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* Views expressed are those of the authors and do not necessarily reflect official positions of De Nederlandsche Bank.

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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 2.35 MPt (expressed in eco points) and its global warming potential (GWP) was 17 million kg CO_2 equivalents (CO_2e). For an average single cash transaction the environmental impact was 637 µPt and the GWP was 4.6 g CO_2e. The operation phase (e.g. energy use of ATMs, transport of banknotes and coins) (64%) and coin production phase (32%) had the largest impact on the environment, while the operation phase also had the largest impact on climate change (88%). Finally, scenario analysis shows that reductions of the environmental impact (51%) and the impact on climate change (55%) 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 2.35 MPt and their GWP was 17 million kg CO_2e.

Keywords: Cash payment system, coins, banknotes, LCA, environmental impact, GWP
JEL classifications: E42, Q54, Q56

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1. Introduction

In 2015, there were approximately 19 billion euro banknotes and 116 billion euro coins in circulation in the euro area[5] with a total value of EUR 1,100 billion (ECB, 2017).[6] Citizens inside and outside the euro area use banknotes and coins to buy goods and services, to make person-to-person payments to each other (e.g. charity, among family members, friends, etc.) and for hoarding. Consumers in the Netherlands made 3.7 billion cash payments representing a total value of EUR 49.6 billion in 2015: 0.5 billion person-to-person payments with a total value of EUR 9.6 billion and 3.2 billion point-of-sale (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 only 31 million POS payments at a total value of 3.2 billion (DNB, 2017). Various stakeholders in the cash payment chain, like central banks, coin minters, printing works, ATM manufacturers, cash-in-transport (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 coins, ATM operation and checking the quality of the banknotes and coins in circulation.

In this study we aim to provide insights into 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 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 contributed data, i.e. De Nederlandsche Bank (DNB, the Dutch central bank), Koninklijke Nederlandse Munt (KNM, Royal Dutch Mint), a commercial bank,

[5] The euro area is a monetary union of 19 countries in the EU which have adopted the euro as their common currency.
[6] The number of banknotes and coins in circulation *in* the Netherlands is unknown since the introduction of the euro in 2002.

a cash logistics services provider, two cash-in-transit (CiT companies), two printing works, an ATM manufacturer and a municipal waste incinerator. To the authors' knowledge, this study is the first to identify the impact of both coins and banknotes in a single economy, and one of 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, but not of coins. Wettstein et al. (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) and Shonfield (2013) 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. They found that the environmental impact of a single debit card payment in the Netherlands in 2015 was 470µPt. 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 takes three endpoint indicators into account (human health, ecosystem quality and resources). 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 Global Warming Potential (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 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*. We use this functional unit to quantify and analyse the environmental impact of the cash payment system as a whole. The second functional unit is *one average cash payment in the Netherlands in 2015*. 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 debit card payment. The Dutch cash circulation consists of both euro banknotes and euro coins, which have 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 Figure 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.

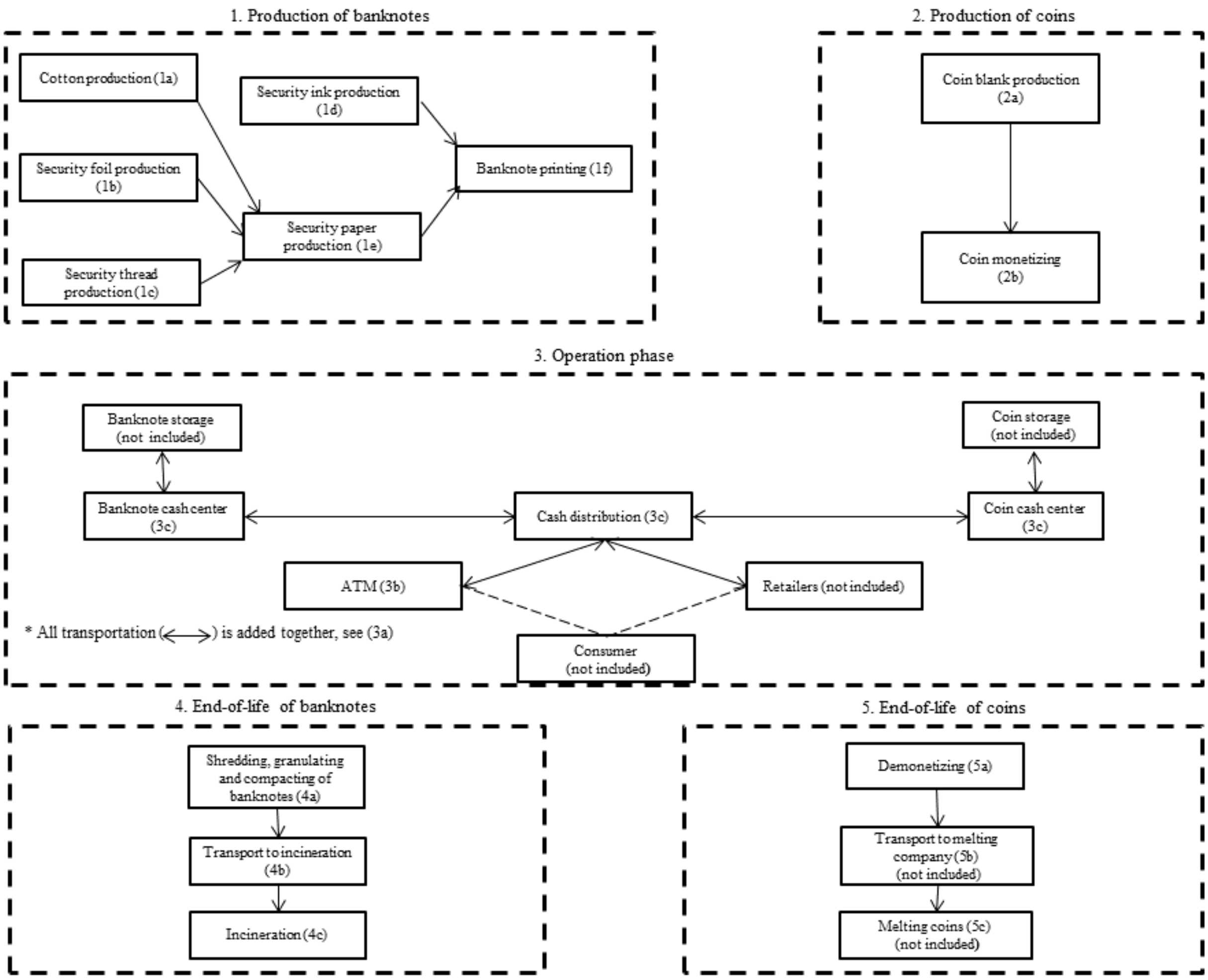

Figure 1. Schematic overview of the cash payment system boundaries, with sub-system compartments and unit processes

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 usage 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).

Table 1. Material and energy inventory inputs per unit process

Unit process	Amount	Inventory input	Source
Cotton production (1a)	$65*10^3$ kg	Cotton fibre {GLO}| market for | Alloc Def, S	Primary
	$38\ *10^3$ kg	(Organic) Cotton fibre {GLO}| market for | Alloc Def, S	Primary
	$54\ *10^3$ kg	Cotton fibre {RoW}| cotton production | Alloc Def, S	Primary
	125 kg	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Def, S	Primary
	2.4 MWh	Electricity, medium voltage {RoW}| market for | Alloc Def, S	Primary
	1085102 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 >100kW/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 >100kW/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 16-32t, 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
	544112 tkm	Transport, lorry >32t, EURO5/RER S	Secondary

Unit process	Amount	Inventory input	Source
Coin	3878615 tkm	Transport, transoceanic freight ship/OCE S	Secondary
Monetizing (2b)	71.6 MWh	Electricity, medium voltage {NL}| market for | Alloc Def, S	Primary
	99845 tkm	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, S	Secondary
Transport (3a)	$10.1*10^3$ MWh	Electricity, medium voltage {NL}| market for | Alloc Def, S	Primary
	$25.1*10^3$ kg	Reinforcing steel {GLO}| market for | Alloc Def, S	Secondary
	169598 tkm	Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Alloc Def, S	Secondary
	122156 tkm	Transport, freight, aircraft {GLO}| market for | Alloc Def, S	Secondary
	14000 km	Transport, passenger car, EURO 5 {RER}| market for | Alloc Def, S	Secondary
	17125 tkm	Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}| market for | Alloc Def, S	Secondary
ATM (3b)	18267370 km	Transport, passenger car, large size, diesel, EURO 5 {GLO}| market for | Alloc Def, S	Primary
	887 pieces	Display, liquid crystal, 17 inches {GLO}| market for | Alloc Def, S	Primary
	887 pieces	Computer, desktop, without screen {GLO}| market for | Alloc Def, S	Primary
	613.8 ton	Reinforcing steel {GLO}| market for | Alloc Def, S	Primary
	$10.1*10^3$ MWh	Electricity, medium voltage {NL}| market for | Alloc Def, S	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 <100kW/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

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 500 banknotes have not been taken into account due to their low occurrence. The fictional (average) banknote contains 0.815 gram of cotton, 0.082 gram of ink, 0.010 gram of thread and 0.049 gram 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) for the production of the security paper and banknotes.

Cotton production (1A)

Cotton is used for the manufacturing of euro banknotes. Based on a similar approach to the ECB (2005), the total amount of cotton that was used for the production of banknotes in the Netherlands in 2015 was calculated to be 108,698 kg. 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 fertilizers or pesticides and the explicit use of only rain water (GOTS, 2017). The Eco invent 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 (8,594 km average distance) and fair trade cotton is mainly produced in Mali, Senegal and Burkina Faso (4,052 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. The bobbins are constantly reused, which results in a consumption of zero plastic bobbins. 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 the production of security paper, similar Ecoinvent processes were used to approximate the environmental impact of security paper production (approximated by newsprint paper production), 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 has 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 in two sub-processes; 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.[7] The low actual coin production in 2015 had two reasons, which are interrelated. First, a large number of coins were produced between 1999–2001 in order to ensure a sufficient number of euro coins in circulation in 2002, the year of euro cash changeover. Second, according to KNM, coins have a relatively long lifespan (approximately 30 years), meaning that coins produced in e.g. 2001 were still used by consumers after 2015. So, different from a

[7] Based on total production (4.1 billion), net matching between euro countries (-700 million) and loss and destruction of coins (-1 - 2% per year). Also confirmed by DNB statistics and expert interviews. In the EU, the same factor (~10x) is seen between coins and banknotes.

situation without a currency changeover, the need to produce coins in 2015 was relatively low.[8] 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 using the following formula:

$$\left(\frac{\text{Euro coins produced up to 2015} - \text{matching up to 2015}}{\text{Number of cash transactions at the POS between 2002 \& 2015}}\right) * \left(\frac{\text{Year 2015} - \text{Year 2002}}{\text{30 years lifetime}}\right) * \text{cash transactions at POS 2015}$$

The first part of the formula reflects the number of coins produced per cash transaction at the POS. [9] It includes all euro coins produced up to 2015 on behalf of the Netherlands, while correcting for the coins matched up to 2015 with other euro countries.[10] It results in a production of 0.05 coins per cash transaction. The second section compensates for the long lifetime of coins. 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. As the average lifespan of coins is approximately 30 years and euro coins have been in circulation for 14 years in 2015, 47% of all produced euro coins is allocated to the period 2002–2015. The third section describes the number of coins that had to be produced in order to account for the total number of cash transactions in 2015 at the POS, which was 3.19 billion (Jonker et al, 2018). The multiplication of the three parts of the equation provides an approximation of the fictional number of coins produced for the Dutch cash payment system in 2015, i.e. 78 million coins. This is 39% higher than the actual production in 2015.

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,

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

[9] When estimating the number of coins produced for 2015, we focus on the trend in cash usage at the POS, even though cash is also used for p2p transactions. However, information on cash usage for p2p payments is unavailable for most years. We assume that the declining trend in cash usage for p2p payments follows the trend in cash usage at the POS, as developments in online and mobile banking have facilitated the usage of electronic payment channels for p2p payment and may have contributed to a declining cash usage for p2p payments. As cash usage volumes appear in both the nominator and denominator of the formula it seems unlikely that it affects the proper estimation of the number of coins produced for the cash payment system in 2015.

[10] Matching is a process in which euro countries trade their surplus of euro coins with other countries who have a deficit. In total, 4.3 billion euro coins were produced and a net of 709 million coins were shipped from the Netherlands to other EU countries, resulting in a total production for the Netherlands of 3.6 billion coins. This total has been divided by the cumulative number of cash transactions at the POS since the introduction of the euro. The total number of cash transactions was estimated at 70 billion payments (own estimation based on Brits and Winder (2005) and Jonker et al. (2018).

2015). A fictional, average coin has been constructed as a tool for calculations in the inventory analysis. The fictional coin weighs 4.501 grams and contains 2.312 grams of copper, 1.775 grams of steel, 0.086 grams of aluminium, 0.184 grams of zinc, 0.017 grams of tin and 0.126 grams 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. 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.[11]

[11] 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[12]. 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 were driven for the transportation of cash by these specialized 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 1,945 kg of steel per vehicle. During a single year, 13 armoured vehicles were consumed, resulting in 25 ton of steel in total.[13]

[12] 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.

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

ATMs (3B)

In total 7,604 ATMs and 1,265 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 700kg 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 hours a day. Furthermore, a CRM consumes more energy than an ATM (ATM idle 160 watt, ATM active 285 watt, CRS idle 214 watt, CRS active 355 watt). 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 hours of activity for an ATM and 2.74 hours 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. However, the 2,237 ATMs of one commercial bank consume contractually purchased green energy. Their energy consumption has not been taken into account in the calculation which reduces the total energy consumption by 4.6 GWh to 10.1 GWh.[14]

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

[14] Debit cards are not only used for debit card payments, but also for cash withdrawals and for authorising online credit transfers. Part of the environmental impact of debit cards can therefore be attributed to the cash payment system (Roos Lindgreen et al, 2018). However, the share of the environmental impact of debit cards that can be attributed to the cash payments system amounts 2,640 Pt, (0.1% of the impact the cash payment system), which is less than the 1% cut off threshold level. Therefore, we decided to exclude the impact of debit cards on the cash payment system.

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 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 ton. The net energy gained from burning one ton of waste was collected from a municipal waste incinerator. This amounts to 1,800 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).

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 demonetized due to defects. According to DNB, 250,000 coins were demonetized in 2015. Once a large number of coins have been demonetized, 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.

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 2.35 MPt. The climate change impact of the cash payment system indicated by Global Warming Potential (GWP) was calculated as 17 million kg CO_2e. For the average single cash transaction in the Netherlands in 2015, the environmental impact was calculated as 637 µPt and the GWP was 4.6 grams 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 (1.07 MPt) and Human Health (0.86 MPt). Both the production of coins (0.75 MPt) and the operation phase (1.49 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 an insignificant impact.

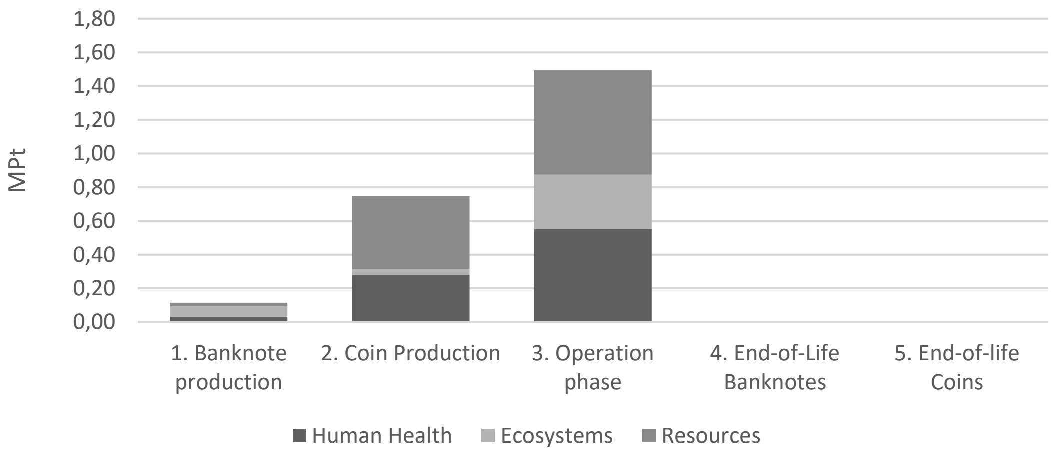

Figure 2. End-point indicators per sub-system

Figure 3 provides an overview of the total environmental impact expressed per mid-point category. It highlights the areas of environmental importance within the cash system. The impact category with the largest contribution to the total impact is fossil depletion (24%). Metal depletion and climate change human health contribute almost equally to the total impact, i.e. by 22% and 20% respectively. The non-renewable energy use in the operation phase (transport and ATM electricity) is the main contributor to fossil depletion, climate change human health and climate change ecosystems. The use of copper in the coin production is the main contributor to metal depletion.

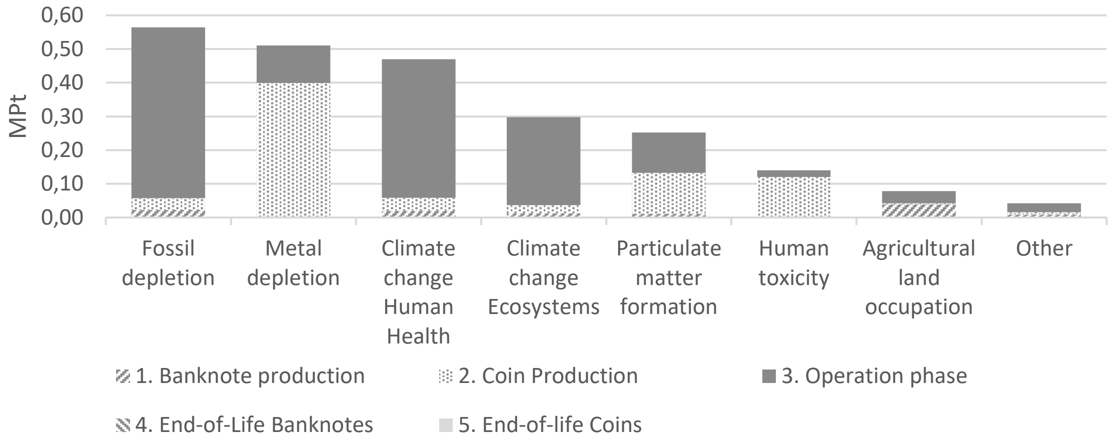

Figure 3. Mid point indicators per sub-system

This can also be seen in Figures 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 uncertainty on the estimation of environmental impact. The contribution of the transport process is mainly due to the use of non-renewable energy in the PUD routes of the banknotes and coins throughout the country. The ATM electricity use is mostly explained by the fact that ATMs are consuming 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 and more. 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, other relevant impacts are GHG related.

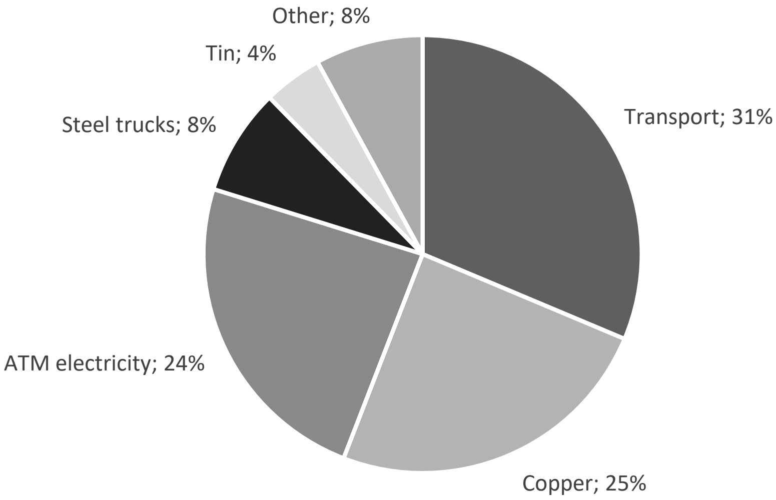

Figure 4. Single score result of the overall impact per unit process

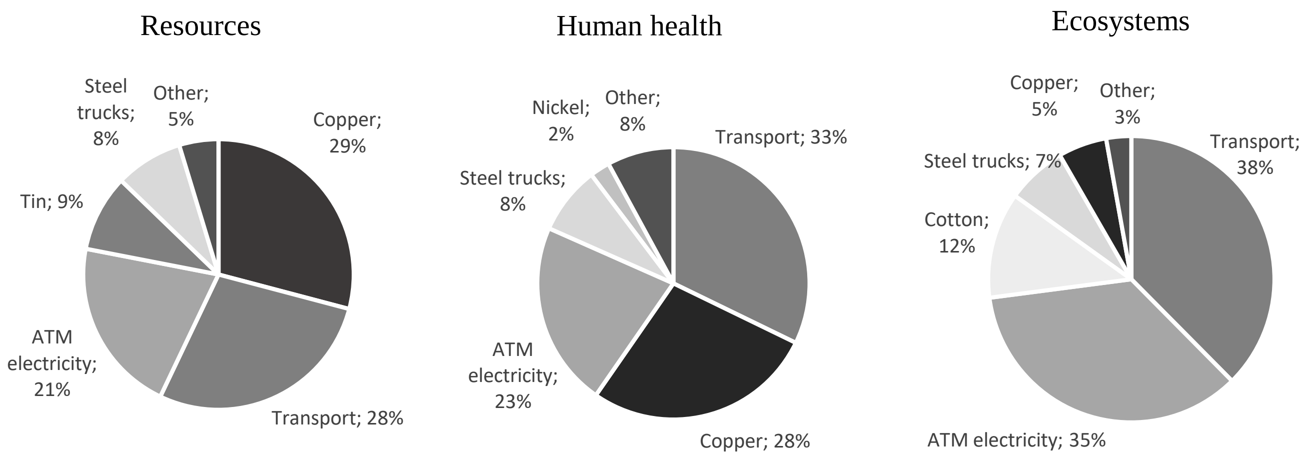

Figure 5. Overall relative environmental impact per unit process on the Endpoint indicators Resources, Human Health and Ecosystems

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 17 million kg of CO_2e, which corresponds to 0.009% of total CO_2 emissions in the Netherlands in 2015. Of the five subsystems, the operational phase accounts for 88% 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 Transport and Electricity used by ATMs in the operation phase have the largest contributions to the GWP with 44% and 37% respectively.

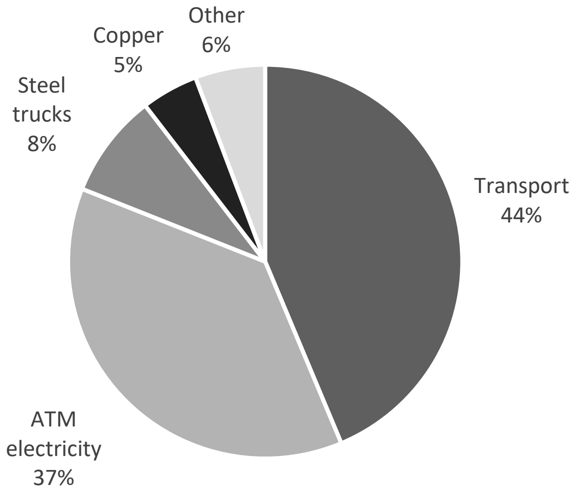

Figure 6. Relative contribution to total CO_2 equivalents per unit process

3.2 Sensitivity analysis

A sensitivity analysis is conducted on the performed LCA to assess to what extent the results are sensitive to the accuracy of the input data, and the assumptions made when input data was lacking. In order to decide which assumptions and uncertainties are most important, based on their contribution to environmental impact, a cut-off rule has been applied. The sensitivity analysis takes into account all of the unit processes that have a share of 4% or higher in the total environmental impact, see Figures 4 and 5. The uncertainty percentage was allocated to the consumed amounts of the input data and depending on the reliability of the input data. In addition, for copper and tin, assumptions on the share of recycled materials were also tested. The following unit processes were included in the sensitivity analysis:

1.	Transportation:	±10% uncertainty in consumed amounts inventory inputs
2.	Copper:	all copper is not recycled vs average recycling copper (baseline)
		± 5% uncertainty in consumed amount of copper
3.	ATM electricity	±5% uncertainty in consumed amount of electricity by ATMs
4.	Steel (used in trucks)	±10% uncertainty in consumed amount of steel in production of trucks
5.	Tin	average recycling tin vs all tin is not recycled (baseline)
		±5% uncertainty in consumed amount of tin
6.	Cotton	±5% uncertainty in consumed amount

The effects of the sensitivity analysis on the environmental impact per sub system are shown in Table 2. All the lower and upper values of the sensitivity analysis have been combined into the ‘minimum’ and ‘maximum’ values for the environmental impact of the cash payment system. Compared to the baseline, the value can differ between 2.22 MPt (-12%) and 2.56 MPt (+9%). The minimum level of the operation phase shows the largest decrease from its baseline (from 1.49 MPt to 1.38 MPt), and the maximum level of the production of coins has the largest increase (from 0.75 MPt to 0.85Mpt).

Table 2. Outcomes sensitivity analysis

Sub system	Minimum	Baseline	Maximum
Production of banknotes	0.12 MPt	0.12 MPt	0.12 MPt
Production of coins	0.72 MPt	0.75 MPt	0.85 MPt
Operation phase	1.38 Mpt	1.49 MPt	1.59 Mpt
End of life banknotes	-0.0025 MPt	-0.0025 MPt	-0.0025 MPt
End of life coins	8.6 Pt	8.6 Pt	8.6 Pt
Total	**2.22 MPt**	**2.35 MPt**	**2.56 MPt**

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 green energy: a switch to green 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. It is known that in 2015, 25.2% of the ATMs were running on contractually purchased green 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.[15]

4. Efficient trading of coins between countries, leading to 50% less production of coins. There is a high potential for environmental impact reduction through avoiding the environmental impacts associated with coin production. However, trading of coins between countries currently takes place on a very limited 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 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. Figure 7 shows the average environmental impact of the cash cycle in the situation in 2015 (baseline) and compares it with the environmental impact in the four scenarios. In addition, it provides an estimation of the environmental impact for all four scenarios combined. In Scenario 1 a switch to renewable energy proves to be an efficient measure, the total environmental impact of the cash cycle is reduced by 21% compared to the current situation. This can be considered a realistic option, since in 2015 already 25% of the ATM network was using green energy. If all the other ATMs were consuming green electricity, this would imply a 21% reduction in the environmental impact. According to Scenario 3 a reduction of 25% in the number of ATMs in the Netherlands will lead to an impact reduction of 8%. 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).

With respect to transportation reduction measures (Scenario 2), it can be seen that a changeover to hybrid armoured trucks leads to a 12% reduction, mainly due to lower fossil fuel consumption. 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

[15] 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.

(Scenario 4) shows to reduce the environmental impact with 16%. 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 51% would be achieved.

The effects of the scenario analysis on GWP are shown in Figure 8. Overall, fairly similar results have been found for the impact of the scenarios on the amount of CO_2e as for the endpoint results. The ATM Green energy scenario leads to the highest decrease in GWP, i.e. by 32%, but now coin matching between countries has the lowest improvement in GWP, i.e. by 4%. If all four scenarios were applied simultaneously, the impact of the cash payment system on GWP would be reduced by 55%.

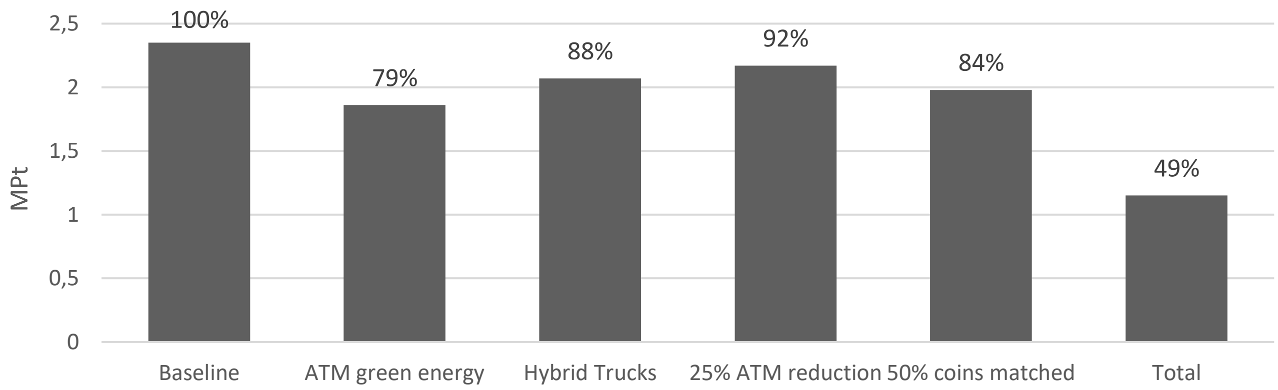

Figure 7. Results of scenario analyses on endpoint results and combined total

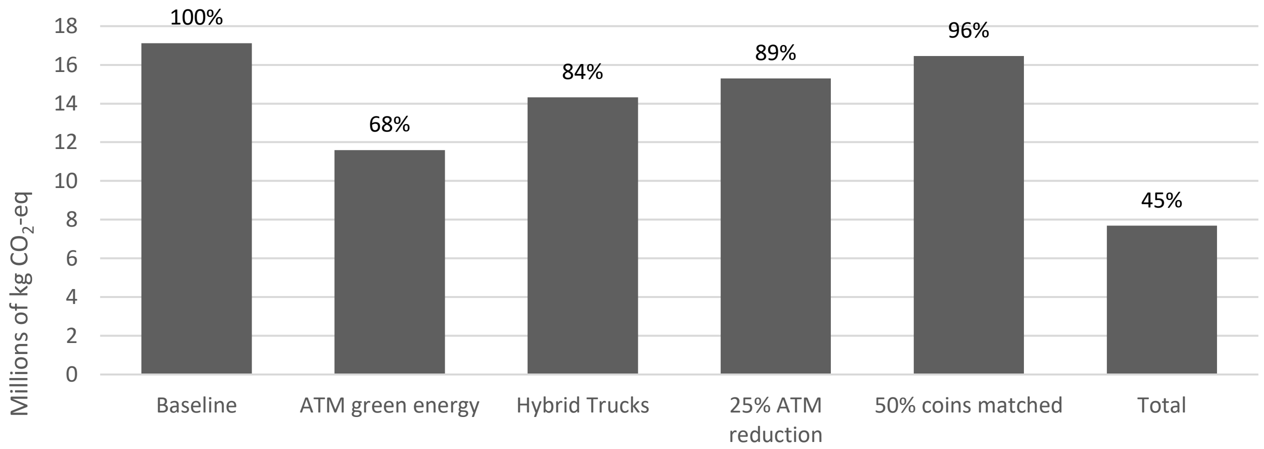

Figure 8. Results of scenario analyses on GWP and combined total

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 the environmental impact of an average cash transaction was 36% higher at 637 µPt and its GWP was 21% higher at 4.6 g CO_2e than that of an average debit card transaction. [16] 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 2.35 mPt, which is 57% 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 is smaller, but still amounts 42%. The differences in impacts on system level is 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

[16] 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.

a whole was 196 billion kg CO_2e (CBS, 2016a). As the GWP of the cash payment system amounts to 17 million kg CO_2e, the GWP of corresponds to 0.009% of the GWP of the Netherlands.[17] 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). This approach boils down to calculating the GWP per billion euro economic value. We use the resource costs of the cash payment system to society as a proxy of its economic value, which was approximately EUR 1.4 billion in 2015, and we use the gross domestic product of the 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).[18] 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 somewhat lower, but of the same order of magnitude, than the impact of the debit card payment system, when scaled with their respective economic values.

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	$17*10^6$	1.4	$12*10^6$
Debit card	$12*10^6$	0.9	$14*10^6$
Dutch economy	$196*10^9$	676.5	$287*10^6$

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

[17] 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.
[18] We proxy the economic importance of the cash and debit card payments in 2015 with their resource costs to society. Costs for cash payments to society (i.e. banks, retailers, CiTs and the central bank) reflect the use of resources in the production, issuance, transportation and carrying out cash payments at the POS. Cost figures for 2009 (Jonker, 2013) for banks, central bank and cost figures for 2014 for retailers (Snoei et al. 2015) have been extrapolated taking into account changes in the main cost drivers for cash. A similar approach was taken in Roos Lindgreen et al. (2018) for the debit card payment system.

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 637 µPt. The environmental impact of the Dutch cash payment system as a whole was 2.35 million Pt. The GWP of an average cash payment amounted to 4.6 gram CO_2e and the Dutch cash cycle as a whole amounted to 17 million kg CO_2e. This corresponds to 0.009% 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 (32%). The share of banknote production on the total environmental impact of cash was relatively small (5%) and the share of the end of life phases of banknotes and coins were both negligible (<0.01%). Within the cash payment system, the midpoint categories with the largest impact was fossil depletion (24%), Metal depletion (22%) had the second largest impact, followed by climate change human health (20%), climate change ecosystems (13%), particulate matter formation (11%) 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 green 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 51% lower environmental impact and a 55% lower GWP. 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 an 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.

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 transportation of cash in the operation phase and 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 an uncertainty and sensitivity analysis, an attempt has been made to assess the extent to which the outcomes are sensitive to the assumptions made. The environmental impact of the cash payment system was shown to vary between -12% and +9%, ranging from 2.22MPt to 2.56 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.

Acknowledgments

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