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REGIONAL TOPICS FROM EUROPE

Life cycle assessment of cash payments in the Netherlands

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Abstract

Purpose This study quantifies the impact of the Dutch cash payment system on the environment and on climate change using a life cycle assessment (LCA). It examines both the impact of coins and of banknotes. In addition, it identifies areas within the cash payment system where the impact on the environment and on the climate can be reduced.

Methods The ReCiPe endpoint (H) impact method was used for this LCA. The cash payment system has been divided into five subsystems: the production of banknotes, the production of coins, the operation phase, the end of life of banknotes and the end of life of coins. Two functional units were used: (1) cumulative cash payments in the Netherlands in 2015 and (2) the average single cash payment in the Netherlands in 2015. Input data for all processes within each subsystem was collected through interviews and literature study. Ten key companies and authorities in the cash payment chain contributed data, i.e. the Dutch central bank, the Royal Dutch Mint, a commercial bank, a cash logistic service provider, two cash-in-transit companies, two printing works, an ATM manufacturer and a municipal waste incinerator.

Results and discussion The environmental impact of the Dutch cash payment system in 2015 was 2.42 MPt (expressed in eco points) and its global warming potential (GWP) was 19 million kg CO_2 equivalents (CO_2e). For an average single cash transaction, the environmental impact was 654 μPt and the GWP was 5.1 g CO_2e. The operation phase (e.g. energy use of ATMs, transport of banknotes and coins) (64%) and coin production phase (31%) had the largest impact on the environment, while the operation phase also had the largest impact on climate change human health (89%) and climate change ecosystems (56%). Finally, scenario analysis shows that reductions of the environmental impact (47%) and the impact on climate change (50%) could be achieved by implementing a number of measures, namely reducing the number of ATMs, stimulating the use of renewable energy in ATMs, introducing hybrid trucks for cash transport and matching coins with other countries in the euro area.

Conclusions This is the first study that investigates the environmental impact and GWP of the cash payment system in the Netherlands, by taking both the impact of banknotes and coins into account. The total environmental impact of cash payments in 2015 was 2.42 MPt and their GWP was 19 million kg CO_2e.

Keywords Banknotes · Cash payment system · Coins · Environmental impact · GWP · LCA

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1 Introduction

Payments are an economically fundamental area. A well-functioning payment system is a major precondition for financial stability and economic prosperity in a country, as it facilitates an efficient exchange of goods and services between consumers and businesses. In this study, we aim to provide insights into the environmental impact of a frequently used means of payment, i.e. cash in the Netherlands in 2015. In 2015, there were approximately 19 billion euro banknotes and 116 billion euro coins in circulation in the euro area[1] with a total value of EUR 1100 billion (ECB 2017).[2] Citizens inside and outside the euro area use banknotes, coins and payment cards to buy goods and services at the point-of-sale (POS), and use banknotes and coins to make person-to-person (P2P) payments to each other (e.g. charity, among family members, friends) and for hoarding. Almost all Dutch households have a payment account with a debit card (Van der Cruijsen and Plooij 2018). They pay a periodic bank fee for a payment package including a current account, a debit card and a credit card (optional). They can use the debit card to withdraw cash (banknotes) from automatic teller machines (ATMs) and to pay for purchases at payment terminals at the physical points-of-sale without having to pay any bank fees. Consumers usually receive coins from retailers as change. Retailers can order coins from their bank or cash-in-transit (CiT) company.

Consumers in the Netherlands made 3.7 billion cash payments representing a total value of EUR 49.6 billion in 2015: 0.5 billion P2P payments with a total value of EUR 9.6 billion and 3.2 billion POS payments with a total value of EUR 40 billion (DNB/DPA 2016). Like in many other countries, the Dutch are increasingly substituting cash with card payments at the POS. In the Netherlands, the debit card is the closest substitute for cash; the Dutch used the debit card for 3.2 billion POS payments with a total value of EUR 92.5 billion, whereas they used the credit card for 31 million POS payments at a total value of 3.2 billion (DNB 2017). In general, Dutch consumers mainly use cash at the POS when they buy a low-value item and they use the debit card when they buy a high-value item. However, since the introduction of contactless debit card payments in 2014, the debit card has become increasingly popular for low amounts as well (Jonker et al. 2018).

One similarity in the functionality of cash and debit cards is that consumers can use them both at almost any physical POS. Credit card acceptance is lower, i.e. 30% (DNB 2018; Panteia 2018).[3] Retailers who accept debit card payments do so for all amounts and without applying surcharges to customers; however, this may not hold for credit card payments. Another important difference in functionality between cash and payment cards is that cash can be used for P2P payments as the transfer of money using cash does not require the usage of a payment terminal or any activities from parties other than the payer and the payee. Consequently, the transfer of money using cash is immediate and anonymous, whereas this does not hold for card payments, as they require several activities from payment service providers in the electronic card payment system.[4] Moreover, as cash payments do not require these activities, they are less vulnerable to disturbances in the electronic payment system than card payments.[5] The anonymity and immediacy of cash incurs a risk that payment cards do not have: criminals may produce counterfeit banknotes and rob civilians, stores and ATMs in order to acquire cash. A difference in functionality from a consumer perspective concerns when cash and payment cards can be used to pay. Essentially, consumers can use cash if they have a sufficient amount of cash on them, they can use the debit card as long as they have sufficient funds on their current account and they can use the credit card as long as they have not exceeded their spending limit. So, cash users have to ensure they have enough cash on them before they are able to make a purchase, whereas card users often do not. However, many cash users state that it is precisely this feature of cash that helps them avoid overspending (Von Kalckreuth et al. 2014; Hernandez et al. 2017).

The goal of this study is to provide insights into the environmental impact of a frequently used means of payment, i.e. cash. Various stakeholders in the cash payment chain, like central banks, coin minters, printing works, ATM manufacturers, CiT companies and banks, are responsible for the quality and the availability of the euro banknotes and coins as well as the smooth operation of the cash payment system. Energy and material-intensive processes are involved within this system, such as banknote and coin production, transportation of banknotes and

[1] The euro area is a monetary union of 19 countries in the EU which have adopted the euro as their common currency.

[2] The number of banknotes and coins in circulation *in* the Netherlands is unknown since the introduction of the euro in 2002.

[3] The acceptance of cash, debit card and credit card differs per market segment. Cash, debit card and credit card acceptance is almost universal at POS locations where many transactions take place and where the transaction amounts can be high, i.e. at petrol stations, supermarkets (low credit card acceptance) and in large stores. Almost all small stores, street vendors, bars and restaurants accept cash, but not all of them accept debit card payments and credit card acceptance is rare.

[4] A card payment needs to be authorised by the bank of the payer and processed by the bank of the payer, an automatic clearing house and the bank of the payee in order to transfer the funds from the payer's account to the payee's account. In case of a debit card payment, this may take a working day, and in case of a credit card payment, this may take a few weeks.

[5] Note that, although the transfer of cash from payer to payee is immediate, the depositing of cash by payees at the bank or cash-in-transit company in order to have the value of the cash deposit transferred to their current account is not immediate, as it also requires processing activities by the payee's CiT company and/or bank.

coins, ATM operation and checking the quality of the banknotes and coins in circulation. We examine the environmental impact of the cash payment system as a whole in the Netherlands in 2015, as well as the environmental impact of an average cash payment of EUR 13.43 using the ReCiPe (H) endpoint method. Subsequent objectives of the research are the identification of areas of heightened environmental concern within different stages of the cash payment system and the proposal of strategic reduction measures aimed at lowering the environmental impact. Ultimately, a comparison is drawn with the environmental impact of debit card payments. Furthermore, we examine the global warming potential (GWP) of the Dutch cash payment system, as the Dutch banking sector aims to contribute to the reduction of CO_2 emissions (NVB 2015). A life cycle assessment (LCA) is conducted using input data from ten key companies and authorities in the Dutch cash payment chain, i.e. De Nederlandsche Bank (DNB, the Dutch central bank), Koninklijke Nederlandse Munt (KNM, Royal Dutch Mint), a commercial bank, a cash logistics services provider, two CiT companies two printing works, an ATM manufacturer and a municipal waste incinerator. To the authors' knowledge, an important novelty of this study compared to earlier studies is that it also takes the environmental impact of coins into account, not only of banknotes, in a single economy. Furthermore, it is one of the first to assess the impact of possible changes in the cash payment infrastructure on the environment and on climate change and it is the first to compare the environmental impact of cash with debit card payments. Even though the results are based on the situation in the Netherlands, they are also relevant for other countries, within and outside the euro area.

Earlier studies only considered the environmental impact of banknotes not of coins. Wettstein and Lieb (2000) conducted an LCA on Swiss banknotes and the ECB (2005) on euro banknotes. They find that the operation phase has the largest environmental impact stemming from the transportation of banknotes and the energy use of ATMs. Marincovic et al. (2011), Shonfield (2013) and Luján-Ornelas et al. (2018) conducted LCAs in which they compared paper banknotes with polymer banknotes. They conclude that polymer banknotes have environmental benefits over paper banknotes, except for the midpoint indicator photochemical ozone creation (Shonfield 2013). Roos Lindgreen et al. (2018) were the first to examine the environmental impact of debit card payments. It showed that the environmental impact of a single debit card payment in the Netherlands in 2015 was 470 μPt. The impact of the subsystem POS payment terminals was dominant (75%), followed by debit card production (15%) and datacentres (11%).

2 Methodology

The environmental impact of cash payments is calculated by conducting a full LCA, according to the ISO 14044 methodology. This methodology requires that an LCA study includes the following phases: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation (ISO 14044 2006). We chose the attributional LCA type, which is characterised by its focus on describing the environmental impact of a system. It can be used to identify the impact throughout the system and to find opportunities for reducing the impact in different parts of it (Brander et al. 2009). We apply the impact assessment method ReCiPe 2008 (H) which consists of 18 midpoint impact categories and three endpoint indicators (human health, ecosystem and resources). The three endpoints are the results of aggregating the impacts of the midpoint categories. The ReCiPe methodology allows the conversion of the three endpoint indicators by weighting into a single environmental indicator, the so-called Eco-indicator 99. The value of the Eco-indicator 99 is expressed in points (Pt). The advantage of this indicator is that it allows for a comparison of the environmental impact between products that are substitutes, like between cash and debit card payments. A caveat of this approach is that it is based on a certain perspective and weighting, and is therefore subject to some degree of uncertainty and scientific debate (Goedkoop et al. 2009). In this study, we apply the hierarchist perspective which is 'based on the most common policy principles with respect to time-frame and other issues' (Goedkoop et al. 2009). Furthermore, we use the IPCC GWP method to calculate the climate change impact of the cash payment system, expressed in CO2 equivalents (CO_2e).

2.1 Goals and scope definition

The goal of this study is to gain quantitative insight into the environmental impact of cash transactions in the Netherlands in 2015. The study was commissioned by DNB and the results are intended for general publication. We use two functional units. The first functional unit is the *entire cash payment system in the Netherlands with all cash transactions in 2015*. The total number of cash payments in 2015, including both POS payments and P2P payments, was 3.7 billion with a total value of EUR 49.6 billion. We use this functional unit to quantify and analyse the environmental impact and the GWP of the cash payment system as a whole, as well as its impact on midpoint categories. We relate the cash payments' GWP to the overall impact of the Dutch economy on climate change in 2015. Furthermore, by identifying environmental hotspots in the cash payment system, effective reduction measures can be identified, which form the basis of the scenario analysis, presented in Section 3.3. Implementing these measures could slow down the depletion of natural resources, as well as global warming. The second functional unit is *one average cash payment in the Netherlands in 2015*. The average value of a cash payment was EUR 13.42. This additional functional unit is employed to compare the environmental impact of a sole cash payment at a Dutch POS with the impact of a single debit card payment, while correcting for different usage levels: cash was used 3.7 billion times, whereas the debit card was used 3.2 billion times. Such a comparison is useful as it provides insight into how the ongoing substitution process of cash by debit card payments influences the environmental impact and GWP of the Dutch POS payment system.

One of the functional units in this study, i.e. an average debit card payment in the Netherlands in 2015, is similar to the functional unit chosen by Roos Lindgreen et al. (2018) due to the similarity in the study's goals, i.e. 'to identify, analyse and quantify the environmental impact of a debit card payment based on the POS debit card system in the Netherlands in 2015' (Roos Lindgreen et al. 2018).[6] The functional unit of Marincovic et al. (2011), Shonfield (2013) and Luján-Ornelas et al. (2018) who study the environmental impact of the introduction of new polymer banknotes compared to (HD) paper-based cotton banknotes is slightly different.[7] The main difference concerns the determination of a specific time span depending on the expected longer lifecycle of the polymer banknotes compared to cotton-based paper banknotes, instead of a reference year. This allows them to assess the environmental impact of fewer production cycles and end of life cycles in the same amount of time due to the longer lifetime of the polymer banknotes. Another difference is that they examine the environmental impact of (specific) banknotes, whereas we examine all coins and banknotes. However, in general, the way the LCAs have been conducted in the different cash/banknote studies is to a large extent the same. In that respect, the outcomes of the studies can be compared, when keeping in mind any differences in system boundaries.

The Dutch cash circulation consists of both euro banknotes and euro coins of different denominations which have different lifetimes and different life cycles. We have therefore divided the cash payment system into five subsystems: the production of banknotes, the production of coins, the operation phase of banknotes and coins in which they are distributed to ATMs, bank branches and retailers in the cash payment system, the end-of-life phase of banknotes and the end-of-life phase of coins (see Fig. 1). Due to the complexity of the studied system, the subsystems are further divided into groups of unit processes that are detailed within the life cycle inventory, i.e. 1A–5C. Sensitivity analysis has been used to assess the influence of applying different assumptions regarding the lifespan of euro coins and the share of recycled metals in euro coin production on the environmental impact of the Dutch cash payment system.

2.2 Data and assumptions

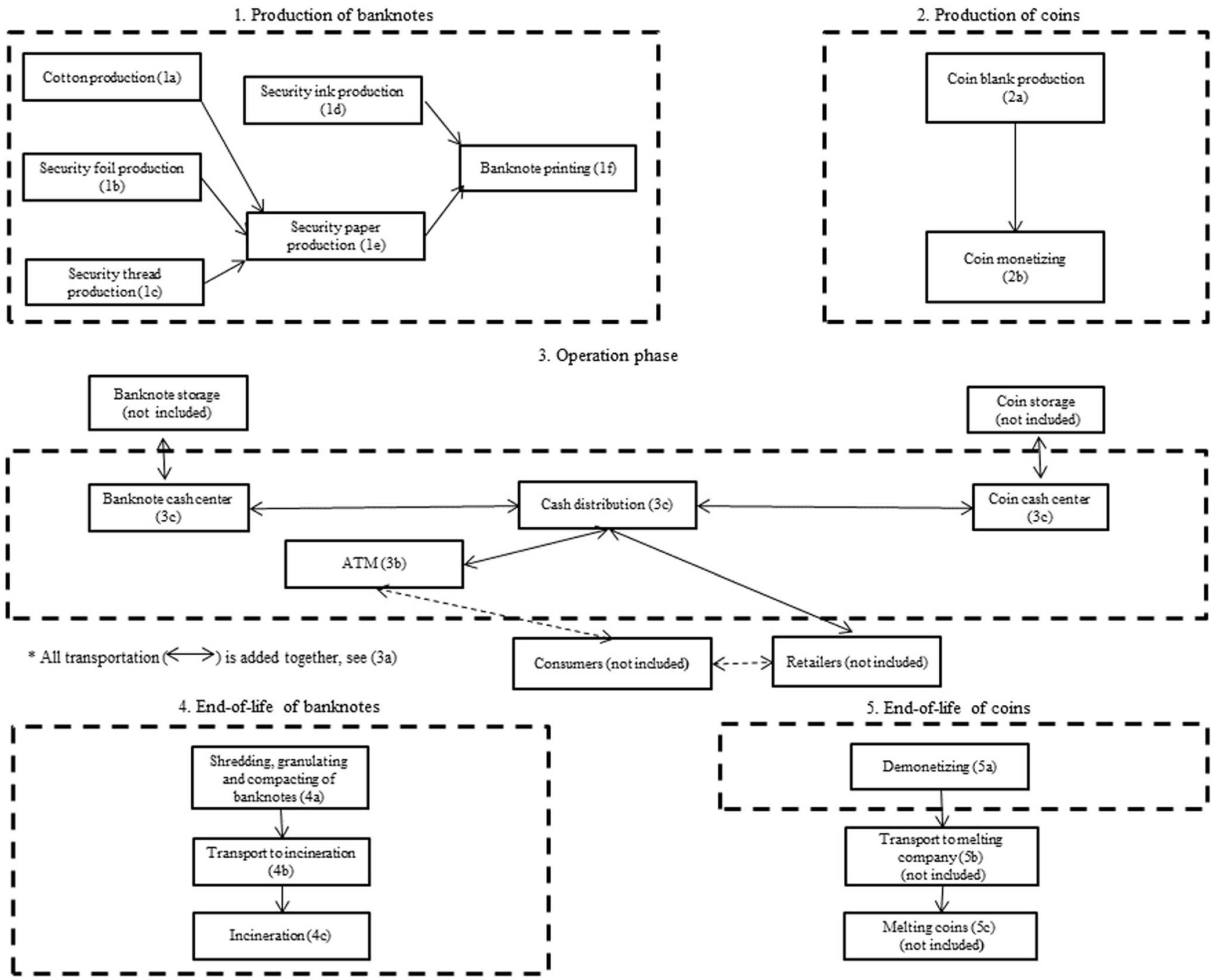
The cash payment system has been divided into five subsystems. This division has also been used for the inventory analysis and for the calculation of the environmental impact per subsystem. In this section, all data inputs and assumptions are discussed separately for each of these sub-processes. Table 1 provides an overview of all inventory inputs, ordered per subsystem.

2.2.1 Production of banknotes

The production of banknotes involves the use of four main products (cotton, thread, foil and ink), which are combined in two different processes, i.e. security paper production and banknote printing (see Table 1 for an overview of the inventory inputs of banknote production in six unit processes (1A–1F)). Euro banknotes are produced in seven different denominations. The distribution over the different denominations has been derived from the official banknote sorting data at DNB and from two professional CiT companies. The distribution is as follows: EUR 5 (6.8%), EUR 10 (26.8%), EUR 20 (26.5%), EUR 50 (36.7%), EUR 100 (2.6%), EUR 200 (0.4%) and EUR 500 (0.3%). The banknote distribution has been used to create a fictional (average) banknote, which is used as a tool for calculations. The EUR 200 and EUR 500 banknotes have not been taken into account due to their low occurrence. The fictional (average) banknote contains 0.815 g of cotton, 0.082 g of ink, 0.010 g of thread and 0.049 g of foil. In total, 157 million banknotes were produced in 2015, 7.5% of them were not issued in circulation, as they did not meet the quality standards, according to the printing works. These unfit banknotes have been treated as waste and their inputs have been added on top of all the inputs (cotton, foil, thread, ink production) for the production of the security paper and banknotes. It is assumed that there is negligible waste

[6] Roos Lindgreen et al. (2018) use one average debit card payment of EUR 28.68 at the POS in the Netherlands in 2015 as functional unit.

[7] Marincovic et al. (2011) use the provision of CAN 2000 of cash value over a time span of 7.5 years as functional unit, Shonfield (2013) uses the provision and use of GBP 1000 of cash value over 10 years and Luján-Ornelas et al. (2018) use the number of banknotes required to provide an average Mexican household with a monthly cash amount of MXN 12,708 in MXN 200 banknotes in HD paper and polymeric substrate over a period of 5 years.



during cotton, foil, thread and ink production, because they get recycled during production.

Cotton production (1A) Two by-products of cotton production, combers and linters, are used for the manufacturing of euro banknotes. In total, 2.5 million kg of cotton would have to be harvested in order to produce the correct amount of combers and linters for the production of 146 million euro banknotes for the Netherlands in 2015. However, the harvested cotton is not only used for the combers and linters, but also for the yarn, cotton seed oil and other products made from cotton seed used in the manufacturing of other goods. Therefore, only a share of the environmental impact of the 2.5 million kg raw cotton needs to be allocated to the combers and linters and the remainder to other products made with raw cotton. An allocation rule based on economic value of the combers, linters and the other products has been used, indicating that the impact of 128,031 kg of the 2.5 million kg raw cotton can be allocated to the production of euro banknotes in the Netherlands in 2015. Three types of cotton were used for the production of banknotes, i.e. traditional cotton (60%), organic cotton (35%) and fair trade cotton (5%). Organic cotton is grown without the use of any synthetic agricultural chemicals such as fertilisers or pesticides and the explicit use of only rain water (GOTS 2017). The Ecoinvent process for cotton has been adapted to better reflect the environmental impact of organic cotton by removing the use of water and chemicals.

The cotton's country of origin is unknown. Therefore, it was assumed that the cotton originated from the top three cotton-producing countries. According to their official websites, industrial cotton is mainly produced in China, India and the USA (11,113 km average distance from the paper production factory in France), organic cotton is mainly produced in India, China and Turkey

Table 1 Material and energy inventory inputs per unit process

Unit process	Amount	Inventory input	Source
Cotton production (1a)	77×10^3 kg	Cotton fibre {GLO}| market for | Alloc Def, S	Primary
	45×10^3 kg	(Organic) Cotton fibre {GLO}| market for | Alloc Def, S	Primary
	6.4×10^3 kg	Cotton fibre {RoW}| cotton production | Alloc Def, S	Primary
	147 kg	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Def, S	Primary
	2.9 MWh	Electricity, medium voltage {RoW}| market for | Alloc Def, S	Primary
	1,278,196 tkm	Transport, transoceanic freight ship/OCE S	Primary
Foil production (1b)	2.4×10^3 kg	Polyester-complexed starch biopolymer {GLO}| market for | Alloc Def, S	Primary
	1.6×10^3 kg	Aluminium, production mix, at plant/RER S	Primary
	3.6×10^3 kg	Polyester resin, unsaturated {GLO}| market for | Alloc Def, S	Primary
	1.4 MWh	Electricity, medium voltage {GR}| market for | Alloc Def, S	Primary
	380 MJ	Heat, natural gas, at industrial furnace > 100 kW/RER S	Primary
Thread production (1c)	915 kg	Aluminium, primary, at plant/RER S	Primary
	678 kg	Polyester-complexed starch biopolymer {GLO}| market for | Alloc Def, S	Primary
	257.0×10^{-3} MWh	Electricity, medium voltage {GR}| market for | Alloc Def, S	Primary
	71 MJ	Natural gas, burned in industrial furnace > 100 kW/RER S	Primary
Paper production (1d)	5.1×10^3 kg	Sulfate pulp {GLO}| market for | Alloc Def, S	Primary
	6.4×10^3 kg	Chemi-thermomechanical pulp {GLO}| market for | Alloc Def, S	Primary
	128.0×10^3 kg	Paper, newsprint, at plant/CH S	Primary
	546 kg	Packaging, corrugated board, mixed fibre, single wall, at plant/CH S	Primary
	98 kg	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Def, S	Primary
	127.0×10^3 kg	Paper, newsprint, at plant/CH S	Primary
	7.8 MWh	Electricity, medium voltage {GR}| market for | Alloc Def, S	Primary
Ink production (1e)	9.9×10^3 kg	Printing ink, offset, without solvent, in 47.5% solution state {GLO}| market for | Alloc Def, S	Primary
	8085 tkm	Transport, lorry 16–32 t, EURO5/RER S	Primary
Banknote printing (1f)	16.6×10^3 kg	Acetone, liquid {GLO}| market for | Alloc Def, S	Primary
	10.7×10^3 kg	Waste newspaper {GLO}| market for | Alloc Rec, S	Primary
	2.9×10^3 kg	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Def, S	Primary
	792 kg	Polyethylene, low density, granulate {GLO}| market for | Alloc Def, S	Primary
	17.0×10^3 kg	Corrugated board box {GLO}| market for corrugated board box | Alloc Def, S	Primary
	610 kg	Waste paperboard, sorted {GLO}| market for | Alloc Def, S	Primary
	232.0 MWh	Electricity, medium voltage {FR}| market for | Alloc Def, S	Primary
	445 kg	Nickel, 99.5% {GLO}| market for | Alloc Def, S	Primary
	445 kg	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Def, S	Primary
Coin blank production (2a)	138.4×10^3 kg	Steel, low-alloy {GLO}| market for | Alloc Def, S	Secondary
	180.4×10^3 kg	Copper {GLO}| market for | Alloc Rec, S	Secondary
	6.7×10^3 kg	Aluminium, primary, ingot {GLO}| market for | Alloc Def, S	Secondary
	14.5×10^3 kg	Zinc {GLO}| market for | Alloc Def, S	Secondary
	1.3×10^3 kg	Tin {GLO}| market for | Alloc Def, S	Secondary
	9.8×10^3 kg	Nickel, 99.5%, at plant/GLO S	Secondary
	544,112 tkm	Transport, lorry > 32 t, EURO5/RER S	Secondary
Coin monetizing (2b)	3,878,615 tkm	Transport, transoceanic freight ship/OCE S	Secondary
	71.6 MWh	Electricity, medium voltage {NL}| market for | Alloc Def, S	Primary
	99,845 tkm	Transport, freight, lorry > 32 metric ton, EURO5 {GLO}| market for | Alloc Def, S	Secondary

Table 1 (continued)

Unit process	Amount	Inventory input	Source
Transport (3a)	25.1×10^3 kg	Reinforcing steel {GLO}| market for | Alloc Def, S	Secondary
	169,598 tkm	Transport, freight, lorry 16–32 metric ton, EURO5 {GLO}| market for | Alloc Def, S	Secondary
	122,156 tkm	Transport, freight, aircraft {GLO}| market for | Alloc Def, S	Secondary
	14,000 km	Transport, passenger car, EURO 5 {RER}| market for | Alloc Def, S	Secondary
	17,125 tkm	Transport, freight, lorry 3.5–7.5 metric ton, EURO5 {GLO}| market for | Alloc Def, S	Secondary
ATM (3b)	18,267,370 km	Transport, passenger car, large size, diesel, EURO 5 {GLO}| market for | Alloc Def, S	Primary
	887 pieces	Display, liquid crystal, 17 in. {GLO}| market for | Alloc Def, S	Primary
	887 pieces	Computer, desktop, without screen {GLO}| market for | Alloc Def, S	Primary
	613.8 tons	Reinforcing steel {GLO}| market for | Alloc Def, S	Primary
	10.1×10^3 MWh	Electricity, medium voltage {NL}| market for | Alloc Def, S	Primary
	0.2×10^3 MWh	Electricity, production mix photovoltaic, at plant/NL S	Primary
	43 MWh	Electricity, hydropower, at plant/NL S	Primary
	2.1×10^3 MWh	Electricity, at wind power plant 800 kW/RER S	Primary
	2.2×10^3 MWh	Electricity, at cogen, biogas agricultural mix, allocation	Primary
Cash handling (3c)	752.0 MWh	Electricity, medium voltage {NL}| market for | Alloc Def, S	Secondary
	750 kg	Kraft paper, unbleached, at plant/RER S	Secondary
Shredding, granulating and compacting of banknotes (4a)	45.5 MWh	Natural gas, burned in boiler modulating < 100 kW/RER S	Primary
	350 kg	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Def, S	Primary
	113.0 MWh	Electricity, medium voltage {NL}| market for | Alloc Def, S	Primary
Transport to incineration (4b)	2785 tkm	Transport, freight, lorry 16–32 metric ton, EURO5 {GLO}| market for | Alloc Def, S	Primary
Incineration (4c)	− 189.2 MWh	Electricity, medium voltage {NL}| market for | Alloc Def, S	Primary
Demonetization coins (5a)	17.6×10^{-3} MWh	Electricity, medium voltage {NL}| market for | Alloc Def, S	Primary

(8594 km average distance) and fair trade cotton is mainly produced in Mali, Senegal and Burkina Faso (4052 km average distance) (Fairtrade International 2017; USDA 2018; OTA 2014). The cotton is transported by transoceanic freight ships.

Foil and thread production (1B and 1C) Foil and thread are security features used in the production of banknotes. Due to confidentiality, the composition of the thread and foil shown in this research is simplified, using information from DNB. The foil is composed of equal amounts of polyester, resin and aluminium and the thread contains polyester and aluminium. Furthermore, plastic bobbins are used as packaging material for the foil and thread. Due to a very high level of reuse of the bobbins, their environmental impact is therefore assumed to be negligible. Therefore, packaging has not been included in Table 1.

Paper production (1D) Security paper is produced by mixing cotton, additives, chemicals and 99% water into a pulp. During the manufacturing process, most of the water is vaporised. This results in paper composed of cotton (85%), water (6%), additives and chemicals (9%). As no primary data was available on physical flows within the production of security paper (i.e. energy, water consumption, waste treatment), similar Ecoinvent processes were used to approximate the environmental impact of security paper production, i.e. newsprint paper production (which uses a similar production process of creating paper reels out of a water-rich pulp by sieving, drying and flattening), sulphate pulp additives and chemical additives (see Table 1).

Ink production (1E) The inputs for security ink production are highly classified and could not be obtained. Therefore, the assumption was made that the environmental impact of security ink can be approximated by that of normal ink, by using a comparable Ecoinvent process (see Table 1). The exact quantities of ink used for the production of banknotes and the energy used by the printing machines have been obtained from a banknote printing company and are provided in Table 1.

Banknote printing (1F) Four different printing steps are used for the production of banknotes. During two printing stages, PET printing plates and chromed-nickel printing plates are consumed. Their lifespans and environmental impacts have been included in the analysis. Furthermore, the use of a cleaning solution is included.

2.2.2 Production of euro coins

The production of coins has been divided into two subprocesses: the production of coin blanks (2A) and monetizing of coins (2B). According to KNM, 57 million coins were produced in 2015 for the Netherlands. This number is not representative for the number of coins in coin circulation, which is estimated to be around 3 billion.[8] The low actual coin production in 2015 had two reasons, which are interrelated. First, a large number of coins were produced between 1999 and 2001 in order to ensure a sufficient number of euro coins in circulation in 2002, the year of the euro cash changeover. Second, according to KNM, coins have a relatively long lifespan (approximately 30 years), meaning that coins produced in, for example, 2001 were still used by consumers after 2015. So, different from a situation without a currency changeover, the need to produce coins in 2015 was relatively low.[9] As we would 'underestimate' the impact of coin production on the cash payment system in 2015, by only taking into account the actual number of coins produced in 2015, we approximate the 'fictional' number of euro coins produced in 2015. Ideally, we would have used the following formula to estimate the number of euro coins that were produced and put into circulation in the Netherlands between 2002 and 2015 and which can be attributed to cash usage (POS and P2P) in the Netherlands in 2015:

$$\left(\frac{\text{Number of euro coins produced up to 2015} - \text{net matching euro coins up to 2015}}{\text{Number of cash transactions for P2P and POS involving euro coins between 2002\&2015}}\right)$$

$$*\left(\frac{\text{End of the year 2015} - \text{Start of the year 2002}}{\text{30 years lifetime}}\right)$$

$$*\text{Number of cash transactions for P2P and POS involving euro coins in 2015}$$

'Matching of euro coins' is a process in which euro countries trade their surplus of euro coins with other countries who have a deficit. As a result, the production of euro coins for the euro area as a whole is reduced. By 'net matching euro coins up to 2015' we mean the total number of euro coins that were shipped to the Netherlands from other euro countries until the end of 2015 minus the total number of euro coins that were shipped from the Netherlands to other euro countries which had a deficit of these euro coins until the end of 2015.[10]

The three parts of the formula to estimate the number of euro coins produced for the Netherlands in 2015 are explained below. The first part reflects the average number of euro coins produced per cash transaction at the POS and P2P between 2002 and 2015 that can be attributed to the Netherlands. The numerator is equal to the total number of euro coins produced up to 2015 on behalf of the Netherlands, while correcting for the net number of euro coins matched with other euro countries until the end of the year 2015. The second part adjusts for the long lifetime of euro coins (approximately 30 years). Because many coins will still be used in the future, only a part of the environmental impact of their production should be accredited to the period 2002–2015. The third part is the total number of cash transactions in 2015 at the POS and P2P. The multiplication of the three parts equals the number of euro coins that were produced and put into circulation in the Netherlands between 2002 and 2015 that can be attributed to cash usage (POS and P2P) in the Netherlands in 2015.

However, we could not use the 'ideal' formula because no information is available on (1) the number of cash transactions at the POS and P2P involving coins and (2) the exact number of cash transactions (POS and P2P) in 2002, as information on P2P transactions in 2002 was unavailable. Therefore, 'cash transactions at the POS' has been used as a proxy for 'cash transactions at the POS and P2P involving coins', changing the formula into:

$$\left(\frac{\text{Number of euro coins produced up to 2015} - \text{net matching euro coins up to 2015}}{\text{Number of cash transactions at the POS between 2002\&2015}}\right)*$$

$$\left(\frac{\text{End of the year 2015} - \text{Start of the year 2002}}{\text{30 years lifetime}}\right)$$

$$*\text{Number of cash transactions at the POS in 2015}$$

By doing so, the assumption was made that the decline in the number of cash transactions at the POS and P2P involving

[8] Based on total production of euro coins (4.3 billion euro coins), net matching of euro coins between euro countries (−700 million euro coins) and loss and destruction of euro coins (−1 to 2% of the euro coins in circulation per year). Also confirmed by DNB statistics and expert interviews. In the EU, the same factor (~ 10×) is seen between coins and banknotes.

[9] The following production figures illustrate this: the production of coins before 2002 was over 2 billion euro coins per year, whereas, in the years thereafter, the number of annually produced euro coins declined from around 150 million euro coins to 50 million euro coins (KNM 2015).

[10] Matching does not occur on a large scale in the euro area. Only a handful of euro countries are currently matching euro coins.

coins between 2002 and 2015 followed the same trend as the decline in the number of cash payments involving notes and/or coins at the POS between 2002 and 2015. This assumption seems realistic as usually when paying in cash at a POS, both notes and coins are involved (coins are often given as change). Furthermore, with respect to the assumption that the trend in the number of cash payments for P2P payments follows that of POS and P2P payments, developments in online and mobile banking have facilitated the substitution of cash by electronic payment channels for P2P payments, like card payments have done at the POS.

Below you can find the equation for the approximation of the fictional number of coins produced for the Dutch cash payment system in 2015, including the appropriate figures and a further explanation:

$$\left(\frac{4.3*10^9-0.7*10^9}{70*10^9}\right)*\left(\frac{14}{30}\right)*3.19*10^9$$
$$= 0.051*0.47*3.19*10^9 = 77 \text{ million.}$$

The first part of the formula results in a production of 0.051 euro coins per cash transaction between 2002 and 2015. In total, 4.3 billion euro coins were produced for the Netherlands until 2015. We adjusted this number for net matching of euro coins by subtracting the total net number of 709 million euro coins that were shipped from the Netherlands to other euro countries and vice versa. So, 3.6 billion of the 4.3 billion euro coins were actually used for cash payments in the Netherlands. This total has been divided by the cumulative number of cash transactions at the POS since the introduction of the euro until 2015, i.e. 70 billion cash payments, to get an estimate for the number of coins produced per cash payment between 2002 and 2015.[11] As the average lifespan of euro coins is approximately 30 years and euro coins have been in circulation for only 14 years in 2015, 47% of all produced euro coins is allocated to the period 2002–2015, leading to an average of 0.051 * 0.47 = 0.024 euro coins produced per cash payment until 2015. Regarding the third and last part, there were 3.19 billion cash transactions at the POS in the Netherlands in 2015, so the total number of euro coins produced for cash usage in the Netherlands in the year 2015 is 0.024 * 3.19 billion = 77 million euro coins, which is 39% higher than the actual production in 2015 (Jonker et al. 2018).

Table 1 provides an overview of the inventory inputs used for coin blank production. Euro coins have eight denominations. The share of each denomination in the total number of coins produced for usage in the Netherlands in 2015 is assumed to be as follows: EUR 0.01 (17%), EUR 0.02 (17%), EUR 0.05 (25%), EUR 0.10 (12%), EUR 0.20 (9%), EUR 0.50 (9%), EUR 1 (5%) and EUR 2 (6%). This distribution is based on the share of each denomination in the total production of euro coins for the Netherlands in 1999–2015 (KNM 2015). A fictional, average coin has been constructed as a tool for calculations in the inventory analysis. The fictional coin weighs 4.501 g and contains 2.312 g of copper, 1.775 g of steel, 0.086 g of aluminium, 0.184 g of zinc, 0.017 g of tin and 0.126 g of nickel.

Coin blank production (2A) No direct data could be obtained regarding the production process of coin blanks. This process includes refining, pressing, blanking, annealing and upsetting of metals. Instead, we used secondary information from the Ecoinvent 3.0 database to approximate the environmental impact of the metals (Table 1). We assumed that the metals steel, aluminium, nickel, zinc and tin used in coin blanks were not recycled, as according to minting experts at DNB and KNM, a very high degree of purity is required for coin blank production. Due to the relatively high amount of copper used, we assumed that a combination of primary and recycled copper was used for coin blanks manufacturing, based on the global market share of recycled copper. Furthermore, it is considered that waste produced during coin blank production is recycled, and as a result is negligible. In Section 3.2, we assess the impact of alternative assumptions regarding the share of recycled metals.

Coin monetizing (2B) No data could be obtained on the geographical origin of the coin blanks in 2015. However, three main coin blank producers were identified and the average transportation distance between these factories were calculated. It is assumed that the coin blanks have been transported in equal amounts from South Korea, Spain and Germany to KNM in Utrecht. Three types of transportation were included: from factory to harbour, from harbour to harbour and from harbour to KNM.

2.2.3 Operation phase euro banknotes and coins

The operation phase of coins and banknotes is very complex and involves many different processes. This phase starts at the factory gate (coins, banknotes) and ends when the coins or banknotes are deemed unfit. The unit processes have been grouped into three main categories: transportation, ATMs and cash handling. Table 1 provides an overview of the inventory inputs of the three unit processes.[12]

[11] Own estimation based on the estimate by Brits and Winder (2005) of 7.1 billion cash payments at the POS in 2002 and by Jonker et al. (2018) of 3.2 billion cash payments at the POS in the Netherlands in 2015. We have estimated cash usage in the years 2003–2014 by linear interpolation. This is a reasonable assumption as debit card usage, the substitute of cash in NL, grew fairly linearly between 2002 and 2014, with an average y-o-y growth rate of 8% (see DNB 2017).

[12] We excluded storage from the analysis as the environmental impact of storage is below the 1% cut-off threshold.

Transport (3A) Different logistic routes are distinguished during the operation phase. Firstly, coins and banknotes are transported from the factory to DNB. In 2015, coins were transported from Utrecht to DNB's coin storage location in Wassenaar by truck. Banknotes were transported by air from banknote printing works to Eindhoven airport, and from Eindhoven by truck to DNB in Amsterdam. Extra vehicles required for security were included. Secondly, two types of storage are used before cash is sent into circulation. Coins and banknotes first go to coin-specific or banknote-specific storage locations. From there, coins and banknotes are delivered to distribution centres and together are put into circulation.[13] Furthermore, cash is transported between storage and distribution centres through matching, which is a process in which a company with a deficit of coins trades with a company in a surplus of coins without an intermediary. Matching takes place between CiT companies and between DNB and CiT companies. Thirdly, during the circulation, most of the cash is transported by CiT companies. Two main types of transportation routes have been identified. ATM routes are used only to refill ATMs with banknotes (57% of transport). Pick up & delivery (PUD) routes take over the coins and the rest of the banknote transportation between companies (mostly retailers) and the distribution storages (43% of transport). The CiT companies mostly use specialised armoured and diesel-powered trucks for these rides. According to the two CiT companies, 8.7 million km was driven for the transportation of cash by these specialised armoured trucks during the operation phase.

Since specialised armoured trucks are not used for anything else, they are fully allocated to the cash payment system. Information on the type and weight of the vehicles was provided by two CiT companies and compared to the specifications of the vehicle types. We assumed that the difference between the actual vehicle weight and the vehicle specifications consists of additional reinforced steel. This amounts to an average 1945 kg of steel per vehicle. During a single year, 13 armoured vehicles were consumed, resulting in 25 tons of steel in total.[14]

ATMs (3B) In total, 7604 ATMs and 1265 cash recycling machines (CRMs) were available throughout the Netherlands in 2015. CRMs can be used to withdraw and deposit cash, whereas ATMs can only be used for withdrawal of banknotes. CRMs therefore consume more energy, but reduce transportation requirements. Since both ATMs and CRMs are required for the cash payment system, their full impact has been taken into account. Kanazawa and Sato (2001) show that the most impactful categories are the materials used for their production and their electricity consumption. The materials used for the composition of an ATM have been simplified into 1 personal computer, 1 screen and 700 kg of reinforced steel (information ATM manufacturer), over a 10-year lifetime. In total, 613 tons of steel, 887 computers and 887 screens were consumed in 2015.

The energy consumed by ATMs can be split into two parts: idle energy use and active energy use. Idle energy consumption and active energy consumption have been provided by an ATM manufacturer. It is assumed that ATMs are online for 24 h a day. Furthermore, a CRM consumes more energy than an ATM (ATM idle 160 W, ATM active 285 W, CRS idle 214 W, CRS active 355 W). The total active energy consumption was based on the total number of ATM withdrawals in 2015. In total, 351 million ATM withdrawals took place in 2015, which results in an average of 110 transactions per ATM per day, or 1.84 h of activity for an ATM and 2.74 h for a CRS. Using this data, one ATM consumes 4.1 kWh per day and one CRS consumes 5.5 kWh per day. This amounts to 11.1 GWh for all ATMs, 2.5 GWh for all CRSs and 14.74 GWh for all ATMs and CRSs. Two thousand two hundred thirty-seven ATMs of one commercial bank consume contractually purchased renewable energy, meaning that 4.6 GWh of the total 14.74 GWh is produced with renewable energy sources (RES). The proportion of each RES (i.e. solar, wind energy, hydropower or biomass) used for the ATMs is based on the average Dutch fuel mix in the same year (CBS 2015). For the modelling of the remaining 10.1 GWh, the average Dutch electricity mix was assumed.

Cash handling (3C) Cash handling involves counting and inspection of banknotes as well as packaging used for coins. One of the printing works provided information on the energy consumption of counting machines used for counting and checking of banknotes: 207.6 KWh per million counted and checked banknotes. Due to the unavailability of information on the energy consumption of such machines used in cash distribution centres for counting and checking banknotes and coins, it was assumed that the energy consumption of their counting equipment was equal to that of the equipment used by printing works. This assumption was based on the fact that there are only limited types of counting machines available, which function in similar ways. In total, 2 billion banknotes and 1.1 billion coins were checked at cash centres, and 474 million banknotes were checked at DNB, resulting in an estimate of energy consumption for cash handling of 752 MWh.

2.2.4 End of life euro banknotes (4A, 4B, 4C)

If banknotes are considered unfit by DNB, they are instantly shredded. The shredded banknotes are granulated, compacted

[13] The data provided by CiT companies includes the total number of kilometres driven for the transportation of cash in 2015. Other types of transportation, e.g. matching and transport of unfit cash, are included in the total environmental impact of transportation in the operation phase.

[14] According to one of the CiT companies, the average lifetime of an armoured truck is 675,000 km. As 8.7 million km was driven, 13 armoured vehicles were consumed in 2015.

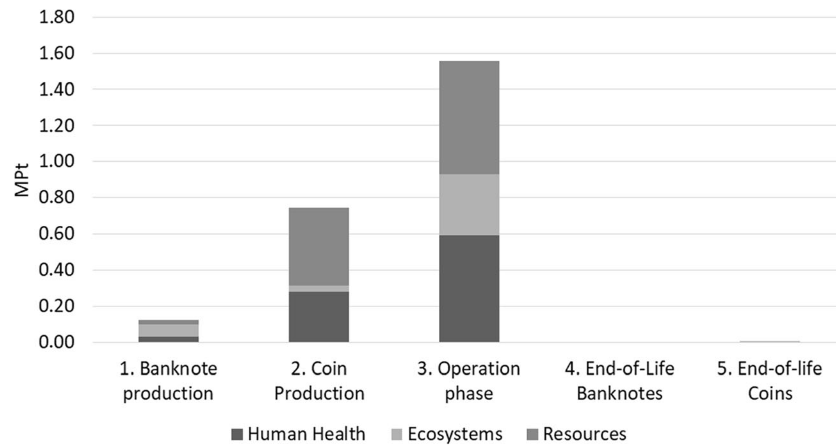


Fig. 2 Endpoint indicators per sub-system

and delivered in bags of 600 kg. The banknotes are then transported to a municipal solid waste incinerator and the banknotes are incinerated with the rest of the garbage. In total, 110 million banknotes were destroyed in 2015, which weigh a total of 105 tons. The net energy gained from burning 1 ton of waste was collected from a municipal waste incinerator. This amounts to 1800 kWh per ton, 189 MWh in total. The total thermal and electric energy consumed during this process per ton waste have been retrieved from a secondary source, which is 0.142 MWh per ton for electricity (14 MWh total) and 0.433 MWh per ton for thermal energy (45 MWh total) (European Commission 2006). The environmental impact of the incineration process is taken into account, by using the 'incineration of newspaper by a municipal waste incinerator' process from the Ecoinvent database to approximate the incineration of shredded banknotes by a municipal waste incinerator.

2.2.5 End of life euro coins (5A)

Due to the long lifespan of coins, a very small amount of coins needs to be destroyed or demonetised due to defects. According to DNB, 250,000 coins were demonetised in 2015. Once a large number of coins have been demonetised, they are transported to a melting company. This LCA does not take the impact of melting companies into account, because the coins are not reused for the production of new coins, but for other products. Therefore, resulting impacts should be accredited to the production of the future products and not to the end of life of coins.

3 Results

3.1 Main results environmental impact and GWP

The total environmental impact of the Dutch cash payment system in 2015 is calculated using the ReCiPe (H) endpoint method and results in 2.42 MPt. The climate change impact of the cash payment system indicated by global warming potential (GWP) was calculated as 19 million kg CO_2e. For the average single-cash transaction in the Netherlands in 2015, the environmental impact was calculated as 654 μPt and the GWP was 5.1 g CO_2e.

3.1.1 Environmental impact

Figure 2 shows the environmental impact of each sub-process per endpoint category. The impact is highest on endpoint indicators resources (1.08 MPt) and human health (0.90 MPt). Both the production of coins (0.75 MPt) and the operation phase (1.56 MPt) dominate the environmental impact of the cash payment system. The production of banknotes has a low impact (0.12 MPt) and both end-of-life phases of coins and banknotes have a small impact.

Figure 3 provides an overview of the total environmental impact expressed per midpoint category. It highlights the areas of environmental importance within the cash system. The midpoint category with the largest contribution to the total impact is fossil depletion (24%). Metal depletion and climate change human health contribute equally to the total impact, i.e. by 21%. Climate change ecosystems account for 13% of the total impact, particulate matter formation for 10%, human toxicity for 6% and agricultural land occupation for 3%. The other midpoint categories together account for 2% of the total environmental impact.[15] The non-renewable energy use in the operation phase (cash transport and ATM electricity) is the main contributor to fossil depletion, climate change human health and climate change ecosystems. It accounts for 90% to the impact on climate change human health and ecosystems, followed by coin production (6%) and banknote production (4%). The findings regarding the relative contribution of

[15] Unlike Luján-Ornelas et al. (2018) who made an LCA of Mexican banknote in the Netherlands, the impact of the cash payment system on water depletion is negligible, as hydroelectric activities are hardly used to generate electricity.

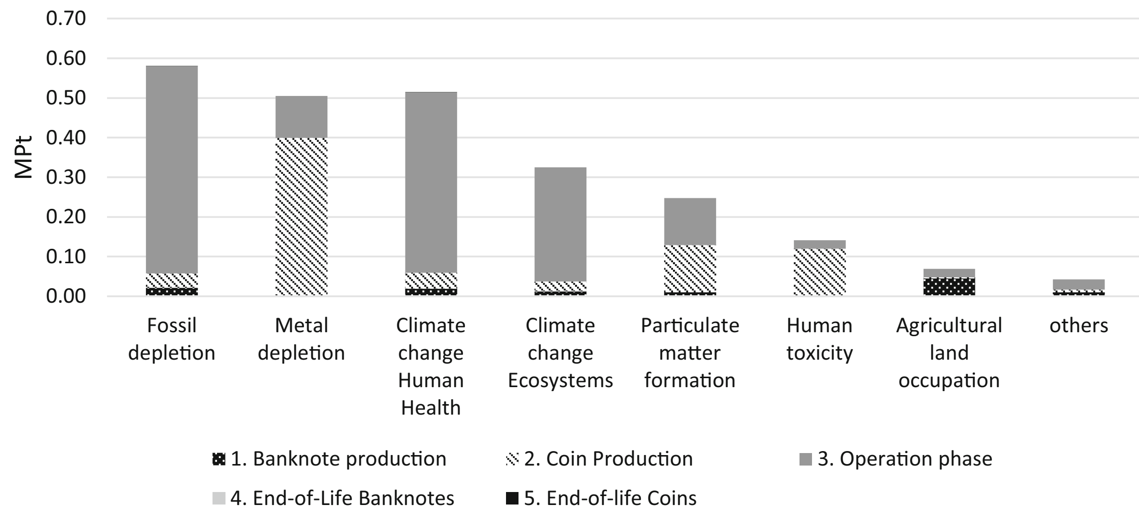


Fig. 3 Midpoint indicators per sub-system

the operation phase and banknote production phase are in line with those by Shonfield (2013) and Luján-Ornelas et al. (2018). The use of copper in the coin production is the main contributor to metal depletion. Apart from coin production (79%), also the operation phase (21%) has a substantial contribution to metal depletion, and banknote production accounts for less than 0.5% of metal depletion. The findings for the operation phase and banknote production correspond with the results obtained by Luján-Ornelas et al. (2018). With respect to particulate matter formation, coin production and the operation phase of cash both account for almost half of the particulate matter formation and banknote production for 4%. The emission of particulate matters into the air in the use phase stems from the combustion of fossil fuels by the vehicles transporting cash. With respect to coin production, metal particles enter the atmosphere as a disposal of metal-enriched sewage sludge and sewage effluents or as a by-product of metal mining processes. Coin production accounts for almost 85% of human toxicity, the use phase for almost 15% and banknote production for 1%. The much higher contribution of the use phase to human toxicity than banknote productions has also been found by, for example, Luján-Ornelas et al. (2018). However, the impact of coin production to human toxicity is more than five times higher than of these two sub-systems together. Banknote production makes the largest contribution to agricultural land occupation, due to the usage of large areas of agricultural land for the production and harvest of cotton.

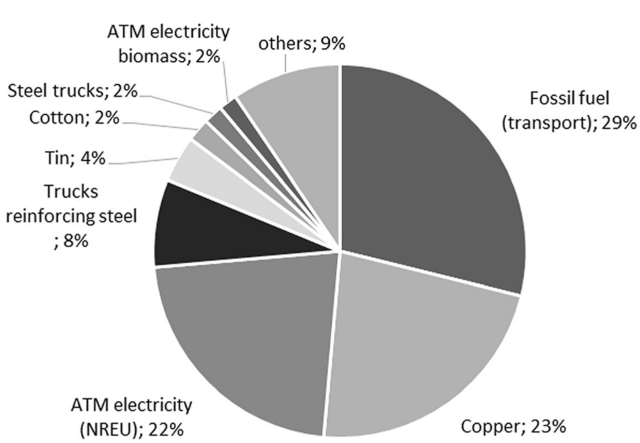


Fig. 4 Single score result of the overall impact per unit process

This can also be seen in Figs. 4 and 5, where the single score result per unit process and the total impact of each unit process on the endpoint indicators human health, ecosystems and resources are shown. It should be noted that the actual data on the recycled content of metals in coin production is lacking. Section 3.2 pays attention to the impact of the assumptions made with respect to the recycling of metals on the estimation of environmental impact using a sensitivity analysis. The contribution of the transport process is mainly due to the use of non-renewable energy by the vehicles in the PUD routes of the banknotes and coins throughout the country. The large impact of ATM electricity use is mostly explained by the fact that ATMs are mainly consuming non-renewable energy in both idle and active mode constantly. The large impact of copper is caused by the depletion of metal, within the endpoint indicator resources. Furthermore, several released gasses and toxins are responsible for the large impact on human health. The most impactful air pollutants from copper mining are sulphur dioxide, arsenic, particulates, ammonia and nitrogen oxide. The impact on ecosystems is very little and mostly relates to land occupation and the effect of climate change on ecosystems. The impact of cotton in ecosystems is mainly caused by agricultural land occupation of crop and forest area, and other relevant impacts are GHG related.

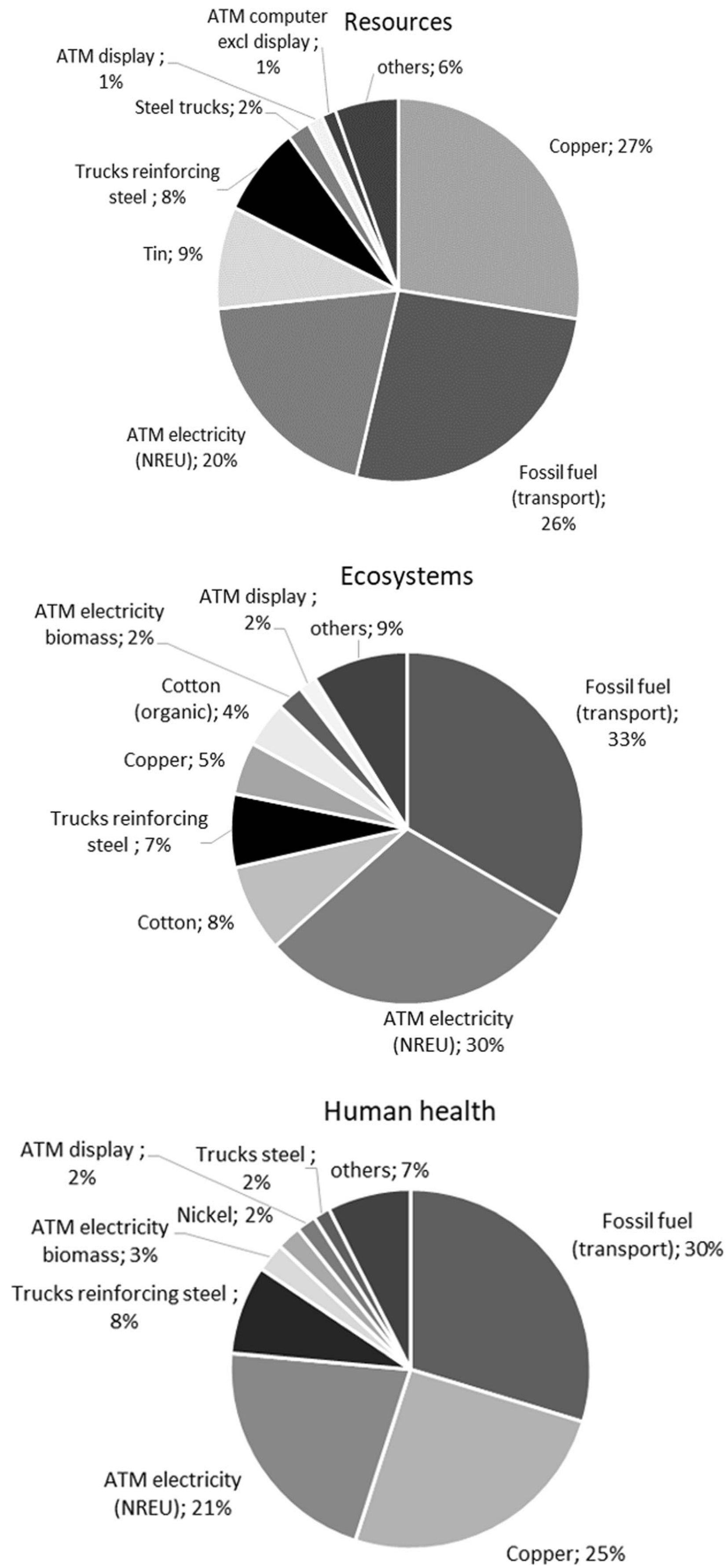


Fig. 5 Overall relative environmental impact per unit process on the endpoint indicators resources, human health and ecosystems

3.1.2 Global warming potential

Using the IPCC GWP method, the climate change impact indicated by GWP of the cash payment system was calculated as 19 million kg of CO_2e, which corresponds to 0.01% of total CO_2 emissions in the Netherlands in 2015. Of the five subsystems, the operational phase accounts for 89% of the GWP of the cash payment system, followed by coin production (8%) and banknote production (4%). The impact of the end-of-life phase of banknotes and coins is negligible. Figure 6 shows the contribution of each unit process to the GWP. The unit processes fossil fuel usage in transport and electricity usage by ATMs (NREU) in the operation phase have the largest contributions to the GWP with 38% and 35% respectively. These findings correspond with those reported by Marincovic et al. (2011) for paper cotton-based banknotes in Canada. Shonfield (2013) and Luján-Ornelas et al. (2018) find that energy consumption by ATMs has the largest contribution to GWP, but in their studies, the impact of transport is relatively small. This may be due to differences in scope. Unlike our study, the transportation of banknotes from cash centres to bank branches, retailers and ATMs is not included in Luján-Ornelas et al. (2018) and also does not seem to be included in Shonfield (2013).

3.2 Uncertainty and sensitivity analyses

Overall, we decided to focus on conducting a sensitivity analysis with respect to assumptions made when data was lacking, as the level of uncertainty in the data provided by the manufacturers was fairly low. Consequently, uncertainty in the data provided is not expected to have a large impact on the main results. In order to assess the uncertainty in the input data, we gathered information on the reliability of the information provided by the ten key companies in the cash payment system. Data quality was defined by the manufacturers, either by specifying their own uncertainty estimate or by identifying the data as 'direct', 'indirect' or 'estimates'. On average, the uncertainty in the data they provided was in the 5–10% range, indicating that the data were rather precise. Consequently, it is not to be expected that any uncertainty in the data that was provided by companies has a large impact on the main results.

Regarding the sensitivity analysis, the assumptions made with respect to unavailable data in the banknote production and operation phase are quite solid. However, in the coin production phase, there were some potentially impactful assumptions. The impact of three assumptions were tested, i.e. (1) the average lifetime of euro coins in circulation, (2) the share of recycled materials in metals used for coin production and (3) the distribution of the different denominations as reflected in the fictional coin. Table 2 presents the total environmental impact of the three sensitivities by life cycle stage according to the single score indicator and Fig. 7 shows their impact on midpoint categories compared to the baseline.

Firstly, in the baseline, an average lifespan of euro coins in circulation of 30 years was assumed, following the advice by KNM. However, in everyday life especially, low-value coins may be in circulation for less than 30 years, as they get easily lost or are deposited in containers by consumers in order to avoid having over-stuffed purses or wallets. On the other hand, the coins themselves may still be fit for circulation after 30 years. In the sensitivity analysis, we therefore use two alternative average lifetimes, i.e. 20 years and 40 years. If euro coins are assumed to be in circulation for 20 years, the number of euro coins produced that can be attributed to 2015 rises

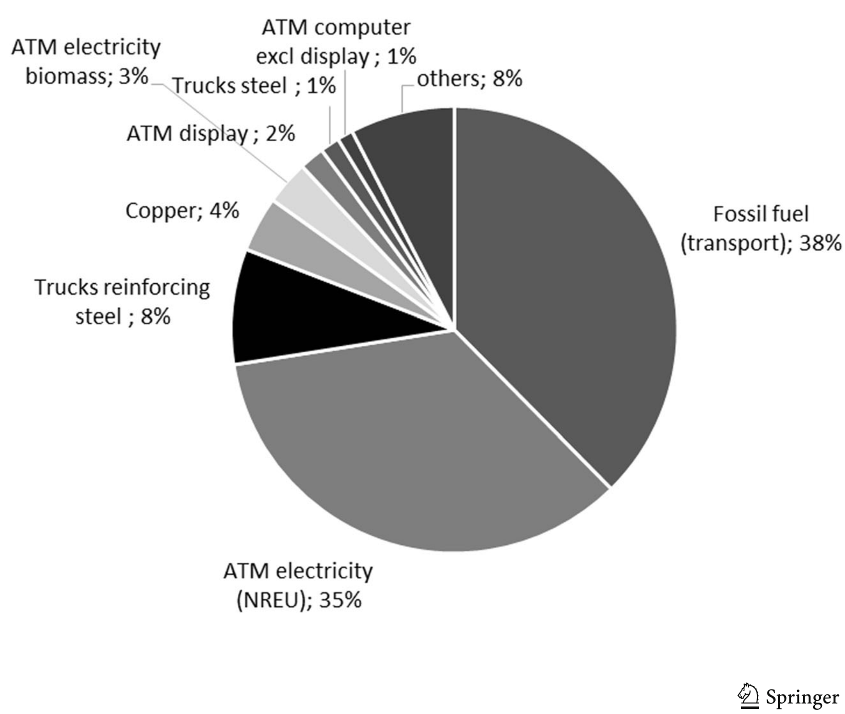


Fig. 6 Relative contribution to total CO_2 equivalents per unit process

Table 2 Outcome sensitivity analysis: single score results per sub-system (in MPt)

Sub-system	Baseline	Average lifetime euro coins		No recycling metals copper and tin in coin blank manufacturing	Fictional coin: based on distribution denominations in counting machines
		20 years	40 years		
Banknote production	0.12	0.12	0.12	0.12	0.12
Coin production	0.75	1.11	0.32	0.82	1.38
Operation phase	1.56	1.56	1.56	1.56	1.56
End-of-life phase banknotes	− 0.0025	− 0.0025	− 0.0025	− 0.0025	− 0.0025
End-of-life phase coins	8.67×10^{-7}	1.30×10^{-6}	6.51×10^{-7}	8.67×10^{-7}	8.67×10^{-7}
Total	2.42	2.79	2.24	2.50	3.05

from 77 million to 116 million. Alternatively, if the average lifetime is 40 years, the number of coins produced for 2015 decreases to 58 million. The results of the sensitivity analysis show that if the average lifetime is 20 years, then the environmental impact of the sub-systems coin production and end-of-life coins would rise by 48% and the overall environmental impact of the cash payment system in the Netherlands in 2015 would be 2.79 MPt instead of 2.42 MPt, an increase of 15%. Alternatively, if the average lifetime of euro coins were 40 years, then the environmental impact of coin production and end-of-life of coins would decline by 57% and the overall environmental impact would be 2.24 MPt instead of 2.42 MPt, a decline of 8%. Reducing (increasing) the expected lifetime of a euro coin by 10 years has a relatively large impact on the three midpoint categories human toxicity, metal depletion and particulate matter formation, but hardly affects the midpoint categories climate change human health and ecosystems, agricultural land occupation and fossil depletion (see Fig. 7).

Secondly, the assumption on the share of recycled materials in copper and tin used for manufacturing coin blanks were tested. We focus on these metals as they have the largest environmental impact according to Fig. 4. Furthermore, it is known that steel is always recycled. In the sensitivity analysis, it was assumed that all copper and tin used to manufacture coin blanks was not recycled, implying that the amounts of non-recycled copper and tin increase by 5% compared to the baseline, where it was assumed that the share of recycled metals (copper and tin) corresponds with the global market share. If non-recycled copper and tin were used for coin blank manufacturing, then the overall environmental impact of coin production would increase by 9% to 0.82 MPt and that of the cash payment system as a whole would be 2.50 MPt instead of 2.42 MPt, an increase of 3%. The impact of this sensitivity on the midpoint categories is limited; it has the largest impact on agricultural land occupation, i.e. + 8%, followed by its impact on climate change ecosystems and human health (+ 4%). It increases the impact of metal depletion by 1%. This small effect is probably due to the already low share of non-recycled metals in the baseline.

Thirdly, the assumption regarding the decomposition of the fictional coin. We use an alternative assumption by taking more directly into account which denominations are actually in usage in 2015, by adjusting the fictional coin in such a way that it reflects the denominations of the coins that are counted by official counting machines. The share of each denomination in the alternative fictional coin is as follows: EUR 0.01 (2%), EUR 0.02 (3%), EUR 0.05 (13%), EUR 0.10 (15%), EUR 0.20 (20%), EUR 0.50 (16%), EUR 1 (15%) and EUR 2 (16%). The number of coins produced is kept constant at 77 million. A downside is that lower denominations, which have

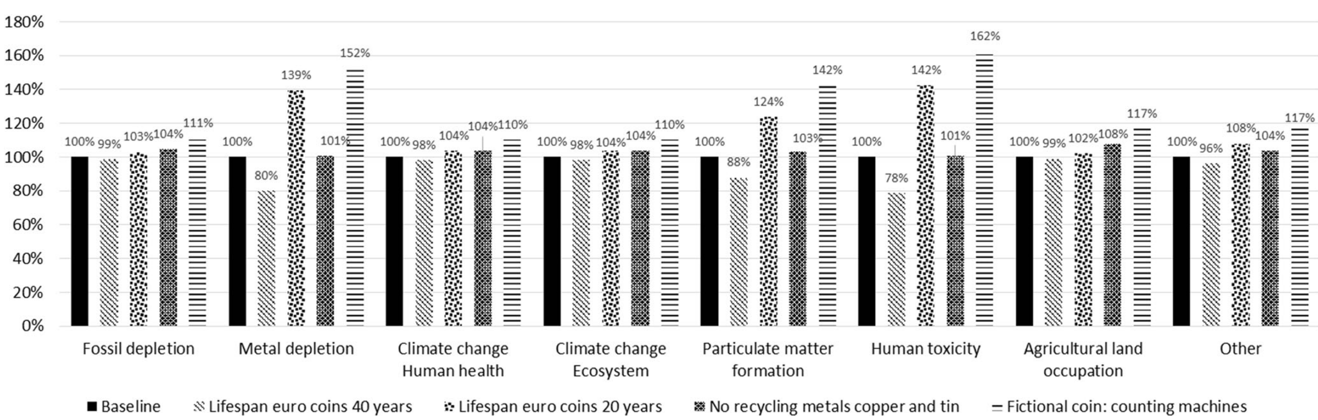


Fig. 7 Results of sensitivity analyses per midpoint category relative to the baseline

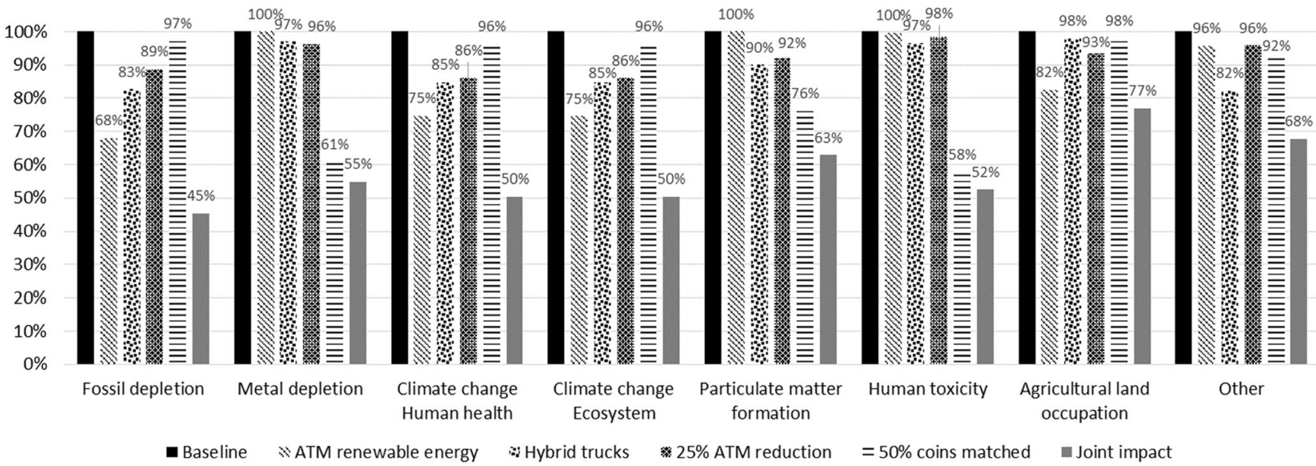


Fig. 8 Results of scenario analyses per midpoint category relative to the baseline

a relatively low weight, are much more frequently used for change and appear relatively less in counting machines. Therefore, the weight of the fictional coin under this alternative assumption is higher than the weight of the fictional coin used in the baseline, i.e. 6.139 g instead of 4.501 g. The sensitivity analysis shows that under this alternative assumption, the total environmental impact of coin production would rise by 84% to 1.38 MPt and the total environmental impact of the cash payment system would increase by 26% to 3.05 MPt. The alternative assumption regarding the decomposition of the fictional coin has a relatively large impact on the midpoint categories human toxicity (+ 62%), metal depletion (+ 52%) and particulate matter formation (+ 42%). The impact of this assumption on midpoint categories is relatively high compared to those of the other two sensitivities. This is caused by the higher weight and the higher share of copper in the alternative fictional coin than in the baseline fictional coin.

Overall, the sensitivity analysis shows that the estimated impact of the cash payment system in the Netherlands is to some extent sensitive to variations in the assumptions underlying coin production, although the main results turn out to be fairly robust. The decomposition of the fictional coin has the largest impact, followed by the average lifetime of coins. Changing the share of recycled metals used in coin blank manufacturing has a minor effect.

3.3 Scenario analysis

After the process-level analysis, we examined the environmental impact of four possible changes in the cash payment system. We formulated the following four scenarios:

1. ATM renewable energy: a switch to renewable energy by all ATMs in use in the Dutch cash system. Considering the large impact of ATM electricity on the environmental impact, it is interesting to investigate what reduction would be achieved after a switch to 100% renewable energy. In the baseline estimates, 25.2% of the ATMs owned by one commercial bank were running on contractually purchased renewable energy (considered in this research to be from 100% renewable sources).
2. The use of hybrid trucks in transport of banknotes and coins by CiT companies. The large impact of transport is mostly explained by the total amount of kilometres driven per year. Considering that the efficiency of the current logistics is perceived as quite high, an improvement can be achieved by reducing the impact of the trucks. Hybrid trucks run partly on electricity, which can be especially beneficial when driving in urban areas and making numerous starts and stops.
3. Lowering the total number of ATMs in the Netherlands by 25% will reduce total energy consumption. A lower number of ATMs would mostly lead to less electricity consumption. It is assumed that there would be no impact on transportations, as other ATMs would be used more frequently and would need to be serviced more frequently.[16]
4. Efficient trading of coins between countries, leading to 50% less production of coins in this scenario. There is a high potential for environmental impact reduction through avoiding the environmental impacts associated with coin production by matching/trading of euro coins. However, currently trading of coins between countries is observed at well-below the possible scale.

These scenarios are considered realistic, in terms of investment costs for stakeholders in the cash cycle (see the details of the scenarios below). Furthermore, they are in line with the

[16] We reduced the total energy consumption by 25% in this scenario. Note that this may be slightly overestimated, as we did not take into account any change in the ratio of idle/in use time of the remaining ATMs because of intensified usage.

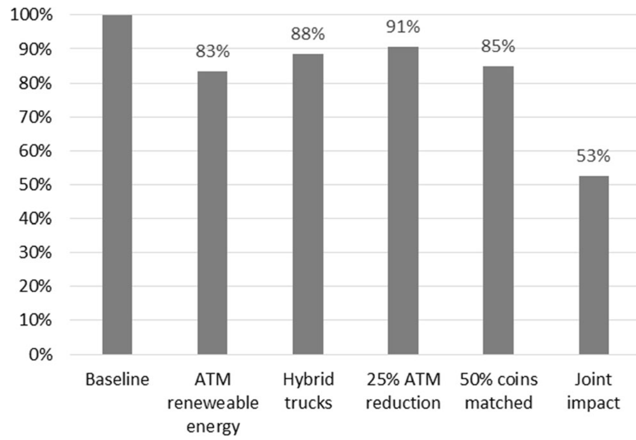


Fig. 9 Baseline, results of scenario analyses and their joint impact on endpoint results

Dutch government's aim to increase renewable energy usage from 5% in 2015 to 14% in 2020 and 100% in 2050 (SER 2013; Dicou et al. 2016). Note that the transition to higher sustainable energy consumption in payments will not immediately lead to a lower ecological footprint. After all, it takes time to implement the necessary changes in energy generation.

Figures 8 and 9 show the impact of the cash cycle in the situation in 2015 (baseline) on several midpoint categories and on the environment as a whole and compare them with those in the four scenarios. In addition, it provides an estimation of the joint impact for all four scenarios combined. In scenario 1, a switch to renewable energy for ATMs proves to be an efficient measure to reduce the impact on the midpoint categories fossil depletion (−32%), climate change human health and ecosystems (−25%) and agricultural land occupation (−18%) compared to the baseline. The impact on fossil depletion and climate change is mainly due to the fact that no fossil fuels are needed for the generation of renewable energy, and consequently, the amount of CO_2 emitted is drastically reduced. The impact on the other considered midpoint categories is fairly small. In this scenario, the total environmental impact of the cash cycle is reduced by 17% compared to the baseline situation (Fig. 8). This can be considered a realistic option, since in 2015, already 25% of the ATM network was using green energy. According to scenario 3, a reduction of 25% in the number of ATMs in the Netherlands would lead to a reduction in climate change, human health and ecosystems (−14%) and fossil depletion (−11%). The impact on climate change and fossil depletion is mainly due to the fact that less electricity is consumed by ATMs, and consequently, less fossil fuel is consumed to generate the electricity for the ATMs. The impact on the other midpoint categories is fairly small. In this scenario, the total environmental impact of the cash payment system is reduced by 9% compared to the baseline situation in 2015. This scenario is realistic, as earlier research showed that a reduction of 20–35% of the total number of ATMs can be achieved without compromising the minimum availability standard (MOB 2014).

Introducing hybrid trucks for cash transport (scenario 2) results in a relatively large reduction in the midpoint categories fossil depletion (−17%), climate change, human health and ecosystems (−15%) and formation of particulate matter (−10%) compared to the baseline situation. The impact on fossil depletion and climate change is mainly due to the fact that less fossil fuel is consumed by hybrid trucks than by the trucks that currently transport cash, and consequently, less CO_2 and particulate matter is emitted by them. In this scenario, the total environmental impact of the cash payment system is reduced by 12% compared to the baseline situation. It should be noted however that although these trucks appear to be available, not much detailed information is known about them. For example, in the scenario analysis, the fuel savings of a private hybrid car was therefore considered (Cerovsky and Mindl 2008).

Lastly, a more efficient trading system for coins and banknotes between countries (scenario 4) shows to reduce the environmental impact with 15% compared to the baseline, mainly due to the reduction of the impact on human toxicity (−42%), less depletion of metals (−39%) and less formation of particulate matter (−24%). Higher shares of matching coins and banknotes within the Netherlands is expected to have a limited environmental reduction potential, since the share of banknotes matched within the Netherlands is already high. The percentage of matched coins in the Netherlands is low and transportation of coins is understood to a lower degree.

In the best case scenario, if all four proposed scenarios were applied in the Dutch cash cycle simultaneously, a reduction in environmental impact of 47% would be achieved and a reduction in the impact on climate change of 50%.

4 Discussion

4.1 Putting the LCA of cash payment system into perspective

To put the environmental impact and GWP of an average cash transaction in the Netherlands in 2015 into perspective, we compare the impacts with those of its closest substitute, i.e. a debit card transaction. Roos Lindgreen et al. (2018) show that the environmental impact of an average debit card transaction in the Netherlands in 2015 was 470 μPt and its GWP was 3.8 g CO_2e. These results indicate that although the environmental impact and the GWP of an average cash transaction were higher, they were still of the same order of magnitude as those of an average debit card transaction. The ongoing substitution of cash by debit cards in the Netherlands will therefore have a positive, though moderate impact on the sustainability of the Dutch retail payment system as a whole. To be more specific, the environmental impact of an average cash transaction was 39% higher at 654 μPt and its GWP was 35% higher at 5.1 g CO_2e than that of an average debit card transaction.[17] The relatively higher impact of cash on the environment is largely due the influence of metal depletion for coin production (2a), which is one of the hotspots in the cash payment system. An interesting similarity between cash and debit cards is that for both types of transactions, energy usage in the standby time (ATMs for cash and POS payment terminals for debit cards) is one of the hotspots. Both ATMs (3a) and card payment terminals are never or rarely ever switched off, when they are not being used by consumers.

We also compare the environmental and climate change impacts of the cash payment system as a whole with those of the debit card system (Table 3). The environmental burden of the cash payment system was approximately 2.42 MPt, which is 61% higher than the burden of the debit card payment system (1.5 MPt; see Roos Lindgreen et al. 2018). The difference between cash and the debit card payment system with respect to their GWPs amounts 58%. The differences in impacts on system level are higher than on transaction level, as there are more transactions (including P2P transactions) in the cash payment system than in the debit card payment system. Although the LCAs of both the debit card and cash have uncertainties, the results are in the same order of magnitude. The differences in outcomes suggest that—without any of the impact reducing scenarios being implemented—the ongoing substitution of cash by debit card payments may enhance the sustainability of the retail payment system as a whole.

With respect to climate change, we are also able to compare the GWP of the cash payment system with the GWP of the goods and services produced in the Dutch economy. In 2015, the GWP of the Dutch economy as a whole was 196 billion kg CO_2e (CBS 2016a). As the GWP of the cash payment system amounts to 19 million kg CO_2e, its GWP corresponds to 0.01% of the GWP of the Netherlands.[18] In order to compare the impact on climate change of the cash payment system with that of the Dutch economy as a whole, while taking into account their differences in economic value, we follow the approach taken by Roos Lindgreen et al. (2018).[19,20] This approach essentially involves calculating the GWP per billion euro economic value of a product. We use the resource costs measured in euros of the cash payment system to society as a proxy of its economic value, which was approximately EUR 1.4 billion in 2015 and equal to 0.15% of the Dutch gross domestic product (GDP) in 2015. This figure is in line with the resource costs for the cash payment system in other countries, expressed in % GDP, i.e. the costs of the cash payment system for Canada amounted to 0.31% of Canada's GDP in 2014 (Kosse et al. 2017). Kosse et al. (2017) also provide an overview of the resource costs of cash in other countries: Australia (0.19% GDP), Austria (0.36% GDP), Denmark (0.27% GDP), Norway (0.07% GDP), Sweden (0.28% GDP) and the EU (0.49% GDP). We use the GDP of the

[17] We did not take into account the possible impact of differences in average transaction value of a cash payments and a debit card payment. For debit card payments, the value of the transaction does not affect the environmental impact. With respect to cash, it is not clear a priori whether the number of coins and banknotes used for a transaction, which influence their impact, depends on the transaction value, due to the usage of different denominations.

[18] As the total environmental impact of the Dutch economy is unknown, but its GWP is known, the GWP of the cash payment system is compared with the GWP of the Dutch economy.

[19] We use the Dutch economy's GDP in 2015 as a proxy of the economic value of all goods and services used in the Netherlands in 2015. A country's GDP measures the monetary value of final goods and services—that is, those that are bought by the final user—in a country in a given period of time (say a quarter or a year). It counts all of the output generated within the borders of a country (see the definition provided by the IMF) at https://www.imf.org/external/pubs/ft/fandd/basics/gdp.htm. GDP is composed of goods and services produced for sale in the market and it also includes some non-market production, such as defence, healthcare and education provided by the government. There may be a difference between the resource costs for all products sold and the total monetary value according to market prices, i.e. the profit made by sellers which is included in the market prices, but not in resource costs. However, at a country level, the difference between the two is expected to be fairly small due to market competition, as in a perfectly competitive market, the marginal costs of a product equal its market price.

[20] We proxy the economic importance of the cash and debit card payments in 2015 with their resource costs to society. This method has been well established in central bank studies on estimating the cost of the retail payment system (see e.g. Brits and Winder 2005, Schmiedel et al. 2012 or World Bank 2016 for extensive descriptions of the cost methodology). Costs for cash payments to society reflect the costs of the use of resources in the production and issuance of coins and banknotes, cash transportation, labour time costs associated with carrying out cash payments at the POS, capital cost and labour time cost made by market parties such as the central bank, retail banks and CiTs. We have used cost figures for banks and the central bank in the Netherlands in 2009 (Jonker 2013) and cost figures of cash payments for 2014 for retailers (Snoei et al. 2015), which we extrapolated to the year 2015 by taking into account changes in the main cost drivers (i.e. for banks: numbers of ATMs, bank branches delivering cash services, sorted banknotes, bank employees) to estimate the resource costs of the Dutch cash payment system in 2015. A similar approach was taken in Roos Lindgreen et al. (2018) for the debit card payment system.

Table 3 GWP cash payment system relative to the debit card payment system and the Dutch economy, 2015

	CO_2e (in kg)	Economic value (in EUR billion)	GWP—economic value ratio (kg CO_2e per EUR billion)
Cash	19×10^6	1.4	14×10^6
Debit card	12×10^6	0.9	14×10^6
Dutch economy	196×10^9	676.5	287×10^6

Netherlands in 2015 as the proxy for the economic value of all products and services produced in the Netherlands, which was EUR 676.5 billion (CBS 2016b).

The results indicate that the cash payment system's impact on climate change is 24 times smaller than that of the Dutch economy as a whole, when taking into account their economic value. This implies that the impact of cash is in fact relatively modest compared to the overall impact of goods and services produced for the Dutch economy. Furthermore, the results show that the cash payment system's impact on climate change is of the same order of magnitude as the impact of the debit card payment system, when scaled with their respective economic values.

The relatively low contribution of the cash payment system relative to its economic value to the Dutch GWP in 2015 may be explained by the fact that unlike most other consumer goods, banknotes and coins are constantly recycled, until they are lost or taken out of circulation by the central bank. For other consumer products with a high contribution to GWP, like food (especially meat), heating or transport, recycling is not feasible, as they are single-use items. Furthermore, it may be argued that cash (and other payment products) are relatively costly due to the high security standards they have to meet, in order to prevent counterfeiting and theft.

5 Conclusions and limitations

In this study, we use life cycle assessment to evaluate the environmental impact of an average cash payment and of the cash payment system as a whole in the Netherlands in 2015. We distinguish five different subsystems, i.e. the production of banknotes (1), the production of coins (2), the operation phase of cash (3), the end-of-life phase of banknotes (4) and the end-of-life phase of coins (5). For each subsystem, we have collected data by conducting interviews and by reviewing the literature.

Using the ReCiPe (H) endpoint method, we find that the environmental impact of an average cash transaction was 654 μPt. The environmental impact of the Dutch cash payment system as a whole was 2.42 million Pt. The GWP of an average cash payment amounted to 5.1 g CO_2e and the Dutch cash cycle as a whole amounted to 19 million kg CO_2e. This corresponds to 0.01% of the total GWP of the Dutch economy in 2015 (CBS 2016b). The operation phase of cash had the largest share in the total environmental impact of the cash payment system (64%), followed by coin production (31%). The share of banknote production on the total environmental impact of cash was relatively small (5%) and the shares of the end-of-life phases of banknotes and coins were both negligible (< 0.01%). Within the cash payment system, the midpoint category with the largest impact was fossil depletion (24%). Metal depletion and climate change human health (21%) had the second largest impact, followed by climate change ecosystems (13%), particulate matter formation (10%) and human toxicity (6%). Fuel consumption by vehicles used to transport banknotes and coins during the operation phase, electricity consumption by ATMs and the depletion of copper for coin manufacturing are their key contributors.

In order to examine to what extent the environmental impact of the Dutch cash payment system can be lowered, four scenarios have been evaluated, i.e. all ATMs use renewable energy, usage of hybrid trucks, a reduction of the number of ATMs by 25% and less coin production by increased matching of coins by CiT companies and between euro area countries. The combined effect of these four scenarios together results in a 47% lower environmental impact and a 50% lower impact on climate change. A comparison to the impact of the debit card payment system (Roos Lindgreen et al. 2018) and the cash payment system shows, taking uncertainty margins into account, that in 2015 cash payments had with respect to the order of magnitude a similar, but higher impact on the environment and climate change than debit card payments. The GWP of the cash payment system is fairly modest when compared with the GWP of all goods and services produced in the Dutch economy.

An important take away of this study for central banks which want to enhance the sustainability of the cash payment system is that they should not only put effort in producing more durable banknotes, but that they may also look for other ways to enhance the sustainability of the cash payment system as a whole. They may join forces with other central banks and payment service providers in the cash payment system and look for joint measures which result in lower coin production or lead to a lower consumption of (fossil) energy by ATMs and trucks used for cash transportation. This is the first study on the environmental impact and GWP of the cash payment system, including both coins and banknotes. A limitation of the study is the scarcity of primary data for some processes, such as the share of recycled metals in coin production. Obtaining access to primary data for these processes was problematic due to a combination of confidentiality issues and omission of data. By means of a sensitivity analysis, an attempt has been made to assess the extent to which the outcomes are sensitive to the assumptions made when data was lacking. Three assumptions were tested, i.e. the average lifetime of coins, the share of recycled metals used in coin blank manufacturing and the distribution of the denominations in coin production. The environmental impact of the cash payment system was shown to vary between −8% (average lifetime euro coins 40 instead of 30 years) and +26% (alternative distribution of denominations), ranging from 2.24 MPt to 3.05 MPt, indicating that the outcomes are fairly robust. The results of the study may be strengthened by future research if more detailed primary data become available.

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