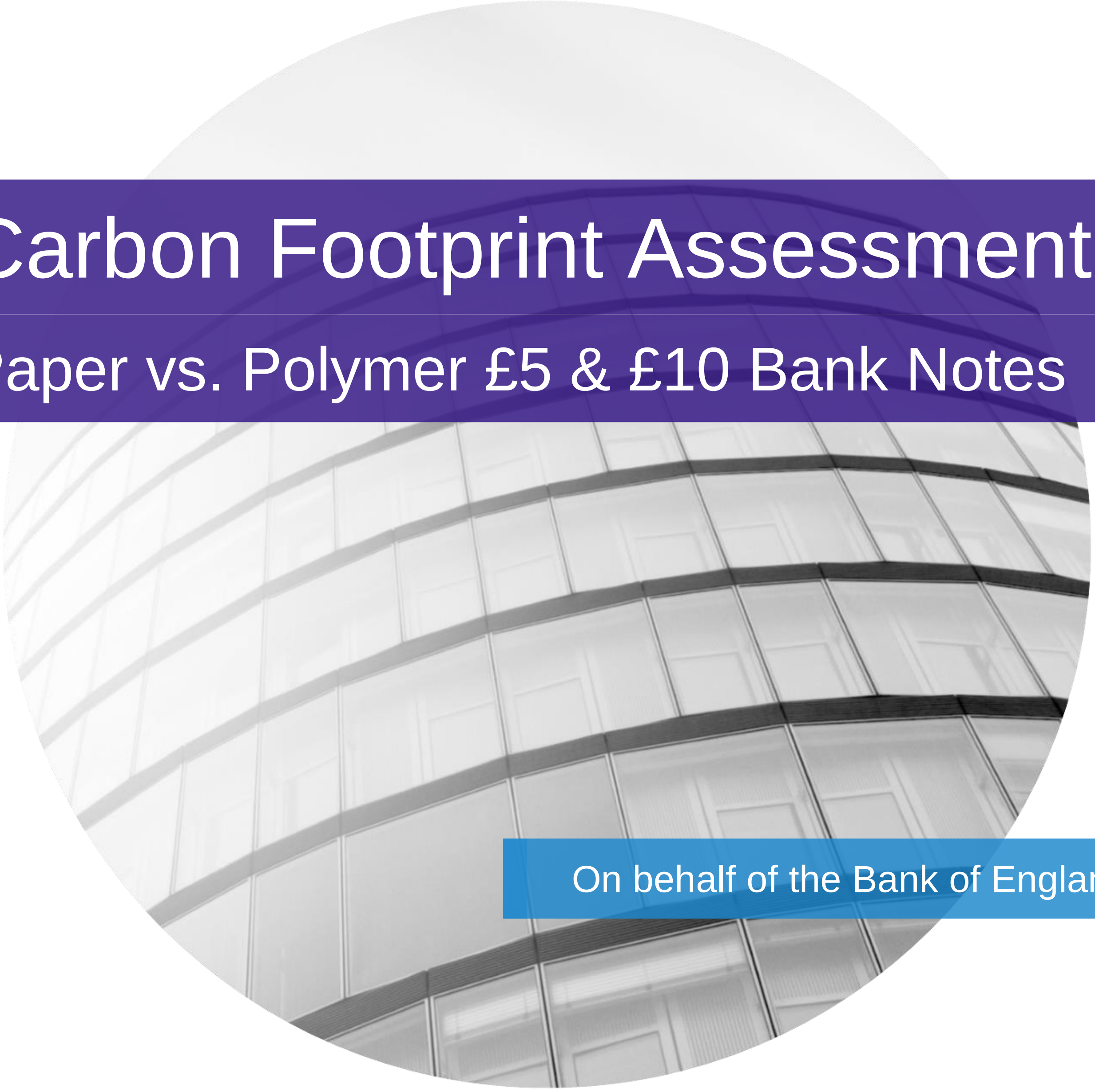
Carbon Footprint Assessment

Paper vs. Polymer £5 & £10 Bank Notes



On behalf of the Bank of England

Client: **Bank of England**

Title: **Carbon Footprint Assessment: Paper vs. Polymer £5 & £10 Bank Notes**

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On behalf of thinkstep AG and its subsidiaries

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List of Acronyms

BOPP	Biaxially Oriented Polypropylene
CHP	Combined Heat and Power
CML	Centre of Environmental Science at Leiden
ELCD	European Life Cycle Database
EoL	End-of-Life
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
ILCD	International Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NMVOC	Non-Methane Volatile Organic Compound
PP	Polypropylene
VOC	Volatile Organic Compound

Glossary

Carbon footprint (global warming potential)

Factor describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to an equivalent unit of CO2 over a given period of time (BSI, 2012).

Life cycle

A view of a product system as “consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal” (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land and water.

Life cycle assessment (LCA)

“Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 14040:2006, section 3.2)

Life cycle inventory (LCI)

“Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle” (ISO 14040:2006, section 3.3)

Life cycle impact assessment (LCIA)

“Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product” (ISO 14040:2006, section 3.4)

Life cycle interpretation

“Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations” (ISO 14040:2006, section 3.5)

Functional unit

“Quantified performance of a product system for use as a reference unit” (ISO 14040:2006, section 3.20)

Allocation

“Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” (ISO 14040:2006, section 3.17)

Closed-loop and open-loop allocation of recycled material

“An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.”

“A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.”

(ISO 14044:2006, section 4.3.4.3.3)

Foreground system

“Those processes of the system that are specific to it … and/or directly affected by decisions analysed in the study.” (JRC, 2010, p. 97) This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

Background system

“Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process … and/or those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good….” (JRC, 2010, pp. 97-98) As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

Critical Review

“Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment” (ISO 14044:2006, section 3.45).

Executive Summary

In 2016 the Bank of England introduced into circulation in the UK the first bank notes made from balanced biaxially oriented polypropylene (‘polymer’). These £5 denomination notes are due to be followed in 2017 by polymer £10 notes.

The Bank of England has commissioned thinkstep to carry out a carbon footprint assessment to evaluate the performance of the new polymer bank notes and compare this with those of the previous cotton paper (‘paper’) bank notes. The study has been certified by the Carbon Trust to ensure conformity to the requirements of PAS 2050:2011 (BSI, 2011) and the Carbon Trust Standard for Carbon.

The expected audience for the study will, initially, be internal to the Bank of England. However, the final report, or selected results taken from the study, may be reported more widely to external stakeholders or the general public.

The statement that the new polymer bank notes have been certified to the Carbon Trust Standard for Carbon will be used in external communication to demonstrate the efforts made by the Bank of England to reduce the environmental impact of its activities.

The scope of the study is from cradle-to-grave, accounting for raw material production (i.e. cotton, polypropylene), manufacturing of paper and polymer substrates; printing, distribution of bank notes into circulation, use of ATMs, note sorting at regional cash centres and the final disposal of unfit bank notes.

The functional unit selected for the assessment is:

> *‘Provision and use of 1000 bank notes over 10 years, considering an average bank note life cycle where notes are introduced into circulation through an ATM’*

The average lifetime of bank notes varies depending on denomination and choice of substrate. As polymer bank notes were only introduced into circulation in September 2016, insufficient time has passed to fully understand how long they will remain fit for circulation. The assumption made in this study is that polymer bank notes will have a lifetime 2.5 times greater than that of paper bank notes. This is likely to be a conservative assumption as other countries have found that much longer lifetimes can be achieved – for example, in Australia polymer bank notes were found to last between six and nine times longer than paper bank notes, depending on the denomination (Rush, 2015).

Table E-1: Results of the carbon footprint assessment, both including and excluding circulation, in kg CO_2e per functional unit

Indicator	£5			£10		
	Paper	Polymer	% change	Paper	Polymer	% change
Carbon footprint (inc. circulation)	187	157	-16%	471	436	-8%
Carbon footprint (exc. circulation)	59	30	-50%	65	31	-53%

The top-level results of the carbon footprint assessment are shown in Table E-1. For both £5 and £10 bank notes, the carbon footprint is dominated by impacts associated with circulation in the economy, particularly due to electricity generation required to operate ATMs. This is most noticeable for £10 notes; these have about the same overall lifetime as £5 notes but have a much higher *circulation velocity*[1], which means that they are sorted and reissued more often than £5 notes and spend more time in ATMs. It should be noted that the impacts associated with circulation are the same for both paper and polymer bank notes, so this life cycle stage does not contribute to differences between the two substrate choices.

After circulation, the life cycle stages with the largest contribution to the overall carbon footprint are substrate production and printing. Other life cycle stages, such as raw material production, transport and disposal at end of life are of less significance.

When comparing bank note substrates, the results of the carbon footprint assessment show that for both £5 and £10 denominations, polymer bank notes outperform paper bank notes. Considered over the full life cycle, polymer £5 notes have 16% lower impacts than paper £5 notes, while polymer £10 notes have 8% lower impacts than paper £10 notes. However, as noted above, a large proportion of the overall impacts is due to the circulation stage of the life cycle, which will be the same for both paper and polymer bank notes. If impacts due to circulation are excluded, the GHG emissions reductions are 50% and 53%, respectively.

The benefits of using polymer notes do not derive from lower GHG emissions from production or disposal of a given bank note—indeed, on a note-for-note basis £5 polymer bank notes have similar impacts to paper notes, while £10 polymer bank notes have higher GHG emissions than their paper equivalents, even though the notes themselves are slightly smaller. Instead, these benefits are due to the greatly extended lifetime of polymer bank notes. This means that substantially fewer polymer notes are required to provide the same functionality as a given quantity of paper bank notes. Accordingly, fewer raw materials are needed and less processing is required to produce the quantity of notes required.

A sensitivity analysis was carried out to better understand the influence of bank note lifetime on GHG emissions. This showed that polymer bank notes need only last slightly longer than paper bank notes to achieve an improvement in overall GHG emissions—a 6% increase in lifetime is required for £10 polymer bank notes, but no increase at all is needed for £5 polymer bank notes. Given that polymer bank notes are known to have lifetimes several times longer than paper bank notes this gives great confidence that the switch to polymer bank notes will result in real GHG savings, even if there is still uncertainty around the precise lifetime of polymer bank notes in circulation in the UK.

The results of this study are strongly influenced by specific UK conditions and cannot reliably be extrapolated to other countries/regions.

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[1] Circulation velocity refers to the length of time a bank note remains in circulation before being sent for sorting and reissuing to the public (e.g. through an ATM).

1. Goal of the Study

The Bank of England is the central bank of the United Kingdom and, among other things, is responsible for ensuring low inflation, trust in bank notes and the stability of the financial system.

Traditionally, UK bank notes have been manufactured from cotton paper. However, in 2016 the first polymer £5 notes were introduced into circulation and a polymer £10 is scheduled to be introduced in 2017. A life cycle assessment study conducted prior to the launch indicated that there would be significant environmental benefits from using polymer bank notes (PE International, 2013). That study used projections to estimate the impact of printing polymer bank notes, but actual data are now available on the printing of polymer bank notes. Based on this new information, the Bank of England wants to revisit and update this study to better understand the relative impact on climate change of using paper and balanced biaxially oriented polypropylene (BOPP) (hereafter referred to as 'paper' and 'polymer' respectively).

As such, the Bank of England has commissioned thinkstep, a global consulting company providing sustainability services and solutions, to undertake a carbon footprint assessment to calculate the impacts on climate change of polymer bank notes in the UK for two denominations—£5 notes and £10 notes—and identify the main drivers contributing to these impacts. These results will be compared to the impacts of producing paper bank notes based on data supplied in the previous LCA study.

The assessment of paper bank notes is based on the specification of the last £5 notes in circulation and the current £10 notes, including specific security features such as security thread and foil patch holograms. Polymer notes are assessed based on the specification of notes currently in circulation (£5) or planned for distribution later in 2017 (£10). Some of the security features on the polymer bank notes vary from those on current paper bank notes and these differences have been taken into account (see Table 2-1).

The expected audience for the study will be the Bank of England, external stakeholders and the general public.

This report will form the basis for a carbon footprint label certified by the Carbon Trust and based on PAS 2050 (BSI, 2011).

2. Scope of the Study

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function, functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

2.1. Product System(s)

This study quantifies the cradle-to-grave carbon footprint of £5 and £10 notes made using either paper or polymer substrates (a flow chart showing the system boundaries of the study is presented in Figure 2-1 in Section 2.3). The main physical characteristics of each note are reported in Table 2-1 below.

Table 2-1: Description of some key physical properties of the bank notes assessed in this study

Denomination	Substrate	Dimensions [mm]	Grammage [g/m^2]	Note-specific Security Features[a]
£5	Paper	70 x 135	90.0	Security thread, foil patch
	Polymer	65 x 125	88.2	Foil stripe
£10	Paper	75 x 142	83.0	Security thread, foil patch
	Polymer	69 x 132	88.2	Foil stripe

[a] Print-related security features such as raised lettering, UV ink, etc. that are applied to all notes are also assessed in the model.

2.1.1. Description of Paper Bank Note Life Cycle

UK paper bank notes are manufactured from cotton linter and cotton comber noil: both arise as by-products from the normal cotton fibre production process. Cotton comber noil comprises fibres that are too short to make into cotton thread for clothing; it provides strength and tear resistance to the paper. Cotton linter comprises the fine silky fibres that stick to the cotton seeds during ginning (the process of separating seeds, seed hulls, and other small objects from the cotton fibres); it is used as filler and also promotes the formation of good watermarks in the paper.

When these cotton fibres are turned into paper, security features such as metallic thread and watermarks are added. The paper is then sent for printing, which is a four step process as follows:

1. lithographic printing: applies the main design to the bank note;
2. application of holographic foil patch security device;
3. intaglio printing: creates raised print in certain areas of the note; and
4. letterpress printing: applies a unique number to each bank note.

After printing the notes are chopped using a manual guillotine. Each note is then automatically inspected using a single note inspection machine before being packaged ready for distribution.

On leaving the printworks the notes are initially sent to one of two Bank of England Cash Centres: in Debden (next to the printworks) or in Leeds. Some notes are also held as contingency stock at Threadneedle Street. This aspect has not been modelled as the contingency stock quantities are continually changing and because this simply represents an interim step prior to distribution into circulation through the usual channels via the Bank of England's North and South Cash Centres.

Notes are sent from the Bank of England Cash Centres to 20 regional cash centres run by commercial wholesalers: members of the Note Circulation Scheme (NCS). These include G4S, the Post Office, the Royal Bank of Scotland (RBS) and Vaultex. NCS members manage the distribution of notes to major retailers, banks and ATMs.

NCS members also manage deposits returned from these organisations. When notes are returned they are automatically sorted to separate notes that are no longer considered fit for use. Fit notes are re-circulated while unfit notes are returned to the Bank of England cash centres.

A sample of returned notes is inspected again to test for fitness, authenticity and quantity. Finally, the notes are destroyed by being granulated and then compacted. The destroyed bank notes are composted and used as a soil improver.

2.1.2. Description of Polymer Bank Note Life Cycle

Polymer bank notes are made from polypropylene resin. BOPP film is produced using a blown extrusion process whereby polymer melt is extruded through a die to form a thin walled tube. Air is then introduced via a hole in the centre of the die to blow up the tube like a balloon. Mounted on the die, a high-speed air ring blows onto the hot film to cool it. The tube of film then travels downwards, continually cooling, until it passes through nip rolls where the tube is flattened before being slit to convert it to a layer of film.

The resulting clear BOPP film then undergoes gravure printing to produce an opaque film ready for printing bank notes (a small patch is left clear forming the transparent window in the note).

The printing process for polymer bank notes involves the same steps as that for paper notes, although an additional varnish is applied in a final step to ensure that the applied inks stay fast to the note and are not rubbed off during use.

The treatment of polymer notes in circulation is the same as for paper notes, with distribution to Bank of England and NCS cash centres before circulation into the wider economy.

Unfit polymer notes are returned to the Bank of England to be destroyed. In this case the polymer bank notes are shredded and then sent to be recycled into further polymer products.

2.2. Product Function(s) and Functional Unit

The function of UK bank notes is to serve as legal tender in the UK for meeting financial obligations.

The functional unit for the assessment is:

'Provision and use of 1000 bank notes over 10 years, considering an average bank note life cycle where notes are introduced into circulation through an ATM'

Accordingly, the reference flows will be dependent upon the:

- dimensions and density of the bank notes
- lifetime of the bank note (this will vary according to the denomination and the choice of substrate). E.g. if a bank note has an average lifetime of four years then 2.5 bank notes will be required over a 10 year period (the number of notes required is not rounded up to the nearest whole note)[2].

The 10 year time span selected in the functional unit is a subjective choice but seems reasonable given the bank note lifetimes modelled in this study and is in line with the previous LCA study. Selecting a longer or shorter time span would alter the absolute values reported in the results but would not affect the relative performance of the different bank note substrates.

Table 2-2 gives information on the circulation lifetimes of different paper bank note denominations in the UK. These are based on statistics provided by the Bank of England covering the time period January – August 2016. Data are only available for paper bank notes as £5 polymer notes were introduced in September 2016, too recently for circulation data to be collected, while £10 polymer notes are yet to be issued.

These data show that an average paper £5 note returns to a NCS cash centre every 5.1 months, and has a note life of 16.1 months. After its 3rd sort (at 15.3 months) it will not be considered unfit, and will circulate for a further 5.1 months, until it is sorted again. It will therefore have circulated for a total of 20.4 months; 4.3 months longer than its expected note life.

Table 2-2: Circulation characteristics of different denominations of paper bank notes

Denomination	Velocity of circulation [months][a]	Note life [months]	Circulations before removal[b]	Circulation beyond note life [months][c]	Total circulation time [months]
£5	5.1	16.1	4	4.3	20.4
£10	1.6	17.7	12	1.5	19.2

[a] average interval between being sorted at a NCS cash centre.

[b] the number of times the note is sorted at a NCS cash centre and still considered fit for use.

[c] unfit notes are only removed from circulation once they are sorted at a NCS cash centre. Hence unfit notes will remain in circulation for a period beyond their ‘fit’ note life.

The lifetime of polymer bank notes is forecast based on statistical data from countries that already use polymer notes, combined with consideration of how this might be influenced by the specific characteristics of the UK situation. For the purposes of the baseline scenario for this study it is assumed that polymer notes have a lifetime 2.5 times greater than that of paper notes; this is in line with an LCA study for the Bank of Canada (PE Americas and Tryskele, 2011) and with the previous

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[2] Consideration of the design lifetime of the bank notes (i.e. implementing new note designs, issuing new notes and recalling and destroying existing notes) is outside the scope of this study.

LCA study conducted for the Bank of England on paper and polymer bank notes (PE International, 2013). However, it is likely that this assumption is conservative and that actual polymer bank note lifetime will be significantly greater than this; a recent study on polymer notes used in Australia shows that, depending on the denomination used, current polymer bank notes have lifetimes between six and nine times longer than previously used paper bank notes (Rush, 2015).

Based on this assumption regarding bank note lifetime the circulation characteristics of polymer bank notes are given in Table 2-3. The impact on the results of uncertainty relating to bank note lifetime is the focus of a sensitivity analysis (see Section 4.4).

Table 2-3: Assumed circulation characteristics of different denominations of polymer bank notes

Denomination	Velocity of circulation [months][a]	Note life [months]	Circulations before removal[b]	Circulation beyond note life [months][c]	Total circulation time [months]
£5	5.1	40.3	8	0.5	40.8
£10	1.6	44.3	28	0.5	44.8

[a] average interval between being sorted at a NCS cash centre.

[b] represents the number of times the note is sorted at a NCS cash centre and is still considered fit for use.

[c] unfit notes are only removed from circulation once they are sorted at a NCS cash centre. Hence unfit notes will remain in circulation for a period beyond their ‘fit’ note life.

The functional unit also specifies that in the use phase all notes will be modelled as being introduced into circulation through ATMs. In practice, notes are also introduced into circulation in other ways (e.g. via banks) but the impacts associated with these alternatives are very diverse and difficult to quantify. The assumption that notes are dispensed via ATMs avoids this uncertainty. The significance of this assumption on the comparison between paper and polymer bank notes is low as circulation impacts will be the same in both cases. Hence this assumption alters the absolute values reported in the carbon footprints but does not affect the difference between the results for the two substrate options.

The reference flows for the different note denominations used in this carbon footprint assessment are given in Table 2-4. As the notes are still in circulation and being used as currency even after their note life, the reference flow is based on the total circulation time (i.e. including the period in which they circulate while technically unfit, after exceeding their expected note life). The reference flow refers to the functional unit of ‘provision and use of 1000 bank notes over 10 years’. Therefore a longer total circulation time means fewer bank notes are required and lower overall reference mass is observed.

Table 2-4: Reference flows for each bank note option based on the specified functional unit

Denomination	Substrate	Mass [g/note]	Total circulation time [months]	Reference flow [g/FU]
£5	Paper	0.851	20.4	5,006
	Polymer	0.717	40.8	2,109
£10	Paper	0.884	19.2	5,525
	Polymer	0.803	44.8	2,151

2.3. System Boundary

This study is a cradle to grave carbon footprint assessment considering impacts across all life cycle stages from extraction of raw materials from the environment through to final disposal at end of life. The system boundaries are described in Figure 2-1 below.

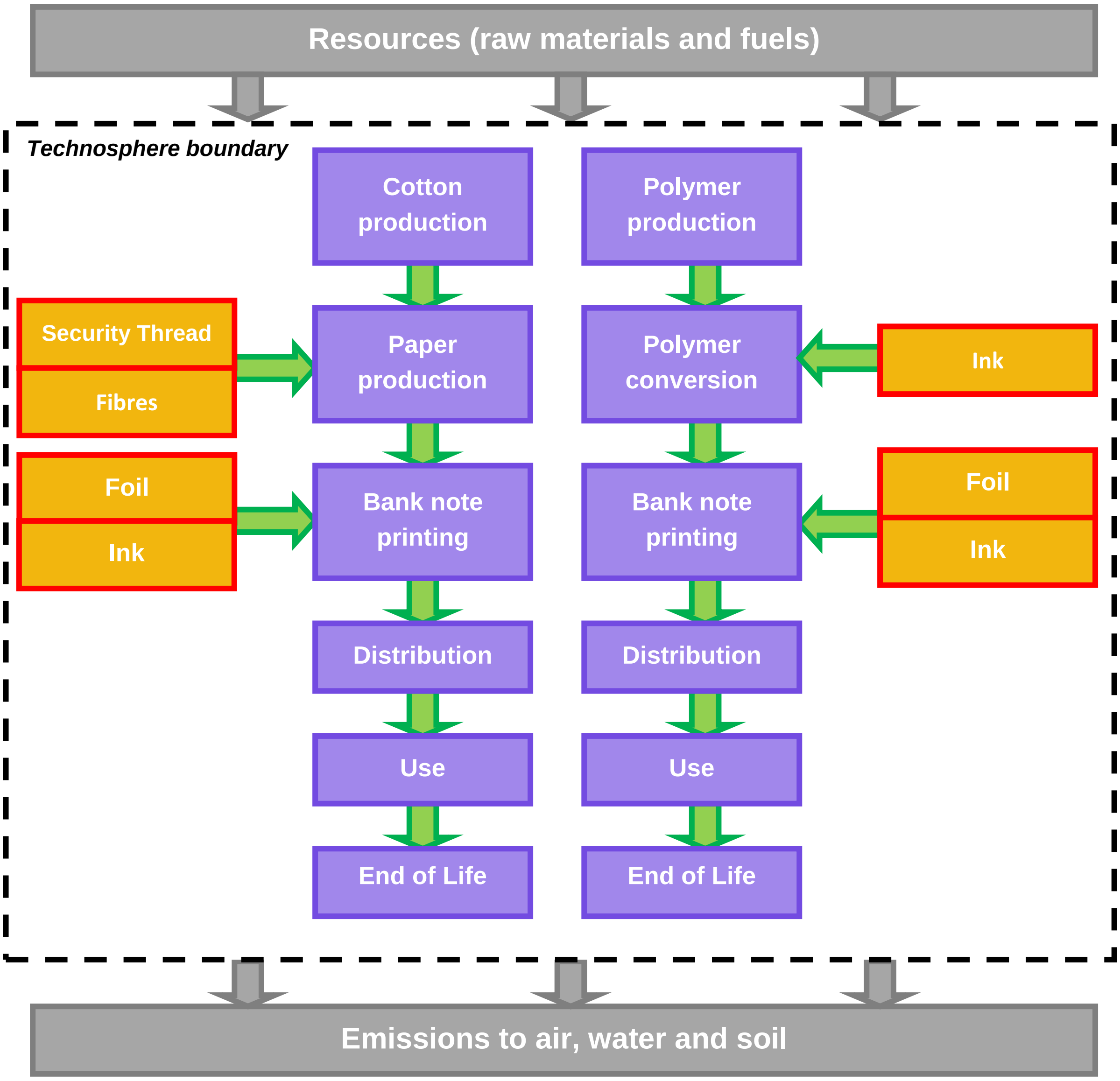

Figure 2-1: System boundary for the paper and polymer bank notes

The following aspects are considered within the scope of this assessment:

- production and processing of raw materials (i.e. cotton cultivation and separation of comber and noil from cotton fibre and seeds, polypropylene granulate production);
- transport of raw materials from production site to intermediate manufacturing facility (e.g. paper mill, plastic film converter);
- manufacturing of intermediate products (paper and polymer substrates);

- transport of substrate to printworks;
- printing of bank notes;
- packaging of material related to the final product;
- disposal of production wastes;
- distribution of bank notes from printworks to Bank of England cash centres;
- distribution of bank notes from Bank of England cash centres to regional cash centres operated by Note Circulation Scheme (NCS) members;
- distribution of bank notes from NCS cash centres to retailers, banks, ATMs, etc. and their subsequent return to NCS cash centres;
- use phase impacts associated with ATMs;
- sorting and counterfeit-checking of notes at NCS cash centres;
- return of unfit bank notes to the Bank of England cash centres;
- checking of representative sample of unfit bank notes at Bank of England cash centres; and
- transport and final disposal of unfit bank notes.

The following aspects have been excluded from this cradle to grave LCA:

- construction of capital equipment – it is considered that these impacts will be negligible compared to the impacts of bank notes themselves and they are specifically excluded from consideration by PAS2050;
- packaging materials associated with delivery of raw materials, chemicals and other inputs to the production processes (packaging data could not be collected consistently through both the polymer and paper bank note supply chains, however, based on experience from previous studies, such packaging is not expected to have a significant impact on the results); and
- energy consumption of heater used in 'through the wall' ATMs when temperature drops below zero degrees Celsius (this will affect paper and polymer notes to an equal extent).

2.3.1. Time Coverage

The target reference year for the polymer bank note study is 2016. Data on paper bank notes have been sourced from the earlier LCA study that had a reference year of 2012.

Background data (mainly raw materials, energies, fuels, and ancillary materials) have mostly been obtained from the GaBi Database 2017 (thinkstep, 2017) and are representative of the years 2013-2016[3].

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[3] These datasets may be based on primary data collected at an earlier time but have been checked for technological representativeness (i.e. that the same production processes, etc. are still used) and are updated to reflect changes in grid mix, fuel supply, inputs of raw materials, etc..

2.3.2. Technology Coverage

Table 2-5 shows an overview of the technology used at each step of the life cycle. The technology is representative of the current technology in use for the production of UK paper bank notes, as well as the projected technology for the polymer bank notes.

Farming methods for cotton cultivation vary in different parts of the world and this is one factor that may lead to differences in the impact of cotton production in different regions. However, a sensitivity analysis carried out in the previous LCA study showed that the carbon footprint results are not sensitive to this issue (changing the impact of cotton cultivation by ±50% altered the overall life cycle results for £5 and £10 paper bank notes by only 1-2%).

Table 2-5: Overview of technological coverage

Life cycle step	Technology Description
Cotton production	Agricultural production of cotton
Polymer production	PP granulate production
Film production	Conversion of PP granulate into BOPP film using a blown extrusion process
Cotton paper production	Cotton paper production includes the making the paper itself with addition of thread and UV active fibres
Thread manufacturing	Coating process on polymer (PET) film
Foil production	Metallised polymer (PET)
Polymer conversion	Substrate production with BOPP followed by opacification using gravure printing
Bank note printing	Offset, intaglio and letterpress printing with foil patch application and associated pre- and post-press activities and materials
Ink	Ink for gravure, lithographic, intaglio and letterpress printing
Distribution	Sorting, storage and distribution (armoured cars) at Bank of England and NCS cash centres
Use	ATMs
End of life	Granulation, compaction and composting (paper notes); granulation and mechanical recycling (polymer notes)

2.3.3. Geographical Coverage

The distribution and use of the bank notes is modelled for the UK. The raw materials for production are sourced from various areas of the world and the geographical coverage varies depending upon the location of the manufacturing plants. The first batch of polymer £5 bank notes was made in Australia but all new notes are being produced in the UK, so UK production has been modelled in this study. The cotton paper substrate is made in the UK.

2.4. Allocation

2.4.1. Multi-output Allocation

Multi-output allocation follows the requirements of PAS 2050, Chapter 8. When allocation becomes necessary during the data collection phase, the allocation rule most suitable for the respective process step has been applied and is documented along with the process details in Chapter 0.

Allocation of background data (energy and materials) taken from the GaBi 2017 databases is documented online at http://www.gabi-software.com/support/gabi/gabi-database-2017-lci-documentation/ and is modelled in accordance with ISO 14044, section 4.3.4.2.

Cotton fibre production yields several by-products including:

- cotton comber noil;
- cotton linter; and
- cotton seeds

Cotton comber noil and cotton linter are used to produce paper bank notes. Impacts associated with the cotton production process have been allocated based on the economic value of these co-products. Economic allocation is considered to be the most appropriate approach for assigning impacts between the various co-products as this best reflects the economic drivers behind the activity (i.e. the reason the cotton is being grown at all).

thinkstep has previously worked with Cotton Inc., an organisation representing US cotton producers and importers, to develop a detailed LCA model for cotton representing average production in the US, India and China. Cotton Inc. has kindly given permission for their model to be used in this study to assess the impact of cotton linter and cotton comber noil and has provided cost information that has been used to allocate impacts.

Cotton linters are long fibres that are attached to the seeds and are separated from the raw cotton during the ginning process. The relative masses and economic values of these different co-products from the ginning process are presented in Table 2-6. This implies that 1 kg linter has equivalent impacts to 0.136 kg raw cotton fibres.

Table 2-6: Mass and Relative Economic Value[a] of Co-products from Cotton Ginning

Aspect	Raw cotton	Seed	Linter
Mass, kg	1.00	1.29	0.112
Relative Value	84.0%	14.7%	1.28%

[a] based on economic data provided by Cotton Inc. (2013)

Impacts associated with cotton comber noil were calculated by applying economic allocation to the detailed Cotton Inc. LCA model, which assesses production from a range of cotton manufacturers. Different manufacturers show different yields of comber noil/combed cotton but this is typically in the range 0.20-0.25 kg/kg. Economic allocation was applied assuming that combed cotton has a value of €1.28/kg and cotton comber noil a value of €0.86/kg.

During paper production some waste paper generated from this process is used as animal bedding. It has been assumed that this substitutes for straw from winter wheat.

In the polymer production route allocation has been applied to the energy generated using the CHP system at Innovia Film's production site in Wigton, Cumbria. This is a natural gas fuelled turbine-based CHP system so emissions per MJ electricity to emissions per MJ heat have been allocated in the ratio of 2:1. This supplies energy to both the BOPP film production and opacification processes used to make the finished substrate.

Allocation of impacts in background data (energy and materials):

- ✓ for all refinery products, allocation by mass and net calorific value is applied. The manufacturing route of every refinery product is modelled so the effort of the production of these products is calculated specifically. Two allocation rules are applied: 1. the raw material (crude oil) consumption of the respective stages, which is necessary for the production of a product or an intermediate product, is allocated by energy (mass of the product multiplied by the calorific value of the product); and 2. the energy consumption (thermal energy, steam, electricity) of a process, e.g. atmospheric distillation, being required by a product or an intermediate product, are charged on the product according to the share of the throughput of the stage (mass allocation).
- ✓ materials and chemicals needed during manufacturing are modelled using the allocation rule most suitable for the respective product. For further information on a specific product see http://www.gabi-software.com/support/gabi/gabi-database-2017-lci-documentation/.

2.4.2. End-of-Life Allocation

End-of-Life allocation follows the requirements specified in PAS 2050, Annex D.

Unfit paper bank notes are returned to the Bank of England where they are granulated and compacted before being sent for composting. The main value of compost is as a soil improver. Many other materials are also described as soil improvers, e.g. blood and bone meal, peat, coffee grounds, manure, straw, vermiculite, lime, hydroabsorbant polymers and sphagnum moss, but it is not clear how the benefits from applying compost compare to those from applying these other materials. They may each benefit the soil in different ways, e.g. by adjusting pH, nutrient levels, water retention, soil structure, etc. As such, it is difficult to say that application of a given quantity of compost substitutes for a given amount of an alternative soil improver. Instead, the benefits of composting have been assessed based on avoiding production of an equivalent nutrient value of chemical fertilisers.

Unfit polymer bank notes are returned to the Bank of England where they are granulated before being sent for mechanical recycling. Recycling is modelled using the 'closed-loop approximation method'. Recycled polymer is not used as an input for making polymer bank notes so all the waste polymer is modelled as going to recycling. The original burden of the primary material input is allocated between the current and subsequent life cycles using the mass of recovered secondary material to scale the substituted primary material, i.e. applying a credit for the substitution of primary material so as to distribute burdens appropriately among the different product life cycles. These subsequent process steps are modelled using industry average inventories.

The plates used for intaglio printing are predominantly made from nickel and those for lithographic printing and for the foiler and varnishing processes are made from steel. These are modelled as being recycled after use using the same 'closed-loop approximation method' described above for polymer recycling. No datasets were available for recycling nickel so this process was modelled using a secondary steel dataset as a proxy.

Elsewhere in the life cycle (e.g. during manufacturing), where materials are sent to waste incineration they are linked to an inventory that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. Credits are only assigned for power outputs as thermal energy recovery is not widespread in the UK; electricity credits are calculated using the UK average grid mix.

In cases where materials are sent to landfill, they are linked to an inventory that accounts for waste composition, regional leakage rates, landfill gas capture as well as utilisation rates (flaring vs. power production). A credit is assigned for electricity output using the UK average grid mix.

2.5. Cut-off Criteria

No cut-off criteria have been defined for this assessment as, wherever possible, all reported data have been incorporated and modelled using the best available LCI data. Where specific datasets are not available for a given input or process these have been modelled using proxy data.

The choice of proxy data and the few instances where data have been omitted from the study are described and justified in Section 3.2.

2.6. Selection of Carbon Footprint LCIA Methodology

As specified by PAS 2050, the carbon footprint has been assessed using the emission factors reported in the IPCC publication *Climate Change 2007: Synthesis Report* (IPCC, 2007).

It should be noted that the carbon footprint represents an impact *potential*, i.e. it is an approximation of environmental impacts that could occur if the emissions would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the functional unit (relative approach). A carbon footprint is therefore a relative expression only and does not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

2.7. Modelling of Biogenic Carbon

In accordance with PAS 2050, biogenic carbon flows have been modelled in this study. These flows are primarily of relevance to paper bank notes as polymer bank notes are all obtained from petrochemical sources (although there are also some biogenic flows associated with energy production where biomass is used as a fuel).

When modelling biogenic carbon in the cotton raw material that is used to make the paper bank notes the total removals have been calculated based on the amount of carbon embedded within the finished product (i.e. it is assumed that any biogenic carbon in waste flows from the production process is returned to the atmosphere as carbon dioxide within a short time period).

At the end of life stage, biogenic emissions of carbon dioxide, methane and nitrous oxide are modelled from the composting process, while some of the carbon in the bank notes remains sequestered in the compost itself (see Section 3.2.8). This is the only case where carbon storage is considered in this study (this is where removed carbon is not emitted back to the atmosphere within the 100-year assessment period). As shown in Table 2-2, £5 and £10 paper bank notes typically have relatively short lifetimes of around 20 months, so no carbon has been modelled as being stored within the bank notes themselves during circulation.

2.8. Land Use Change

The effects of land use change associated with cotton production have not been considered in this assessment due to lack of specific data on this activity. UK paper bank notes are made using cotton comber noil and linter sourced from many different locations. Data on changes in the quantities of cotton cultivated in each country and how these might impact on land use change (as opposed to just changing from one crop to another) are not available.

2.9. Interpretation to Be Used

The results of the carbon footprint have been interpreted in line with the goal and scope. The interpretation addresses the following topics:

- identification of significant findings, such as the main process steps, materials, and/or emissions contributing to the overall results,
- evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data,
- conclusions and limitations.

2.10. Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

- measured primary data are considered to be of the highest precision, followed by calculated data, literature data, and estimated data. The goal is to model all relevant foreground processes using measured or calculated primary data.
- completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data in this regard.
- consistency refers to modelling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modelling choices, data sources, emission factors, or other artefacts.
- reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report. The goal is to provide enough transparency with this report so that third parties are able to approximate the reported results. This ability may be limited by the exclusion of confidential primary data and access to the same background data sources.

- representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study's goal and scope. The goal is to use the most representative primary data for all foreground processes and the most representative industry-average data for all background processes. Whenever such data were not available (e.g. no industry-average data available for a certain country), best-available proxy data were employed.

An evaluation of the data quality with regard to these requirements is provided in Chapter 5 of this report. In Appendix D, data quality has been assessed and reported using the pedigree matrix described in the GHG Protocol Product Life Cycle Accounting and Reporting Standard (WRI, 2011; Weidema, 1996).

2.11. Type and format of the report

In accordance with the requirement of PAS 2050 (BSI, 2011) this document aims to report the results and conclusions of the carbon footprint completely, accurately and without bias to the intended audience. The results, data, methods, assumptions and limitations are presented in a transparent manner and in sufficient detail to convey the complexities, limitations, and trade-offs inherent in the carbon footprint to the reader. This allows the results to be interpreted and used in a manner consistent with the goals of the study.

2.12. Software and Database

The LCA model was created using the GaBi ts Software system for life cycle engineering, developed by thinkstep AG. The GaBi 2017 LCI database provides the life cycle inventory data for the raw and processed materials, energy, fuels and supporting processes in the background system.

2.13. Certification

The study has been certified by the Carbon Trust to ensure conformity to the requirements of PAS 2050:2011 (BSI, 2011) and the Carbon Trust Standard for Carbon.

The certification was undertaken by:

- John Kazer – Certification Manager, Carbon Trust;
- Ana Goncalves – Certification Manager, Carbon Trust.

The Carbon Footprint Label, Certificate of Achievement and other documents relating to the certification process can be found in Annex A.

3. Life Cycle Inventory Analysis

3.1. Data Collection Procedure

3.1.1. Data Collection & Quality Assessment Procedure

All primary data were collected using customised data collection templates that were sent out by email to data providers participating in the study. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, stoichiometry, and benchmarking. If gaps, outliers, or other inconsistencies occurred, thinkstep engaged with the data provider to resolve any open issues.

The key primary data used in this study are presented in Section 3.2 and Appendix B.

3.1.2. Secondary Data

Data for upstream and downstream raw materials and unit processes, and for fuel inputs and electricity grid mixes, were obtained from the GaBi ts database 2017. Documentation for all non-project-specific datasets can be found at http://www.gabi-software.com/support/gabi/gabi-database-2017-lci-documentation/.

Further information relating to the representativeness and quality of the secondary data sources can be found in Appendix C.

3.1.3. Transportation

Transportation distances and modes of transport used for distribution of raw materials, semi-finished products and finished bank notes to Bank of England cash centres were obtained from suppliers or assessed using web-based calculation tools (Google, 2017; Sea-distances.org, 2017). Average transportation distances for distributing notes to NCS cash centres and out into the wider economy were obtained from G4S and assumed to be representative of all NCS members.

GaBi data for transportation vehicles and fuels were used to model transportation. This provides representative datasets for a wide range of transport options for different vehicle types, sizes and technologies (e.g. different Euro-rated engines for trucks). These datasets are parameterised and have been adjusted to fit the specific vehicle loading efficiencies, carrying capacities, transport distances, etc. wherever transport processes are required.

Bank notes are, by their nature, high value products and are transported using armoured vehicles. Primary data on the fuel consumption of armoured vehicles were sourced from G4S, one of the NCS members and a leading contractor supplying transport services for cash distribution.

3.1.4. Emissions to Air, Water and Soil

All emissions reported by suppliers for the manufacturing phase have been taken into account in the study (data used for official reporting). All gate-to-gate emissions data were obtained from the suppliers.

Emissions associated with transportation were determined by modelling the logistical operations associated with each process stage based on primary data supplied by the companies involved. Energy use and the associated emissions were calculated using pre-configured transportation models from the GaBi ts database 2017, adapted with transportation supplier data (specific fuel economy, specific emissions, etc.).

3.2. Assumptions and Limitations

Assumptions and limitations in the life cycle modelling of bank notes and their anticipated effect on the study results are described in this section.

3.2.1. Cotton Production

Information on the environmental impacts of cotton production is based on secondary data supplied by Cotton Inc. This is derived from a study based on average data for cotton production in the US, China and India.

UK bank notes are made using cotton comber noil and linter sourced from many different locations. The Cotton Inc. dataset may not be representative of cotton production in all these locations as the impacts will be dependent upon many factors including soil type, climate, farming practices, available technology, choice of fertilisers and pesticides, etc., that can vary from place to place. However, this study is constrained by available data on cotton production and we consider the Cotton Inc. data to be the best available. An assessment in the previous LCA study showed that, in the context of the full life cycle, the results were not sensitive to the impacts of cotton production.

Cotton comber noil and cotton linter are both co-products of the cotton fibre production process. The approach used to allocate impacts to these co-products is described in Section 2.4.1**.**

The carbon content of bank notes is assumed to be the same as that of cotton. Cotton is predominantly cellulose (91.0%), the remainder being mostly water (7.9%) with small amounts of protoplasm, pectins, waxes and mineral salts (Wikipedia, 2017). The carbon content of cellulose is around 44% (Lui, 1997; Heukelekian, 1925) so the carbon content of cotton is estimated at 40%.

3.2.2. Papermaking

Paper production takes place at De La Rue’s Overton Paper Mill in Basingstoke, UK. Raw cotton comber is received and treated with sodium hydroxide and hydrogen peroxide to ‘whiten’ it and remove natural fats/oils. Both this treated comber and linter are then mechanically treated and forwarded to paper machines where performance chemicals and details such as security threads and fibres are added and finished sheets of paper are produced. This output is slit, trimmed and inspected for defects to give the finished cotton paper substrate.

Waste paper from this process is used as animal bedding and is assumed to substitute for an equivalent mass of straw, thereby providing a credit to the system. Waste 'paper crumble'—fibrous material recovered from the waste water treatment plant—is provided to local farmers as a soil improver for land spreading. Impacts related to this disposal option are modelled as being the same as for composting of paper bank notes at end of life (see Section 3.2.8).

3.2.3. Polymer Film Production

The base polymer film is manufactured by Innovia Films at their production facility located in Wigton, UK.

The uncoated biaxially-oriented polypropylene (BOPP) film is produced using a blown extrusion process whereby polypropylene plastic melt is extruded through a circular die to form a thin walled tube. Air is then introduced through a hole in the centre of the die and blows the tube up like a balloon. Mounted on the die, a high-speed air ring blows onto the hot film to cool it. The tube of film then travels downwards, continually cooling, until it passes through nip rolls where the tube is flattened before being slit to convert it to a layer of film.

3.2.4. Polymer Substrate Production

To convert the polymer film into substrate suitable for printing it undergoes a gravure printing process to opacify the film. This process is carried out by CCL Secure, which is co-located with Innovia Films' manufacturing facility in Wigton, UK.

Data on some inputs to the polymer substrate conversion process are commercially sensitive and a detailed description was not available for this study. Titanium dioxide has been used a proxy dataset for all the pigments and toners (white ink is used in this process). Titanium dioxide is a relatively high impact material (4.8 kg CO_2e/kg) compared to many other pigments so this is likely to be a conservative assumption.

3.2.5. Printing

Bank note printing takes place at the De La Rue's Debden printworks located in Loughton, UK. Bank notes undergo a four-stage printing process as follows:

- lithographic printing: a dry offset printing process is used to apply ink to the substrate according to a design specific to the denomination;
- foil application: a holographic foil patch is applied as an additional security detail;
- intaglio printing: intaglio presses are used to give bank notes their characteristic feel by generating areas of raised print; and
- letterpress printing: unique serial numbers are applied to each note using a letterpress process

Polymer bank notes undergo an additional process where a layer of varnish is applied. This ensures that the applied inks stay fast to the note and are not rubbed off during use.

Before each print run commences the machines are tested using ‘pink’ substrate. For paper bank notes pink paper is used (this is standard kraft paper, not cotton paper). For polymer bank notes, both pink paper and pink polymer are used.

Data on inks for paper bank notes have been provided by SICPA, the main supplier of inks for printing UK bank notes. The composition of inks for polymer bank notes will vary somewhat to those for paper printing, but the overall proportion of resins, pigments/extenders and additives is broadly similar. As such, the same ink data have been applied for modelling both paper and polymer bank notes.

After printing, the sheets of printed notes are cut into individual bank notes using a manual guillotine. The quality of the finished notes is then checked using a single note inspection machine before being packed ready for distribution. The packaging comprises a paper band around each stack of 100 notes and shrinkwrap around bundles of 1000 and 5000 notes along with paper labels.

The energy consumption of the printing stage in the life cycle is modelled based on the electricity used by each machine in the process, which are metered individually. However, to maintain paper quality, the temperature and humidity of the print works and associated paper/bank note storage areas have to be carefully controlled. The Bank of England has supplied information on energy consumption associated with the HVAC system and on fugitive emissions of refrigerant used.

3.2.6. Note Circulation Characteristics

After printing, bank notes are transferred to Bank of England Cash Centres. Of these, 60% go to the South Cash Centre, which is co-located with the print works in Debden, London. The remaining 40% are sent to the North Cash Centre, located in Leeds, West Yorkshire.

Some notes are also held as contingency stock at Threadneedle Street. This aspect has not been modelled as the contingency stock quantities are continually changing and because this simply represents an interim step prior to distribution into circulation through the usual channels via the Bank of England’s North and South Cash Centres.

From the Bank of England Cash Centres the notes are then distributed to regional cash centres run by the Note Circulation Scheme (NCS), whose members include:

- Royal Bank of Scotland;
- Post Office;
- G4S; and
- Vaultex.

The NCS members are responsible for managing the circulation of the notes to banks, retail institutions and ATMs. Notes paid into banks are also collected by NCS members and are sorted to assess their fitness for reissue and prepare them for re-circulation.

Table 2-2 shows the bank note lifetimes and sorting frequency of each bank note, and illustrates large differences between £5 and £10 denominations. Both denominations have similar overall lifetimes but £10 bank notes circulate around three times faster than £5 bank notes. £10 bank notes therefore go through three times as many sorts and are redistributed into circulation via ATMs three times more often than £5 bank notes.

Data on the energy consumption of ATMs were provided by Diebold, an ATM manufacturer operating in the UK. ATMs come in two main variants: ‘lobby’ ATMs (often found inside shops or banks) and 'through the wall' ATMs found on high streets. The energy consumption of through the wall ATMs is somewhat higher than that of lobby ATMs. Of more than 70,000 ATMs installed in the UK it is estimated that 37% are through the wall ATMs and 63% are lobby ATMs (Thomas, 2013).

ATMs consume energy both when vending cash and while in stand-by mode. Although they come in many different designs and capacities a typical ATM will hold four cassettes each containing 2,500 notes (10,000 notes in total). It is assumed that each transaction consists of the ATM vending six notes and that there are 166 transactions of 6 notes per day (this was considered a representative usage scenario by Diebold, although clearly there will be a very large degree of variation).

If each transaction takes one minute then the ATM will be in stand-by mode for 21.2 hours/day, assuming they are operational 24 hours/day. The energy consumption of operating the ATM in stand-by mode over this time needs to be allocated between all the notes contained within the machine. If well managed, the ATM will be refilled when there are only a few hundred notes remaining. If there are 166 transactions of 6 notes per day the ATM will need to be refilled every 10 days. Hence the energy consumption impacts from stand-by mode operation over this time must be allocated between 10,000 notes.

Table 3-1 shows the energy consumption for transactions and stand-by mode operation for each type of ATM and the weighted average values used in the carbon footprint model. These data are derived from the information provided by Diebold as presented in Table B-3 in Appendix B.

Table 3-1: Energy demand of ATMs

ATM	Vending [kWh/6 note transaction]	Stand-by mode [kWh/ATM.day]	Total per note[c] [kWh/circulation cycle]
Lobby ATM	4.76×10^{-3}	4.03	8.89×10^{-3}
Through the Wall ATM	5.72×10^{-3}	5.30	1.16×10^{-2}
Through the Wall ATM (below 0ºC)[a]	1.57×10^{-2}	18.04	3.89×10^{-2}
Weighted average[b]	5.51×10^{-3}	5.01	9.89×10^{-3}

[a] If the temperature drops below zero Celsius a heater is required for through the wall ATMs that significantly increases energy consumption.

[b] Assuming that the heater is required for 10% of days each year

[c] Sum of energy consumption per transaction and stand-by mode over 10 days allocated on a per note basis

More polymer bank notes can be loaded into an ATM cassette than is possible with paper bank notes. However, this will not affect the impact associated with each bank note in the ATM. Putting more notes in an ATM means that it will vend for longer before running out of cash. As such, it spends a greater amount of time in stand-by mode before being refilled and the energy required for this must be allocated across the larger number of notes in the ATM. Hence, the energy consumption per note is unchanged.

3.2.7. Transport

The transport distances used in the model are given in Table 3-2. For modelling the supply of raw materials and transport of substrates to the printworks it is assumed that road transport uses lorries with a maximum payload of 22 tonnes, operating with 85% loading (by mass). Sea transport is assumed to be a container ship with a payload capacity of 27,500 deadweight tonnes. Only the one-way distance is considered as it is assumed that efficient logistics planning will ensure that vehicles do not return empty.

Table 3-2: Transport distances applied in the model

Journey	Paper Bank Note	Polymer Bank Note
Raw Material input to substrate production	Cotton linter: Road: 485 km[a] Ship: 4,641 km[a] Cotton comber noil: Road: 557 km[a] Ship: 8,484 km[a] Other raw materials: Road: 400 km[b]	Polypropylene granulate: Road: 180 km[a] Other raw materials to film production: Road: 600 km[b] Solvent (opacification): Road: 185 km[a] White ink (opacification): Road: 127 km[a] Other inks & additives (opacification): Sea: 16898 km[a] Road: 100 km[a]
Substrate Production to Printworks	Paper: Road: 141 km[c]	Polymer film: Road: 450 km[c]
Print works to Bank of England Cash Centre	Bank of England North Cash Centre: Road: 317 km[b] Bank of England South Cash Centre: No transport required as it is co-located with the print works	
Bank of England Cash Centre to NCS Cash Centres	From Bank of England North Cash Centre: Road: 34 km[a] From Bank of England South Cash Centre: Road: 109 km[a]	
NCS Cash Centres to Banks, Retailers, ATMs.	Road: 91 km[a]	
Transport to Disposal	Composter (Debden): Road: 35 km[a] Composter (Leeds): Road: 30 km[a]	Recycling facility (Debden): Road: 45 km[a] Recycling facility (Leeds): Road: 45 km[d]

[a] distance provided by supplier;
[b] distance based on estimate of supply from neighbouring countries in Europe;
[c] calculated distance (Google, 2017);
[d] polymer bank notes are not currently being destroyed at Leeds. Distance is modelled as being the same as for Debden.

For modelling the impact of bank note distribution and circulation, the impact of diesel combustion has been assessed using a GaBi background dataset for a truck with a maximum payload of 5 tonnes, but scaled to fit a fuel consumption of 15.5 mpg (equivalent to 0.179 l/km). This value is based on a fleet average for armoured vehicles operated by G4S.

3.2.8. Composting of Paper Bank Notes

Modelling composting processes is challenging as emissions from composting are affected by a wide range of parameters. These include, amongst others:

- feedstock characteristics (e.g. carbon/nitrogen ratio);
- moisture;
- temperature;
- maturation time; and
- compost management regime (e.g. how often it is turned).

Compacted and granulated paper bank notes are blended with other biodegradable waste materials and composted using an open air windrow system. In this study, data on composting paper bank notes were taken from a paper on modelling composting in LCA studies (Amlinger, 2008). It is assumed that composting of paper bank notes results in the same emissions as windrow composting of biowaste over a total time period of 11 weeks.

The composting model accounts for the emission of carbon dioxide, nitrous oxide, methane and ammonia and calculation of the nutrient content of the compost (Vegetable Resource and Information Centre, 2009; Eunomia, 2002; WRAP, 2016). The main parameters used in the model are presented in Table 3-3. It is assumed that the proportion of carbon that remains in the compost is not re-emitted at some later date (i.e. it remains locked in the compost for the 100 year period during which GHG emissions are evaluated). This assumption will be dependent upon farm management practices.

Table 3-3: Key parameters for modelling emissions from composting (Amlinger, 2008).

Parameter	Unit	Value
Carbon dioxide emissions	g/t fresh matter [a]	115,000
Methane emissions	g/t fresh matter [a]	243
Ammonia emissions	g/t fresh matter [a]	576
Nitrous oxide emissions	g/t fresh matter [a]	116
Mass loss during rotting	%	53

[a] It is assumed that fresh matter has a water content of 50%. Water input to the composting process has been modelled to bring the water content of paper bank notes (assumed to be 5%) to this level – ideal for composting. The resulting compost is assumed to have a water content of 40%.

Compost is used as a soil improver, but it also contains some nutrients that can offset the use of chemical fertilisers and thus credit the product system. The nutrient content of compost is dependent upon the feedstock and the composting conditions. For this study, it is assumed that the nutrient content of compost made from paper bank notes is the same as that for green compost (from plant matter). The values used in the model are taken from WRAP's Compost Calculator and are given in Table 3-4. These show that the typical nutrient content in compost is quite low; its main benefit is as a soil improver rather than a fertiliser.

Table 3-4: Readily available nutrient content of compost (WRAP, 2016).

Parameter	Unit	Value
N content of compost	kg/tonne	0
P content of compost	kg/tonne	0.66
K content of compost	kg/tonne	3.61

It is assumed that the nutrient content in the compost substitutes for an equivalent amount of nutrients supplied from the following chemical fertilisers:

- Nitrogen in compost substitutes for that supplied from urea;
- Phosphorus in compost substitutes for that supplied from triple super phosphate; and
- Potassium in compost substitutes for that supplied from potassium chloride.

3.2.9. Mechanical Recycling of Polymer Bank Notes

Mechanical recycling of polymer bank notes is based on secondary datasets for modelling granulation, removal of metal impurities, washing, further granulation and a final pelletising and compounding process. As the waste stream of polymer bank notes will have uniform characteristics and low soiling it should be possible to produce a high quality recyclate. It is assumed that the recycled material substitutes for the production of an equivalent amount of virgin polypropylene.

4. Carbon Footprint Results

This chapter provides the results of the carbon footprint assessment. It shall be reiterated at this point that these represent impact potentials, i.e. they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory reflects the environmental load corresponding to the functional unit (the provision and use of 1000 bank notes over a period of 10 years) which is devised to provide the clearest comparison of the bank notes under study.

Carbon footprint results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

4.1. Top-level results

The top-level results for the total carbon footprint (both fossil and biogenic) of each bank note type are shown in Table 4-1 and Figures 4-1 and 4-2.

Table 4-1: Top-level results for global warming potential (kg CO_2e/FU)

Carbon Footprint (kg CO_2e/FU)	Paper £5	Polymer £5	Paper £10	Polymer £10
Biogenic GHG emissions and removals	-5.48	0.606	-5.00	1.73
Fossil GHG emissions and removals	192	156	476	434
Total carbon footprint	**187**	**157**	**471**	**436**

These results indicate that polymer bank notes have lower GHG emissions than paper bank notes. This is primarily due to lower impacts associated with the raw material and substrate production life cycle stages resulting from the longer lifetimes of the polymer notes.

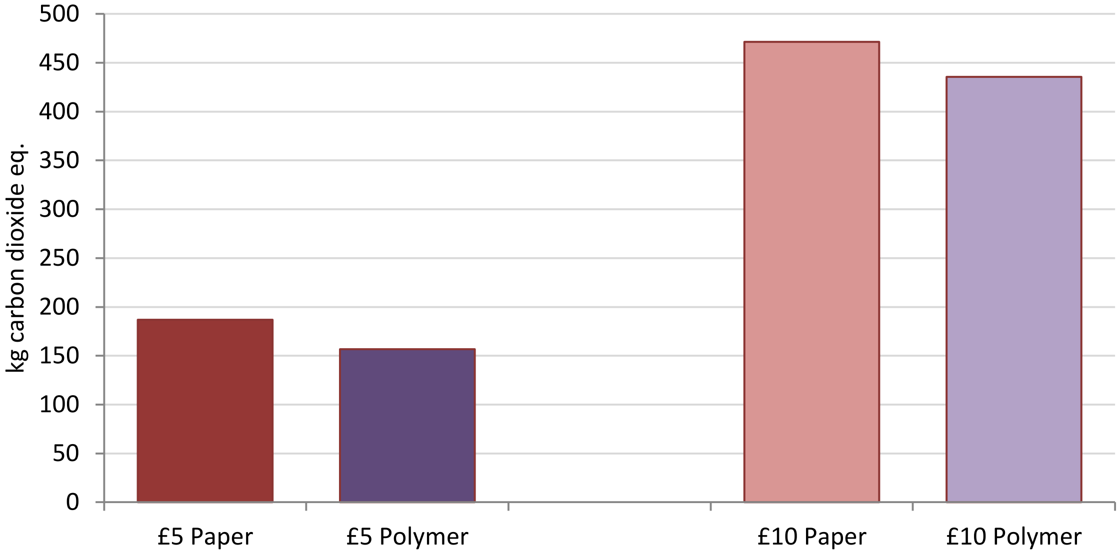


Figure 4-1: Top-level results for global warming potential (fossil and biogenic)

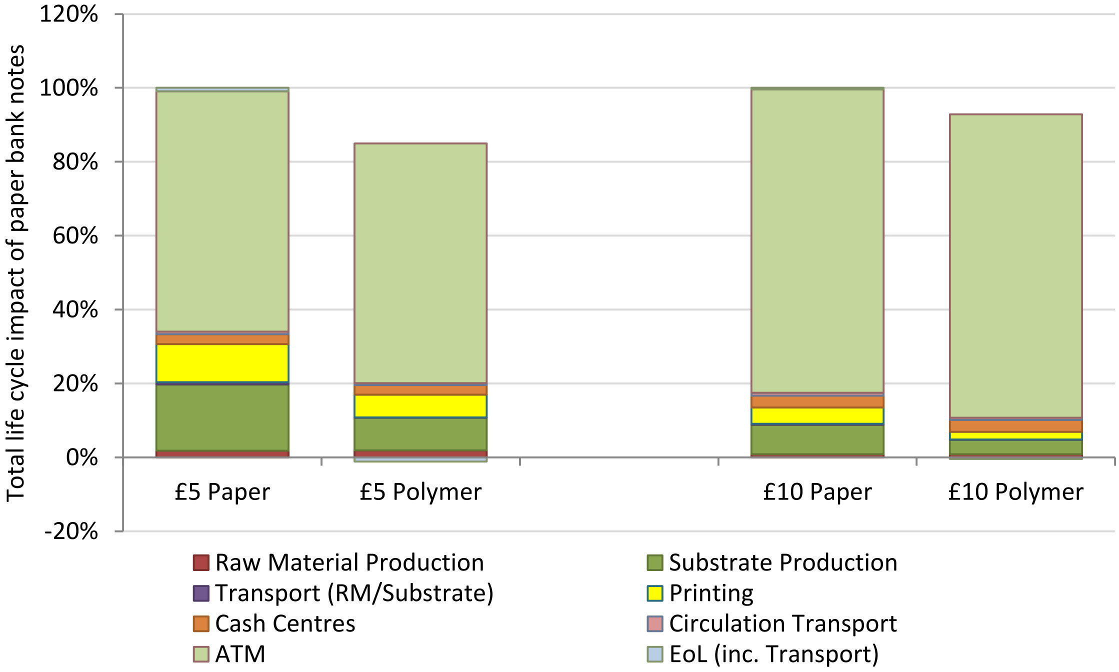


Figure 4-2: Contribution by life cycle stage to global warming potential (fossil and biogenic)

The high impact associated with the use of ATMs (which is common to both paper and polymer bank notes) means that the relative differences between the paper and polymer substrates appear fairly small. These differences appear much more significant when impacts from circulation are excluded, as shown in Figure 4-3.

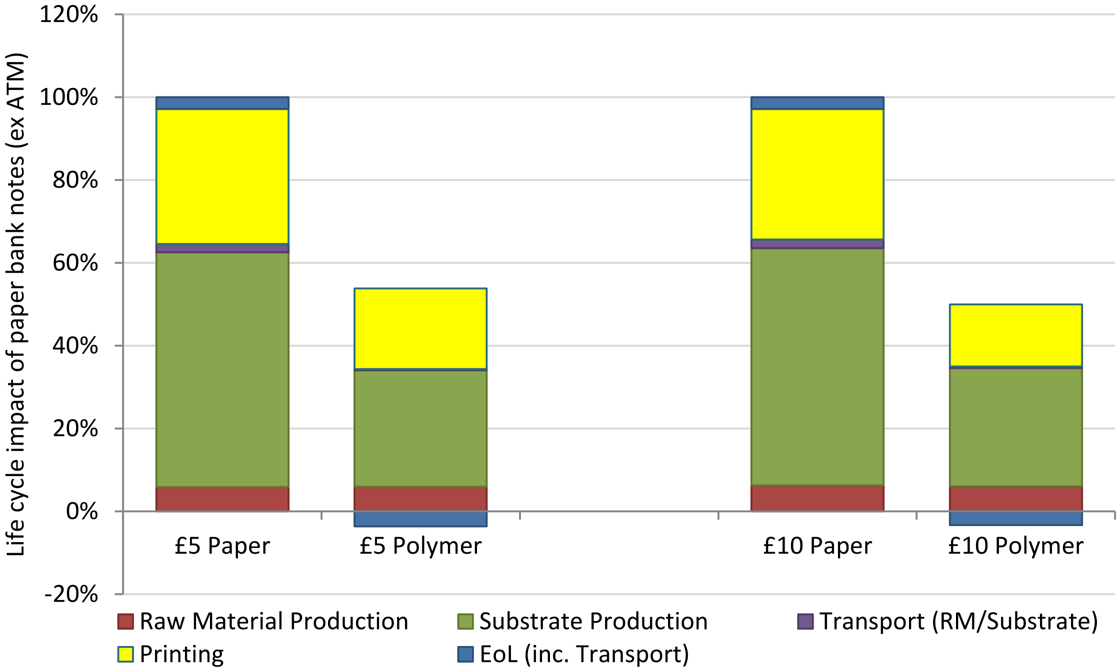


Figure 4-3: Contribution by life cycle stage to global warming potential (fossil and biogenic) excluding impacts from circulation

Figure 4-4 shows the contribution to the total carbon footprint by type of GHG emission. Carbon dioxide is the dominant emission accounting for well over 90% of the total. Methane emissions account for around 6% and nitrous oxide makes up most of the remaining contribution.

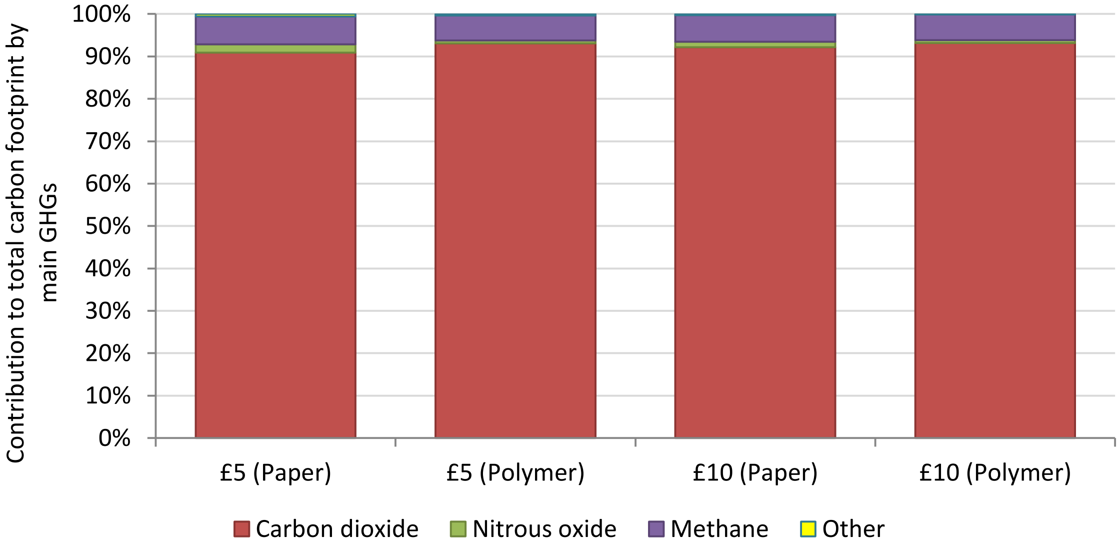


Figure 4-4: Contribution to total carbon footprint by type of GHG

Figure 4-5 shows the carbon footprint associated with the production and disposal of a single bank note. It is notable that paper bank notes have a lower production impact than polymer bank notes when viewed on the basis of a single note. However, at end of life paper notes are composted, resulting in GHG emissions, whereas polymer bank notes are recycled, effectively reducing the GHG emissions. This means that, for the £5 note, the impacts *per note* are essentially the same as for paper bank notes. For the £10 note the credit from recycling is not quite sufficient to make the overall GHG emissions associated with the polymer note equivalent to that of the paper note, so on a note-for-note basis, the polymer note has the higher GHG emissions.

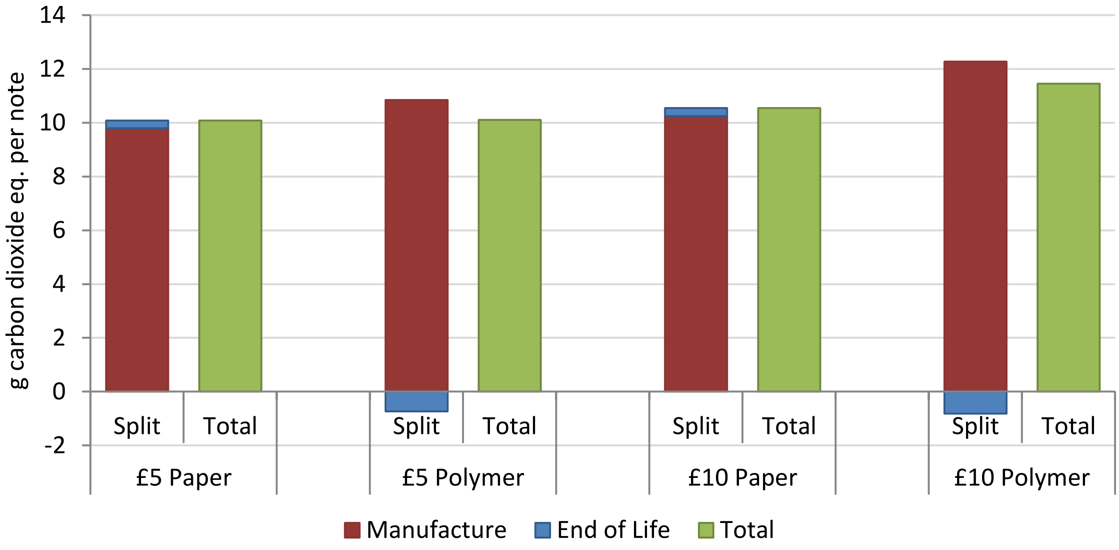


Figure 4-5: Carbon footprint of manufacturing and disposing of one bank note

However, in the context of the functional unit, the much better durability and resulting longer lifetime of the polymer notes means that many fewer are required to be produced during a given period of circulation. Based on the assumptions used in this study, *each polymer note effectively substitutes for 2.5 paper notes.* This explains why, when measured based on functionality, the polymer notes have lower GHG emissions than paper notes.

The following sections provide a more detailed discussion of GHG emissions, considering fossil and biogenic GHG removals and emissions separately.

4.2. Fossil GHG Emissions

Figures 4-6, 4-7 and 4-8 give the top-level results and the contribution analysis by life cycle stage for global warming potential from fossil sources (with and without the circulation life cycle stage).

The majority of fossil GHG emissions are related to the combustion of fossil fuels; hence the eco-profile for this impact category is very closely aligned with that of non-renewable primary energy demand. For both £5 and £10 notes the largest fractions of emissions are accounted for by the use of electricity in ATMs during the use phase. The polymer note shows lower GHG emissions than the paper note primarily because of longer circulation lifetimes which require fewer notes to be produced over the 10 year period.

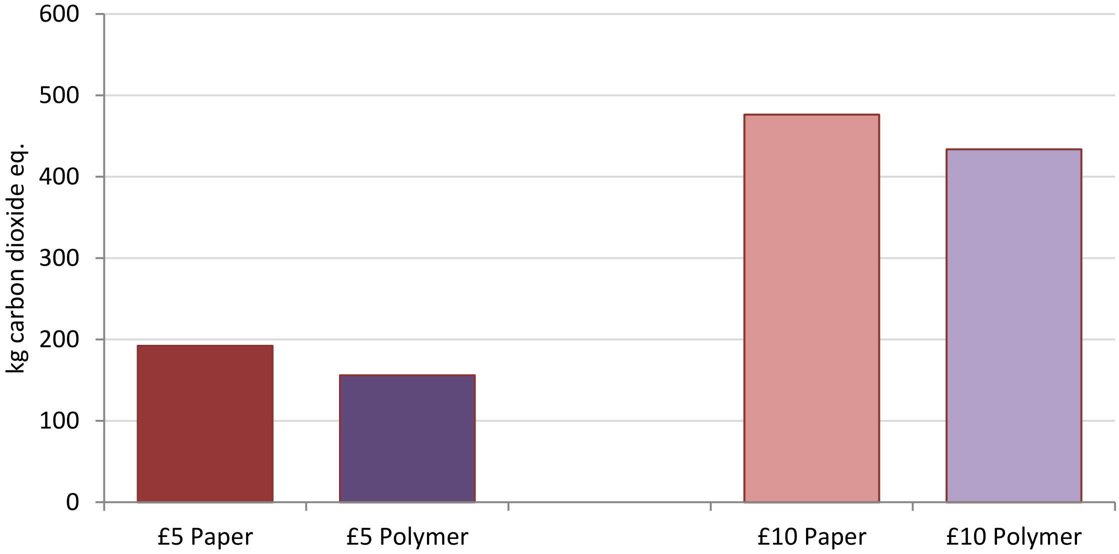


Figure 4-6: Top level results for global warming potential (fossil)

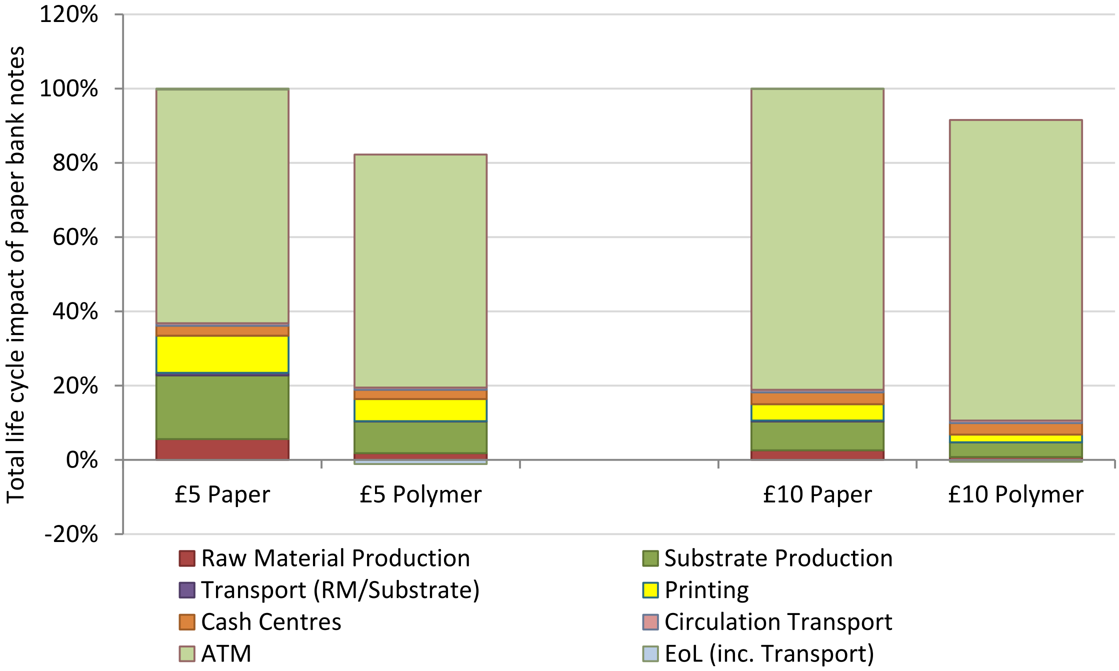


Figure 4-7: Contribution by life cycle stage to global warming potential (fossil)

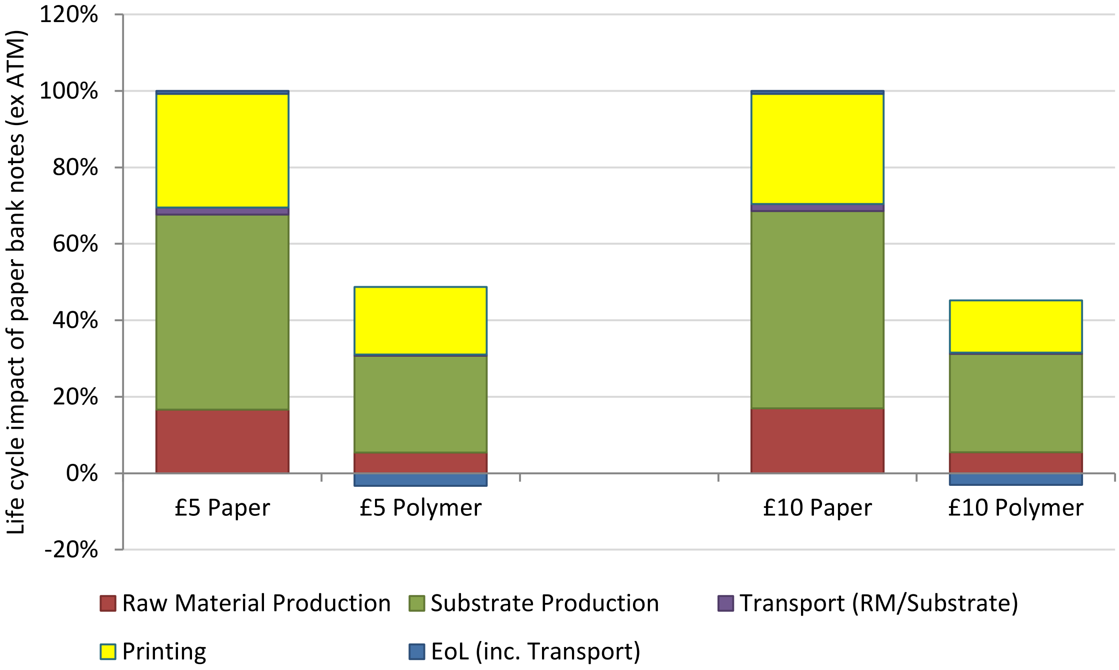


Figure 4-8: Contribution by life cycle stage to global warming potential (fossil) excluding impacts from circulation

4.3. Biogenic GHG Emissions

Figures 4-9, 4-10 and 4-11 give the top-level results and the contribution analysis by life cycle stage for global warming potential from biogenic sources (with and without the circulation life cycle stage).

The biogenic carbon profile is very different to that of the fossil emissions due to differences in emission sources and the ability of biogenic carbon to be sequestered. Although the capture of biogenic carbon seen in these results is a benefit, the scale of impacts from biogenic sources is much smaller than for fossil emissions, as can be seen when comparing the scale of Figure 4-8 with that of Figure 4-6.

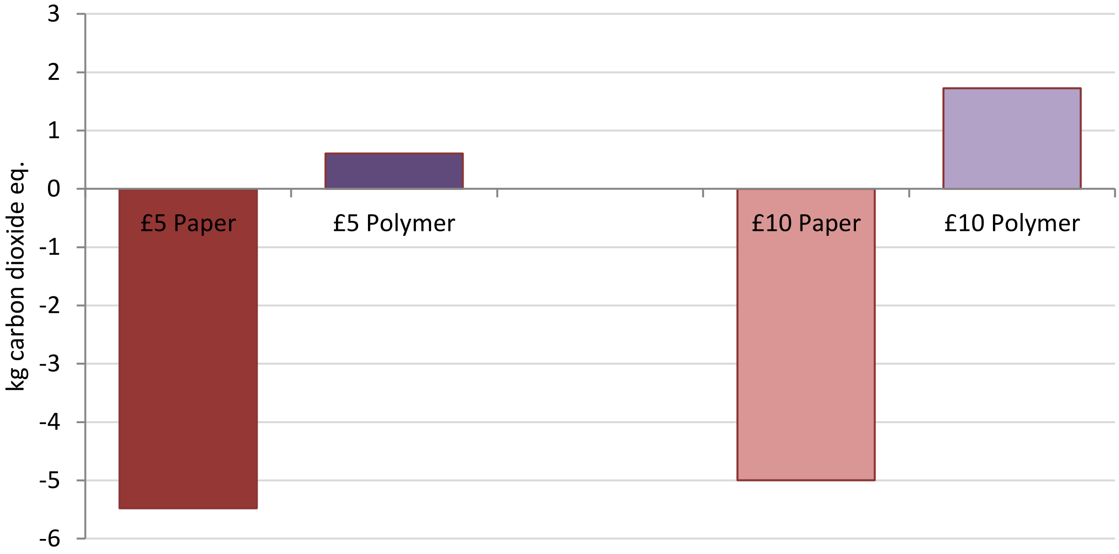


Figure 4-9: Top level results for global warming potential (biogenic)

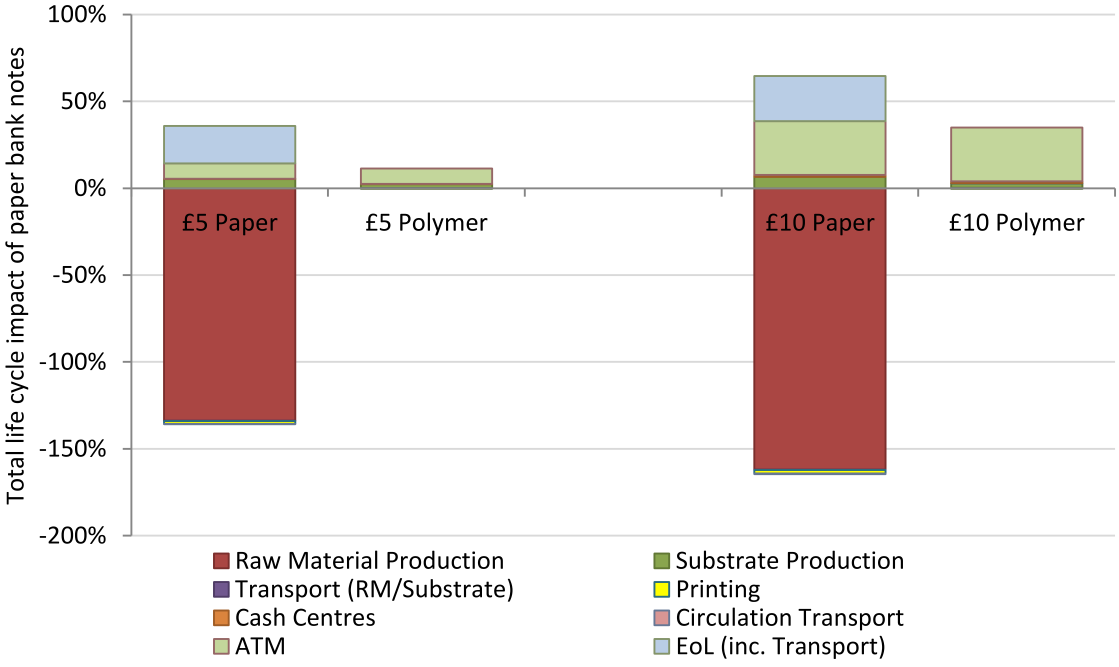


Figure 4-10: Contribution by life cycle stage to global warming potential (biogenic)

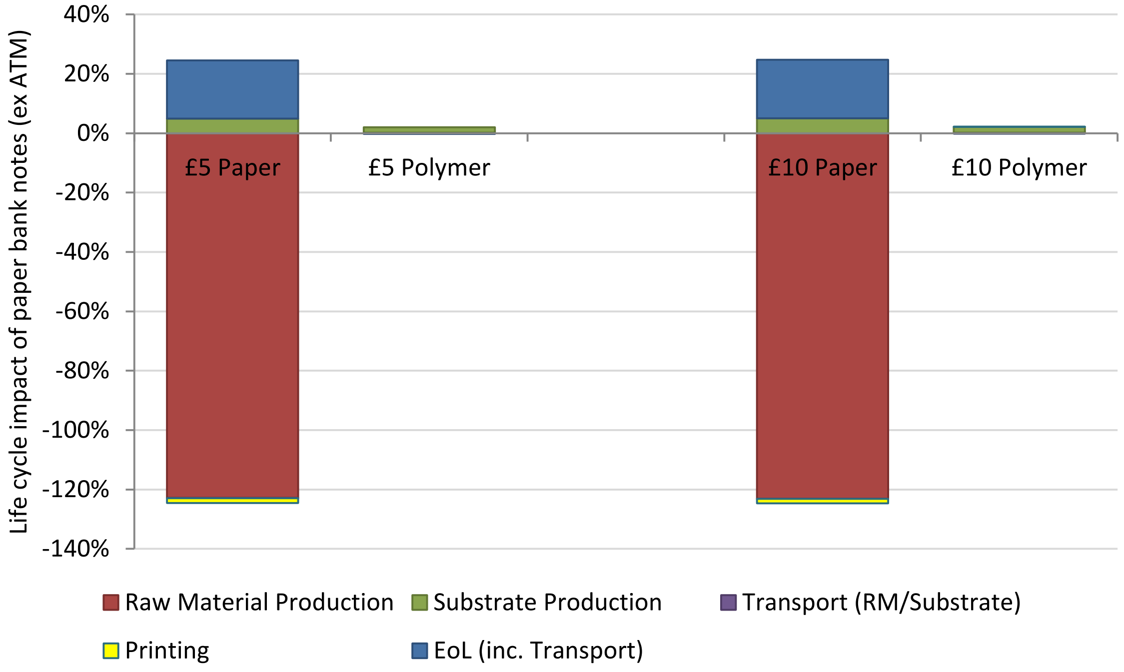


Figure 4-11: Contribution by life cycle stage to global warming potential (biogenic) excluding impacts from circulation

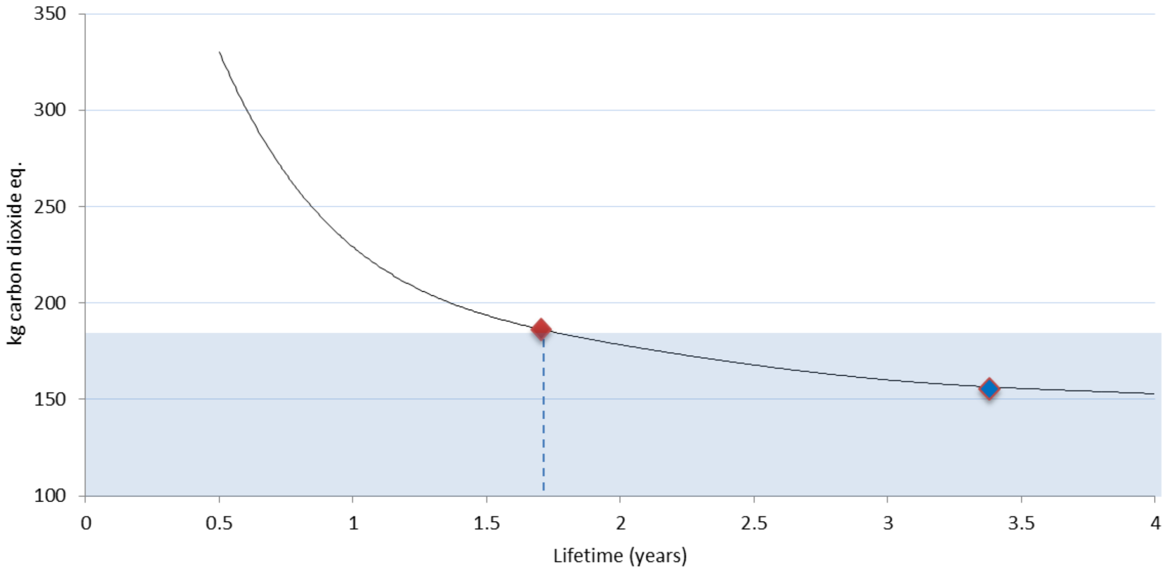
The dominant activity contributing to the difference between the fossil and biogenic profiles is the beneficial impact seen for the paper bank note. This arises because more carbon dioxide is being removed from the atmosphere during cotton production than is returned to it through composting at end of life, resulting in a net sink of biogenic carbon dioxide over the life cycle. The small beneficial impact seen from printing is due to the use of biomass-derived ingredients in the inks. Compared to GHG emissions from fossil sources the influence of emissions from biogenic sources on overall carbon footprint results is small.

4.4. Sensitivity Analysis

As noted earlier in this report, there is significant uncertainty regarding the lifetime of polymer bank notes in the UK. The default assumption in this study is that polymer bank notes have a lifetime 2.5 times greater than that of paper bank notes. A recent study on polymer notes in Australia indicate that they last between six and nine times longer than paper notes so this is a very conservative estimate (Rush, 2015).

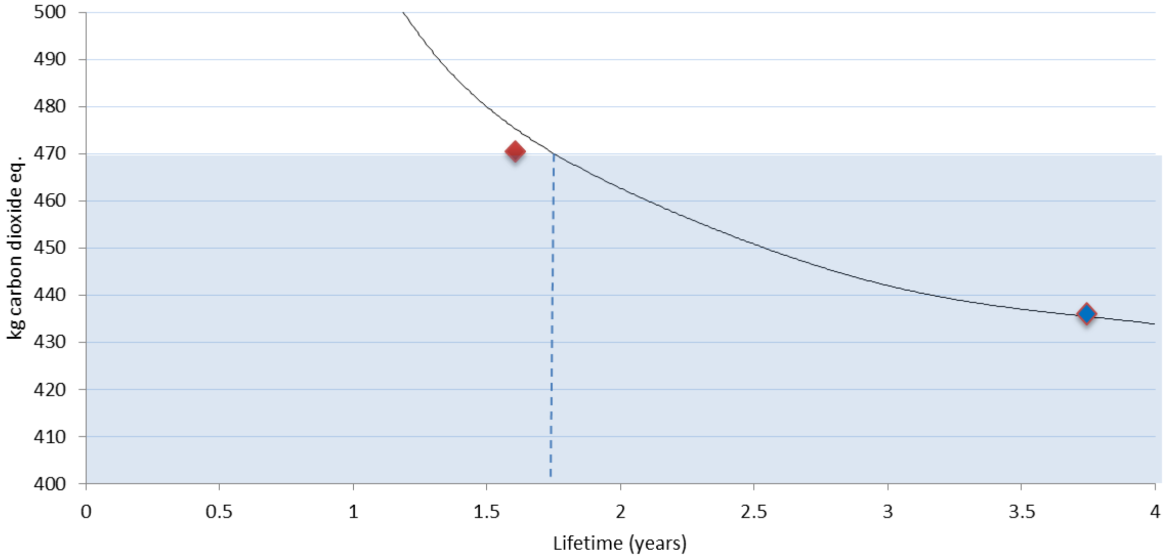
This sensitivity analysis seeks to identify the ‘break-even’ lifetimes required for polymer bank notes to have equivalent impacts to paper bank notes. If polymer bank notes exceed this break-even lifetime it will have lower overall GHG emissions than paper bank notes.

Figures 4-12 and 4-13 show the effect on the global warming potential of varying the lifetime of the polymer note. These charts are created by running the carbon footprint assessment model for a range of polymer bank note lifetimes. The resulting plot points are very well described by a polynomial regression calculated using the ‘trendline’ function in Excel. Please note that the y-axes in these charts do not start at the origin.



*Red diamond represents paper bank note, blue diamond represents polymer bank note (with lifetime 2.5 times greater than paper bank note). The blue region shows results having lower GHG emissions than the paper note.

Figure 4-12: Variation in global warming potential with lifetime of £5 polymer note



*Red diamond represents paper bank note, blue diamond represents polymer bank note (with lifetime 2.5 times greater than paper bank note). The blue region shows results having lower GHG emissions than the paper note.

Figure 4-13: Variation in global warming potential with lifetime of £10 polymer note

There is an inverse relationship between bank note lifetime and global warming potential: as the lifetime of the polymer note reduces, so the global warming potential impact increases. This relationship is also non-linear: as the lifetime gets shorter still, so the rate of increase in global warming potential becomes steadily greater.

The threshold for the polymer to outperform the paper note is shown by the blue region in the charts (equivalent to the GHG emissions from paper bank notes) and the break-even lifetime is indicated by the dotted lines.

Table 4-2 summarises the results of this sensitivity analysis. This shows that for £5 bank notes, the break-even lifetime is essentially the same as the lifetime of the paper bank note. This means that as long as the polymer note lasts longer than a paper note it will have lower GHG emissions.

For the £10 bank note, the break-even lifetime for the polymer note is slightly longer than the lifetime of the paper note. Polymer notes need to last at least 6.3% longer than paper notes to ensure that GHG emissions over their life cycle are lower.

Table 4-2: Summary of break-even lifetimes for polymer bank notes compared to paper bank notes

Denomination	Lifetime of paper bank note [years]	Break-even lifetime of polymer bank note [years]	Difference [%]
£5	1.7	1.7	0
£10	1.6	1.7	6.3

These results are supported by the findings presented in Figure 4.5 that show that on a *per note* basis GHG emissions associated with manufacturing and disposing of paper £5 notes are essentially the same as for paper bank notes, while for the £10 denomination, the polymer notes have slightly higher GHG emissions.

5. Interpretation

This section of the report summarises the results of the study considering the quality of the data used and discusses the key trends and conclusions.

5.1. Identification of Relevant Findings

The main findings of the LCA study can be summarised as follows:

- Over the full life cycle, polymer £5 and £10 bank notes have smaller carbon footprints (fewer GHG emissions) than paper bank notes of the same denomination.
- The carbon footprints of both paper and polymer bank notes are dominated by impacts associated with electricity generation required to operate ATMs, which are the same for both substrates. This has the effect of reducing the relative differences that arise from the other life cycle stages due to variations in impacts among the substrates.
- The UK grid mix is changing rapidly and is expected to become significantly less carbon intensive in future. Some forecasts estimate reductions of around 60% by 2030 and 80% by 2050 compared to 1990 levels (Hewicker, 2011). Even if such large reductions are not realised it seems inevitable that there will be significant decarbonisation of the UK grid in the coming years. As such, the contribution of ATMs to the total life cycle impact is expected to reduce substantially over time and will make the impact of other life cycle stages more noticeable in contrast.
- For both paper and polymer bank notes, substrate manufacturing is the next most significant impact, followed by printing.
- For paper notes, raw material production has a significant contribution to global warming potential from biogenic sources, resulting in a credit due to more carbon dioxide being removed from the atmosphere during plant growth than is returned at end of life. However, when considering fossil and biogenic GHG sources combined, this effect is not a significant contributor overall.
- Manufacturing a polymer bank note results in *more* GHG emissions than manufacturing a paper bank note, even though the new polymer bank notes are slightly smaller than the old paper bank notes. When emissions associated with disposing of notes at the end of their life are also considered the paper and polymer £5 notes are seen to have equivalent impacts while the £10 polymer note has slightly higher impacts than the paper equivalent. However, when assessing the different substrates on the more meaningful basis of *equivalent functionality*, polymer bank notes outperform paper bank notes because their superior durability means that many fewer polymer bank notes are needed overall (the assumption used in this study is that each polymer bank note will effectively substitute for 2.5 paper bank notes due to their longer lifetimes; this is probably a significant underestimate of their actual lifetime).
- The sensitivity analyses show that polymer £10 notes need last only 6% longer than paper bank notes to have lower overall GHG emissions. For £5 bank notes no additional lifetime is required.

- Differences between the profiles of £5 and £10 notes are mainly due to the circulation characteristics. Both notes have a similar lifetime but £10 notes circulate much faster (once every 1.6 months for £10 notes vs 5.1 months for £5 notes) and therefore incur much greater impacts from ATMs and from transport and sorting at NCS cash centres.
- The carbon footprint is dominated by carbon dioxide emissions (92-94%), followed by methane (6%), nitrous oxide (~1%) and minor contributions from other GHGs.

5.2. Data Quality Assessment and the PAS 2050 Principles

Assessments that claim conformity to PAS2050 must demonstrate that they adhere to the principles of relevance, completeness, consistency, accuracy and transparency specified in Clause 4.2 of the standard. Clause 7.2 additionally requires that completeness, consistency, reproducibility and data sources are all documented. In addition to these aspects it is good practice in LCA studies to report on the geographical, temporal, and technological representativeness of the data used.

These data quality relevant issues are discussed below. In Appendix D, data quality is further described semi-quantitatively using a pedigree matrix approach.

5.2.1. Relevance

The methodology applied and the data sources used for the study meet the requirements of PAS2050.

5.2.2. Completeness

All relevant process steps for each product have been considered and modelled to represent the actual product system. The process chains for both paper and polymer bank notes are considered sufficiently complete with regards to the goal and scope of this study.

Table 5-1: Percentage of measured data used in this assessment

Life cycle stage	Paper bank notes	Polymer bank notes
Raw material production	0%	0%
Substrate production	100%	100%
Substrate transport	100%	100%
Printing	100%	100%
Circulation	100%	100%
End of life	0%	0%

Each unit process has been checked for mass balance and completeness of the emission inventory. No data have been knowingly omitted except as described in Section 3.2. The data are generally very specific to the particular products being assessed (e.g. separate data for paper production are used for £5 and £10 denominations, printing data are also specific to both the denomination and substrate choice).

Table 5-1 indicates the proportion of measured data used in each life cycle stage. Raw material production data (on PP granulate and cotton production) were based on secondary datasets, as were the end of life options (composting and mechanical recycling). All other data were collected from primary sources.

5.2.3. Consistency

To ensure consistency, all primary data were collected with the same level of detail, while almost all background data were sourced from the GaBi databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

Differences in background data quality were minimised by using LCI data from the GaBi ts 2017 databases.

5.2.4. Accuracy

Extensive primary data have been collected for this study covering both upstream and downstream activities. Annual variations were generally balanced out by using yearly averages (for paper production at De La Rue a two year average was taken to balance annual variations), although data for printing were provided *per million bank notes*. The data for paper bank note production have not been updated and relate to information collected for the previous LCA study, but are representative of, and accurately reflect, production conditions during this time.

Consistent background LCA information from the GaBi LCI database were used throughout (with the exceptions of cotton data and composting). The LCI datasets from the GaBi LCI database are widely distributed and used with the GaBi ts Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

5.2.5. Transparency & Reproducibility

The methodology and modelling descriptions along with the data presented in this report should provide a clear explanation of how the carbon footprint results have been calculated. It should be possible for a third party to replicate the results of this study and produce approximately equivalent results using the same data and modelling approaches.

For general external communication the confidential primary data reported in Annex B will be removed. However, the description of the results and the interpretation should still allow a third party to have confidence in and understanding of the results.

5.2.6. Primary Data Sources

Table 5-2 describes the data sources used for primary data in this study. Some data are presented in the body of this report but confidential data are reported in Appendix B.

Table 5-2: Sources of primary data used in this study

Activity	Source(s)
Polymer (BOPP) film production	Innovia Films
Polymer substrate conversion	CCL Secure
Cotton paper production	De La Rue
Bank note printing	De La Rue
Printing inks	SICPA
Bank of England Cash Centres	Bank of England
NCS Cash Centres	Royal Bank of Scotland, G4S
Circulation transport	G4S
ATM operation	Diebold

5.2.7. Secondary Data Sources

Data on cotton production were sourced from Cotton Inc. and data on composting were taken from literature sources (Amlinger, 2008; Eunomia, 2002; Vegetable Resource and Information Centre, 2009; WRAP, 2016). All other secondary data were obtained from the GaBi 2017 LCI database. Secondary data are described in more detail in Appendix C.

5.2.8. Temporal Representativeness

Data on bank note circulation were supplied by the Bank of England for 2016. Information on polymer film production is based on data for production in 2016. Primary data on opacification of the polymer film to produce the final substrate were collected for a four week period from 22nd May to 16th June 2017. Data on polymer bank note printing were obtained for 2016/17. Information on papermaking and paper bank note printing were sourced from the previous LCA study, which collected data for a two year period (financial years April 2010 to May 2012) to even out differences in annual production. Data for manufacturing inks and for sorting and distribution/circulation were also sourced from the previous LCA study and were based on year 2011. Almost all secondary data come from the GaBi 2017 databases and are representative of the years 2013-2016. Data on cotton production are representative of year 2010 and data on composting refer to 2008. As the study is intended to compare the product systems for the reference year 2016, temporal representativeness is considered to be fair/good.

5.2.9. Geographical Representativeness

Most primary and secondary data were collected specific to the countries/regions under study. Where country / region specific data were unavailable, proxy data were used. Geographical representativeness is considered to be very good.

5.2.10. Technological Representativeness

Most primary and secondary data were modelled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used. As mentioned above the data for paper printing were sourced from the previous LCA study. Since then, the Debden printworks has been outfitted with new printing machines so the results for printing are less representative for paper bank notes than for the new polymer bank notes. Overall, the technological representativeness is considered to be very good.

5.3. Conclusions, Limitations and Assumptions

5.3.1. Conclusions

This carbon footprint assessment clearly shows that polymer bank notes have a lower carbon footprint than paper bank notes, assuming that their circulation lifetime is 2.5 times greater due to their improved durability. A recent study on polymer notes in Australia indicate that polymer bank notes last between six and nine times longer than the previously used paper notes, so this is a very conservative estimate (Rush, 2015).

Considered over the full life cycle, polymer £5 notes have 16% lower impacts than paper £5 notes, while polymer £10 notes have 8% lower impacts than paper £10 notes. The difference in relative benefit is due to the much higher circulation velocity of £10 notes which greatly increases the impacts from the circulation life stage. This raises the total carbon footprint of both paper and polymer notes by the same amount and thereby reduces the relative differences in performance. If impacts due to circulation are excluded, polymer £5 notes have 50% lower impacts than paper £5 notes, while polymer £10 notes have 53% lower impacts than paper £10 notes.

The benefits of using polymer notes do not derive from lower GHG emissions from production or disposal of a given bank note—indeed, on a note-for-note basis £5 polymer bank notes have similar impacts to paper notes, while £10 polymer bank notes have higher GHG emissions than their paper equivalents, even though the notes themselves are slightly smaller. Instead, these benefits are due to the greatly extended lifetime of polymer bank notes. This means that substantially fewer polymer notes are required to provide the same function as a given quantity of paper bank notes. Accordingly, fewer raw materials are needed and less processing is required to produce the quantity of notes required.

The sensitivity analysis focusing on bank note lifetime showed that polymer bank notes need only last slightly longer than paper bank notes to achieve an improvement in overall GHG emissions—a 6% increase in lifetime is required for £10 polymer bank notes, but no increase at all is needed for £5 polymer bank notes. Given that polymer bank notes are known to have lifetimes several times longer than paper bank notes this gives great confidence that the switch to polymer bank notes will result in real GHG savings, even if there is still uncertainty around the precise lifetime of polymer bank notes in circulation in the UK.

Reinforcing the message from the previous LCA study, an interesting finding is that use phase impacts at the ATM dominate the environmental profiles. Even relatively small improvements in the efficiency of ATMs would yield significant benefits in the lifecycle of both polymer and paper bank notes. As noted in Section 5.1, the UK grid mix is changing rapidly and this is expected to result in large reductions in GHG emissions per kWh over the next 20 years. Even if no efficiency gains are made in the operation of ATMs this will significantly reduce their contribution to the total life cycle impact of bank notes.

5.3.2. Limitations & Assumptions

The main assumptions relating to the data used in the model are described in detail in Section 3.2. The quality of the foreground and background data used in this study are reported in Section 5.2 and Appendix C. Areas where data used were of lower quality or resulted in a data gaps, are summarised below.

- Composting – the impacts of composting can vary significantly according to the composting conditions. However, the overall results are not very sensitive to emissions in this life cycle stage;
- Note lifetime – insufficient time has passed since polymer bank notes were first issued to establish their lifetime in circulation in the UK. The assumed lifetime of 2.5 times that of paper bank notes is based on experience of use in other countries but is considered to be a rather conservative assumption; a study of polymer bank notes in Australia found that they lasted between six and nine times longer than previously used paper notes (Rush, 2015).
- Transport distance in circulation – data used to estimate the transport distance associated with distributing notes to NCS cash centres and out into the wider economy were obtained from G4S and assumed to be representative of all NCS members. There will be some variation in this distance depending on the specific location of the cash centre and its relation to nearby population centres. However, based on the G4S data, this aspect contributes less than 1% to total life cycle GHG emissions and will be the same for both paper and polymer notes. As such, uncertainties in this value will not significantly influence the overall findings of the study.

In addition, all the designs and supply chain data represent the specific situation relevant for UK bank notes. The conclusions and recommendations are directed to the Bank of England and cannot be reliably extrapolated to other regions/countries as they are strongly influenced by specific UK conditions.

At a more general level, some further limitations of this study that may influence the decision of whether to move from paper to polymer bank notes are noted below:

- Consideration of the design lifetime of bank notes has been excluded from this study but may have bearing on the relative environmental performance of paper and polymer bank notes. In the UK, when a new bank note design is released existing bank notes with the previous design are recalled and destroyed. Clearly, if the lifetime of a given bank note design is shorter than the lifetime of the bank notes themselves, then the environmental benefits of having a long bank note lifetime will not be fully realised. This issue is more likely to be relevant for larger denomination bank notes such as £50 notes, which have much longer lifetimes as they tend to be used as a store of value rather than in everyday commercial transactions. In these cases, even paper bank notes may have a technical lifetime in circulation that exceeds the design lifetime of the note.

- Consequential effects of moving to polymer bank notes have not been addressed in this study. A move to polymer bank notes would reduce the demand for cotton noil and linter. Although assessing the environmental impacts of this change is outside the scope of this study it is likely that if these materials are not being used by the bank note industry that their value would fall due to reduced demand. However, it is not expected that they would become wastes as there would still be demand for cotton paper in other applications (e.g. high quality stationery and art papers, or as a component of printed circuit board substrates), while cotton noil have other uses (such as in cotton wool for cosmetics).

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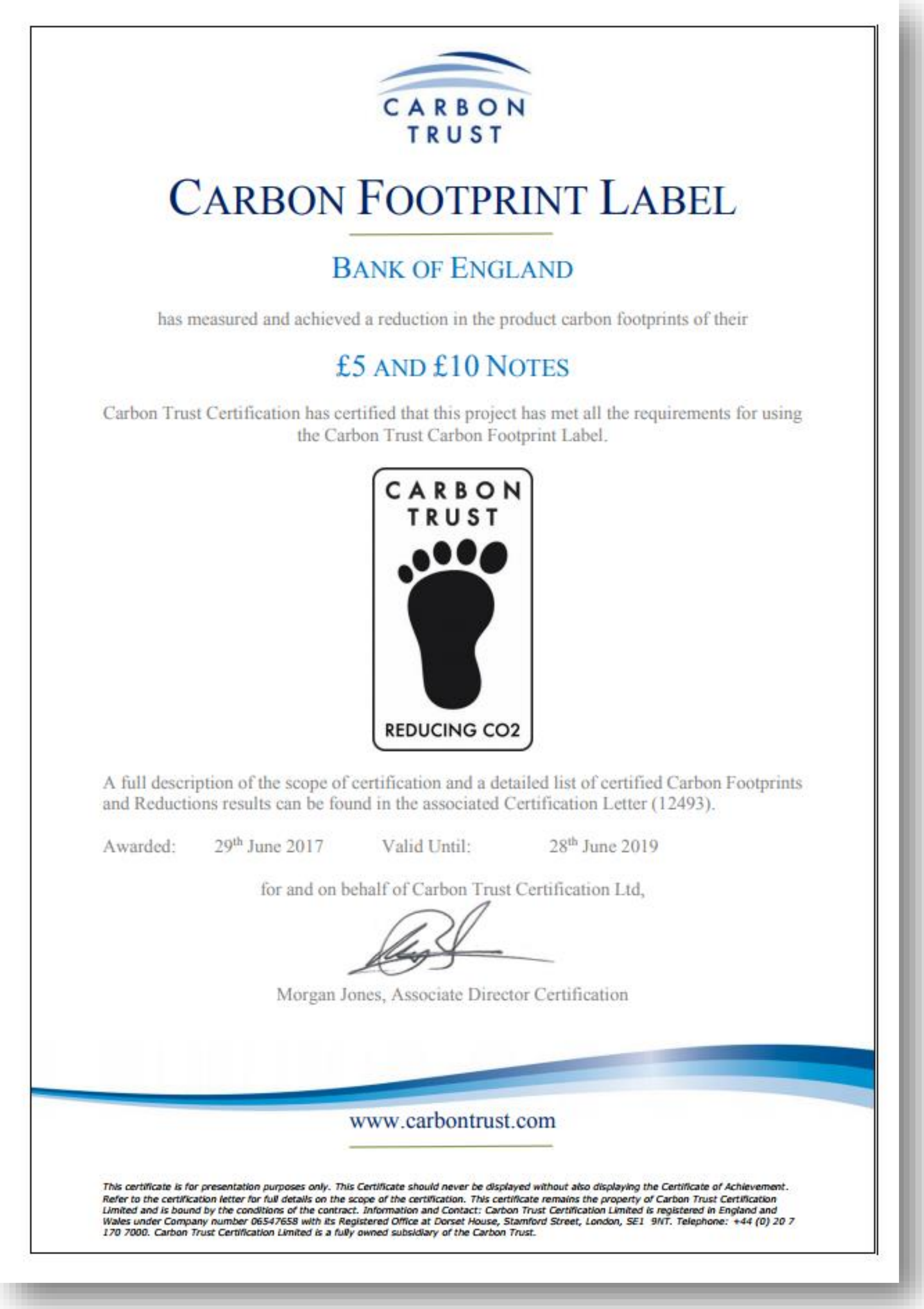
Annex A: Certification Documents

This Annex contains the following information provided by the Carbon Trust as a result of the certification process:

- Carbon Footprint Label – confirming that the study meets the requirements of the Carbon Trust Carbon Footprint Label
- Certificate of Achievement – confirming that Carbon Trust Certification Limited certifies that the Bank of England has calculated four Carbon Footprints and achieved a reduction in two Products provided Cradle-to-Grave (Business-to-Consumer) in the UK
- Product Carbon Footprint and Reduction Certification Letter – providing detailed feedback from the certification review process.



CARBON TRUST

CARBON FOOTPRINT LABEL

BANK OF ENGLAND

has measured and achieved a reduction in the product carbon footprints of their

£5 AND £10 NOTES

Carbon Trust Certification has certified that this project has met all the requirements for using the Carbon Trust Carbon Footprint Label.

CARBON TRUST

REDUCING CO2

A full description of the scope of certification and a detailed list of certified Carbon Footprints and Reductions results can be found in the associated Certification Letter (12493).

Awarded: 29th June 2017 Valid Until: 28th June 2019

for and on behalf of Carbon Trust Certification Ltd,

Morgan Jones, Associate Director Certification

www.carbontrust.com

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CARBON TRUST

CERTIFICATE OF ACHIEVEMENT

BANK OF ENGLAND

has measured and achieved a reduction in the product carbon footprints of their

£5 AND £10 NOTES

Carbon Trust Certification Limited certifies that the Bank of England has calculated 4 Carbon Footprints and achieved a reduction in 2 Products provided Cradle-to-Grave (Business-to-Consumer) in the UK, in accordance with:

- PAS 2050: 2011 – Specification for the assessment of the life cycle greenhouse gas emissions of goods and services
- Product Carbon Footprint Protocol (parts 1 & 2)
- Footprint Expert™ Guide version 4.2

A detailed list of certified Carbon Footprints and Reductions results can be found in the associated Certification Letter (12493).

Awarded: 29th June 2017 Valid Until: 28th June 2019

Carbon Trust Certification Limited is accredited by the United Kingdom Accreditation Service to ISO 14065:2013 to provide greenhouse gas verification to PAS 2050: 2011.

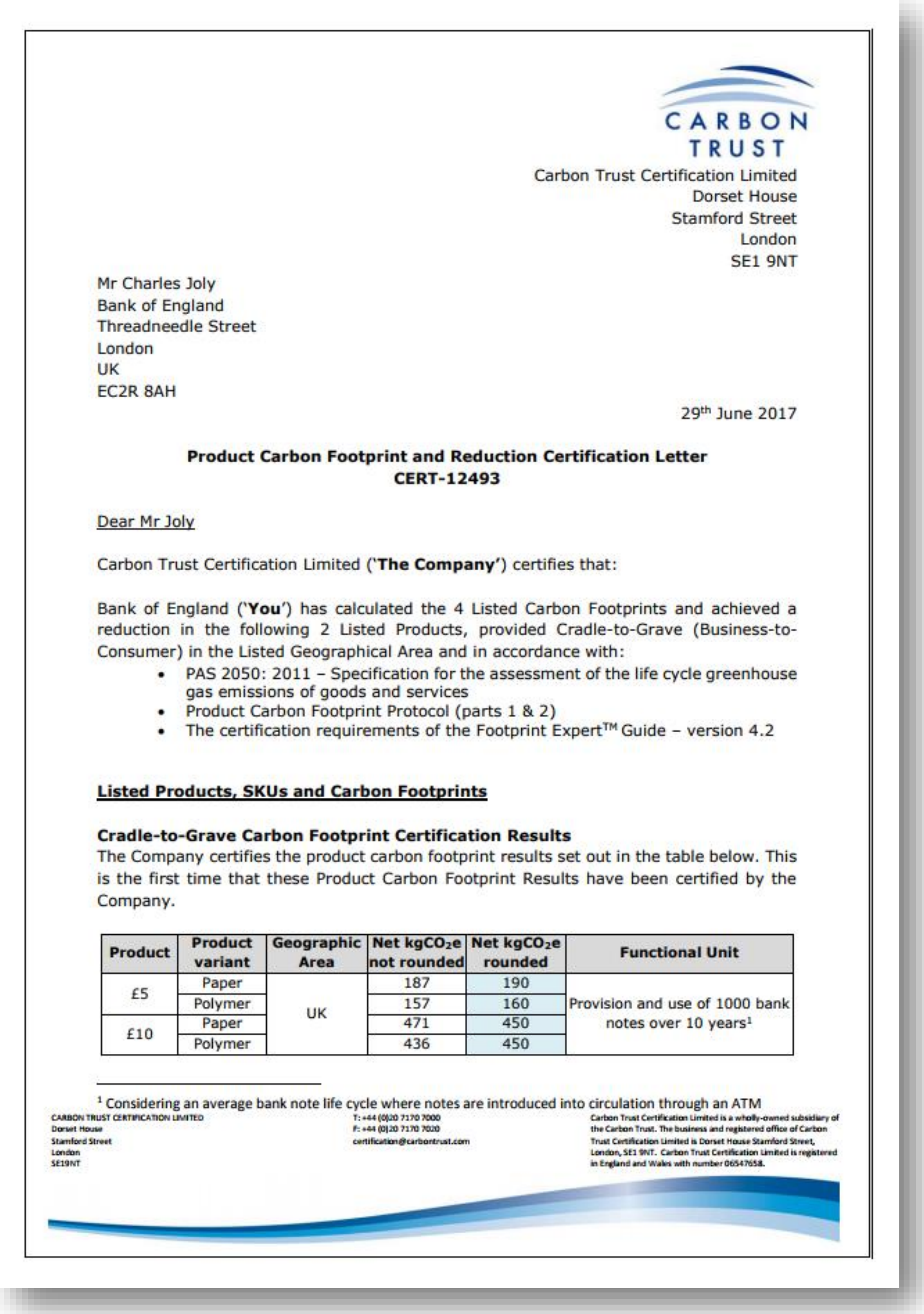
UKAS
VERIFICATION
4381

for and on behalf of Carbon Trust Certification Ltd,

Morgan Jones, Associate Director Certification

www.carbontrust.com

This certificate is for presentation purposes only. Please do not copy or circulate this certificate without the Certification Letter and associated Annexes where full details on the scope of the certification are documented. This certificate remains the property of Carbon Trust Certification Limited and is bound by the conditions of the contract. Information and Contact: Carbon Trust Certification Limited is registered in England and Wales under Company number 06547658 with its Registered Office at Dorset House, Stamford Street, London, SE1 9NT. Telephone: +44 (0) 20 7 170 7000. Carbon Trust Certification Limited is a fully owned subsidiary of the Carbon Trust.



CARBON TRUST
Carbon Trust Certification Limited
Dorset House
Stamford Street
London
SE1 9NT

Mr Charles Joly
Bank of England
Threadneedle Street
London
UK
EC2R 8AH

29th June 2017

Product Carbon Footprint and Reduction Certification Letter
CERT-12493

Dear Mr Joly

Carbon Trust Certification Limited ('**The Company**') certifies that:

Bank of England ('**You**') has calculated the 4 Listed Carbon Footprints and achieved a reduction in the following 2 Listed Products, provided Cradle-to-Grave (Business-to-Consumer) in the Listed Geographical Area and in accordance with:

- PAS 2050: 2011 – Specification for the assessment of the life cycle greenhouse gas emissions of goods and services
- Product Carbon Footprint Protocol (parts 1 & 2)
- The certification requirements of the Footprint Expert™ Guide – version 4.2

Listed Products, SKUs and Carbon Footprints

Cradle-to-Grave Carbon Footprint Certification Results

The Company certifies the product carbon footprint results set out in the table below. This is the first time that these Product Carbon Footprint Results have been certified by the Company.

Product	Product variant	Geographic Area	Net $kgCO_2e$ not rounded	Net $kgCO_2e$ rounded	Functional Unit
£5	Paper	UK	187	190	Provision and use of 1000 bank notes over 10 years[1]
	Polymer		157	160	
£10	Paper		471	450	
	Polymer		436	450	

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[1] Considering an average bank note life cycle where notes are introduced into circulation through an ATM

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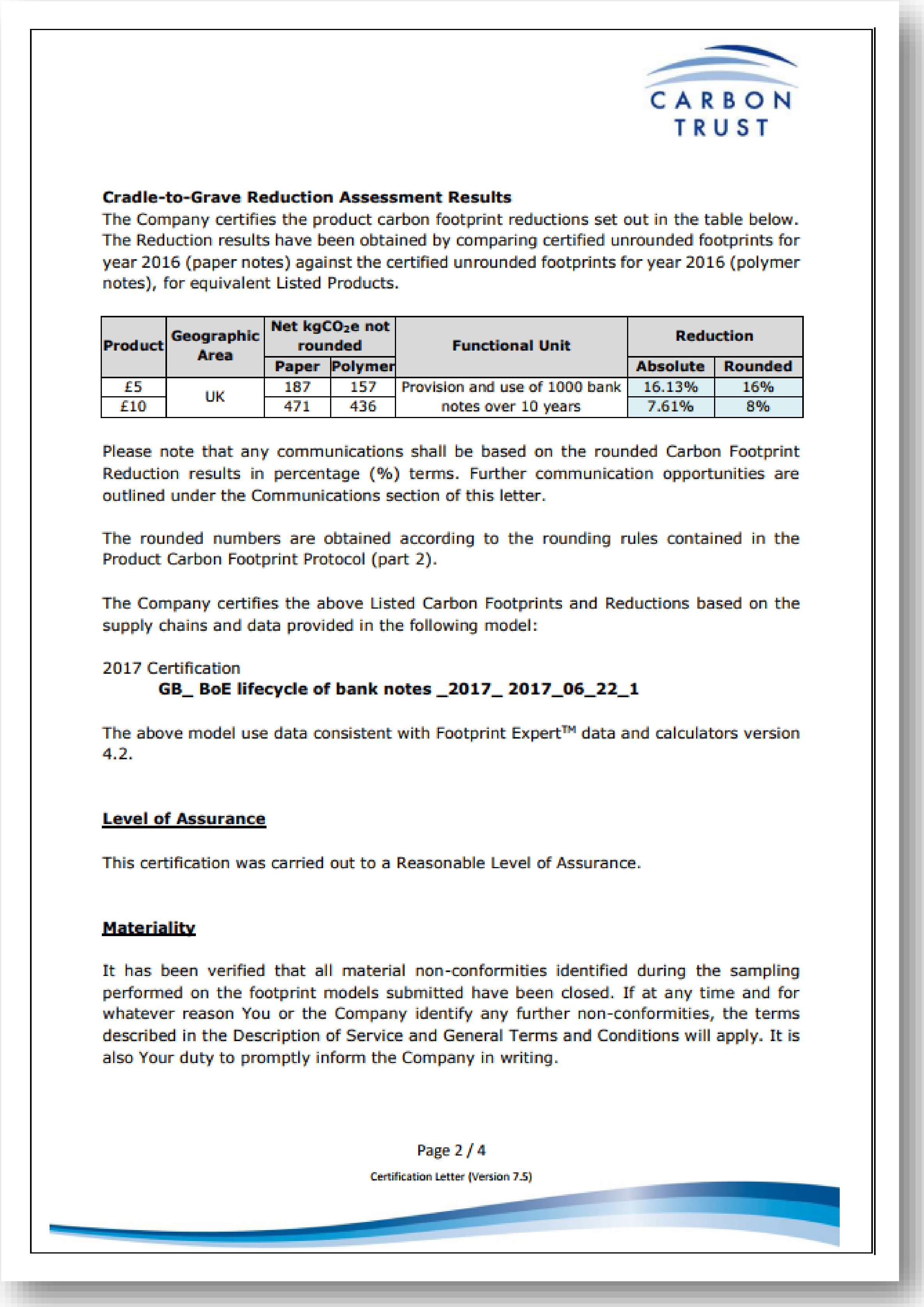

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Cradle-to-Grave Reduction Assessment Results

The Company certifies the product carbon footprint reductions set out in the table below. The Reduction results have been obtained by comparing certified unrounded footprints for year 2016 (paper notes) against the certified unrounded footprints for year 2016 (polymer notes), for equivalent Listed Products.

Product	Geographic Area	Net kgCO_2e not rounded		Functional Unit	Reduction	
		Paper	Polymer		Absolute	Rounded
£5	UK	187	157	Provision and use of 1000 bank notes over 10 years	16.13%	16%
£10		471	436		7.61%	8%

Please note that any communications shall be based on the rounded Carbon Footprint Reduction results in percentage (%) terms. Further communication opportunities are outlined under the Communications section of this letter.

The rounded numbers are obtained according to the rounding rules contained in the Product Carbon Footprint Protocol (part 2).

The Company certifies the above Listed Carbon Footprints and Reductions based on the supply chains and data provided in the following model:

2017 Certification

GB_ BoE lifecycle of bank notes _2017_ 2017_06_22_1

The above model use data consistent with Footprint Expert™ data and calculators version 4.2.

Level of Assurance

This certification was carried out to a Reasonable Level of Assurance.

Materiality

It has been verified that all material non-conformities identified during the sampling performed on the footprint models submitted have been closed. If at any time and for whatever reason You or the Company identify any further non-conformities, the terms described in the Description of Service and General Terms and Conditions will apply. It is also Your duty to promptly inform the Company in writing.

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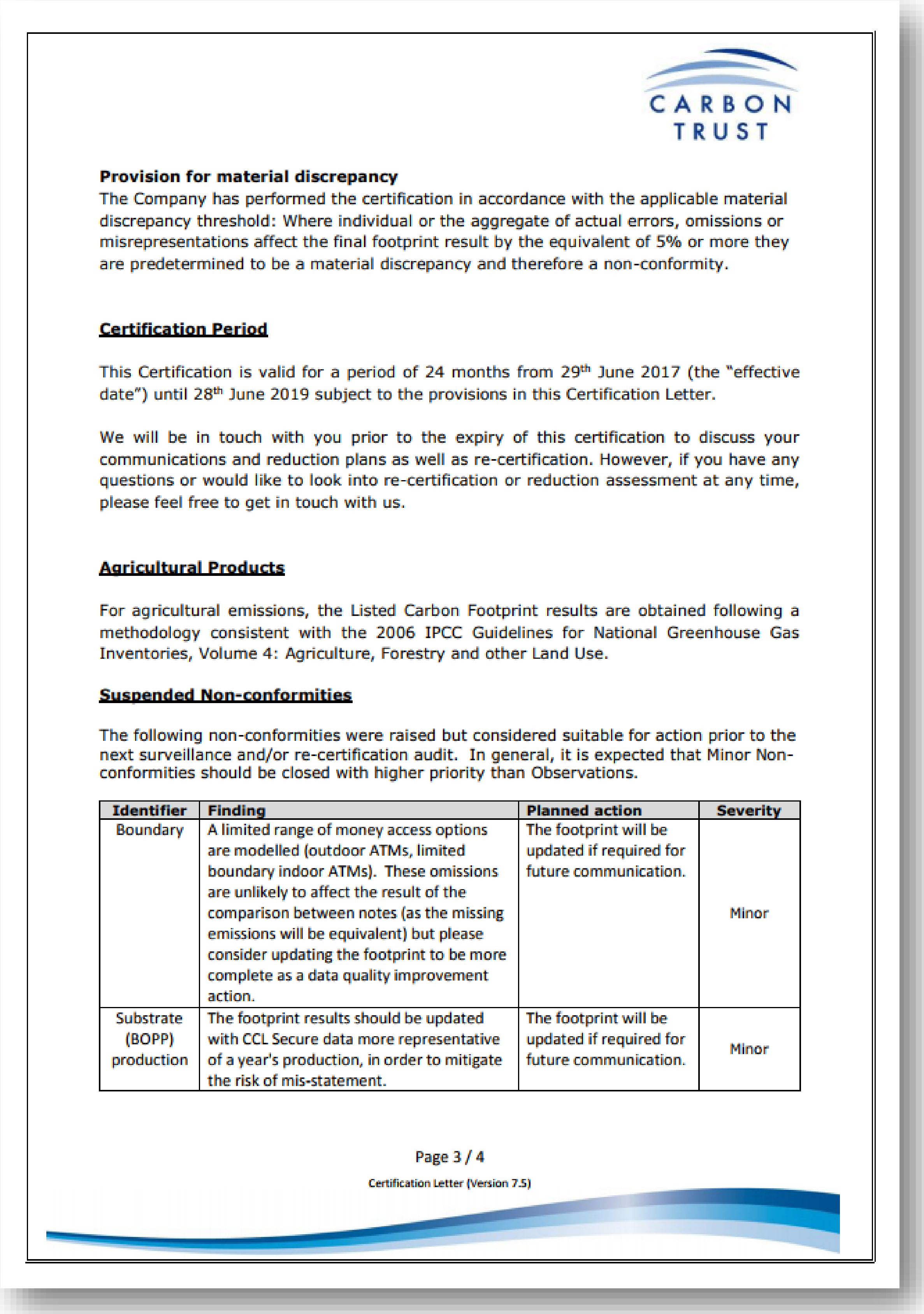
Certification Letter (Version 7.5)



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Provision for material discrepancy
The Company has performed the certification in accordance with the applicable material discrepancy threshold: Where individual or the aggregate of actual errors, omissions or misrepresentations affect the final footprint result by the equivalent of 5% or more they are predetermined to be a material discrepancy and therefore a non-conformity.

Certification Period

This Certification is valid for a period of 24 months from 29th June 2017 (the "effective date") until 28th June 2019 subject to the provisions in this Certification Letter.

We will be in touch with you prior to the expiry of this certification to discuss your communications and reduction plans as well as re-certification. However, if you have any questions or would like to look into re-certification or reduction assessment at any time, please feel free to get in touch with us.

Agricultural Products

For agricultural emissions, the Listed Carbon Footprint results are obtained following a methodology consistent with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and other Land Use.

Suspended Non-conformities

The following non-conformities were raised but considered suitable for action prior to the next surveillance and/or re-certification audit. In general, it is expected that Minor Non-conformities should be closed with higher priority than Observations.

Identifier	Finding	Planned action	Severity
Boundary	A limited range of money access options are modelled (outdoor ATMs, limited boundary indoor ATMs). These omissions are unlikely to affect the result of the comparison between notes (as the missing emissions will be equivalent) but please consider updating the footprint to be more complete as a data quality improvement action.	The footprint will be updated if required for future communication.	Minor
Substrate (BOPP) production	The footprint results should be updated with CCL Secure data more representative of a year's production, in order to mitigate the risk of mis-statement.	The footprint will be updated if required for future communication.	Minor

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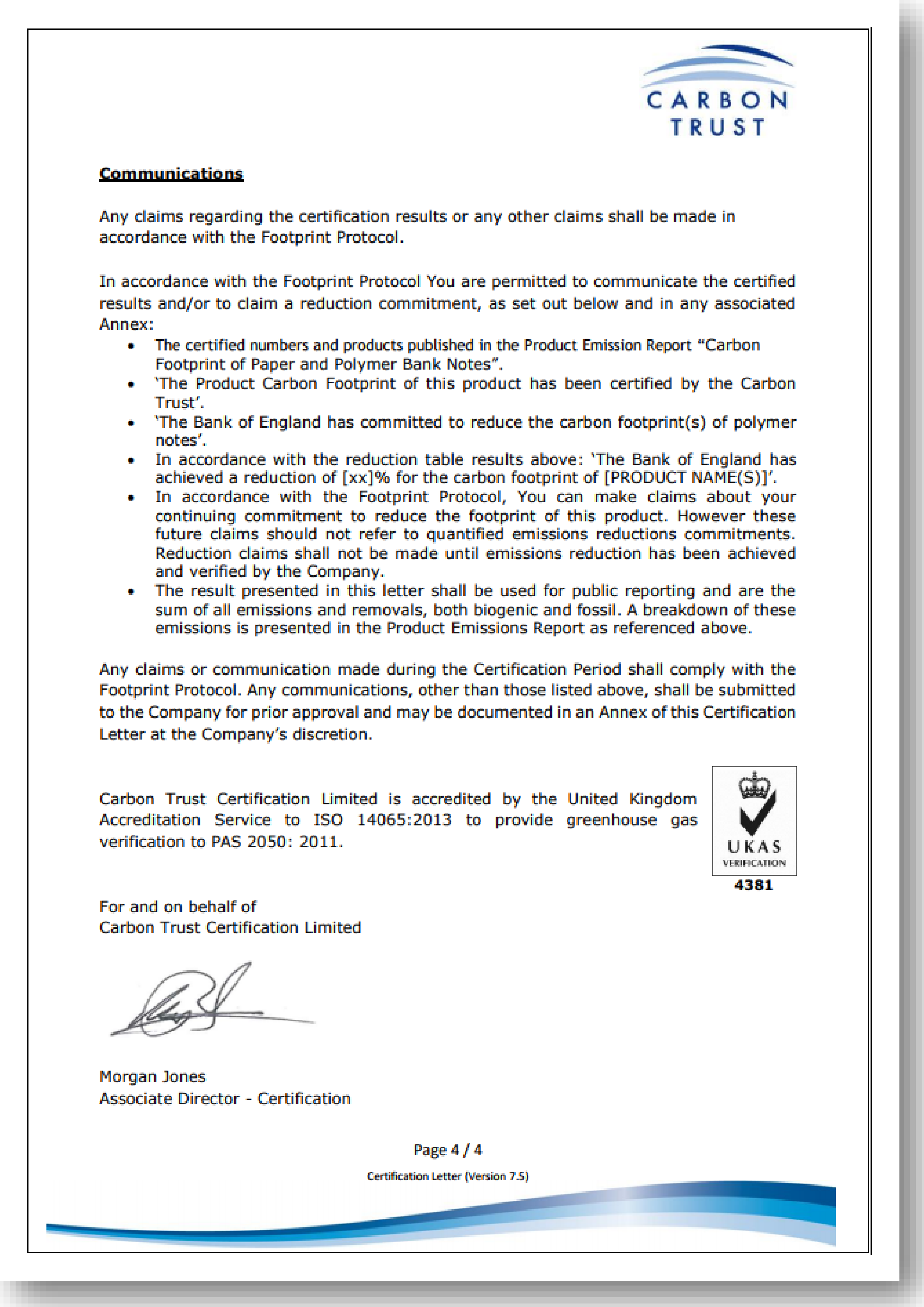

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Communications

Any claims regarding the certification results or any other claims shall be made in accordance with the Footprint Protocol.

In accordance with the Footprint Protocol You are permitted to communicate the certified results and/or to claim a reduction commitment, as set out below and in any associated Annex:

- The certified numbers and products published in the Product Emission Report "Carbon Footprint of Paper and Polymer Bank Notes".
- 'The Product Carbon Footprint of this product has been certified by the Carbon Trust'.
- 'The Bank of England has committed to reduce the carbon footprint(s) of polymer notes'.
- In accordance with the reduction table results above: 'The Bank of England has achieved a reduction of [xx]% for the carbon footprint of [PRODUCT NAME(S)]'.
- In accordance with the Footprint Protocol, You can make claims about your continuing commitment to reduce the footprint of this product. However these future claims should not refer to quantified emissions reductions commitments. Reduction claims shall not be made until emissions reduction has been achieved and verified by the Company.
- The result presented in this letter shall be used for public reporting and are the sum of all emissions and removals, both biogenic and fossil. A breakdown of these emissions is presented in the Product Emissions Report as referenced above.

Any claims or communication made during the Certification Period shall comply with the Footprint Protocol. Any communications, other than those listed above, shall be submitted to the Company for prior approval and may be documented in an Annex of this Certification Letter at the Company's discretion.

Carbon Trust Certification Limited is accredited by the United Kingdom Accreditation Service to ISO 14065:2013 to provide greenhouse gas verification to PAS 2050: 2011.

UKAS VERIFICATION
4381

For and on behalf of
Carbon Trust Certification Limited

Morgan Jones
Associate Director - Certification

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Annex B: Confidential Data

Data reported in this annex have been removed as they are commercially sensitive to the companies that kindly contributed to the study.

Annex C: Background data

Fuels and Energy

National and regional averages for fuel inputs and electricity grid mixes were obtained from the GaBi 6 database 2012. Table C-1 shows the most relevant energy-related LCI datasets used in modelling the product systems and their associated emission factors.

Table C-1: Key energy datasets used in inventory analysis

Energy	Dataset name	Primary source	Year	Geography
Electricity	Electricity grid mix	thinkstep	2013	UK
Technical heat	Thermal energy from natural gas	thinkstep	2013	UK
Fuels	Diesel mix at refinery	thinkstep	2013	EU-27
	Heavy fuel oil at refinery (1.0wt.% S)	thinkstep	2013	EU-27

Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 6 database 2012. Table C-2 shows the most relevant material- and process-related LCI datasets used in modelling the product systems. Documentation for all non-project-specific datasets can be found at www.gabi-software.com/support/gabi/gabi-lci-documentation.

Table C-2: Key material datasets used in inventory analysis

Material/ Process	Dataset name	Primary source	Year	Geography
Adhesive	TPU adhesive	thinkstep	2016	Europe
Alcohol	Ethanol	thinkstep	2016	Germany
Carboxymethyl cellulose	Sodium Carboxy Methylcellulose from cotton/cellulose	thinkstep	2016	Germany
Cotton Fibre	Cotton Fibre	Cotton Inc.	2010	US/China/India
Epichlorohydrin	Epichlorohydrin	thinkstep	2016	Germany
Epoxy resin	Epoxy Resin (EP) Mix	thinkstep	2016	Germany
Hazardous Waste Disposal	Hazardous waste (non-specific) (c rich, worst scenario)	thinkstep	2016	Global

Material/ Process	Dataset name	Primary source	Year	Geography
Hydrogen peroxide	Hydrogen peroxide (100%; H2O2) (Hydrogen from steam reforming)	thinkstep	2016	Germany
K-fertiliser	Potassium chloride (agrarian)	thinkstep	2016	Germany
Landfill	Landfill of paper waste	thinkstep	2016	EU-28
Landfill	Landfill of plastic waste	thinkstep	2016	EU-28
Landfill	Landfill (Commercial waste for municipal disposal; FR, UK, FI, NO)	thinkstep	2016	UK
MEK	Methyl ethyl ketone (MEK)	thinkstep	2016	US
Metal salts	Manganese sulphate (estimation)	thinkstep	2016	Germany
MIBK	Methyl-isobutylketone (MIBK)	thinkstep	2016	Germany
Modified alkyd resin	Phthalic anhydride Glycerine	thinkstep thinkstep	2016 2016	Germany Germany
Modified phenolic resin	Phenol formaldehyde-resin (Novolac)	thinkstep	2016	Europe
N-fertiliser	Urea (agrarian)	thinkstep	2016	Germany
Non-soluble mineral salt	Barium carbonate (estimation, barium sulphide and CO2)	thinkstep	2016	Germany
Organic coloured pigments	Carbon black (furnace black; deep black pigment)	thinkstep	2016	Germany
PA fibres	Polyamide 6.6 fibres (PA 6.6)	thinkstep	2016	EU-28
Paper	Kraft paper	thinkstep	2016	Germany
PET fibres	Polyethylene terephthalate fibres (PET)	thinkstep	2016	EU-28
PET film	Polyethylene terephthalate foil (PET) (without additives)	thinkstep	2016	Germany
P-fertiliser	Triple superphosphate (TSP)	thinkstep	2016	Netherlands
Photo-initiator	Benzoyl Peroxide	thinkstep	2016	US
Polypropylene	Polypropylene granulate	thinkstep	2016	Germany
Polyvinyl alcohol	Polyvinyl Alcohol Granulate (PVAL) Mix	thinkstep	2016	Germany
PP Energy Recovery	Polypropylene (PP) in waste to energy plant (modified based on Veolia data)	thinkstep	2016	Europe
Sea freight	Container ship (27500 DWT)	thinkstep	2016	Global
Shrinkfilm	Polyethylene Film (PE-LD) without additives	thinkstep	2016	Germany
Silica	Silica sand (flour)	thinkstep	2016	Germany
Sodium hydroxide	Caustic soda mix	thinkstep	2016	UK
Sulphonated castor oil	Sun flower oil production	thinkstep	2016	France
Titanium dioxide	Titanium dioxide pigment	thinkstep	2016	Europe
Truck freight	Truck (29-32 t gross weight, Euro V)	thinkstep	2016	Global
Vegetable oil	Rapeseed oil	thinkstep	2016	Germany
Waste plastic compounding	Pelletizing and compounding	thinkstep	2016	Germany

Material/ Process	Dataset name	Primary source	Year	Geography
Waste plastic granulation	Granulator	thinkstep	2016	Germany
Waste plastic washing	Washing (plastic recycling)	thinkstep	2016	Germany
Water	Process water	thinkstep	2016	Europe
Water	Water (desalinated; deionised)	thinkstep	2016	Europe
Water	Tap water from surface water	thinkstep	2016	Germany
Waxes & Mineral Oils	Wax / Paraffins at refinery	thinkstep	2013	EU-28
White spirit	Naphtha at refinery	thinkstep	2013	EU-28
WWT	Waste water treatment	thinkstep	2016	EU-28

Annex D: Data Quality Indicators

The quality of the foreground and background data used in this study have been summarised in the pedigree matrices shown in Tables D-2 and D-3 (based on that used in the GHG Protocol Product Life Cycle Accounting and Reporting Standard). This based on the scoring system presented in Table D-1 below.

Table D-1: Scoring system for pedigree matrix

Data Quality Indicator	Very Good	Good	Fair	Poor
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions or a qualified estimate (e.g. by sector expert)	Non-qualified estimate
Completeness	Data from all relevant process sites over an adequate time period to even out normal fluctuations	Data from more than 50% of sites for an adequate time period to even out normal fluctuations	Data from less than 50% of sites for an adequate time period to even out normal fluctuations or from more than 50% of sites but for shorter time period	Data from less than 50% of sites for shorter time period or representativeness is unknown
Temporal	Data with less than 3 years of difference	Data with less than 6 years of difference	Data with less than 10 years of difference	Data with more than 10 years of difference or the age of the data are unknown
Geographical	Data from the same area	Data from a similar area	Data from a different area	Data from an area that is unknown
Technological	Data generated using the same technology	Data generated using a similar but different technology	Data generated using a different technology	Data where technology is unknown

Table D-2: Pedigree matrix for foreground data used in this study

Data Point	Reliability	Completeness	Temporal	Geographical	Technological
Papermaking	Very good	Very good	Fair	Very good	Very good
Polymer film production	Very good	Very good	Very good	Very good	Very good
Polymer film conversion	Very good	Good	Very good	Very good	Very good
Inks production	Good	Very good	Fair	Very good	Very good
Printing	Very good	Very good	Fair (paper) /Very good (polymer)	Very good	Very good
NCS note sorting and distribution	Good	Good	Fair	Very good	Very good
Bank of England note sorting and destruction	Very good	Very good	Fair	Very good	Very good

Table D-3: Pedigree matrix for background data used in this study

Data Point	Reliability	Completeness	Temporal	Geographical	Technological
Cotton	Very good	Very good	Good	Fair/good	Very good
Polymer granulate	Good	Very good	Very good	Good	Very good
Components of inks/varnishes	Good/very good	Fair/good	Very good	Fair/good	Very good
Electricity grid	Very good	Very good	Good	Very good	Very good
Thermal energy	Very good	Very good	Good	Very good	Very good
Truck transport	Good	Very good	Very good	Very good	Good
Ship transport	Good	Very good	Very good	Very good	Good
Energy from waste	Good	Very good	Very good	Very good	Very good
Plastic recycling	Fair	Good	Very good	Good	Good
Composting	Poor	Poor	Fair	Good	Good

thinkstep