 Scientific and technical validity of the methods applied

In general, the inventory models established are scientifically and technically valid. The review is made on samples of the modelling and data. It cannot not fully and deeply check all models and data.

The LCIA indicators applied follow the requirements of ISO norms.

- The ReCiPe method 2016 can be considered as slightly outdated. To confirm the LCIA method does not influence the comparative assertions, the authors run the baseline model using the Environmental Footprint (EF) method. The results with the Environmental Footprint method are consistent with those of the ReCiPe 2016 method. Thus, this choice can be debated, but the influence on the results as well as on the influence on the comparative assertions seems to be small.

4.3 Appropriateness of data

The report includes a description of the foreground data. There are nearly no primary data e.g. from the commissioner. The whole model is based on a review of different literature sources and a combination of these information in the LCI model. This is due to the complexity of the two systems.

Possible problems on the data quality are discussed in the report and sensitivity analysis has been made for critical points. Critical points for the analysis and comparison are:

- The assumptions regarding driving to the ATM: There was some disagreement between the panel and the authors about how many kilometres of passenger car travel can be assigned to the cash system in the base case scenario. In detail, the review panel questioned the validity of combining data on the average distance to the ATM and the share of transports to the ATM with the sole purpose of withdrawing money.
- The amount of coins and banknotes assigned to a cash payment at POS.
- The amount of infrastructure (including the metals finally used in this infrastructure) and electricity assigned in all activities related to information technology.

The underlying model of life cycle inventory data was provided in SimaPro format. This facilitated the review considerably and is highly acknowledged.

Small amount of data were available by the commissioner of the report for all processes under their control.

The data used in the foreground and in the background can be justified in view of the goal and scope of the study.

For the reviewers, it is not possible to fully ensure the correctness and validity of all calculations within such a review process.

4.4 Assessment of the interpretation in view of limitations and goal and scope

As such, the results presented in the report are well justified.

The interpretation considers the limitations due to the goal and scope of this study.

4.5 Transparency and consistency of study report

All relevant information could be found in the report (or the electronic data). The report is clearly structured and well-readable. With the information, the report is acknowledged as transparent and consistent.

4.6 Self-declaration of reviewer independence & competencies

(According to ISO/PDTS 14071, Annex B)

We (Niels Jungbluth, Susanne Jorre, Erik Roos Lindgreen), hereby declare that:

- We are not a full- or part-time employee of the study's commissioner or practitioner.
- We have not been involved in scoping or carrying out any of the work to conduct the study at hand, i.e., we have not been part of the commissioner's or practitioner's project team(s).
- We do not have vested financial, political, or other interests in the outcome of the study.

Our combined competencies relevant to the Critical Review at hand include knowledge of and proficiency in:

- ISO 14040, 14044 and 14067.
- LCA methodology and practice, particularly in the context of LCI, (including data set generation and data set review, if applicable).
- Critical Review practice.
- The scientific disciplines relevant to the important impact categories of the study.
- Environmental, technical, and other relevant performance aspects of the product system(s) assessed.
- Language used for the study.

A short CV and a list of relevant references are part of the review report.

We assure that the above statements are truthful and complete.

4.7 Conclusions

The goal and scope are appropriately defined. The methods used are scientifically and technically valid. The data used are with some limitations appropriate and reasonable in view of the goal and scope of the study. The report is complete, clearly structured, and readable. Conclusions and recommendations are based on the results of the analyses, respecting the limitations described in the report.

The two systems compared are quite complex and there might be some variation of environmental impacts depending on the region and the personal behaviour of people using the systems. Allocation choices, setting system boundaries and the foreground data applied can influence the results to a certain extent. Thus, results are only valid as an average assumption, but might look different on an individual basis.

Thus, the reviewers do suggest to not communicate a defined value for the absolute value of the two system nor the potential difference. It is suggested to communicate only a range of possible improvements. In addition, a comprehensive presentation (e.g., by describing the limitations and assumptions) of the results should be chosen and a rejection of communicating only the results of one impact category.

The reviewed study, as outlined in Tab. 1.1 complies with the requirements of the ISO standards 14040/44.

We accept submitting the entire report including this critical review report to the commissioner and/or publishing the full report as outlined in the last version, including this review statement.

Dr. sc. tech. ETH, Niels Jungbluth, ESU-services Ltd., Schaffhausen, on behalf of the review panel

Chief Executive Officer ESU-services Ltd.

Schaffhausen, Friday, 12 April 2024

Susanne Jorre, TÜV Rheinland Energy & Environment GmbH, Sustainability Expert

Cologne, Friday, 12 April 2024

Erik Roos Lindgreen, Roos Sustainability Research, NL

Amsterdam, Friday, 12 April 2024

5 References

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SimaPro 2023 SimaPro (2023) SimaPro 9.5 LCA software package. PRé Sustainability, Amersfoort, NL, retrieved from: https://esu-services.ch/de/simapro/.

6 The reviewers experience

6.1 Dr. Niels Jungbluth

6.1.1 ESU-services Ltd., CH

ESU-services Ltd. was founded in 1998. Its core business is research, consulting, review, and training in the field of Life Cycle Assessment (LCA). This methodology aims to investigate environmental aspects of products and services from cradle to grave, from resource extraction to manufacture, use and end of life treatment.

Fairness, independence, and transparency are the main characteristics of our consulting philosophy. We work issue-related and accomplish our analyses without prejudice. We document our studies and our work in a transparent and comprehensible manner. We offer a fair and competent consultation, which enables our clients to control and continuously improve their environmental performance.

ESU-services covers several economic sectors such as energy, basic minerals, metals, and chemicals, biomass, transportation, waste management, information technology, food and lifestyles. ESU-services also contributes to the development of impact assessment methods such as ecological scarcity 2013. Since 2007, ESU-services runs the Regional SimaPro Competence Centre of Switzerland. Germany, Liechtenstein and Austria.

6.1.2 CV

Niels Jungbluth studied environmental engineering at the Technical University of Berlin. He started working with LCA in 1994 and prepared his diploma thesis during a six month stay at the TATA Energy Research Institute in New Delhi, where he carried out a life cycle assessment for cooking fuels in India. Between 1996 and 2000 he worked on a Ph.D. Project at the Swiss Federal Institute of Technology (ETH) in Zurich at the chair of Natural and Social Science Interface. His Ph.D. thesis on the environmental consequences of food consumption has been awarded the Greenhirn Prize 2000 by the German Öko-Institut. In this thesis, he investigated food consumption patterns by means of life cycle assessment.

He started working with ESU-services in 2000. Since 2006 he has been the owner and managing director. Since 2000 he has worked on more than 400 consultancy projects in the areas food, biomass, energy systems, input-output-analysis, sustainable consumption, as well as several other topics. Besides managing ESU-services, he also conducts critical reviews, verification, and validation according to different standards.

Niels Jungbluth is in the editorial board of the "Int. Journal of LCA" and in the board of the LCA foods conference. He works as reviewer for other scientific journals.

6.1.3 References (selection)

ESU-services has conducted more than 400 projects related to LCA in the past 25 years. See below for a brief list of the most recent and relevant projects involving a review. A full description of the company including a list of several hundred project references can be found on the Internet (www.esu-services.ch/projects/fulllist/). The full list of papers peer-reviewed by Niels Jungbluth can be found on publons.com/author/488732/niels-jungbluth#profile. Since 2000 ESU was involved in more than 90 such evaluations.

Year	Project title	Commissioned by
Since 1999	Peer Reviews of papers	www.publons.com/researcher/488732/niels-jungbluth
Since 2001	Subject Editor "LCA for Energy Systems and Food Products"	The International Journal of LCA
Since 2008	Member of the Scientific Committee and reviewer of abstracts and papers (Niels Jungbluth, PhD)	International Conference on Life Cycle Assessment of Foods
Since 2014	Individual verifier for the international EPD® System	On request
2024	Critical review, chair: The environmental impact of digital over cash payments in Europe: White paper report	European Digital Payments Industry Alliance, EU
2024	Verification: LCA and EPD of Herbicide Reductants (WEED Solut-ioN®)	PT Pandawa Agri Indonesia, ID
2024	Critical review, panellist: Comparative LCA of TemperPack's ClimaCell Insulation System and Expanded Polystyrene Shipping Cooler	TemperPack Technologies, Inc., US
2024	Verification: LCA and EPD of partitions and doors	Strähle Raum-Systeme GmbH, DE
2024	Critical review: LCA of circular textile value chains	RISE Research Institutes of Sweden AB
2024	Verification: LCA and EPD of Concrete Mixture for LVT block production	Vigier Rail AG, CH
2024	Product Environmental Profiles (PEP) of various enclosure systems	ABB STRIEBEL & JOHN GmbH, DE
2024	Product Environmental Profile (PEP) for Dual Single Shunt Trip (verified)	ABB Stotz-Kontakt GmbH, DE
2023	Product Environmental Profile (PEP) for ABB MCB - Miniature Circuit Breaker (verified)	ABB Stotz-Kontakt GmbH, DE
2023	Product Environmental Profile (PEP) for S2C-HxxL series (verified)	ABB Stotz-Kontakt GmbH, DE
2023	Product Environmental Profile (PEP) for S2C Auxiliary Contacts (verified)	ABB Stotz-Kontakt GmbH, DE
2023	Analysis and testing of LCIA methods for biodiversity	Mondi, AT
2023	Critical review, chair: Comparative Life Cycle Assessment of feed additives	Phileo by Lesaffre, FR
2023	Critical review, chair: Comparative Life Cycle Assessment of lubricants	Peter Greven GmbH, DE
2023	Critical review: LCA of a cellulose carbamate fibre	RISE Research Institutes of Sweden AB
2023	Comparative Life Cycle Assessment of Mondi's paper-based solution to conventional LDPE shrink wrap for bundling and carrying PET bottles (panel critical review)	Mondi, AT
2023	Verification: LCA and EPD of electric bus - B19E01 and K9UD	BYD Company Limited, CN
2023	Comparative LCA of tap water and mineral water in Germany (panel critical review)	wvgw Wirtschafts- und Verlagsgesellschaft Gas und Wasser mbH, DE
2023	Critical review: Comparative LCA of packaging kits	Vacheron Constantin, Branch of Richemont International S.A., CH
2023	Critical review, chair: Comparative Life Cycle Assessment: Beef and Veg Burgers	Tesco, UK
2023	Feedback on LCA calculations: Advertising-related emissions and environmental impact in Switzerland	Infras, CH
2023	Critical review, panellist: LCA of liquid fabric enhancers and in-wash fragrance boosters	EarthShiftGlobal, US
2023	Critical review: LCA of plastic foils	Scanfill AB, SE
2023	Comparative carbon footprint of biodegradable polymer compounds (single expert critical review)	Agrana Group, DE
2023	Critical review, panellist: LCA of tofu, A comparison to chicken and beef as protein sources	Long Trail Sustainability, US
2023	Critical review: Carbon footprint of medicine containers	Laboratoire AGUETTANT, FR
2023	PCF assurance: Product Carbon Footprint of kitchen cabinets	Reform Group, DK

6.2 Susanne Jorre

6.2.1 TÜV Rheinland Energy & Environment GmbH, DE

TÜV Rheinland is a global leader in independent inspection services, ensuring quality and safety for people, the environment and technology in nearly all aspects of life. TÜV Rheinland inspects technical equipment, products and services, oversees projects and helps to shape processes for companies around the world. Since 2006 TÜV Rheinland has been a member of the United Nations Global Compact to promote sustainability and combat corruption. With extensive experience in environmental services, TÜV Rheinland can support companies in conducting environmental simulations, acoustic testing and measurement, energy audits and life cycle assessments for their products. TÜV Rheinland carries out and reviews many life cycle assessment studies including energy and resource consumption, emissions to air and water, incidental waste, and toxicity potential of products in order to ensure reliability and validity according to all relevant standards and regulations.

6.2.2 CV

Susanne Jorre studied ecology and environmental protection at the university of applied sciences Zittau/ Görlitz. She started working with PCF and LCA topics in 2013 and prepared her diploma thesis in the chemical sector. Between 2011 and 2013 she did several internships in environmental and energy management in the automotive, chemical and food industry.

Since 2013 she is working for TÜV Rheinland Energy & Environment GmbH as a sustainability expert and deals with calculation and evaluation of environmental impacts and economic aspects over the entire life cycle, analysis of data quality including plausibility checks and data research as well as conducting critical reviews of external studies according to compliance with relevant standards. By end of 2018 she was approved as an official reviewer at Environdec.

6.2.3 References (selection)

Company	Content/ Topic	Source
BMW AG	Data validation life cycle assessments	Link
Toyota Motor Corporation	Critical review of Life Cycle Assessment methodology	Link
Nissan Automobil AG	Critical review of Life Cycle Assessment methodology	Link
Seat S.A.	Critical review of Life Cycle Assessment	Link
Bosch Healthcare Solutions GmbH	Critical review of Product Carbon Footprint	Link
Linde Material Handling AG	Critical review of Life cycle assessments	Link
BEG GmbH	Preparation of Life Cycle Assessments	Link
Telekom Deutschland GmbH	Critical review of Product Carbon Footprint	Link
AIR LIQUIDE Deutschland GmbH	Critical review of Product Carbon Footprint	Link
Evonik Nutrition & Care GmbH	Critical review of Life Cycle Assessment	Link
ASK Chemicals GmbH	Critical review of Life Cycle Assessment	Link
Interstuhl Büromöbel GmbH & Co. KG	Preparation of Life Cycle Assessments	Link
Nestlé Deutschland AG	Critical review of Life Cycle Assessment	Link
SIG Combibloc	Critical review of Life Cycle Assessment	Link
Schindler Fahrtreppen International GmbH	Critical review of Life Cycle Assessment	Link
Heliatek GmbH	Preparation of Life Cycle Assessments	Link
Teijin Aramid BV	Critical review of Life Cycle Assessment methodology	Link
DMK Deutsches Milchkontor GmbH	Preparation of Life Cycle Assessments	Link

6.3 Erik Roos Lindgreen

6.3.1 Roos Sustainability Research, NL

Roos Sustainability Research is a sole proprietorship owned by Erik Roos Lindgreen. Operating since early 2023, it is specialized in sustainability and impact measurement consultancy and research. Roos Sustainability Research realized and contributed to several projects related to impact measurement and LCA. A few examples are setting up and managing a consortium of 20+ scientific and industry partners for the Oiconomy Pricing Foundation (NL); providing LCA support for circular economy businesses in several African countries with Footprints Africa (UK); LCA support for realizing automated LCA software in the food sector with startup Sproutfull (NL); conducting LCA reviews and Product Carbon Footprint (PCF) studies with epi Consulting (UK); and supervising master students in Business Administration with their theses for the Amsterdam Business School (NL).

6.3.2 CV

Erik Roos Lindgreen, PhD is a researcher and consultant from Amsterdam, the Netherlands. He specializes in sustainability impact assessment. His key interest: how to find a balance between scientific accuracy and feasibility when using sustainability impact measurement methods? Consumers need evidence on sustainability claims, and decision-makers need guidance when choosing one sustainability strategy over the other. Researchers have developed intelligent methods to measure environmental and social impacts, but these are not always taken up by businesses and governments, let alone understood by consumers. Erik's work focuses on the question: how can we make these methods and their results more accessible and understandable? And what are the most important factors at play here?

From 2016-2018, Erik worked as a sustainability and LCA consultant at CE Delft (NL), on topics such as biobased plastic, recycling technologies, and packaging materials. Before, he obtained two master’s degrees in Environment & Resource Management and Earth Sciences from the University of Amsterdam and the Free University (VU). In 2018, he moved to Messina, Italy, where he obtained a summa cum laude PhD degree in Economics, Management & Statistics at the University of Messina in 2022. His PhD was part of the H2020 EU-funded project Cresting and focused on quantifying the impact of circular economy practices.

After his PhD, Erik launched Roos Sustainability Research, where he works freelance for clients such as PRé Sustainability, epi Consulting, Footprints Africa, Sproutfull, the Copernicus Institute (University of Utrecht), the Amsterdam Business School, and others. He also publishes scientific articles in journals such as the International Journal of Life Cycle Assessment and Business Strategy and the Environment.

6.3.3 References (selection)

For scientific articles, see https://www.researchgate.net/profile/Erik-Roos-Lindgreen or https://scholar.google.com/citations?user=JY_E_8MAAAAJ&hl=en

For projects, see https://roossustainabilityresearch.com/projects/

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