The Bank of England

LCA of Paper and Polymer Bank Notes

Final Study Report

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PE INTERNATIONAL

On behalf of PE INTERNATIONAL AG and its subsidiaries

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ACRONYMS

ADP	Abiotic Depletion Potential
AP	Acidification Potential
ATM	Automated Teller Machine
BOPP	Bi-axially Oriented Polypropylene
CML	Centre of Environmental Science at Leiden
ELCD	European Life Cycle Database
EoL	End-of-Life
EP	Eutrophication Potential
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
NCS	Note Circulation Scheme
NMVOC	Non-methane Volatile Organic Compound
ODP	Ozone Depletion Potential
PE	PE INTERNATIONAL
POCP	Photochemical Ozone Creation Potential
PP	Polypropylene
VOC	Volatile Organic Compound

GLOSSARY (ISO 14040/44:2006)

ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework, International Organization for Standardization (ISO), Geneva.

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

Biogenic carbon

Carbon that is derived from biomass, but not fossilised or fossil sources

Functional Unit

Quantified performance of a product system for use as a reference unit

Close loop & open loop

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.

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.

Cradle to grave

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of life.

Cradle to gate

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of the production process (“gate of the factory”). It may also include transportation until use phase.

Life cycle

A unit operation’s view of consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal. This includes all materials and energy input as well as waste generated 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

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.

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.

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.

Reference flow

Measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit.

Unfit

Bank notes assessed as no longer being fit for recirculation and sent for disposal.

CRITICAL REVIEW STATEMENT

Background

The study “Life Cycle Assessment of Paper and Polymer Bank Notes” was commissioned by the Bank of England and carried out by PE INTERNATIONAL. The study was critically reviewed by a panel of experts comprising:

- Professor Adisa Azapagic (Panel Chair);
- Michael Sturges; and
- Erik Balodis.

The aim of the review was to ensure that:

- the methods used to carry out the LCA study are consistent with the ISO 14040:2006 and 14044:2006 standards;
- the methods used are scientifically and technically valid given the goal of the study;
- the data used are appropriate and reasonable in relation to the goal of the study;
- the interpretation of the results and the conclusions of the study reflect the goal and the findings of the study; and
- the study report is transparent and consistent.

The critical-review process involved the following steps and activities:

- a review of the Goal and Scope Definition at the outset of the project;
- a review of the draft report and recommendations for improvements to the study and the report;
- a review of the subsequent final study report, in which the authors of the study fully addressed the points as suggested in the draft critical review; and
- the final critical review report (this review statement).

The critical review panel did not view or review the GaBi LCA models created for this project or the parameterised “interactive report” so that all the findings of the critical review are based solely on the LCA report.

Conclusion of the critical review

The panel confirms that this LCA study follows the guidance of and is consistent with the international standards for Life Cycle Assessment (ISO 14040:2006 and 14044:2006).

Professor Adisa Azapagic Michael Sturges Erik Balodis

(Panel Chair)

August 2013

EXECUTIVE SUMMARY

The Bank of England is currently debating the material of choice for future UK bank notes. One important consideration that will feed into this discussion relates to the relative environmental performance of the alternative substrates that can be used.

To better understand these issues the Bank of England has commissioned PE INTERNATIONAL to undertake a life cycle assessment (LCA) study to calculate and compare the environmental impacts of conventional cotton paper (“paper”) and bi-axially oriented polypropylene (“polymer”) bank notes for all UK bank note denominations (£5, £10, £20 and £50). Each bank note denomination was considered separately according to the functional unit specified below (i.e. the mix of bank notes in circulation was not considered).

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 scope of the study is from cradle to grave and accounts 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 £1,000 of cash value over 10 years, considering an average bank note life cycle”

The average lifetime of bank notes varies depending on denomination and choice of substrate. For this study it is assumed that the lifetime of polymer bank notes is 2.5 times greater than that of current paper bank notes. Hence bank note lifetime varies from 22.8 months for £5 paper notes to 1231 months for £50 polymer notes.

The following life cycle inventory indicators have been reported: primary energy demand (both renewable and non-renewable) and freshwater consumption. In addition to these, the following impact categories have been assessed: acidification, ecotoxicity, eutrophication, global warming, human toxicity (both cancer and non-cancer) and photochemical ozone creation potentials.

The results show that, for £5, £10 and £20 bank notes, most indicators are dominated by impacts associated with electricity generation required to operate ATMs. This is particularly noticeable for £10 and £20 notes where a very high proportion of bank notes are sent to ATMs after sorting (91% and 90% respectively). For £5 notes the proportion sent to ATMs is lower at 64%, but this is still sufficient for the impact of ATMs to be the largest contributor to many indicators.

In contrast, only 1% of £50 notes are distributed into circulation through ATMs. For this denomination the impacts of raw material production, conversion into substrate (paper or polymer film) and sorting during the use phase have the biggest contributions to most impact categories. Process steps such as printing, transport and disposal at end of life tend to be of minor significance in comparison.

When the results of the LCA are normalised, human toxicity (cancer) is clearly the most significant impact category, being about an order of magnitude greater than most other impact categories (this is seen for both paper and polymer bank notes). The majority of this impact is from electricity generation associated with the use of ATMs. This reinforces the message that achieving energy efficiency savings during bank note circulation will be an effective way to tackle the most significant impacts associated with the bank note life cycle.

When comparing results across denominations the most important aspects determining the relative environmental performance are:

- the mass of notes required to achieve the functional unit, which is determined by the denomination and lifetime of the bank note;
- the circulation velocity, which determines the number of times a note is sorted and put back into circulation; and
- the proportion of notes sent to an ATM after each sort.

For many indicators, impacts associated with the use phase outweigh those associated with the material production phase (again, this is observed for both paper and polymer bank notes). Hence, even though the total mass of £5 notes is almost three times greater than the mass of £10 notes, the £10 notes often have larger life cycle impacts due to their very high use phase impacts, which are due to a combination of high circulation velocity and a high proportion of notes sent to ATMs after each sort.

When comparing substrates, it is seen that for a given mass of bank notes the paper substrate generally has slightly lower environmental impacts than the polymer substrate. However, because polymer bank notes are assumed to last 2.5 times longer than paper bank notes (the default assumption in this study) a significantly lower mass of polymer bank notes are required to satisfy the functional unit. Hence, overall polymer bank notes have lower environmental impacts than paper bank notes for all impact categories assessed except for photochemical ozone creation potential.

The sensitivity of the results to the default lifetime has been assessed. It was found that polymer bank notes need only have a lifetime 1.33 times greater than that of paper bank notes to achieve a lower global warming potential. Based on experience of from other countries that use polymer bank notes it seems very likely that this lifetime will be exceeded, indicating that the overall conclusions from the study are robust.

Additional sensitivity analyses were conducted to evaluate the influence on the results of uncertainties relating to: impacts of cotton cultivation, emissions from composting paper bank notes at end of life, recycling polymer bank notes instead of incinerating with energy recovery at end of life and ATM energy consumption. For £5, £10 and £20 notes made of either paper or polymer substrate, only the electricity consumption of the ATM was found to have a significant influence on the results. For the £50 note, polymer recycling showed noticeable benefits compared to incineration with energy recovery, but this was less obvious for other denominations due to the dominating contribution from ATMs. If the impact of the ATM is excluded (as it will be the same for both paper and polymer bank notes) then the choice of end of life option makes a noticeable difference for bank notes of all denominations but the influence of cotton cultivation and composting of paper bank notes remains small.

Overall, the results of this study indicate that polymer bank notes have superior environmental performance to paper bank notes based on the impact categories assessed and with due consideration of the limitations of the study. On this basis it is recommended that the Bank of England should move from using paper bank notes to using polymer bank notes.

We further recommend working with ATM providers to assess opportunities for optimising the energy consumption of ATMs, as these are responsible for most impacts for £5, £10 and £20 notes.

If the decision is made to move to polymer bank notes the Bank of England should investigate whether further environmental benefits could be achieved by locating polymer substrate production in the UK rather than importing substrate from Australia. Such benefits seem likely as:

- this would reduce transport impacts, and the
- UK grid mix has lower GHG impacts than electricity generation in Australia, which should lead to lower production impacts.

Finally, we also suggest that further research is undertaken to identify the optimum waste management options for polymer bank notes. In addition to energy from waste and mechanical recycling processes considered in this study, other options, such as pyrolysis, may also be beneficial. This may have a significant influence on the environmental performance of £50 notes, where the life cycle impacts are not dominated by ATM usage.

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, other materials are available and some other countries have introduced, or are considering introducing, bank notes made from polymers. The Bank of England is also debating the material of choice for future bank notes and one important consideration that will feed into this discussion relates to the relative environmental performance of the different substrates that can be used.

In particular the Bank of England is looking to:

- evaluate the life cycle environmental impacts associated with manufacturing, distributing and disposing of UK bank notes based on two different substrates – cotton paper vs. bi-axially oriented polypropylene (BOPP) (hereafter referred to as *"paper"* and *"polymer"* respectively);
- identify substances of concern whether in the form of bank note components or emissions arising from the bank note life cycle;
- reveal those aspects of the bank note life cycle that could be targeted to further reduce environmental impact.

As such, the Bank of England has commissioned PE INTERNATIONAL, a global consulting company and leader in providing sustainability services and solutions, to undertake a life cycle assessment (LCA) study to calculate and compare the environmental impacts of paper and polymer bank notes for all UK bank note denominations (£5, £10, £20 and £50), and identify the main drivers contributing to these impacts.

The assessment of paper bank notes is based on the specification of notes currently in circulation including specific security features such as motion thread and foil patch holograms. Polymer notes are assessed assuming that they have the same dimensions as the current paper notes. 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).

Each bank note is considered separately as the use phase characteristics varies significantly depending upon denomination (i.e. the study does not assess a mix of different denominations).

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.

Because the study results are intended to support comparative assertions that may be disclosed to the public PE has prepared an ISO 14040/44 compliant LCA report that has undergone critical review by a panel of independent experts.

2 SCOPE OF THE STUDY

The following section describes the general scope of the project to achieve the stated goals. This includes the identification of specific products to be assessed and their functions, the supporting product systems (e.g. printing, distribution, etc.), and the boundary of the study, allocation procedures, cut-off criteria and data quality aspects.

2.1 PRODUCT SYSTEMS TO BE STUDIED

This study assesses the life cycle impacts associated with £5, £10, £20 and £50 notes made using both paper and polymer substrates based on the dimensions and designs used in the paper notes currently in circulation (a flow chart showing the system boundaries of the study is given later in Section 2.3, Figure 2-1). The main physical characteristics of each note are provided 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]	Selected Security Features[a]
£5	Paper	70 x 135	90	Security thread, foil patch
	Polymer	70 x 135	82.5	Foil patch
£10	Paper	75 x 142	83	Security thread, foil patch
	Polymer	75 x 142	82.5	Foil patch
£20	Paper	80 x 149	86	Security fibres, Security thread, foil patch
	Polymer	80 x 149	82.5	Foil patch
£50	Paper	85 x 156	93	Security Thread, motion thread
	Polymer	85 x 156	82.5	Foil patch

[a] Excludes print-related security features such as raised lettering, watermarks, UV ink, etc. that are applied to all notes, (although these features are assessed in the model)

The Bank of England is considering moving to bank notes with slightly smaller dimensions in future but these are not assessed in the current study. The bank note dimensions would be the same for polymer and paper bank notes so although the size change would affect the absolute results, the relative performance of the two substrates should be unchanged.

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 waste products from the normal cotton fibre production process. Cotton comber noil comprises fibres too short to make into cotton thread for clothing and provides strength and tear resistance to the paper. Cotton linter comprises 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 in the paper and also enables good watermarks to be added to the paper.

These cotton fibres are then turned into paper. During this process security features such as metallic thread (and motion thread in the £50 note) are added to the paper. The paper is then sent for printing, which is a four step process as follows:

- lithographic printing: applies the main design to the bank note;
- application of holographic foil patch security device (except for the £50 note);
- intaglio printing: creates raised print in certain areas of the note; and
- letterpress printing: applies a unique number to each bank note.

After printing the notes are then 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 printers) or in Leeds.

From here notes are sent out to 27 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 forgeries. 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 film process whereby plastic melt is extruded through a die to form a thin walled tube then air is 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.

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 cannot be rubbed off during use.

The treatment of polymer notes in circulation will be 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 will also be returned to the Bank of England to be destroyed. In this case the polymer bank notes would be granulated and then sent for final disposal which may involve recycling into new polymer products or incineration with energy recovery.

2.2 PRODUCT FUNCTION, FUNCTIONAL UNIT AND REFERENCE FLOWS

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 £1,000 of cash value over 10 years, considering an average bank note life cycle"

Accordingly, the reference flows will be dependent upon the:

- denomination of the bank note (e.g. 20 x £50 notes are required compared with 200 x £5 notes); and the
- 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)[1].

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. Selecting a longer or shorter time span would affect the absolute values reported in the results but would not affect the relative performance of the different bank note substrates[2].

Table 2-2 gives information on the circulation lifetimes of different note denominations in the UK. These are based on statistics provided by the Bank of England covering the year 2012. The exception is lifetime of the £50 which was calculated based on a 12 month average for the period September 2010 to October 2011. This was to exclude the effects of the new £50 note design launched in November 2011 which, due to large numbers of returns, caused note life to fall dramatically and so was considered unrepresentative.

For example, an average £5 returns to a NCS cash centre every 4.8 months, and has a note life of 22.8 months. After its 5th sort (at 19.2 months) it will not be considered unfit, and will circulate for a further 4.8 months, until it is sorted again. It will therefore have circulated for a total of 24.0 months; 1.2 months longer than its note life.

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[1] Consideration of the series lifetime (i.e. implementing new note designs, issuing new notes and recalling and destroying existing notes) is outside the scope of this study. However, this does have implications for larger denomination notes that have longer lifetimes and is commented on further in the interpretation (see Section 6.4.2).

[2] A similar study carried out by PE for the Bank of Canada used a time span of 7.5 years [Bank of Canada 2011]. This was selected because the study focused on a single denomination of $20 (CDN), and 7.5 years was the expected lifetime of the polymer note. As the current study considers a range of denominations, each with different lifetimes, a 10 year reference time span is considered more appropriate.

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	4.80	22.8	5	1.2	24.0
£10	1.43	36.0	26	1.1	37.1
£20	3.43	113	33	0.3	113
£50	17.1	492	29	5.1	497

[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 lifetime of polymer bank notes is forecast based on data from countries that already use polymer notes combined with consideration of how this might be influenced by the specific characteristic of the UK situation (as polymer notes are not in circulation it not possible to provide accurate information on their expected lifetime). 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 assumption is in line with that used in the recent Bank of Canada study [BANK OF CANADA 2011]. This assumption, agreed with the Bank of England, is considered representative based on statistical data on currently used polymer bank notes in other countries. It is acknowledged that there is large uncertainty in this assumption and assessing the impact on the results of this uncertainty is the focus of a sensitivity analysis (see Section 5.1). Based on this assumption the circulation characteristics of polymer bank notes are given in Table 2-3.

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	4.80	57.0	12	0.6	57.6
£10	1.43	90.0	63	0.1	90.1
£20	3.43	283	83	1.7	285
£50	17.1	1230	72	1.2	1231

[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 reference flows for the different note denominations used in this LCA 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 their note life).

Other characteristics of bank note circulation are also dependent upon the denomination of the bank note (e.g. the proportion of bank notes in ATMs is higher for £10 and £20 notes than for £5 and £50 notes). The assumptions used for each bank note are described in detail in Section 2.11.

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	24.0	851
	Polymer	0.780	57.6	325
£10	Paper	0.884	37.1	286
	Polymer	0.879	90.1	117
£20	Paper	1.03	113	54.4
	Polymer	0.983	285	20.7
£50	Paper	1.23	497	5.95
	Polymer	1.09	1231	2.13

2.3 SYSTEM BOUNDARIES

This study is a cradle to grave life cycle 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. Detailed process flow diagrams describing each process stage are given in Appendix A.

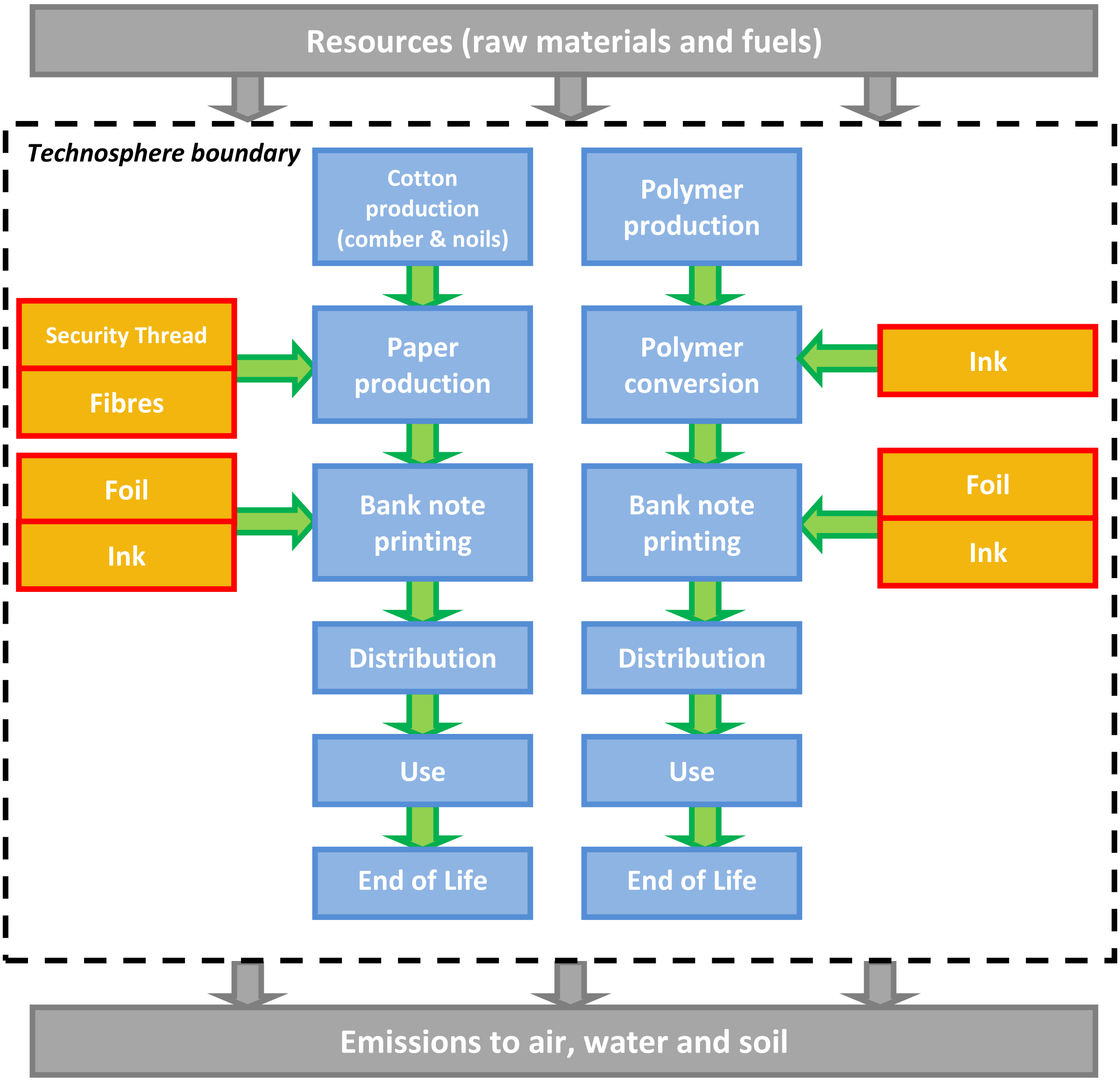

Figure 2-1: System boundary for the paper and polymer bank notes

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 noils 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 of notes at NCS cash centres (this includes counterfeit checking);
- return of unfit bank notes to the Bank of England cash centres;
- sorting 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;
- some chemicals used in relatively small quantities in the polymer substrate production process amounting to around 2% by mass of inputs to this process step (see Section 2.11.4);
- performance chemicals (fillers and additives) for cotton paper production;
- production and disposal of printing plates used in lithographic and intaglio printing;
- 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);
- energy consumption of heater used in "through the wall" ATMs when temperature drops below zero Celsius; and

- use of bank notes by retailers (e.g. cash registers) and the general public (e.g. transport impacts) – the energy requirement for operating cash registers will be the same for all notes and it is common practice in LCA studies to exclude transport impacts associated with consumer use.

2.3.1 Time Coverage

Primary data on polymer substrate conversion, inks and foil production, sorting and distribution/ circulation were collected for the year 2011. Primary data on papermaking and printing were collected for a 2 year period (financial years April 2010 to May 2012) to even out differences in annual production. Primary data on polymer film production is based on data for production in 2009 but is representative of current operation.

The representative background data (mainly raw materials, energies, fuels, and ancillary materials) have been obtained from the GaBi "Database 2012" [PE INTERNATIONAL 2012] and are representative of the years 2009-2011[3].

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 may 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. Uncertainties relating to these differences are addressed in a sensitivity analysis (see Section 2.12.2).

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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..

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 the bubble 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[a]
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 energy-from-waste (polymer notes)

[a] No data were available for production of motion thread used in £50 paper bank notes. This was modelled based on production of standard thread.

2.3.3 Geographical Coverage

The distribution and use of the bank notes is modelled for the UK. The raw materials are produced in various areas of the world and the geographical coverage varies depending upon the location of the manufacturing plants.

2.4 ALLOCATION

This section describes the allocation approaches adopted in the study to assign appropriate impacts to co-products and by-products from the production process.

2.4.1 Treatment of Co- and By-products

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).

PE has previously worked with Cotton Inc. (the organization 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 0.114 kg raw cotton fibres.

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

	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 noils/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 noils a value of €0.86/kg.

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 and 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 documentation.gabi-software.com.

2.4.2 Recovery & Recycling

Unfit paper bank notes are currently granulated, compacted and then composted. 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 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 offsetting production of an equivalent nutrient value of chemical fertilisers.

Consideration of issues such as leaching of inks from the composted notes is outside the scope of this study, but is not expected to be any more significant than for composting of other printed paper products. The ink producer, SICPA, is not aware of any issues relating to leaching from the use of its inks and varnishes.

The disposal options for unfit polymer bank notes are not yet clearly defined. The baseline assumption is that they are incinerated with energy recovery.

A possible alternative to energy recovery is to recycle the polymer. A closed loop approximation approach has been used to account for the benefits of mechanical recycling (i.e. providing credits for recycling at end of life due to the avoided requirement for primary material).

The consequences of these alternative disposal options have been assessed using sensitivity analysis (see Section 2.12).

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 2.11.

2.6 SELECTION OF LCIA METHODOLOGY AND TYPES OF IMPACTS

A set of impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-7 and Table 2-8. The CML impact assessment methodology framework was selected for this assessment. The CML characterisation factors are applicable to the European context and are widely used and respected within the LCA community.

Global warming potential and primary energy demand were chosen because of their relevance to climate change and energy efficiency, which are strongly interlinked, of high public and institutional interest, and deemed to be some of the most pressing environmental issues of our times. Global warming potential in particular is of key interest to the Bank of England.

Eutrophication, acidification, and photochemical ozone creation potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burdens associated with commonly regulated emissions such as NO_x, SO_2, VOC, and others.

It should be noted that there is significant uncertainty relating to the characterisation factors applied to photochemical ozone creation potential, particularly with respect to nitrogen monoxide emissions that are produced during diesel combustion. This is discussed in more detail in the results chapter for POCP (Section 4.8). Due to this uncertainty we recommend to treat the results from this assessment with some caution and we do not recommend that they are used to make comparative assertions.

Table 2-7: Impact Assessment Category Descriptions

Impact Category	Description	Unit	Reference
Global Warming Potential (GWP)	A measure of greenhouse gas emissions, such as CO2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent	[GUINÉE 2001]
Eutrophication Potential	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	kg Phosphate equivalent	[GUINÉE 2001]
Acidification Potential	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	kg SO_2 equivalent	[GUINÉE 2001]
Photochemical Ozone Creation Potential (POCP)	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone, O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.	kg ethene equivalent	[GUINÉE 2001]
Human toxicity, **Ecotoxicity**	A measure of toxic emissions directly harmful to the health of humans and other species.	Cases Potentially affected fraction of species (PAF).m^3.day	[ROSENBAUM 2008]

Water consumption, i.e., the removal of water from its watershed through shipment or evaporation due to human activities, has also been selected due to its high political relevance. The UN estimates that roughly a billion people on the planet don't have access to improved drinking water, which entails a variety of problems around ecosystem quality, health, and nutrition.

Table 2-8: Other Environmental Indicators

Impact Category	Description	Unit	Reference
Primary Energy Demand (PED)	A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.) and energy demand from renewable resources (e.g. hydropower, wind energy, solar, etc.). Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.	MJ (net calorific value)	[GUINÉE 2001]
Life Cycle Inventories of Water Inputs/Outputs	A measure of the net intake and release of fresh water across the life of the product system. This is not a complete indicator of environmental impact without the addition of information about regional water availability.	Litres of Water	GaBi 5 Software database

Additionally, the project includes an evaluation of human and ecotoxicity employing the USEtox characterisation model. The precision of the current USEtox characterisation factors is within a factor of 100–1,000 for human health and 10–100 for freshwater ecotoxicity [ROSENBAUM 2008]. This is a substantial improvement over previously available toxicity characterisation models, but still significantly higher than for the impacts noted above. Given the limitations of the characterisation models for each of these factors, results are reported as 'substances of high concern', but are not to be used to make comparative assertions.

It shall be noted that the impact categories listed above represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emitted molecules would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so.

Therefore LCIA results are relative expressions only; they do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

2.7 MODELLING OF BIOGENIC CARBON

Biogenic carbon flows are 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 in 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 2.11.8). Delayed GHG emissions (e.g. from subsequent release of carbon dioxide from compost in future years) has not been considered.

2.8 INTERPRETATION TO BE USED

The study applies normalisation against yearly EU emissions as a means to establish the order of magnitude of each product systems' contribution to the average environmental burden of a given year. As this is a comparative assertion to be disclosed to third parties, no grouping or further quantitative cross-category weighting has been applied.

2.9 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 the given time and budget constraints.

- Measured primary data are considered to be of the highest precision, followed by calculated and estimated data;
- completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves;
- consistency refers to modelling choices and data sources. The goal is to ensure that differences in results occur due to actual differences between product systems, and not due to inconsistencies in modelling choices, data sources, emission factors, or other;
- representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study's goal and scope.

An evaluation of data quality with regard to these requirements will be provided in the interpretation chapter 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 [GHG PROTOCOL 2011; WEIDEMA & WESNAES 1996].

2.10 DATA COLLECTION

2.10.1 Data Collection & Quality Assessment Procedure

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

The key primary data used in this study are presented in Appendix A.

2.10.2 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 6 database 2012. Documentation for all non-project-specific datasets can be found at www.gabi-software.com/support/gabi/gabi-lci-documentation.

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

2.10.3 Transportation

Transportation distances and modes of transport used for distribution of raw materials, semifinished products and finished bank notes to Bank of England cash centres were obtained from suppliers or assessed using web-based calculation tools [GOOGLE MAPS 2013, SEA-RATES.COM 2013]. Average transportation distances for distributing notes to NCS cash centres and out into the wider economy were obtained from G4S.

The GaBi database for transportation vehicles and fuels was 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 in 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.

2.10.4 Emissions to Air, Water and Soil

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

Data for all upstream materials, electricity, and energy carriers were obtained from the GaBi 6 database 2012. The emissions (CO_2, etc.) due to the use of electricity are accounted for with the use of the database processes.

Emissions associated with transportation were determined by capturing the logistical operations of involved companies. Energy use and the associated emissions were calculated using pre-configured transportation models from the GaBi 6 database 2012, adapted with transportation supplier data (specific fuel economy, specific emissions, etc.).

2.11 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.

2.11.1 Cotton Production

Information on the environmental impacts of cotton production is based on secondary data from Cotton Inc. This is derived from a recent study and represents 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. The sensitivity of the results to this choice of dataset is investigated in a sensitivity analysis.

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%) and the remainder is mostly water (7.9%) with small amounts of protoplasm, pectins, waxes and mineral salts accounting for the remainder [WIKIPEDIA 2013]. The carbon content of cellulose is around 44% [LUI ET AL 1997, HEUKELEKIAN ET AL 1925] so the carbon content of cotton is estimated at 40%.

2.11.2 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 final finished product.

No data were available on motion thread used in £50 notes. Instead this was modelled based on the data provided by De La Rue for production of standard security thread.

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 landspreading. 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 2.11.8).

2.11.3 Polymer Film Production

The polymer film is manufactured by Innovia Films at their facility located in Melbourne, Australia. 99% of the polypropylene granulate used in the production of the polymer substrate is sourced from

Australian producers. In this assessment, supply of granulate from other regions has not been accounted for, i.e., it is assumed that *all* polymer granulate is sourced from within Australia.

Australian polypropylene production was modelled based on GaBi data for European production. It is assumed that the production technology will be the same in both regions. The grid mix and fuel supply datasets have been updated to reflect Australian boundary conditions.

The Plastics Europe datasets are widely used in LCA studies. However, for this study the Plastics Europe dataset for PP granulate was not used because:

- it is aggregated so adjusting the boundary conditions to suit Australian production is not possible;
- it is based on process data from 1999 and so is considered out of date for current life cycle assessments; and
- data on water consumption only account for water input and so are not compatible with water consumption calculations.

The polymer film is produced using a bubble process. 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. The resulting tube of film is then cooled and passes through rolls where the tube is flattened before being slit to produce a finished sheet of film.

2.11.4 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 at Securency, which is co-located with Innovia Films' manufacturing facility in Melbourne, Australia.

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 (white ink is used in this process). The polymer coating is assumed to be propylene-butylene copolymer.

An unspecified reactant is also used in the process but has been omitted from the assessment due to lack of data. This omission amounts to about 2% of the total raw material inputs to this process step.

2.11.5 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 each denomination;
- foil application: a holographic foil patch is applied to £5, £10 and £20 notes as an additional security detail. This is not found on the £50 note which uses alternative security devices such as motion thread, which is applied during the papermaking stage;
- 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 need to undergo an additional process where a layer of varnish is applied. This is required to fix the inks and prevent them from being rubbed off during use.

Before each print run commences the machines are tested using pink paper to ensure that they are working properly. It has been assumed that this pink paper has the same production impacts as normal bank note paper. For modelling polymer printing it is assumed that an equivalent amount of "pink polymer" will be 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 expected to be 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 paper notes along with paper labels.

It was not possible to obtain data on the production of printing plates used in lithographic and intaglio printing. However, combined these account for less than 1% of the input mass to the printing process. The results for both substrates will be equally affected by this data gap so it is not considered likely to have a major influence on either the absolute or relative results from this study.

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.

It has not been possible to obtain information on the energy consumption associated with this air conditioning system so this has been omitted from the model. Although this will have an impact on the absolute results it is not anticipated that this will significantly influence the relative environmental performance of the polymer and paper bank notes. This is because it is expected that the air conditioning system would be operational for printing both paper and polymer bank notes (De La Rue print paper bank notes for many countries, so even if the UK moved to polymer bank notes, the current air quality standards would still need to be maintained).

Printing on polymer substrate cannot be carried out at the same rate as printing on paper. De La Rue estimates that this will raise the energy requirement for polymer printing by 10-20%. For this study an intermediate value of a 15% increase has been modelled.

2.11.6 Note Circulation Characteristics

After printing, bank notes are transferred to Bank of England Cash Centres. 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.

From the Bank of England Cash Centres the notes are then distributed to regional cash centres run by members of the Note Circulation Scheme (NCS), which 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 demonstrates large differences between different denominations. In addition to these differences in note "velocity" there are further differences between note behaviour in the use phase, in particular, as some denominations are much more commonly found in ATMs than others. As ATMs consume energy this influences the note circulation impacts of each denomination. Table 2-9 shows the total number of sorting operations at NCS cash centres for each denomination and the proportion of each denomination that is distributed into general circulation through ATMs after each sort.

Table 2-9: Note circulation characteristics

Denomination	Total number of sorts/FU	% to ATM
£5	5000	64
£10	8410	91
£20	1751	90
£50	140	1

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 65,000 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. ATMs come in many different designs and capacities but a typical ATM can 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 then 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 2-10 shows the energy consumption for transactions and stand-by mode operation for each type of ATM and the weighted average values used in the LCA model. These data are derived from the information provided by Diebold as presented in Table B-3 in Appendix B.

Table 2-10: 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 0°C)[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 remains the same.

2.11.7 Transport

The transport distances used in the model are given in Table 2-11. 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 2-11: 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** Road: 557 km[a] Ship: 8,484 km[a]	**Polypropylene granulate** Road: 72 km[a]
Substrate Production to Printworks	**Paper** Road: 141 km[b]	**Polymer film** Road: 30 km[b] Ship: 20,636 km[b]
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 this 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** Road: 100 km[c]	**Energy from waste plant** Road: 100 km[c] **Recycling facility** Road: 100 km[c]

[a] distance provided by supplier;
[b] calculated distance [Google Maps 2013, Sea-rates.com 2013];
[c] estimated distance.

For modelling the impact of bank note distribution and circulation the impact of diesel combustion is modelled 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.

For transport to end of life a standard distance of 100 km has been assumed for all disposal options.

2.11.8 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).

Paper bank notes are blended with other biodegradable waste materials and composted using an open air windrow system. SICPA, the ink supplier for UK bank notes, has confirmed that there are no known issues relating to leaching from inks and varnishes during composting.

In this study, data on composting paper bank notes were taken from a relatively recent paper on modelling composting in LCA studies [AMLINGER ET AL. 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 [VRIC 2009, EUNOMIA 2002]. The main parameters used in the model are presented in Table 2-12. 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 2-12: Key parameters for modeling emissions from composting [AMLINGER ET AL. 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%.

The main benefit of compost is as a soil improver, however, 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 biodegradable municipal waste [EUNOMIA 2002]. The values used in the model are given in Table 2-13, and show that the typical nutrient content in compost is quite low; its main benefit is as a soil improver rather than a fertiliser.

Table 2-13: Nutrient content of compost [EUNOMIA 2002].

Parameter	Unit	Value from Literature	Value used in Model
N content of compost	(%)	2 – 4	3
P content of compost	(%)	1 – 2	1.5
K content of compost	(%)	1 – 2	1.5

It is assumed that the nutrient content in the compost offsets 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.

The representativeness of using data on the composting of biowaste for assessing composting of paper bank notes may be questioned. The values used in the default scenario are based on the best data we have available but also include a number of assumptions. Indeed, there does appear to be an inconsistency relating to carbon dioxide emissions that suggest the data from the Amlinger study [AMLINGER ET AL. 2008] may underestimate the true carbon dioxide emissions from composting.

In Section 2.11.1 it was estimated that paper bank notes have a carbon content of 40% (dry mass basis). If it is assumed that the biowaste assessed in the Amlinger study has an equivalent carbon content, then an emission of 115,000 g CO_2/tonne fresh matter implies that only 16% of this carbon is lost during composting. Hence the carbon content of the resulting compost would be around 34%.

However, analyses of compost samples show that high quality compost normally has an organic content of around 50% (dry mass basis), and that carbon accounts for around 54% of this [DARLINGTON 2007, AASL 2002]. This implies that the carbon content of the compost is only 27% on a dry mass basis. Based on these assumptions around 33% of the feedstock carbon should be lost during composting. This equates to an emission of around 238,000 g CO_2/t fresh matter, which is just over twice the amount calculated based on the data from Amlinger.

Due to this uncertainty, the impact on the final results of this greater carbon dioxide emission during composting is examined in a sensitivity analysis.

2.11.9 Energy Recovery of Polymer Bank Notes

The incineration with energy recovery of polymer bank notes is based on a secondary dataset for the combustion of polypropylene in a municipal energy-from-waste plant. It is assumed that the full mass of the note is polypropylene so this may not accurately model emissions associated with incineration of inks, varnishes, foil patches, etc.

This dataset has been adjusted to reflect values provided by Veolia (the Bank of England's waste management contractor) on carbon dioxide emissions and electricity generation from this process. A credit is given for recovered electricity based on offsetting the average UK grid mix. Thermal energy is assumed not to be recovered.

2.12 SENSITIVITY ANALYSES

To better understand the influence of uncertain data on the results of the LCA study the following sensitivity analyses have been carried out.

2.12.1 Lifetime of Bank Notes

Several factors affect the lifetime of bank notes in circulation so determining the "typical" lifetime can be complicated. These factors include:

- Sorting frequency – sorting at cash centres is the point in the value chain at which notes are assessed for worthiness. Notes that are sorted frequently will be assessed more regularly and low quality notes identified and removed earlier. The sorting frequency is dependent upon the denomination of the bank note (high value bank notes such as £50 notes are commonly used as a store of value and hoarded rather than being used for financial transactions) and the quantity in circulation (scarcer bank notes may be retained by retailers rather than deposited with cash centres).

- Material – polymer bank notes have a longer expected lifetime than paper bank notes as they are more resilient and less liable to be damaged through every day wear and tear.

- Criteria for determining fitness – the point at which the Bank of England decides that it will cull a note from circulation for being unfit can have a significant effect on the lifetime of bank notes. Fitness criteria for paper and polymer bank notes differ as they fail in different ways: paper bank notes fail because of tears, corner folds and dirt build up, while polymer bank notes fail because the ink and coatings wear off.

The Bank of England has good information on the typical lifetime of paper bank notes in circulation, but there is much greater uncertainty regarding the lifetime of polymer notes[4].

To assess the robustness of the results to this uncertainty a range of different lifetimes have been modelled for each polymer note to enable the "break-even" point to be calculated for global warming potential – that is, the lifetime that a polymer note must achieve to give exactly the same global warming potential as a paper note of the same denomination. This information can be used to determine the level of confidence in claims of environmental superiority of one substrate over the other.

For example, for the £5 denomination the lifetime of the paper note is two years. Hence, if the break-even lifetime is short (say, 2.5 years) then, we can be relatively confident that the polymer bank note will outperform the paper note as this is only 25% greater than the lifetime of the paper bank note (and according to the Bank of England, experience of using of polymer bank notes in other

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[4] However, as noted earlier, most other countries using polymer bank notes report lifetimes in excess of 2.5 times that of paper bank notes (sometimes as high as four times longer).

countries suggests that much greater lifetimes would be expected for the polymer note). However, if the break-even lifetime is long (say, 10 years) then the polymer bank note would be required to last five times longer than the paper bank note to achieve an equivalent environmental performance. In this case we may conclude that the paper note is more likely to have the better environmental performance.

2.12.2 Representativeness of the Cotton Dataset

As discussed in Section 2.11.1 the data for cotton production is sourced from secondary data supplied by Cotton Inc. These data are based on an average for cotton production from the US, China and India. The impacts of crop production can vary widely from region to region and are affected by factors such as climate, soil type, requirement for irrigation, use of fertilisers, pesticides, etc. In addition to uncertainty relating to cultivation practices there will also be variation in the values of the various co-products of cotton production. This will lead to uncertainty in the economic allocation applied to these co-products.

Because of this variation, the average Cotton Inc. data may not be representative of the actual source of the cotton comber and cotton linter used in UK paper bank notes. To investigate the sensitivity of the results of this assessment to variation in the impact of cotton, two scenarios have been modelled as follows:

- The first scenario assumes that the impacts of cotton production are 50% lower than those specified in the Cotton Inc. dataset.

- The second scenario assumed that the impacts of cotton production are 50% greater than the Cotton Inc. dataset.

2.12.3 End of Life Option for Paper Bank Notes

As discussed in Section 2.11.5 there is substantial uncertainty regarding emissions during the composting of paper bank notes. The influence on the results of increased carbon dioxide emissions is considered in this sensitivity analysis.

2.12.4 End of Life Option for Polymer Bank Notes

Polymer bank notes are not currently in use in the UK and so the treatment options available at end of life are based on reasonable scenarios developed following discussion with Veolia, the waste management company responsible for disposal of unfit bank notes. The baseline assumption used in the main report is that unfit polymer bank notes will be incinerated with energy recovery. However, a sensitivity analysis will be undertaken to assess the impact on the results of recycling the waste bank notes as an alternative disposal option.

The recycling of polymer bank notes is based on a secondary dataset modelling mechanical recycling of polymers. This accounts for sorting, washing, granulating and extrusion of bank notes to produce a secondary granulate. It is assumed that this secondary granulate is of sufficient quality to offset production of an equal quantity of primary granulate, resulting in a credit to the product system.

In practice, the presence of security features such foil patches may mean that the actual recycling efficiency will be reduced, or that the resulting recycling is not of sufficient quality to allow for 1:1

replacement of primary granulate. However, this sensitivity analysis will demonstrate the maximum possible benefit that might be achieved compared to the baseline assumption.

2.12.5 ATM Energy Consumption

ATMs come in a wide range of variants that can differ significantly in terms of their energy consumption and cash carrying capacity. Furthermore, the location of an ATM will determine how often it is used, and hence the stand-by energy demand that is allocated to each note.

As such, although the default ATM use scenario is considered to be representative of average ATM performance there is clearly a large degree of uncertainty in these figures. This sensitivity analysis assesses the influence on the results of a change in ATM electricity demand of ±20%.

2.13 SCENARIO ANALYSES

As well as this Final Study Report, an additional deliverable from the project is the provision of a software tool allowing the Bank of England to assess a wide range of “what if...?” scenarios.

This tool will be developed using GaBi Envision to convert the GaBi LCA model created for this project into a parameterised “interactive report”. This will allow the user to adjust key model parameters and have the results of these choices presented in charts and tables in a customised reporting format. The tool will be set up to allow the user to adjust the following parameters:

- Location of polymer substrate production – if the UK adopts polymer bank notes an option for consideration will be to produce the polymer substrate in the UK;
- Bank note size;
- Option to apply varnish coating to extend lifetime of paper bank notes;
- Use of lower carbon intensity electricity grid mix;
- Use of environmentally-friendly sourced cotton; and
- Varying quantity of notes in circulation.

Reporting the results of these assessments is outside the scope of this Final Study Report but the GaBi Envision tool provides standardised reports detailing the results of these scenario comparisons.

2.14 SOFTWARE AND DATABASE

The LCA model has been created using the GaBi 6 Software system for life cycle engineering, developed by PE INTERNATIONAL AG. The GaBi 2012 LCI database provides the life cycle inventory data for many of the raw and process materials required in the background system.

2.15 CRITICAL REVIEW

As this study is intended to provide comparative assertions that may be made available to the public ISO 14040/44 requires that it undergo a critical review. This critical review has been conducted by a panel of three experts:

- Professor Adisa Azapagic (Panel Chair) – LCA Expert
- Michael Sturges – LCA Expert with particular focus on paper making
- Erik Balodis – Bank of Canada

Short biographies of these reviewers are provided in Appendix G.

The panel gave feedback on the Goal and Scope Definition Document produced at the start of the project and also reviewed the Final Study Report provided as the main deliverable from the project. The critical review panel has not viewed or reviewed the GaBi LCA models created for this project or the parameterised “interactive report”.

3 LIFE CYCLE INVENTORY (LCI) ANALYSIS

3.1 LIFE CYCLE INVENTORY ANALYSIS RESULTS

ISO 14044 defines the Life Cycle Inventory Analysis result as the “outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment”. The complete inventory comprises hundreds of flows so in this section we only report on the two key indicators selected for assessment in this project[5]. These are primary energy demand (segregated into renewable and non-renewable energy) and water consumption.

The top level results for these indicators are given below in Table 3-1**.** These are then discussed in more detail in the subsequent sections where, for each indicator, three charts are presented as follows:

- the first chart shows the top-level results presented for each denomination and substrate as scaled to the functional unit;

- the second chart shows the detailed contribution to the total from each process step. Because the impacts per functional unit tend to be much smaller for high denomination notes than lower denomination notes this chart is not scaled according to the functional unit but is presented as a percentage of the total life cycle impacts of the paper note for each denomination. This allows the detail for each denomination to be clearly presented on the same chart.

  For some indicators, certain life cycle stages may give a credit (i.e. a negative contribution to the total, reducing the overall impact). When this occurs the positive contribution from the other life cycle stages may exceed 100%. However, the sum of the positive and negative contributions will equal 100%, which represents the total impact over the full life cycle.

- The third chart shows the same information as the second chart but excludes the contribution from the ATM. The impact of the ATM will be same regardless of the choice of bank note substrate, so this chart more clearly highlights the differences in the life cycle impacts that are due specifically to the choice of paper or polymer bank notes.

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[5] The full life cycle inventory is available upon request from the study authors provided the Bank of England gives consent to release the data.

Table 3-1:: Top level results per functional unit for key inventory indicators

Indicator	Unit	£5		£10		£20		£50	
		Paper	Polymer	Paper	Polymer	Paper	Polymer	Paper	Polymer
Primary Energy Demand (non-renewable)	MJ	332	253	499	471	102	97.7	1.70	1.03
Primary Energy Demand (renewable)	MJ	52.6	13.1	40.4	26.8	7.85	5.58	0.309	4.71E-02
Water Consumption	litres	1922	70.1	754	116	133	24.1	12.7	0.247

3.2 PRIMARY ENERGY DEMAND

The use of primary energy is reported separately for renewable and non-renewable sources.

3.2.1 Non-renewable Energy

Figures 3-1 and 3-2 give the top-level results and the contribution analysis by life cycle stage for non-renewable primary energy consumption.

The non-renewable energy demand associated with £10 and £20 notes (and, to a lesser extent, £5 notes) is dominated by the electricity consumption of ATMs during the use phase. As this is the same for both substrates it largely hides any differences in the production and disposal impacts of the different types of note. This also explains why the energy demand for the £10 note is higher than that for the £5 note even though this relates to a lower mass of notes (see the reference flows in Table 2.8). The circulation velocity of £10 notes is much greater than that of £5 notes so they spend more time in ATMs and being sorted at cash centres, the impacts of which outweigh the additional production impacts of the £5 notes.

The £50 note is very rarely used in ATMs and so, for this denomination, the lower energy demand associated with the production and disposal of the polymer note can be seen more clearly.

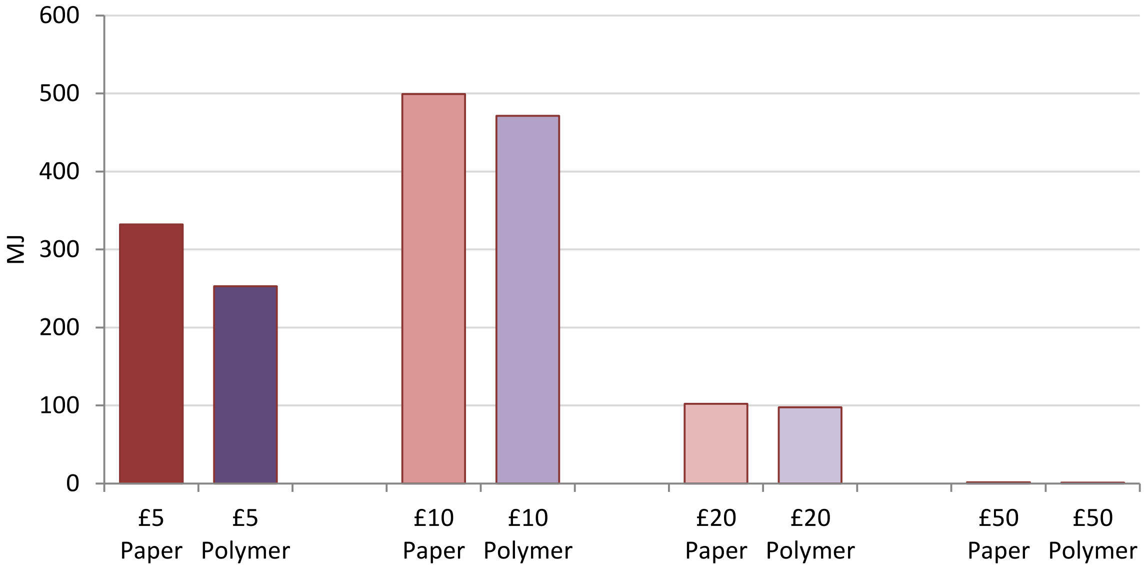

Figure 3-1: Top level results for primary energy demand (non-renewable)

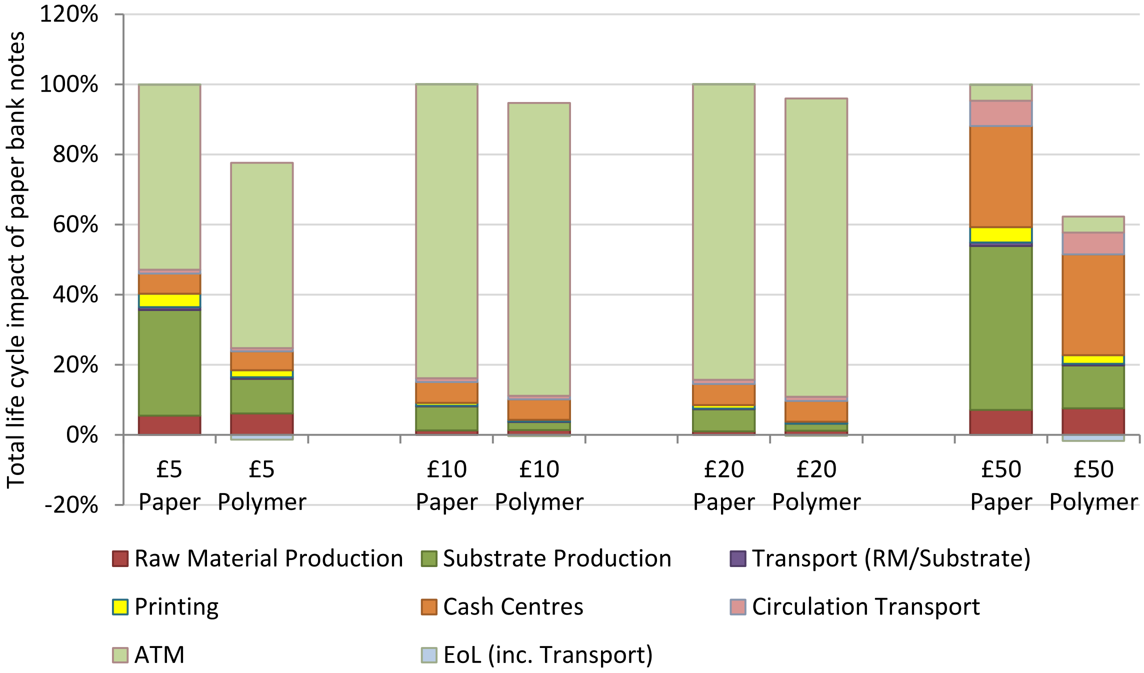

Figure 3-2: Contribution by life cycle stage to primary energy demand (non-renewable)

Considering the limits of accuracy associated with LCA studies, a rule-of-thumb that is commonly applied states that where comparative assertions differ by less than 10% they should be considered to have equivalent environmental performance. Following this rule, it would seem that the polymer substrate has the best performance for the £5 and £50 notes (where the polymer substrate has a 25% and 40% lower energy demand, respectively), but that there is no discernible difference between the substrates for the £10 and £20 denominations.

However, as noted above, the main reason that the results for paper and polymer notes are similar for £10 and £20 notes is that they are both dominated by the impact of ATMs. Furthermore, this impact is the *same* for both substrate types. Hence, although the absolute values of the impacts will be influenced by uncertainty regarding the energy consumption of ATMs, this uncertainty will not have any influence on the *difference in impact* between paper and polymer substrates. For example, if the actual ATM impacts were 10% lower than modelled, then the primary energy requirement would be correspondingly lower, but it would be reduced by the same amount for both substrates.

As such, when applying the “10% difference” rule-of-thumb, those processes, such as ATMs that have an equal impact for both substrates should be excluded. The comparison of non-renewable primary energy demand excluding the impact of ATMs is given in Table 3-3. Here it can clearly be seen that the polymer note has lower primary energy demand than the paper note for all denominations, and that this difference is greater than 10%.

Several other impact categories also show the life cycle impacts for £10 and £20 notes to be almost the same due to the high contribution from ATMs. The same principle holds true in these cases: these small differences are relevant and represent real, distinguishable differences in environmental performance. To make this clear, for every environmental metric considered in this study a chart is included to show the comparison excluding the contribution from the ATM.

An interesting aspect that is clearly seen in this chart is the low contribution from cash centres for the £5 note in comparison to other bank notes. This reflects the relatively low circulation velocity and short note life for this denomination. The £50 note has a lower circulation velocity (see Table 2-2) but has a much greater note lifetime, which compensates for this.

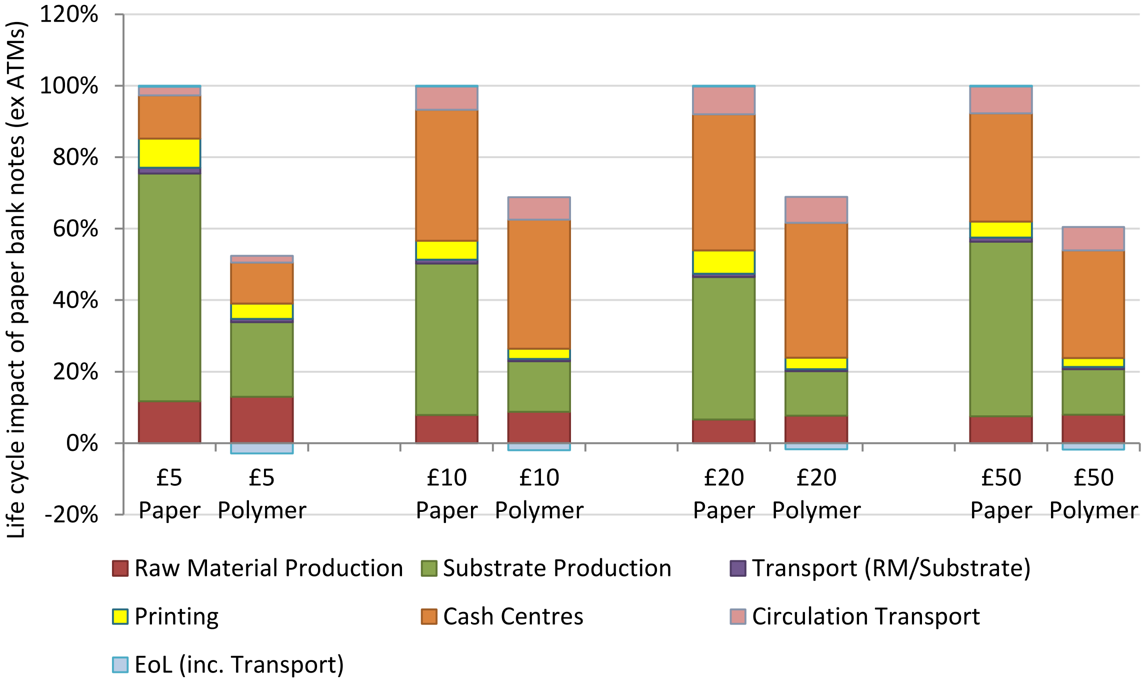

Figure 3-3: Contribution by life cycle stage to primary energy demand (non-renewable) excluding impacts from the ATM

3.2.2 Renewable Energy

Figures 3-4 and 3-5 give the top-level results and the contribution analysis by life cycle stage for renewable primary energy consumption. Over the life cycle the demand for renewable energy is much lower than that for non-renewable energy.

Polymer bank notes have an overall profile that is quite similar to that seen for non-renewable energy consumption, although with even more emphasis on impacts associated with the use of ATMs. However, for notes made from paper there are significant differences. Most noticeably there is a large contribution from raw material production, which accounts for the renewable energy embodied within the cotton fibres used to make the paper notes. In this case the impacts associated with paper production outweigh those of the use phase, so that paper £5 notes are seen to have higher renewable energy demand than paper £10 notes.

In contrast, the embodied energy in polymer bank notes comes from non-renewable sources and can be seen in Figure 3-2 where the impact associated with the polymer production is relatively high.

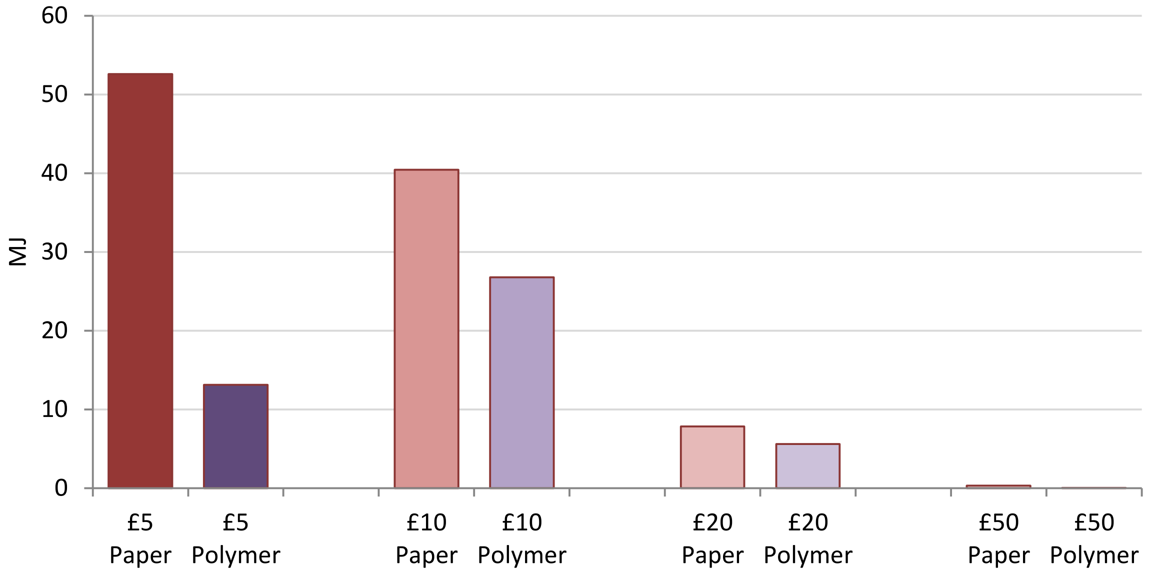

Figure 3-4: Top level results for primary energy demand (renewable)

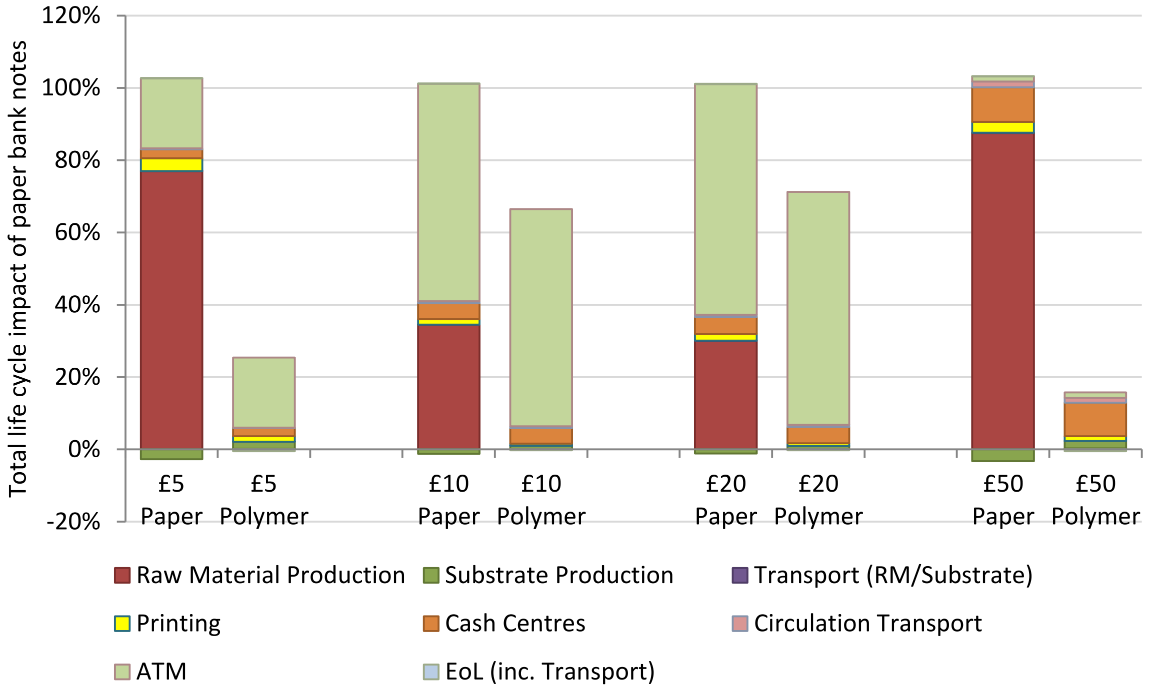

Figure 3-5: Contribution by life cycle stage to primary energy demand (renewable)

Figure 3-6 gives the contribution by life cycle stage when the impacts of the ATM are excluded. The large contribution to the renewable energy demand associated with the embodied energy of the cotton is very clear to see.

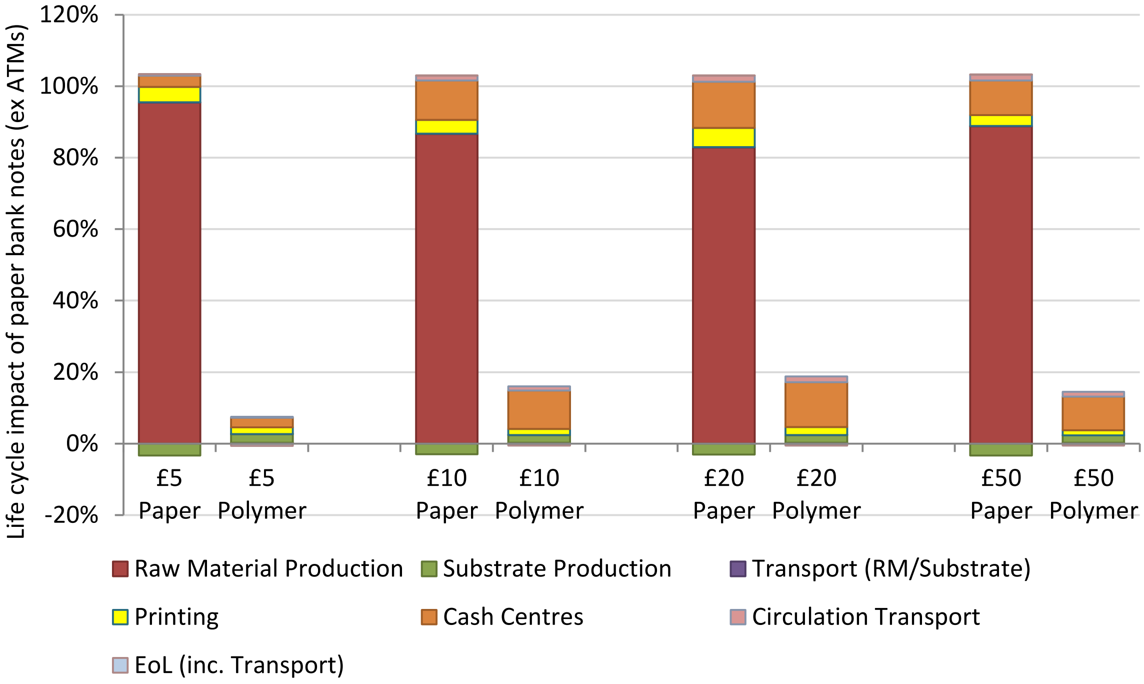

Figure 3-6: Contribution by life cycle stage to primary energy demand (renewable) excluding impacts from the ATM

3.3 WATER CONSUMPTION

Figures 3-7 and 3-8 give the top-level results and the contribution analysis by life cycle stage for water consumption. Figure 3-9 shows the contribution by life cycle stage when the impacts of the ATM are excluded.

The life cycle water consumption associated with paper notes is much greater than that for polymer notes and this is almost entirely due to the large amounts of irrigation water required for cotton production.

For polymer notes the biggest contributor to water consumption is electricity consumption associated with the use of ATMs.

Figure 3-7: Top level results for water consumption

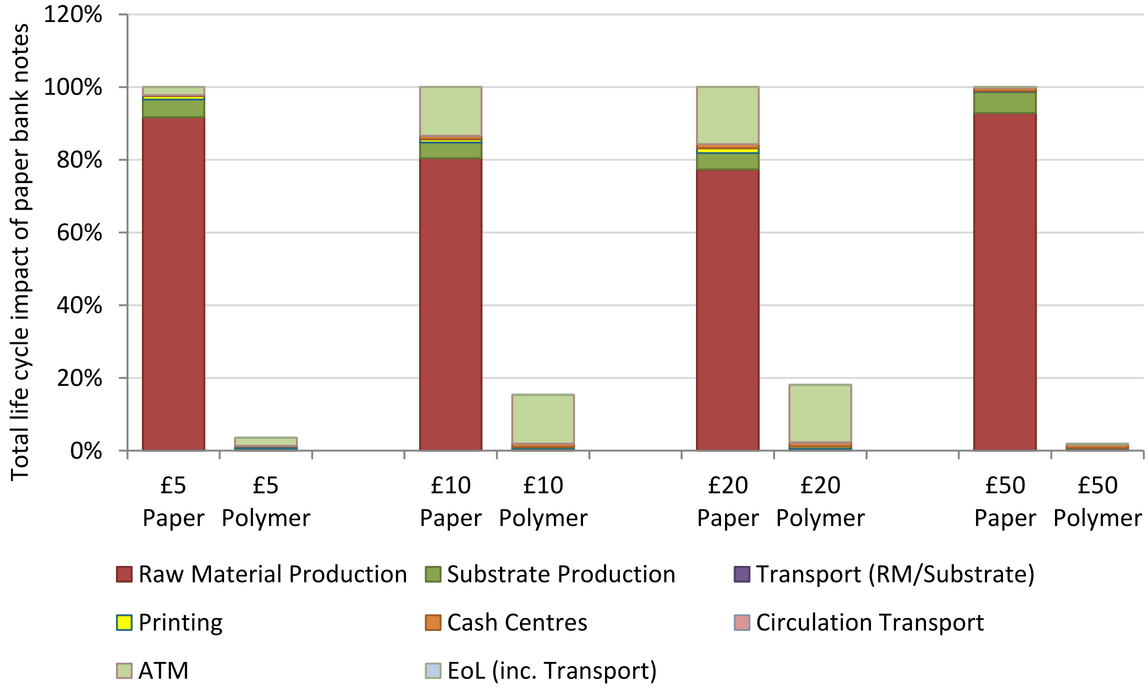

Figure 3-8: Contribution by life cycle stage to water consumption

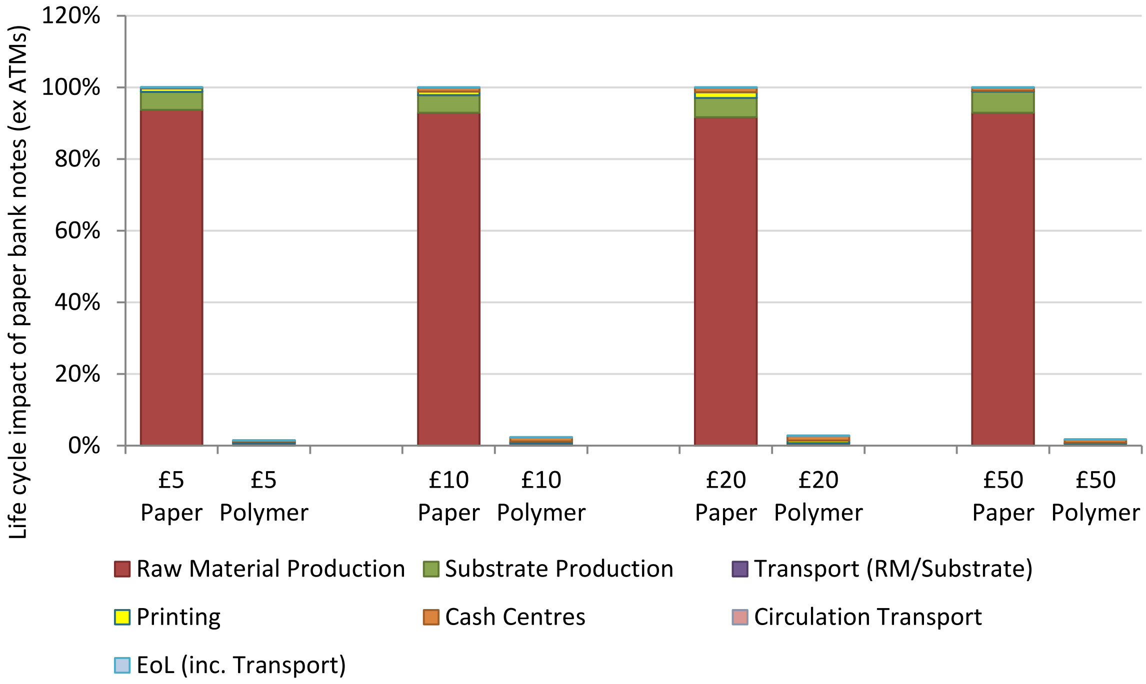

Figure 3-9: Contribution by life cycle stage to water consumption excluding impacts from the ATM

4 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

It shall be reiterated at this point that the reported impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emitted molecules would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so.

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

4.1 LIFE CYCLE IMPACT ASSESSMENT RESULTS

The top level results for the impact assessment categories considered in this study are given in Table 4-1. As for the LCI indicator results these are then discussed in more detail in the subsequent sections where, for each indicator, three charts are presented as follows:

- the first chart shows the top-level results presented for each denomination and substrate as scaled to the functional unit;
- the second chart shows the detailed contribution to the total from each process step. Because the impacts per functional unit tend to be much smaller for high denomination notes than lower denomination notes this chart is not scaled according to the functional unit but is presented as a percentage of the total impacts of the paper note for each denomination. This allows the detail for each denomination to be clearly presented on the same chart.

  For some impact categories, certain life cycle stages may give a credit (i.e. a negative contribution to the total, reducing the overall impact). When this occurs the positive contribution from the other life cycle stages may exceed 100%. However, the sum of the positive and negative contributions will equal 100%, which represents the total impact over the full life cycle.
- The third chart shows the same information as the second chart but excludes the contribution from the ATM. The impact of the ATM will be same regardless of the choice of bank note substrate, so this chart more clearly highlights the differences in the life cycle impacts that are due specifically to the choice of paper or polymer bank notes.

Table 4-1: Top level results per functional unit for impact assessment categories considered in this study

Indicator	Unit	£5		£10		£20		£50	
		Paper	Polymer	Paper	Polymer	Paper	Polymer	Paper	Polymer
Acidification Potential	kg SO_2-eq.	8.72E-02	5.80E-02	0.109	9.89E-02	2.20E-02	2.04E-02	4.70E-04	2.49E-04
Eutrophication Potential	kg PO_4^{3-} eq.	1.24E-02	5.23E-03	1.11E-02	8.63E-03	2.23E-03	1.79E-03	7.44E-05	2.37E-05
Global Warming Potential (fossil)	kg CO_2-eq.	21.6	16.4	30.5	28.7	6.23	5.94	0.114	6.99E-02
Global Warming Potential (biogenic)	kg CO_2-eq.	-1.11	3.14E-02	-0.349	3.47E-02	-6.71E-02	6.49E-03	-7.85E-03	1.40E-04
Photochemical Ozone Creation Potential	kg C_2H_4-eq.	4.22E-03	5.74E-03	5.72E-03	6.24E-03	1.15E-03	1.25E-03	1.62E-05	2.43E-05
Ecotoxicity Potential	CTUeco	29.5	6.35	22.4	14.4	4.34	3.00	0.178	2.01E-02
Human Toxicity Potential (cancer)	CTUh	1.10E-07	5.92E-08	1.41E-07	1.23E-07	2.87E-08	2.56E-08	5.91E-10	2.01E-10
Human Toxicity Potential (non-cancer)	CTUh	1.98E-05	1.51E-05	3.53E-05	3.35E-05	7.25E-06	6.99E-06	8.47E-08	4.88E-08

4.2 ACIDIFICATION POTENTIAL

Figures 4-1 and 4-2 give the top-level results and the contribution analysis by life cycle stage for acidification potential.

Acidification impacts correlate closely with those of non-renewable primary energy demand. This is because the key acidifying emissions, nitrogen oxides (NO_x) and sulphur dioxide (SO_2) gases are predominantly produced as a result of fossil fuel combustion.

Hence, as for non-renewable primary energy demand, the largest contributor to acidification for £5, £10 and £20 note denominations is the consumption of electricity by ATMs during the use phase. For the £50 note the major contributions are from sorting at cash centres during the use phase, and from production of raw materials and substrates.

For every denomination, the polymer bank notes have lower acidification impacts than the paper bank notes because of the lower burdens associated with raw material and substrate production. As noted for primary energy demand (non-renewable), the small differences between paper and polymer bank notes seen for the £10 and £20 notes are significant when the impact of ATMs is excluded (this is the same regardless of choice of substrate).

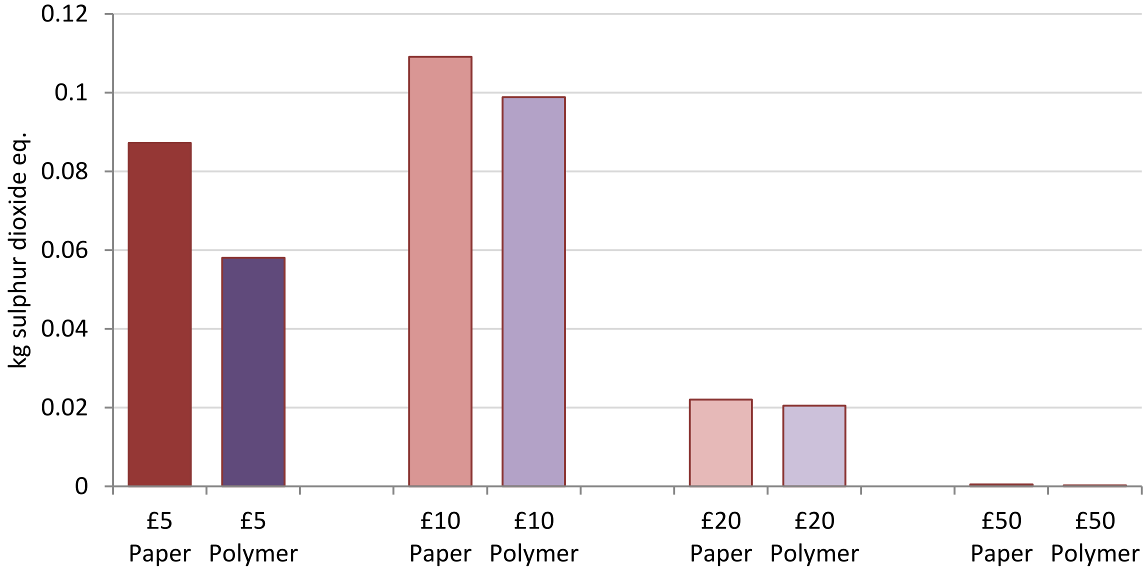

Figure 4-1: Top level results for acidification potential

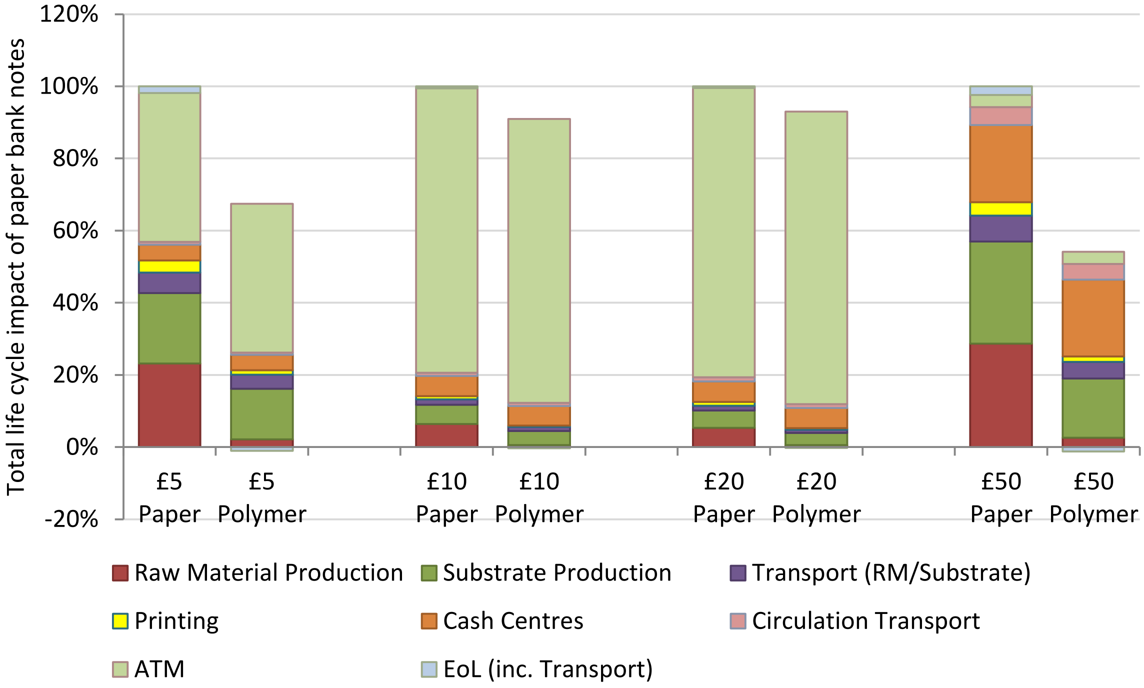

Figure 4-2: Contribution by life cycle stage to acidification potential

Figure 4-3 shows the contribution by life cycle stage when the impacts of the ATM are excluded.

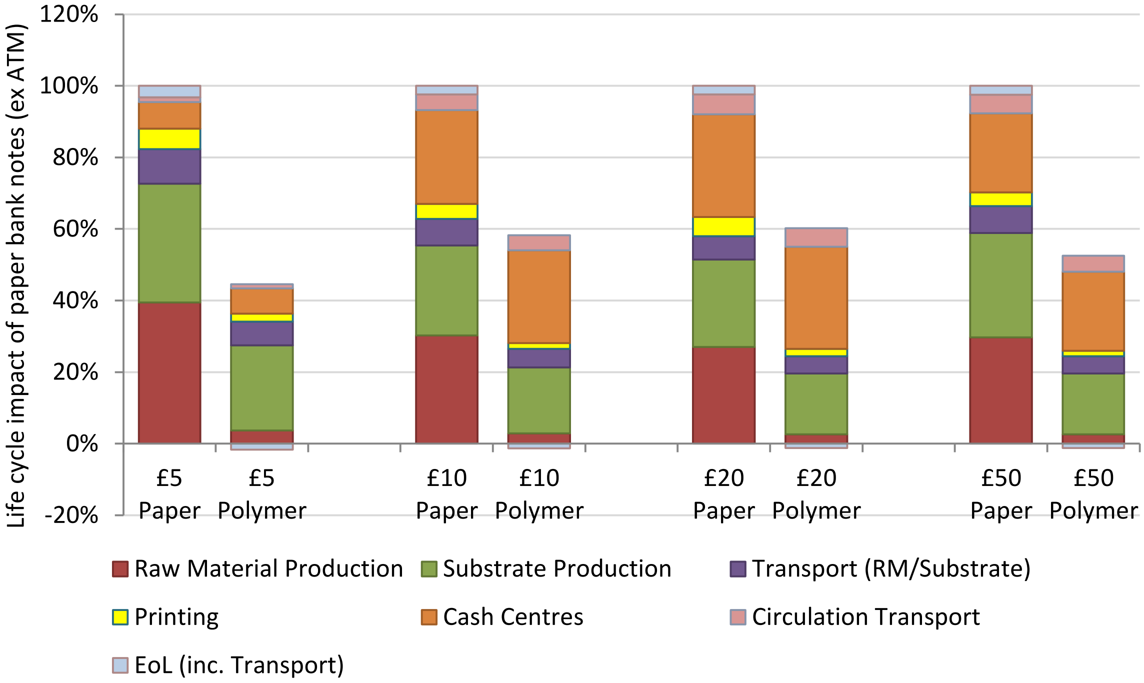

Figure 4-3: Contribution by life cycle stage to acidification potential excluding impacts from the ATM

4.3 EUTROPHICATION POTENTIAL

Figures 4-4 and 4-5 give the top-level results and the contribution analysis by life cycle stage for eutrophication potential.

The dominant emissions contributing to eutrophication are nitrogen oxides, mainly produced as a result of fossil fuel combustion. Hence, the overall profile of eutrophication impacts is quite similar to that for non-renewable primary energy demand, with electricity use by the ATM being dominant for £5, £10 and £20 notes.

For paper notes, emissions of ammonia and nitrous oxide gases also make a noticeable contribution to the total and are associated with the use of fertilisers during crop production and emissions from composting.

For the £50 note the major contributions are from production of raw materials and substrates and from electricity use associated with sorting at cash centres during the use phase.

For every denomination, the polymer bank notes have lower eutrophication impacts than the paper bank notes because of the lower burdens associated with raw material and substrate production.

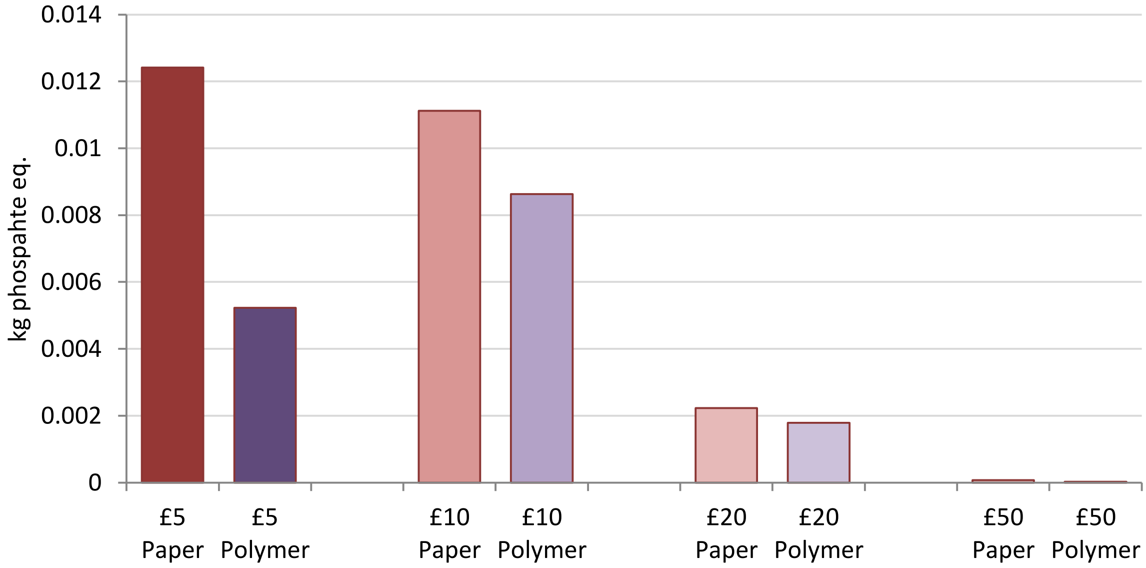

Figure 4-4: Top level results for eutrophication potential

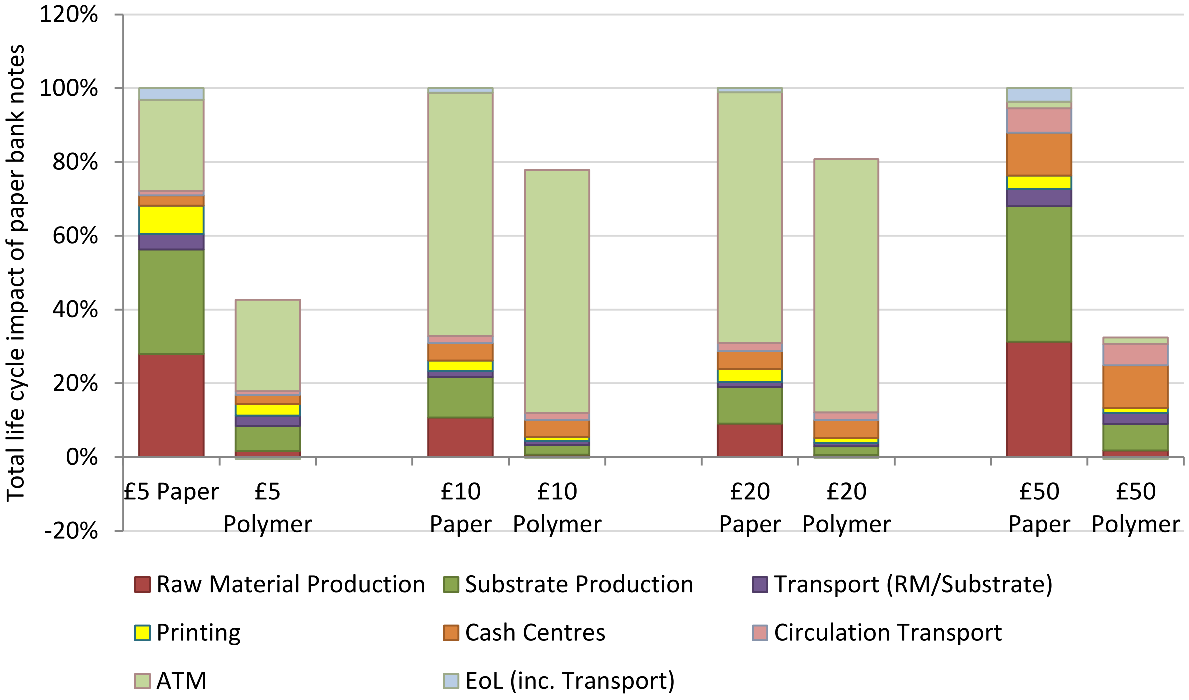

Figure 4-5: Contribution by life cycle stage to eutrophication potential

Figure 4-6 shows the contribution by life cycle stage when the impacts of the ATM are excluded.

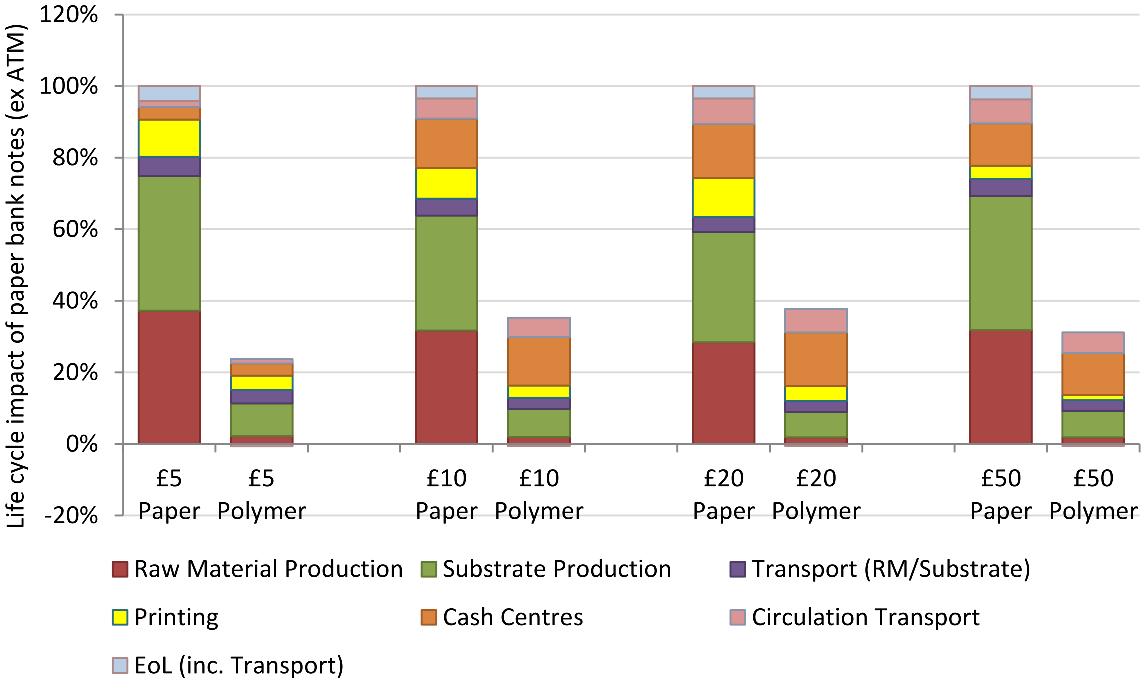

Figure 4-6: Contribution by life cycle stage to eutrophication potential excluding impacts from the ATM

4.4 ECOTOXICITY POTENTIAL

Figures 4-7 and 4-8 give the top-level results and the contribution analysis by life cycle stage for ecotoxicity potential.

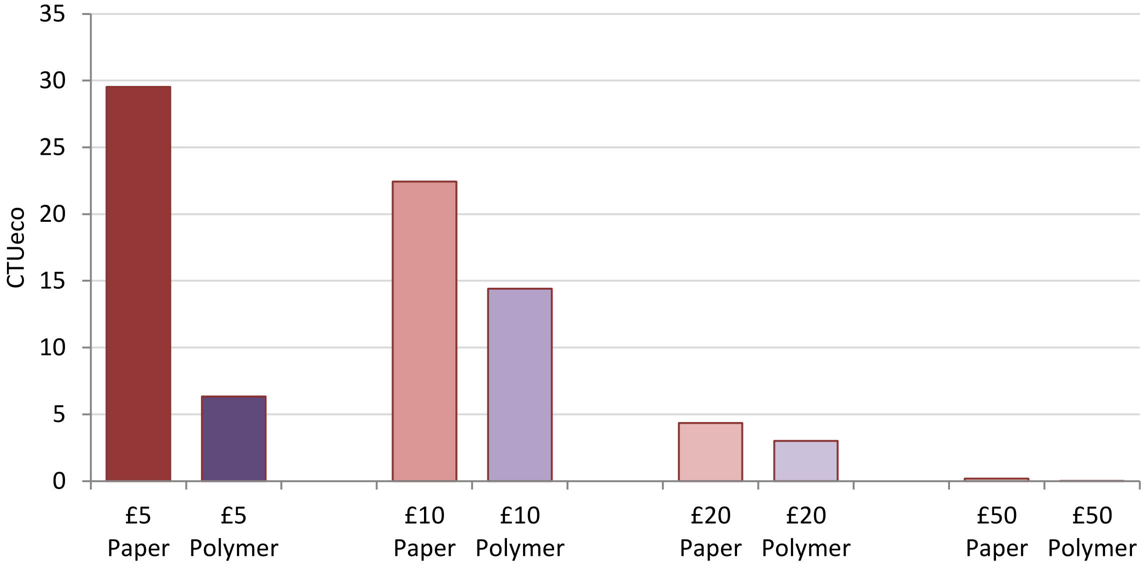

Figure 4-7: Top level results for eco-toxicity potential

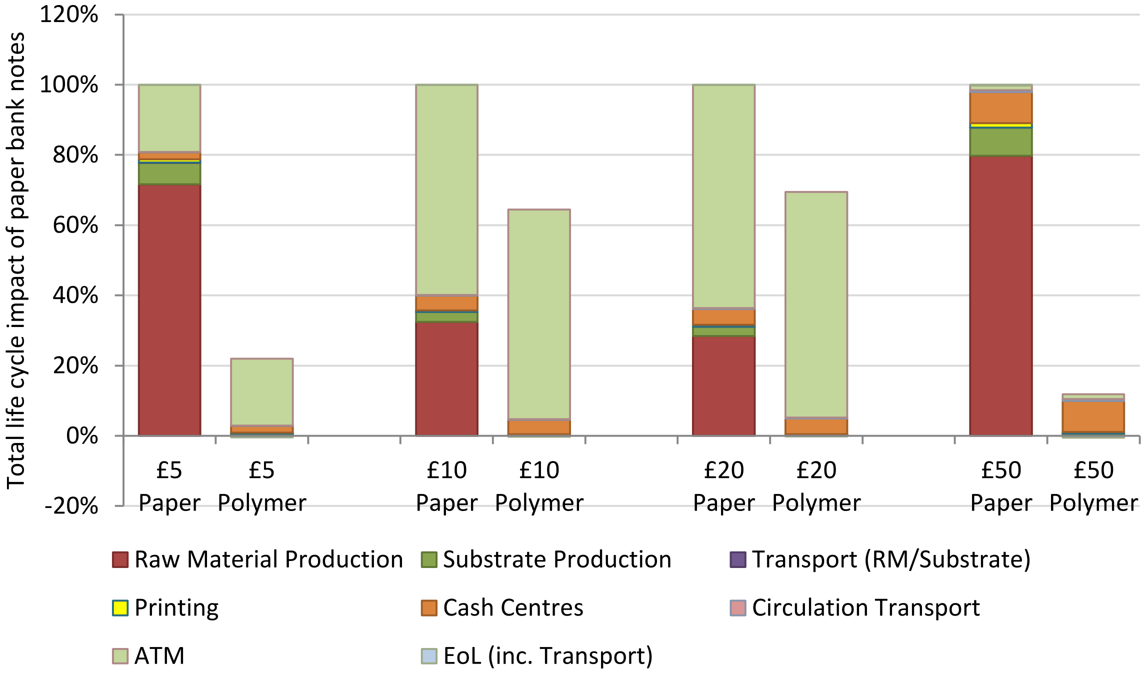

Figure 4-8: Contribution by life cycle stage to eco-toxicity potential

As discussed in Section 2.6, due to the limitations of the characterisation models for this impact category, the results can be used to identify 'substances of high concern' but should not be used to make comparative assertions.

Ecotoxicity impacts are driven by two main groups of emissions:

- heavy metals associated with combustion of fossil fuels and production of electricity; and
- pesticides associated with cotton production (this is only a factor for paper bank notes).

Figure 4-9 shows the contribution by life cycle stage when the impacts of the ATM are excluded. This reinforces the point that the main difference between the paper and polymer substrates is due to impacts associated with cotton production.

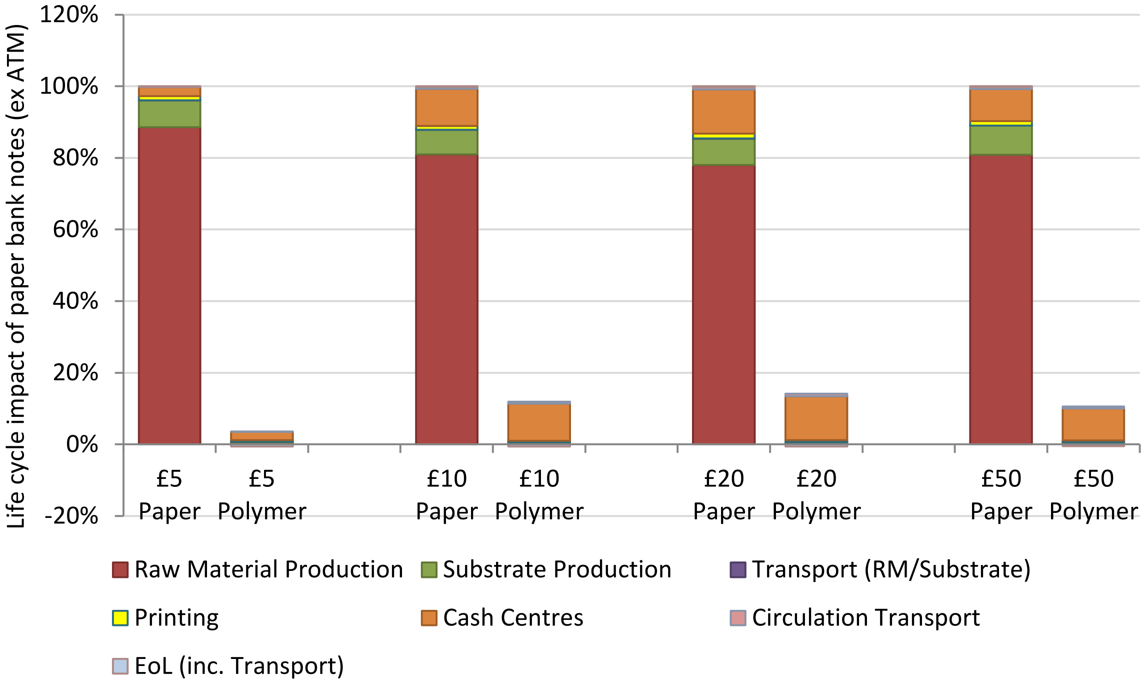

Figure 4-9: Contribution by life cycle stage to eco-toxicity potential excluding impacts from the ATM

4.5 GLOBAL WARMING POTENTIAL

The overall results for global warming potential (both fossil and biogenic) are shown in Figures 4-10 and 4-11.

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

As has been seen for other impact categories, the high impact associated with the use of ATMs means that for £10 and £20 notes the differences between the paper and polymer substrates are very small. However, as noted for non-renewable primary energy demand, the small differences between paper and polymer bank notes seen for the £10 and £20 notes are significant when the impact of ATMs is excluded (this is the same regardless of the choice of substrate).

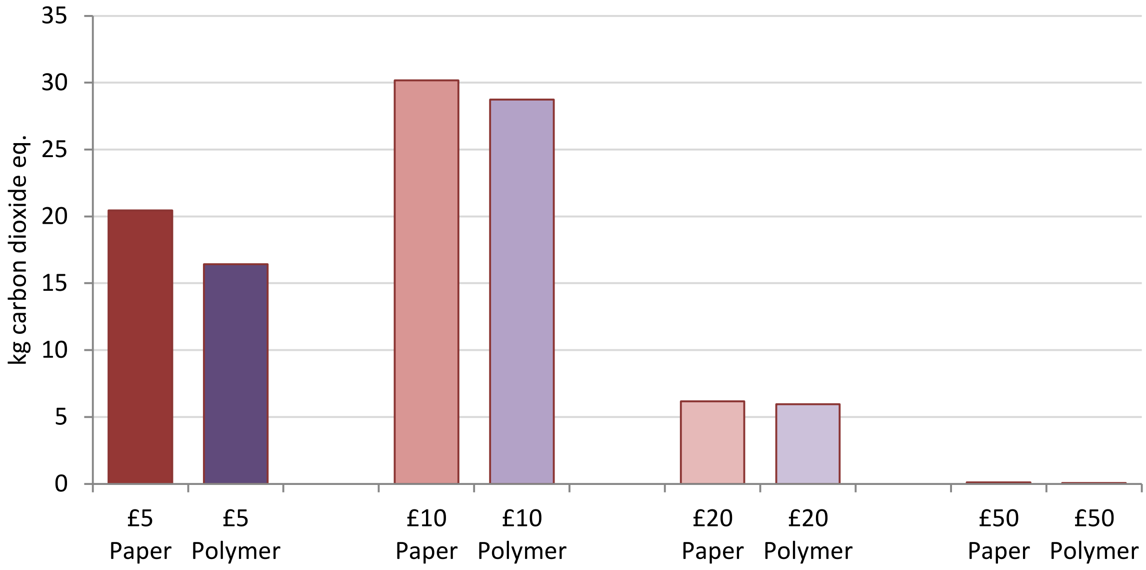

Figure 4-10: Top level results for global warming potential (fossil and biogenic)

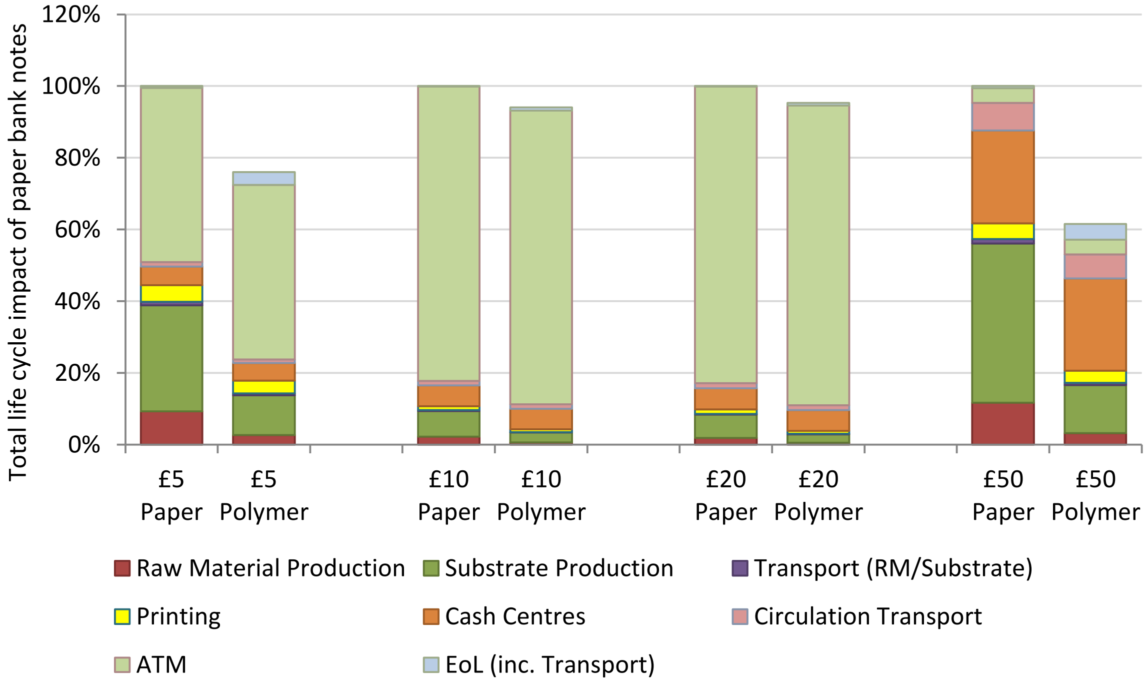

Figure 4-11: Contribution by life cycle stage to global warming potential (fossil and biogenic)

Figure 4-12 shows the contribution by life cycle stage when the impacts of the ATM are excluded.

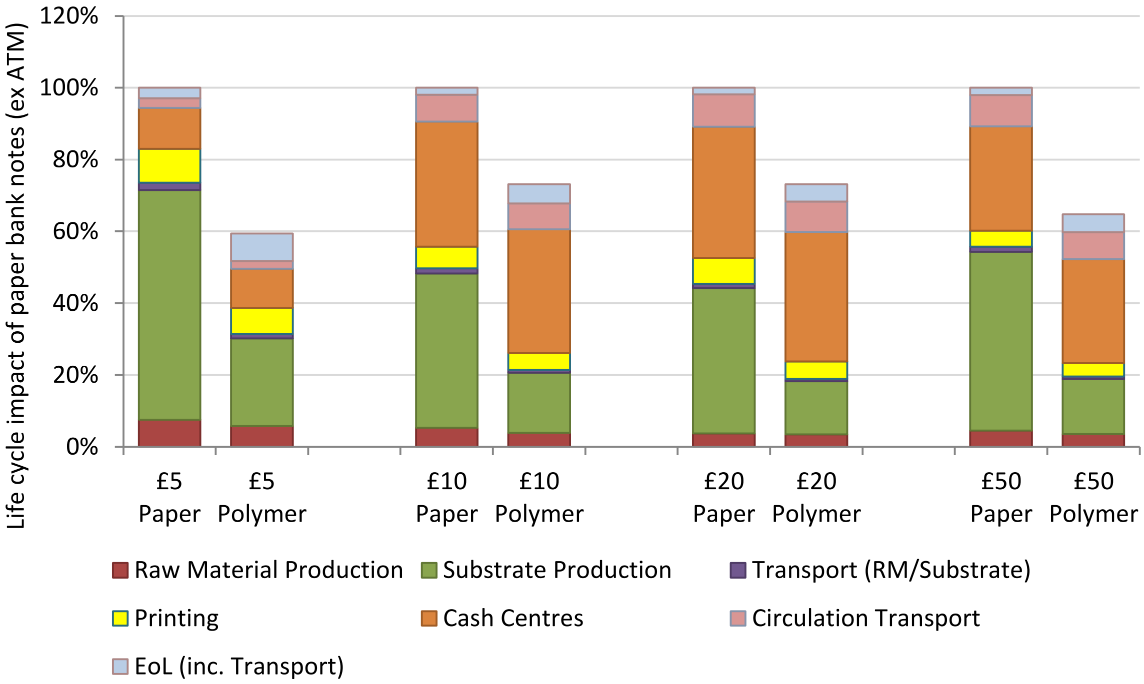

Figure 4-12: Contribution by life cycle stage to global warming potential (fossil and biogenic) excluding impacts from the ATM

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

4.5.1 Fossil GHG Emissions

Figures 4-13 and 4-14 give the top-level results and the contribution analysis by life cycle stage for global warming potential from fossil sources.

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 £5, £10 and £20 notes the biggest emissions are accounted for by the use of electricity in ATMs during the use phase.

For £5 and £50 notes, where the use in ATMs is lower, the differences in production and end of life treatment options can be seen more clearly. The polymer note shows lower GHG emissions than the paper note primarily because of lower energy use in substrate production.

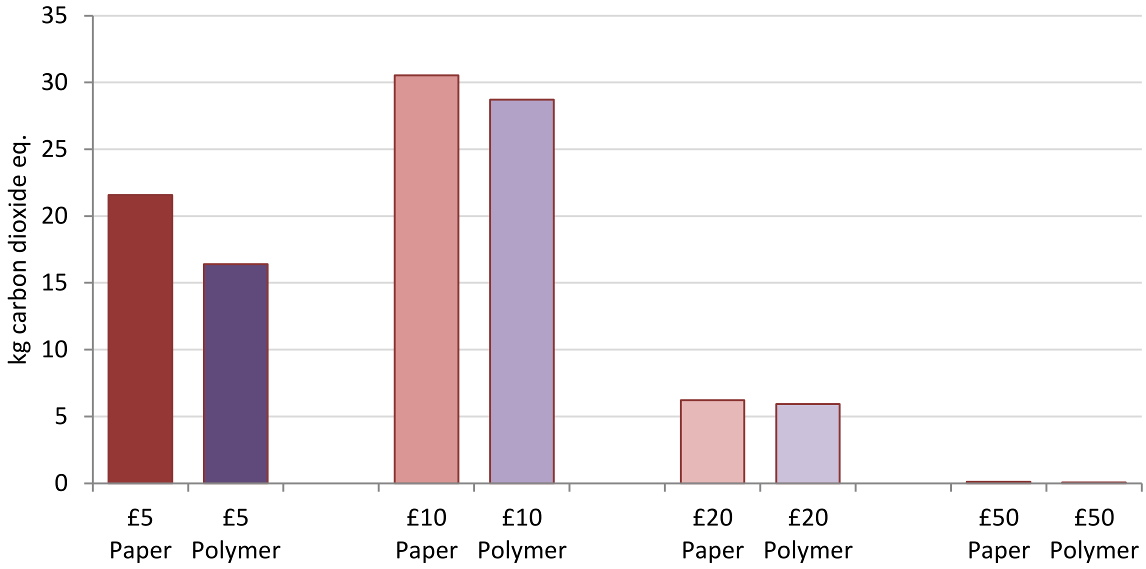

Figure 4-13: Top level results for global warming potential (fossil)

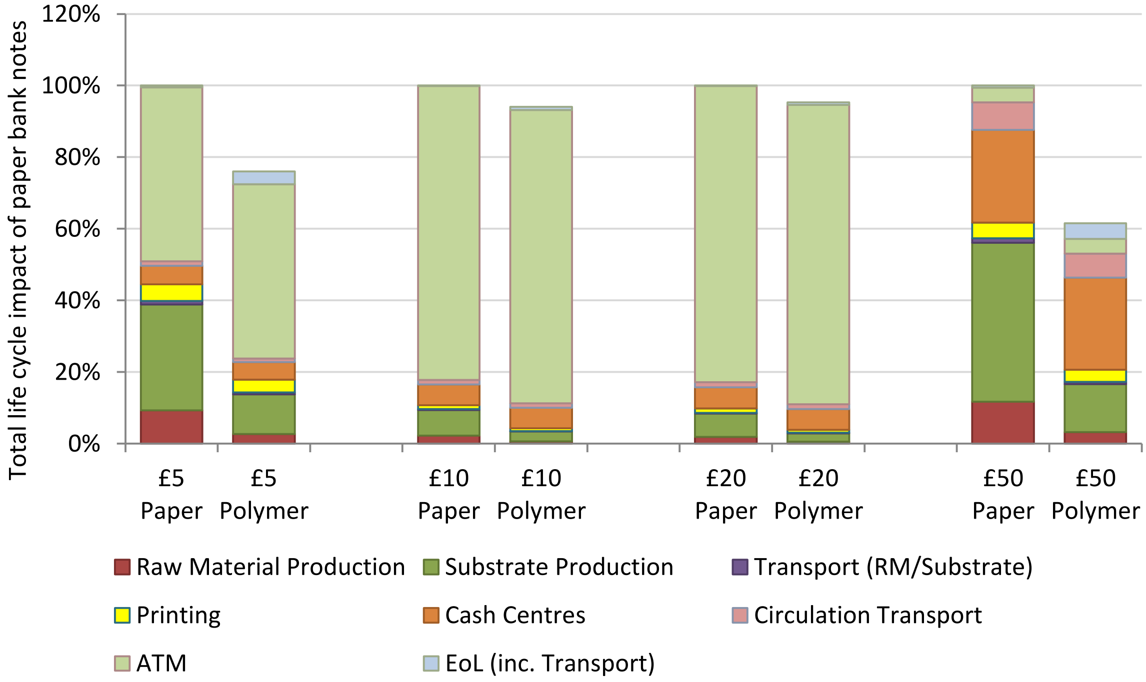

Figure 4-14: Contribution by life cycle stage to global warming potential (fossil)

Figure 4-15 shows the contribution by life cycle stage when the impacts of the ATM are excluded.

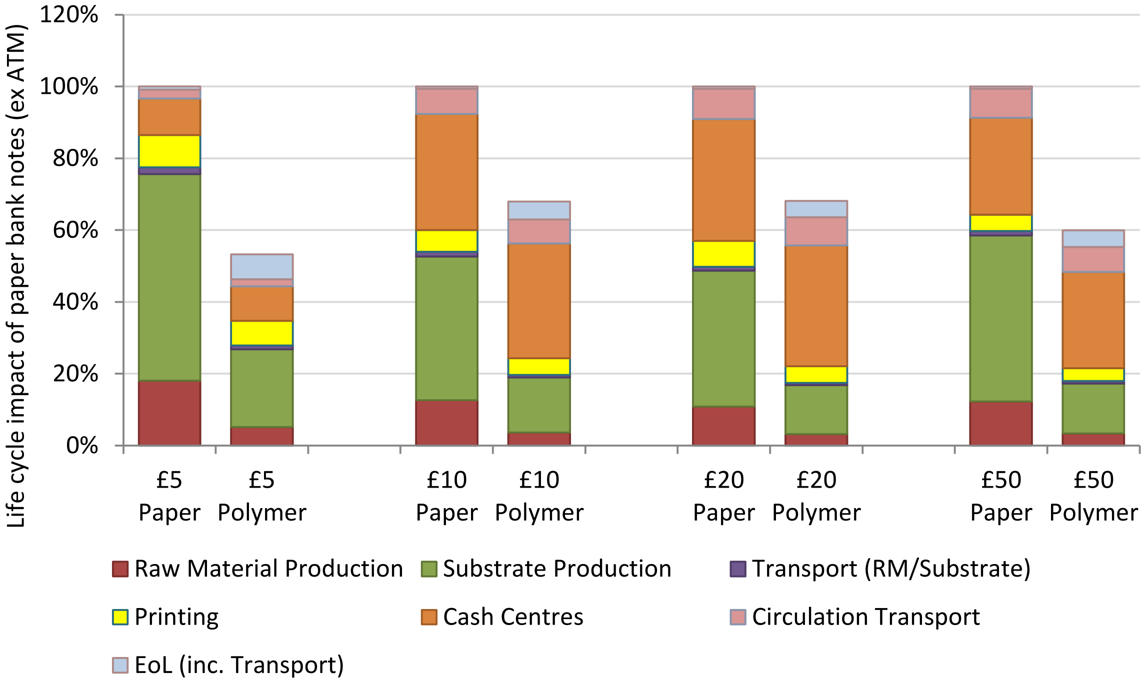

Figure 4-15: Contribution by life cycle stage to global warming potential (fossil) excluding impacts from the ATM

4.5.2 Biogenic GHG Emissions

Figures 4-16 and 4-17 give the top-level results and the contribution analysis by life cycle stage for global warming potential from biogenic sources. It is immediately obvious that this profile is very different to that of the fossil emissions.

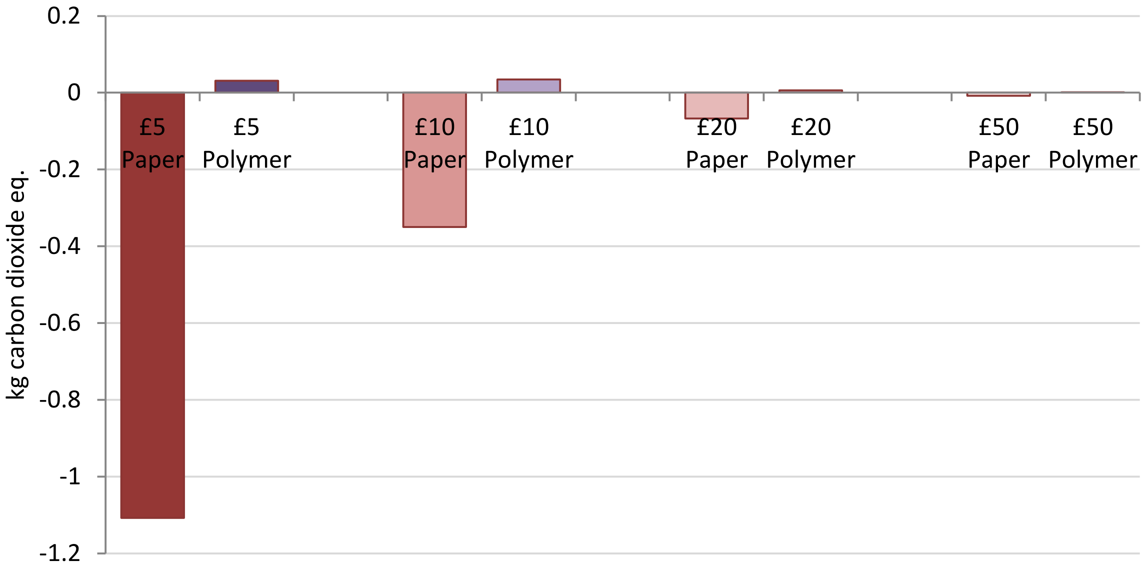

Figure 4-16: Top level results for global warming potential (biogenic)

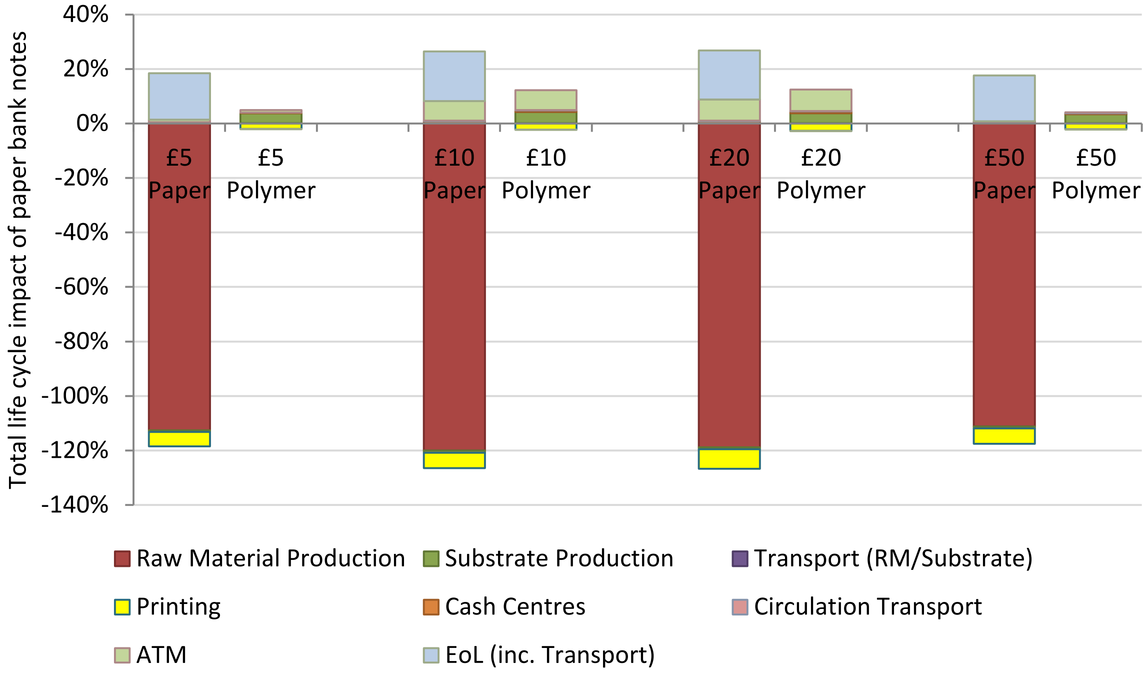

Figure 4-17: Contribution by life cycle stage to global warming potential (biogenic)

The most obvious change is the large beneficial impact seen for the paper bank note. This arises because more carbon dioxide is being removed from the atmosphere during biomass production than is returned to it from composting at end of life, resulting in a net reduction in biogenic GHG emissions over the life cycle. The small beneficial impact seen from printing is due to the use of biomass-derived ingredients in the inks.

However, compared to GHG emissions from fossil sources the influence of emissions from biogenic sources is very small.

Figure 4-15 shows the contribution by life cycle stage when the impacts of the ATM are excluded. As ATMs are not major consumers of renewable energy this is very similar to the profile seen in Figure 4-17 for the full life cycle.

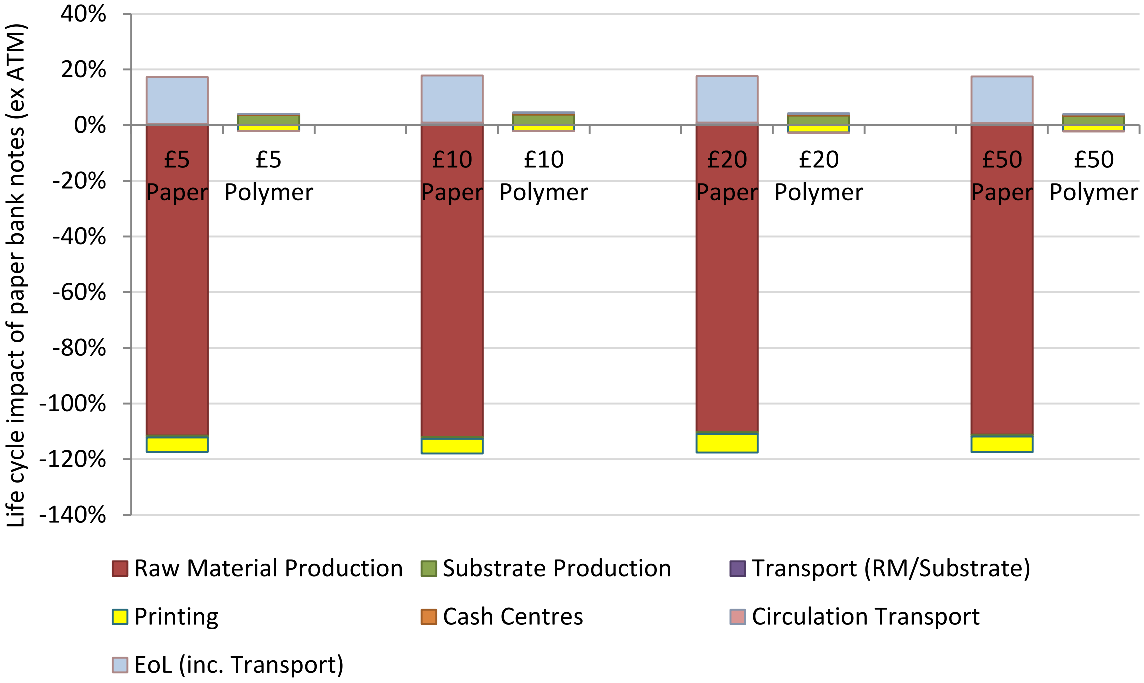

Figure 4-18: Contribution by life cycle stage to global warming potential (biogenic) excluding impacts from the ATM

4.6 HUMAN TOXICITY POTENTIAL (CANCER)

Figures 4-19 and 4-20 give the top-level results and the contribution analysis by life cycle stage for human toxicity potential (cancer). As discussed in Section 2.6, due to the limitations of the characterisation models for this impact category the results can be used to identify 'substances of high concern' but should not be used to make comparative assertions.

Human toxicity (cancer) impacts are dominated by emissions of heavy metals to air, soil and water, which are mainly associated with electricity production. Mercury is a particularly important contributor to this impact category and accounts for the majority of the impact. Chromium emissions to water are also significant. These emissions are mainly associated with electricity production, a waste water treatment and hazardous waste incineration in the paper production process. It should be noted that these waste water treatment and hazardous waste processes are modelled based on generic background data, and so may not accurately reflect emissions associated with paper production, particularly for this impact category which is sensitive to relatively small emissions of heavy metals.

As seen for other impact categories, use phase electricity demand accounts for most of the impacts for £5, £10 and £20 notes. For paper £50 notes the impacts associated with substrate production also make a large contribution to the total.

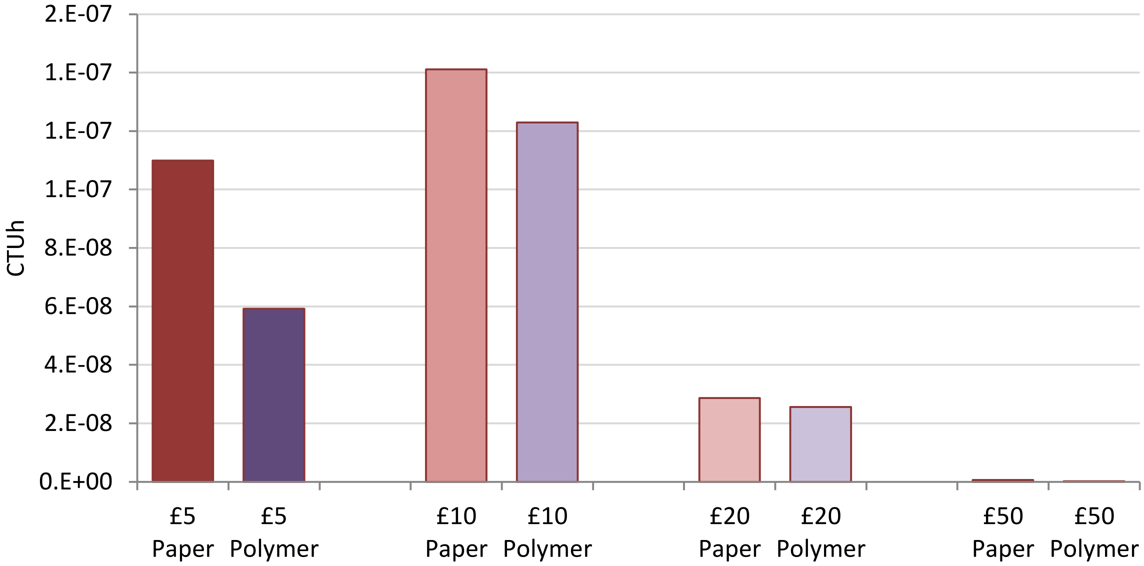

Figure 4-19: Top level results for human toxicity potential (cancer)

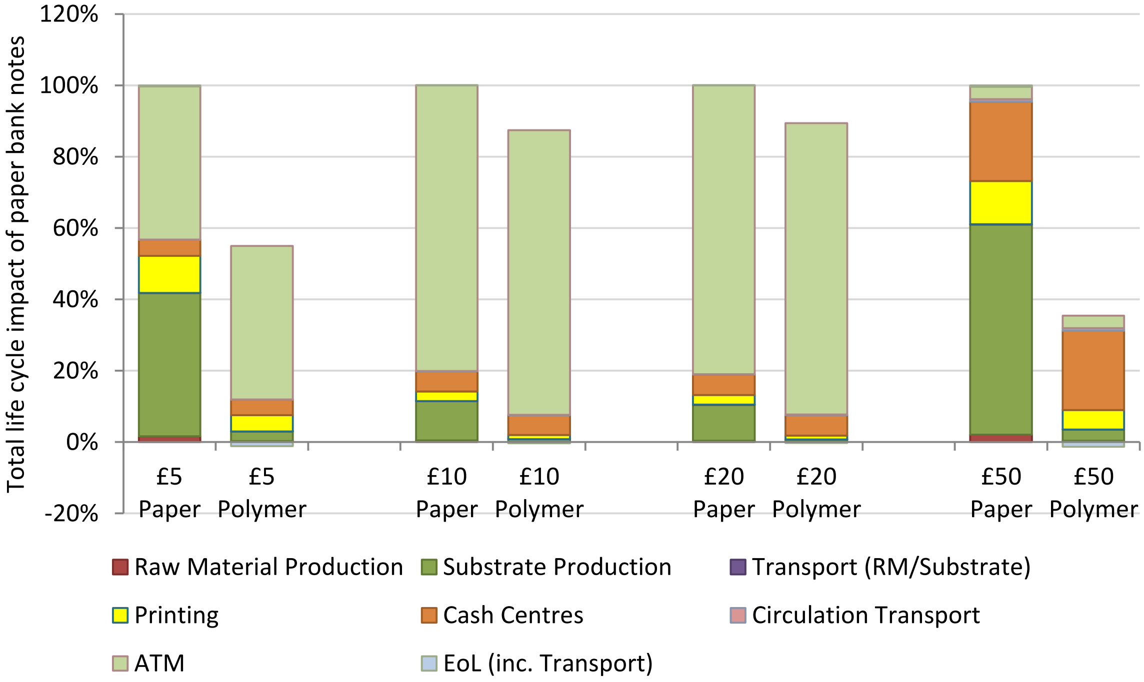

Figure 4-20: Contribution by life cycle stage to human toxicity potential (cancer)

Figure 4-21 shows the contribution by life cycle stage when the impacts of the ATM are excluded.

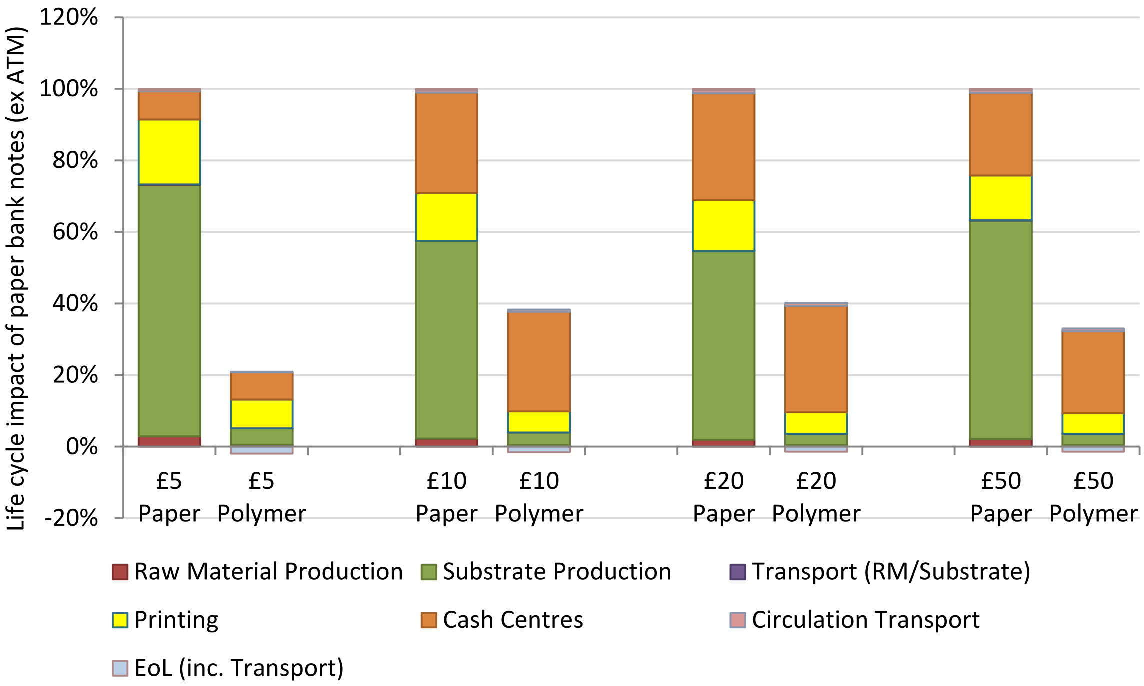

Figure 4-21: Contribution by life cycle stage to human toxicity potential (cancer) excluding impacts from the ATM

4.7 HUMAN TOXICITY POTENTIAL (NON-CANCER)

Figures 4-22 and 4-23 give the top-level results and the contribution analysis by life cycle stage for human toxicity potential (non-cancer).

As discussed in Section 2.6, due to the limitations of the characterisation models for this impact category the results can be used to identify ‘substances of high concern’ but should not be used to make comparative assertions.

Human toxicity (non-cancer) impacts are dominated by emissions of heavy metals to soil, which are mainly associated with electricity production. Zinc and mercury emissions are particularly important contributors to this impact category.

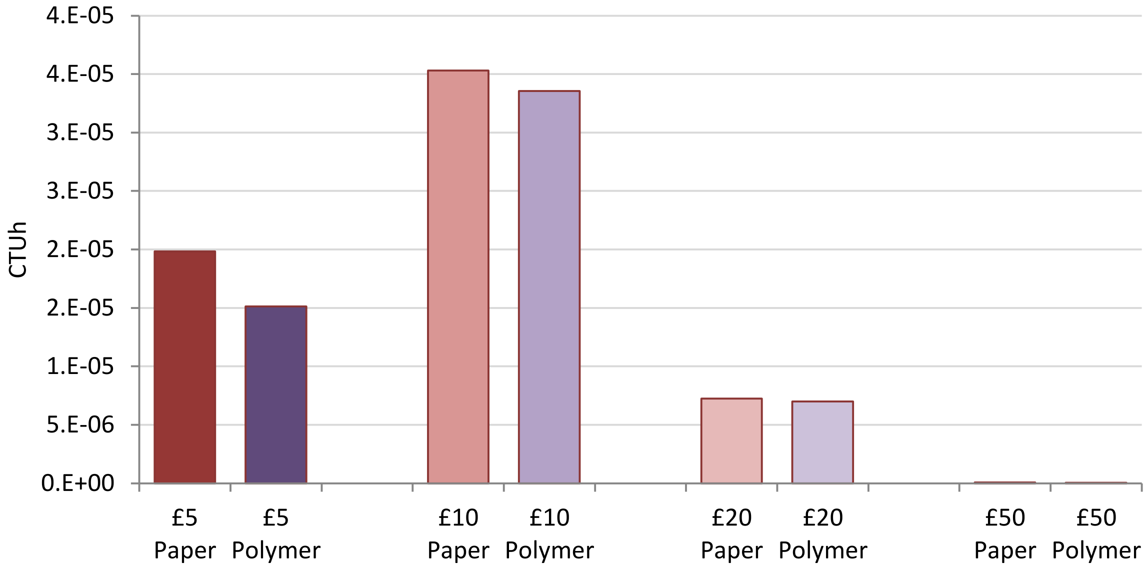

Figure 4-22: Top level results for human toxicity potential (non-cancer)

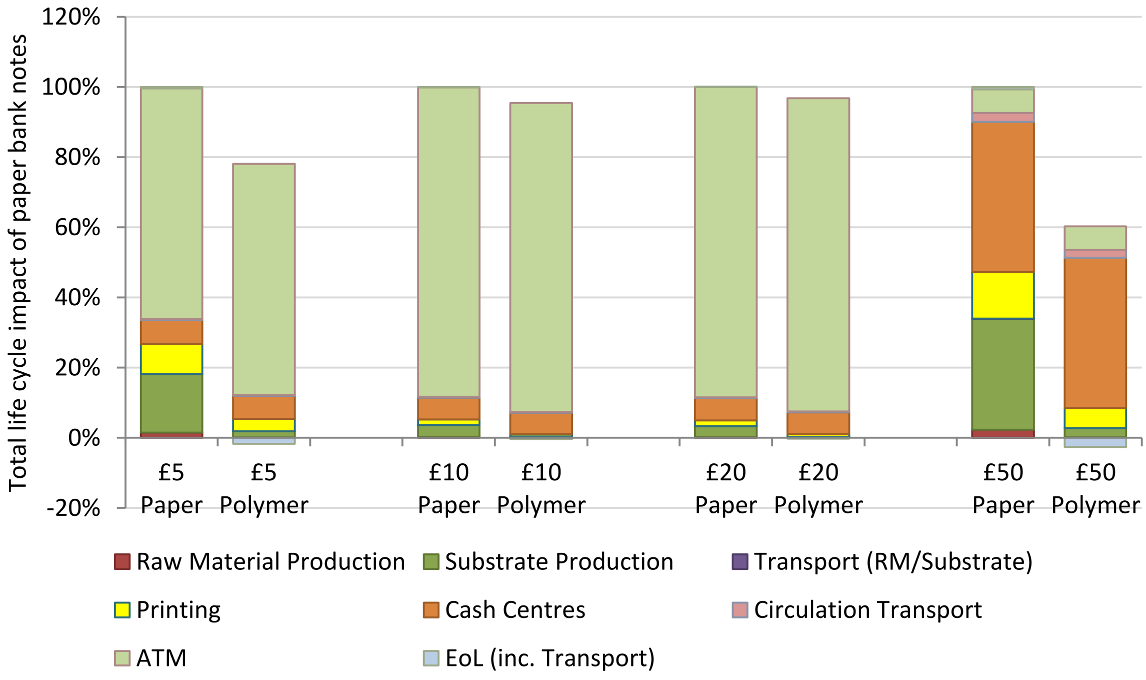

Figure 4-23: Contribution by life cycle stage to human toxicity potential (non-cancer)

Figure 4-24 shows the contribution by life cycle stage when the impacts of the ATM are excluded.

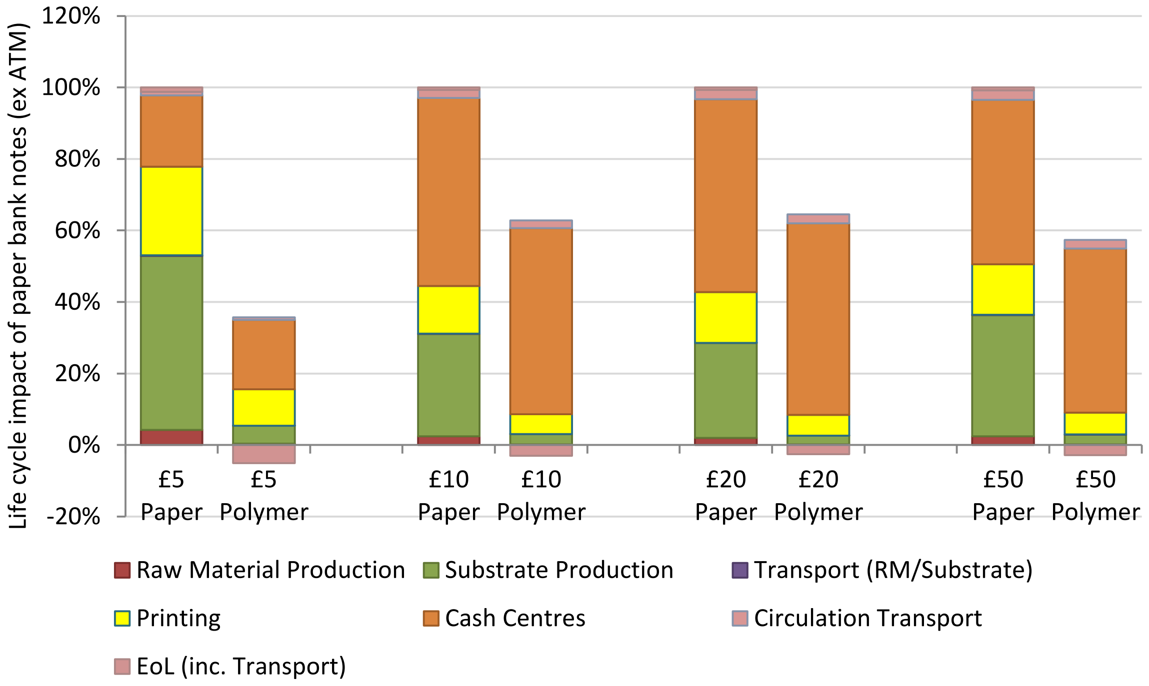

Figure 4-24: Contribution by life cycle stage to human toxicity potential (non-cancer) excluding impacts from the ATM

4.8 PHOTOCHEMICAL OZONE CREATION POTENTIAL

Figures 4-25 and 4-26 give the top-level results and the contribution analysis by life cycle stage for photochemical ozone creation potential.

This impact category shows rather different results to those of other impacts considered in this assessment. For all bank note denominations the polymer notes have higher impacts than the paper notes. This difference is primarily due to VOC emissions associated with the use of solvents in the production of the polymer substrate. However, as for other impact categories, the use phase electricity demand associated with ATMs is the single biggest contributor to the total impact for £5, £10 and £20 bank notes.

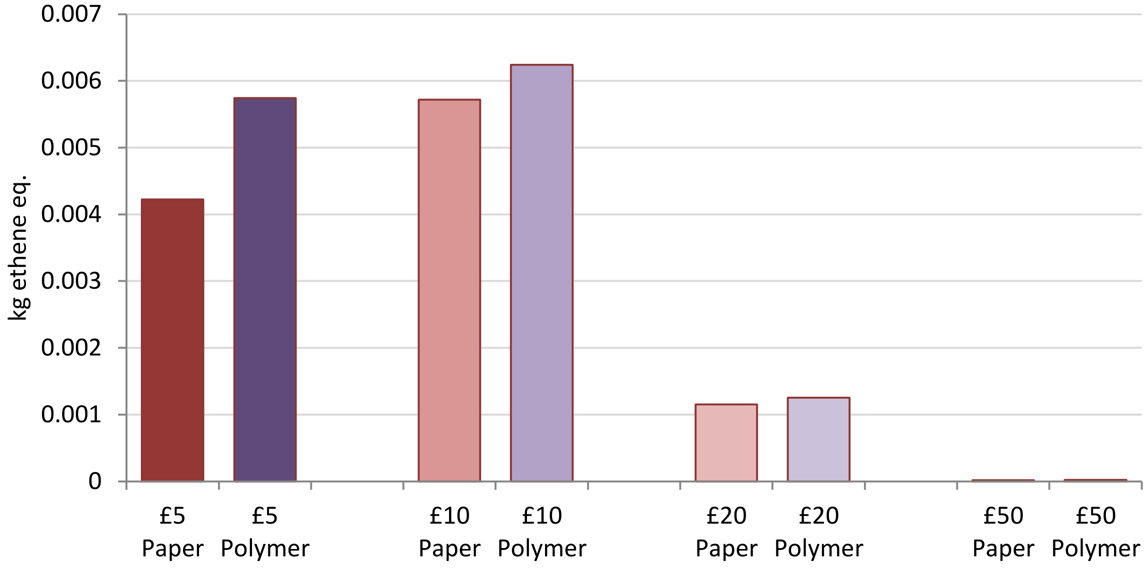

Figure 4-25: Top level results for photochemical ozone creation potential

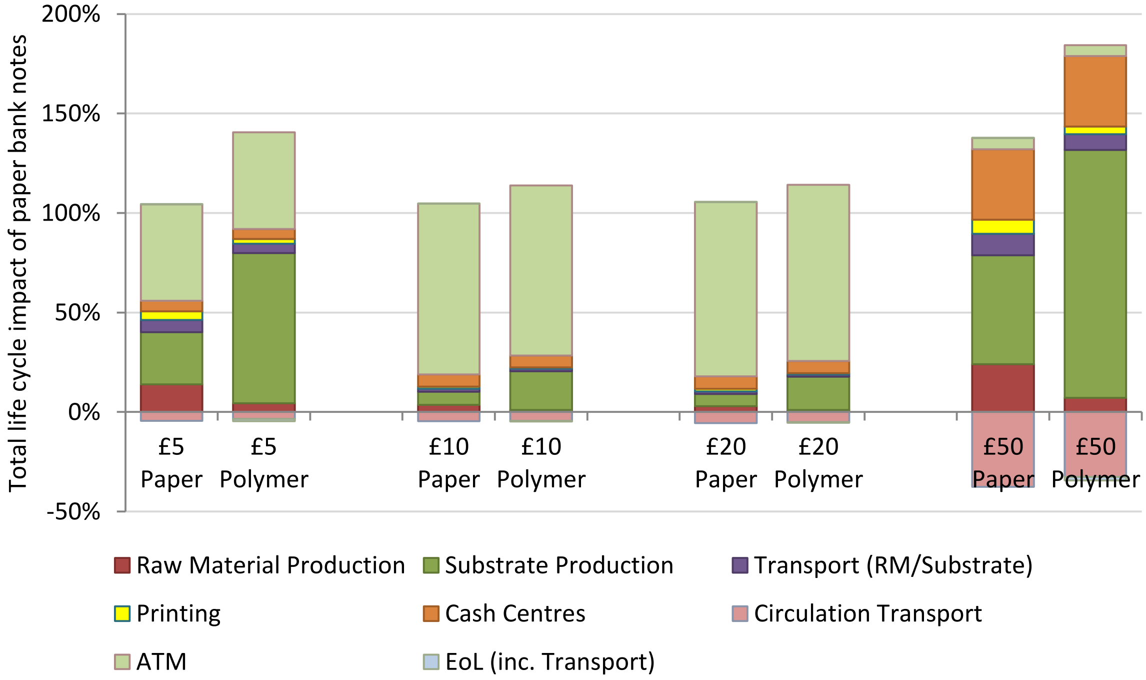

Figure 4-26: Contribution by life cycle stage to photochemical ozone creation potential

Figure 4-27 shows the contribution by life cycle stage when the impacts of the ATM are excluded.

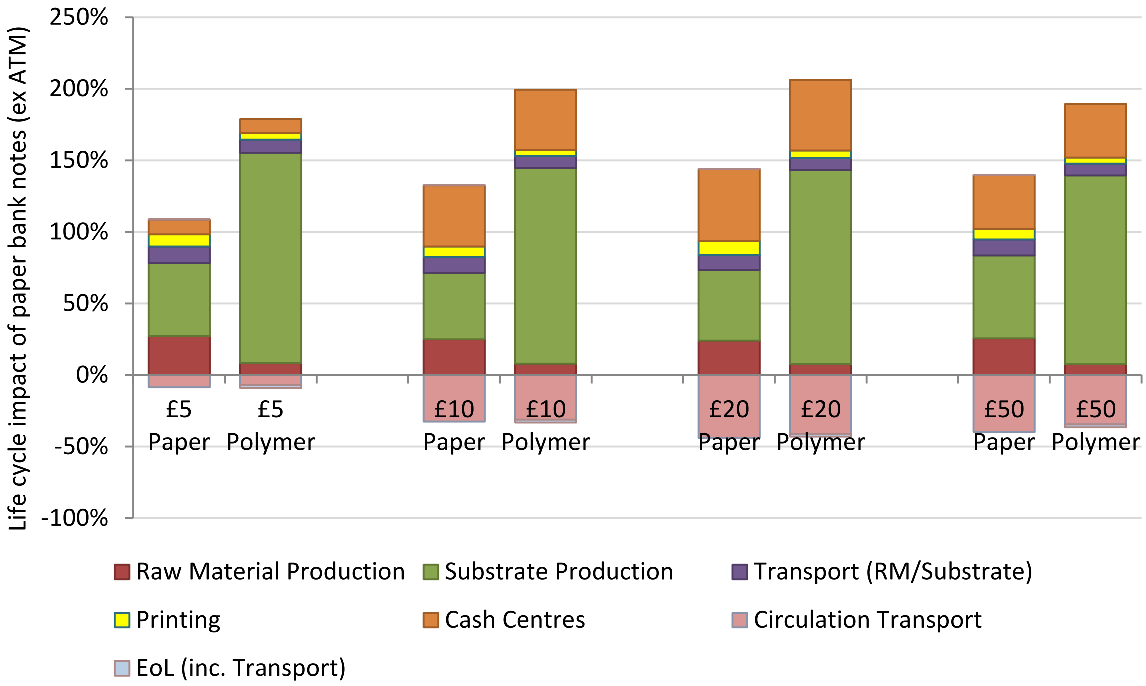

Figure 4-27: Contribution by life cycle stage to photochemical ozone creation potential excluding impacts from the ATM

The impact potential associated with circulation transport appears as "negative", meaning that these transport processes reduce the amount of ozone created by photochemical reactions (i.e. reactions driven by UV rays from sunlight). This reduction is due to the release of nitrogen monoxide from trucks used during its use stage. Nitrogen monoxide (NO) reduces the formation of photochemical ozone in the atmosphere.

The negative characterisation factor given to nitrogen monoxide in the CML methodology is a result of the background modelling assumptions used in the CML methodology (e.g. assuming 100% unbroken sunshine). Other methodologies (e.g. TRACI, ReCiPe) based on different background assumptions do not attribute this negative characterisation factor to nitrogen monoxide and hence show that increased transport results in increased smog impacts. Due to these methodological uncertainties, we recommend treating the results from this impact category with caution and we suggest that they are not used to make comparative assertions.

4.9 NORMALISED NET IMPACT ASSESSMENT RESULTS

Normalisation is a process whereby the impacts calculated for a particular product system are compared against an external reference. It is an optional step in life cycle assessment and is presented here as additional information to give a sense of which impact categories are the most significant in comparison to the external reference and to assist with ranking different products or prioritising areas for improvement.

For this study the selected external reference is *“the impacts associated with an average European citizen in one year”.* For the CML impact categories the baseline year for normalisation data is 2000, while for USETox it is 2004. It is not anticipated that this small difference will affect the results to any great extent. No normalisation data are available for primary energy demand or water consumption so these indicators are omitted from the analysis.

The normalised results are shown in Figure 4-28.

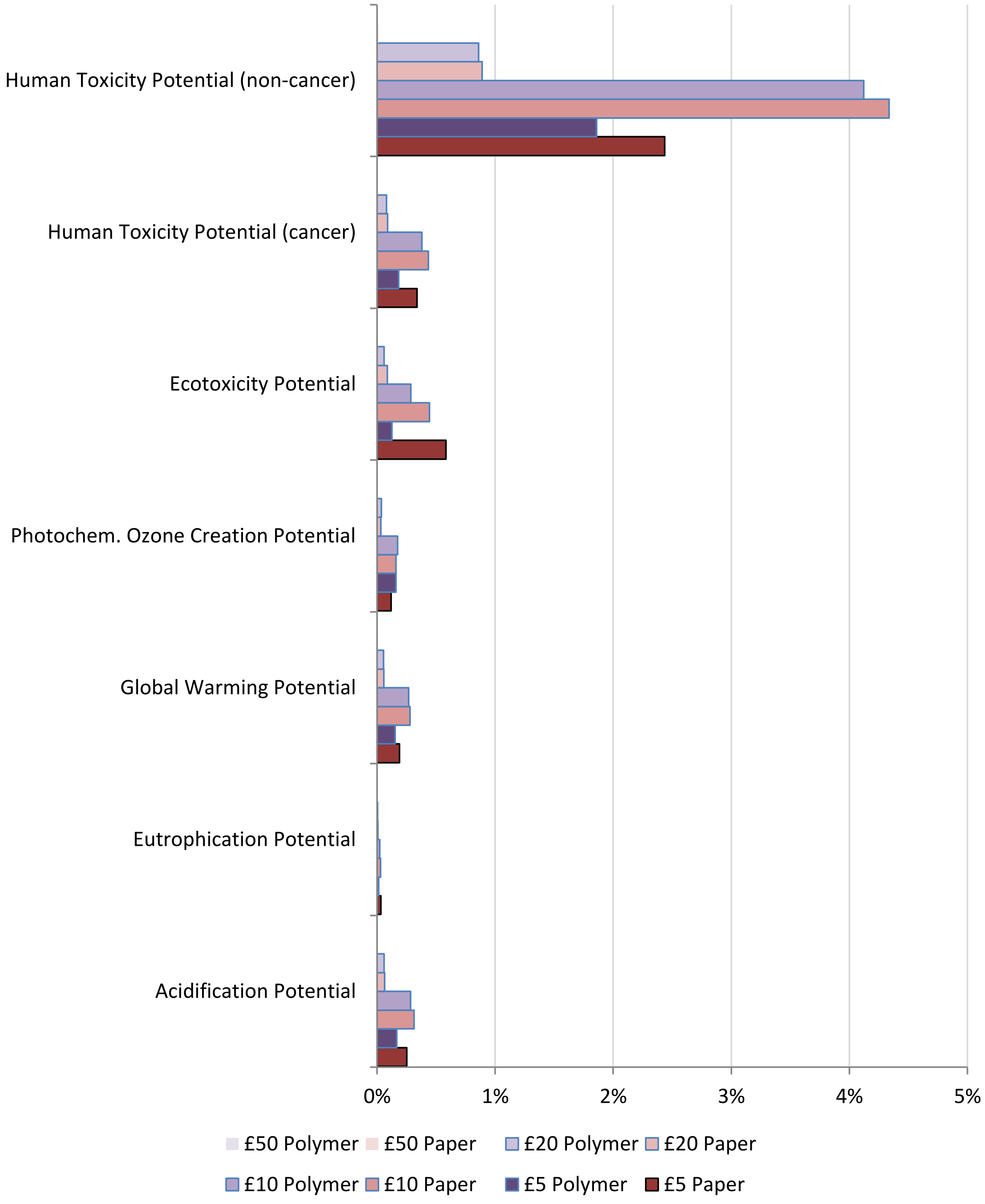

Figure 4-28: Impact category results normalised to impact of an average EU citizen in one year

These normalised results show that human toxicity potential (non-cancer) stands out as being the most significant impact category when compared to the impacts of an average European citizen[6]. The remaining impact categories all have contributions with a similar order of magnitude, with the exception of eutrophication potential, which is negligible in comparison to the others.

The majority of the impact associated with human toxicity potential (non-cancer) derives from the production of electricity to power ATMs. This reinforces the message that achieving energy efficiency savings during bank note circulation will be an effective way to tackle the most significant impacts associated with the bank note life cycle.

As noted in Section 2.6, there is greater uncertainty associated with the assessment of toxicity related impacts than for other impact categories and, although they are useful for identifying elements of concern, we do not recommend using them to make comparative assertions.

The result of this normalisation exercise confirms the overall message seen when considering the results for each impact category in isolation. On balance, the polymer bank notes have a better environmental performance than the paper bank notes[7].

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[6] This does not necessarily imply that human toxicity (cancer) is the most *important* impact category as this cannot be determined without introducing the subjective weighting of different impact categories, which has not been carried out in this study

[7] In contrast, had the normalised results for photochemical oxidation potential been seen to be much more significant than other impact categories this could have changed the interpretation entirely as paper bank notes perform better than polymer notes for this impact category.

5 SENSITIVITY ANALYSIS

This chapter provides the results of the sensitivity analyses described in Section 2.12. The results for the sensitivity analyses are presented for global warming potential only, as this is the key impact category of most concern to the Bank of England. These results are presented as the combined total for both fossil and biogenic GHG emissions.

The full results covering all impact categories are reported in Appendix D.

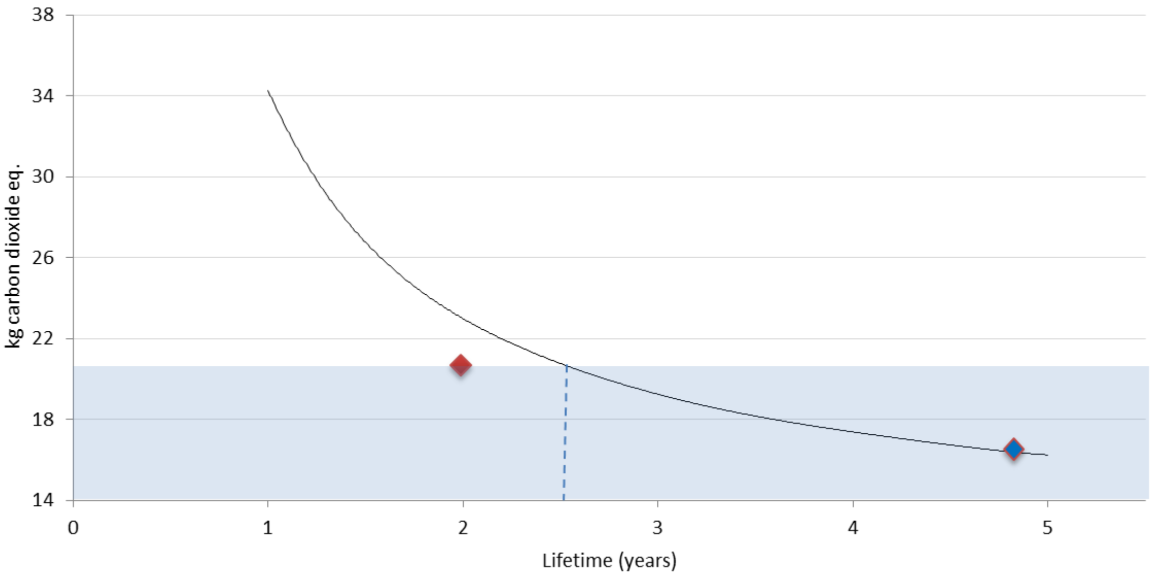
5.1 BANK NOTE LIFETIME

There is great uncertainty regarding the lifetime of polymer bank notes in the UK. In this sensitivity analysis the "break-even" lifetimes required for polymer bank notes to have equivalent impacts to a paper bank notes have been estimated.

Figures 5-1, 5-2, 5-3 and 5-4 show the effect on the global warming potential of varying the lifetime of the polymer note. These charts are created by running the LCA 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.

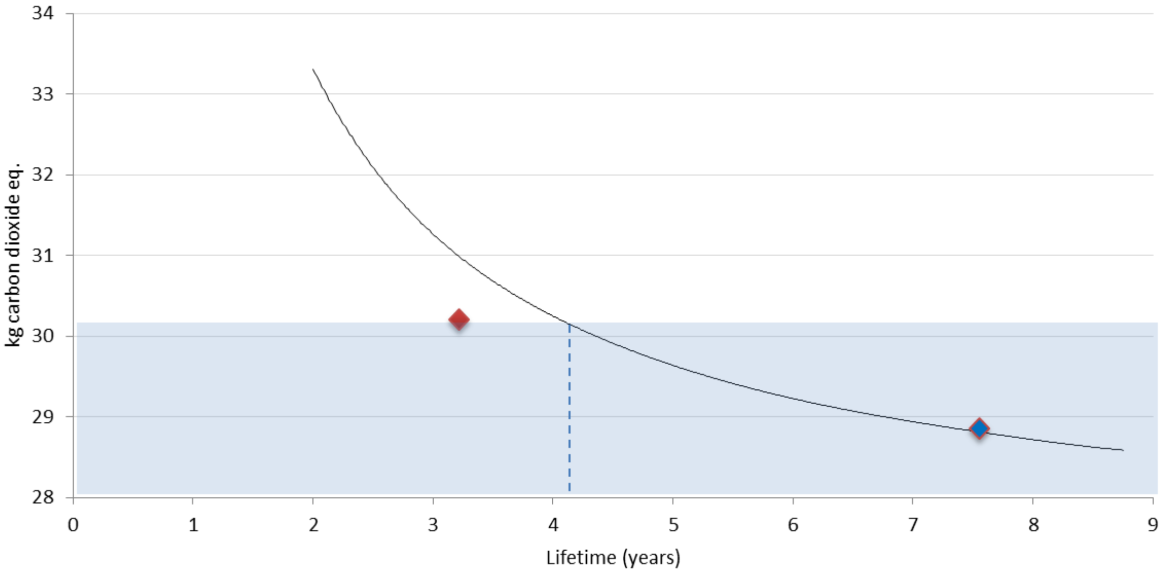
It can be seen that as the lifetime of the polymer note reduces, the global warming potential impact increases, and that as the lifetime gets shorter still, so the rate of increase in global warming potential becomes steadily greater.

The results for the paper bank note are also shown in the charts. The threshold for the polymer to outperform the paper note is shown by the blue region in the charts and the break-even lifetime is indicated by the dotted lines.



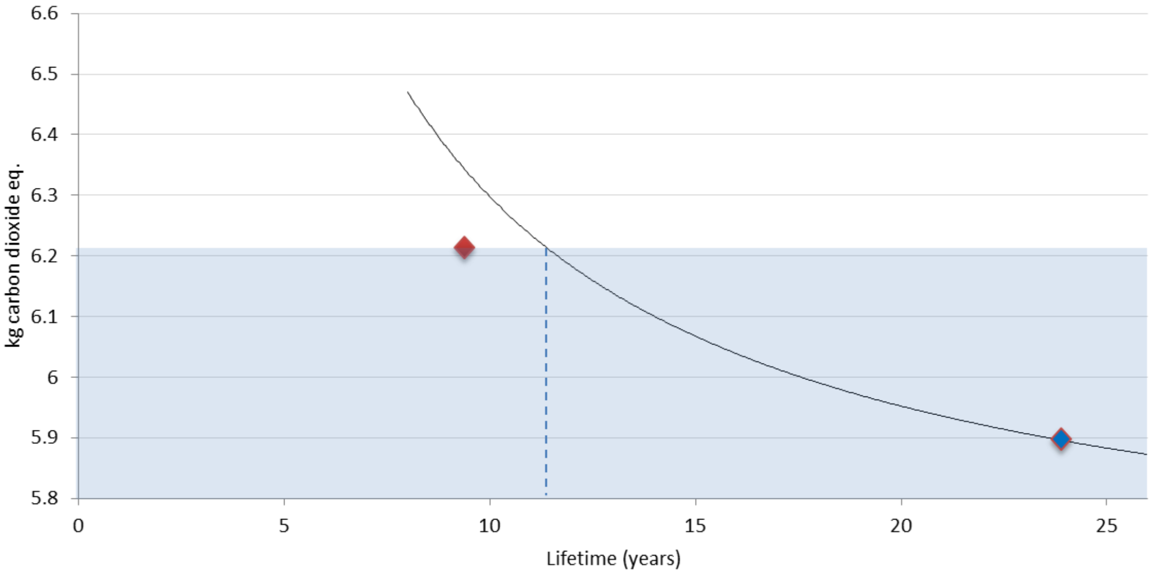
*Red diamond represents paper bank note, blue diamond represents polymer bank note (with lifetime 2.5 times greater than paper bank note). The blue region shows results having lower GHG emissions than the paper note.

Figure 5-1: Variation in global warming potential with lifetime of £5 polymer note



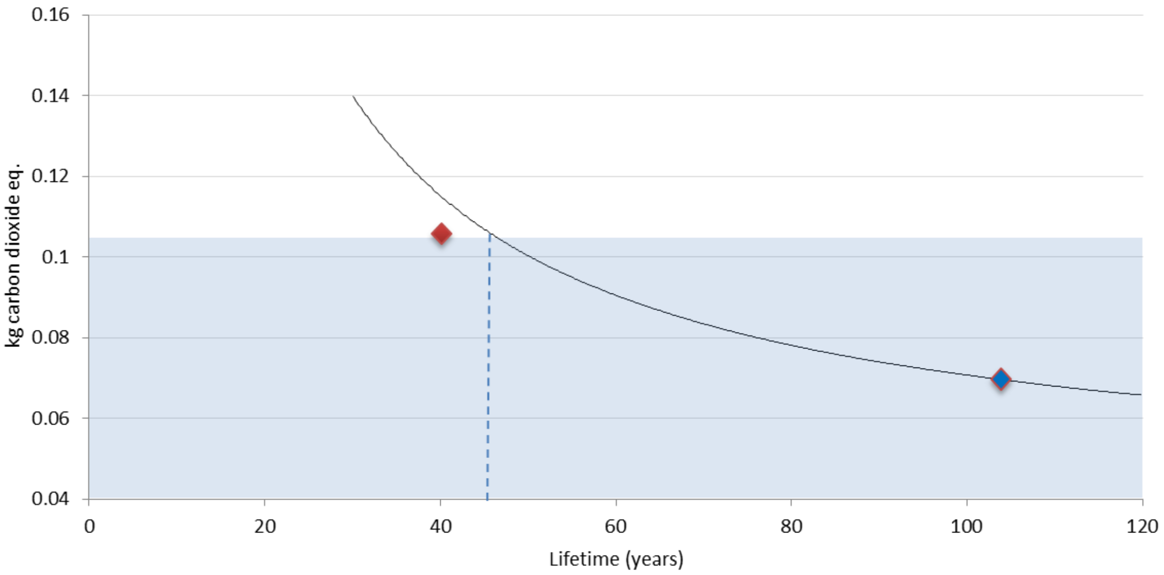
*Red diamond represents paper bank note, blue diamond represents polymer bank note (with lifetime 2.5 times greater than paper bank note). The blue region shows results having lower GHG emissions than the paper note.

Figure 5-2: Variation in global warming potential with lifetime of £10 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 5-3: Variation in global warming potential with lifetime of £20 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 5-4: Variation in global warming potential with lifetime of £50 polymer note

As summarised in Table 5-1, overall, the results show that in the worst case (the £10 and £20 notes) the polymer bank notes need only have a lifetime 33% greater than that of the paper bank notes before they achieve a superior performance for the global warming potential impact category. In the best case (the £50 note), the polymer note need only have a lifetime 9% greater than that of the paper bank notes. Based on the current use of polymer bank notes in other countries it seems very likely that this minimum lifetime will be exceeded. We therefore consider the conclusion that the use of polymer bank notes will lead to a reduction in GHG emissions to be robust for the UK situation.

Table 5-1: 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	2.00	2.45	23
£10	3.09	4.10	33
£20	9.43	12.5	33
£50	41.4	45.0	9

5.2 INFLUENCE OF CHOICE OF COTTON DATASET

The Cotton Inc. dataset used to model cotton production is considered to be high quality but it is representative of average impacts for cotton produced in the US, China and India. Cotton for production of UK paper bank notes is sourced from many countries in addition to those represented by the Cotton Inc. dataset, and it is known that impacts of crop production can vary significantly depending on the growing region. This sensitivity analysis assesses the influence of these uncertainties in the cotton production data.

Figures 5-5 and 5-6 show the results for global warming potential of modelling two additional scenarios, one where cotton 50% lower impact than the default scenario and another where cotton impacts are 50% higher than those of the default scenario.

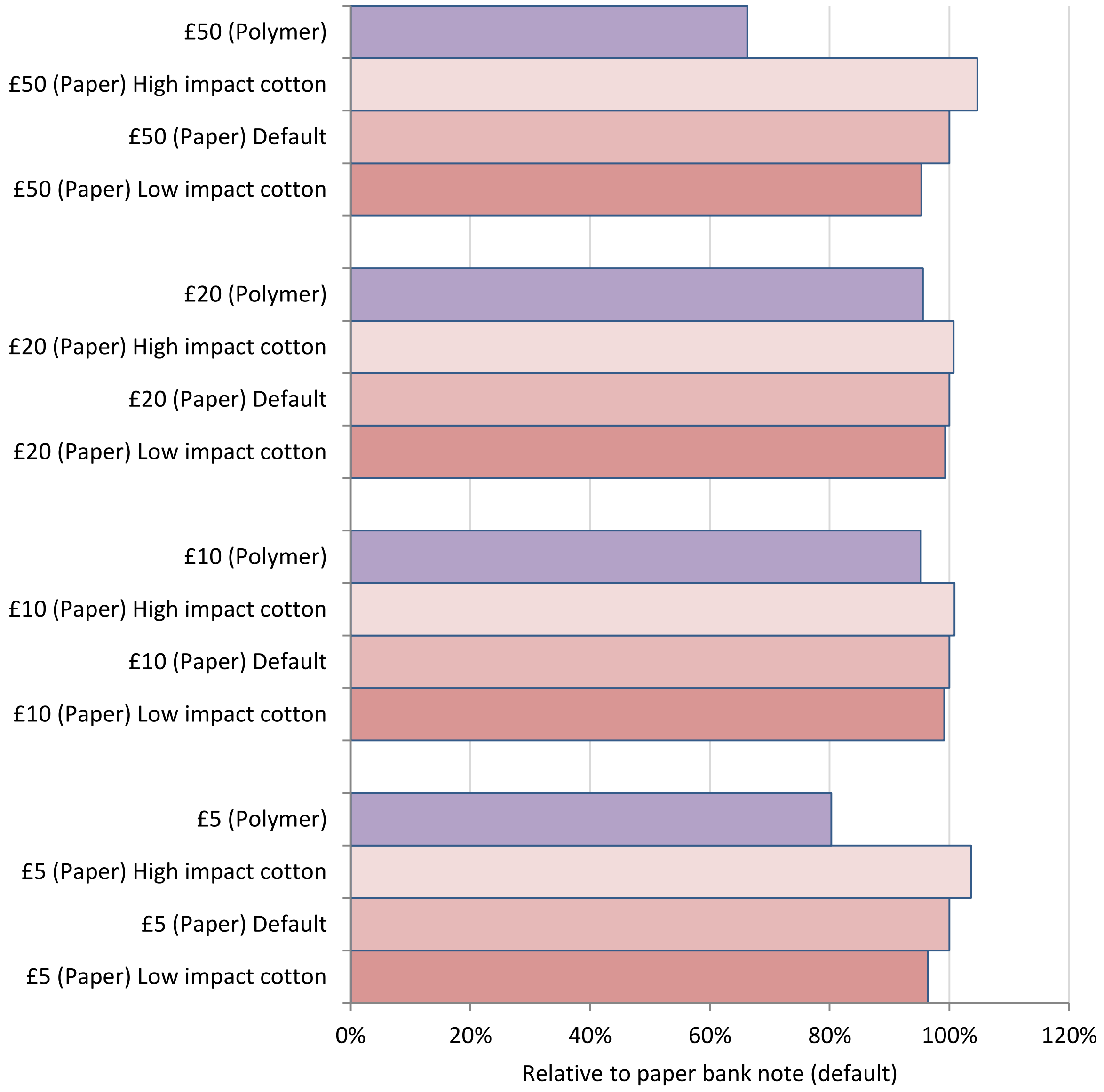


Figure 5-5: Influence of cotton production impacts on global warming potential (inc. ATM impacts)

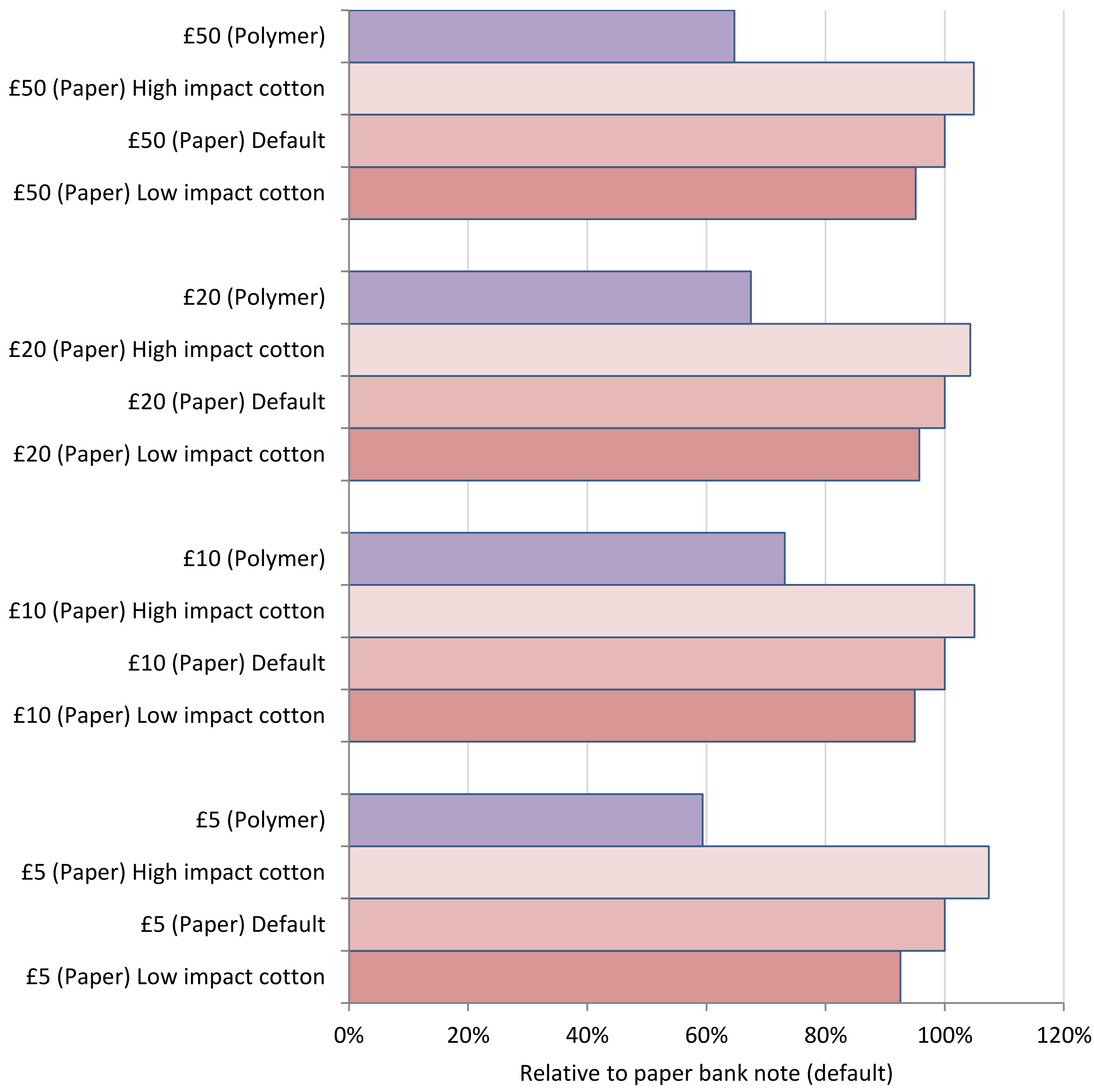


Figure 5-6: Influence of cotton production impacts on global warming potential (ex. ATM impacts)

Figure 5-5 shows the results including ATM impacts to put the changes in context with the full life cycle. Figure 5-6 shows the results excluding ATM impacts since these are essentially the same for both paper and polymer notes. Hence this more clearly shows the differences that are due to the choice of substrates.

These results show that the influence of cotton production impacts on the results of the assessment are very small when ATM impacts are included in the comparison. The biggest difference is seen for the £50 note where the results vary by ±5% compared to the default scenario (this is true whether ATM impacts are included or not as these are very small for this denomination). For no denomination would the use of low impact cotton result in the paper bank note having lower GHG emissions than the equivalent polymer note.

When the impacts of ATMs are excluded the influence of the impact of cotton production on the results are still modest. In this case the biggest difference is seen for the £5 denomination where the results vary by ±7% compared to the default scenario.

5.3 END OF LIFE OPTIONS FOR PAPER BANK NOTES

This sensitivity analysis addresses uncertainties in the modelling of the composting process for paper bank notes as discussed at the end of Section 2.11.8. Based on the calculations shown in this section of the report an alternative composting scenario has been modelled where the carbon dioxide emissions from composting are increased from 115,000 g CO_2/tonne to 238000 g CO_2/tonne feedstock.

As for the previous sensitivity analysis Figure 5-7 shows the results including ATM impacts to put the changes in context with the full life cycle while Figure 5-8 shows the results excluding ATM impacts. These indicate that no denomination of paper note is significantly affected by this change. Because the polymer bank notes have lower GHG emissions than paper bank notes when compared with the default scenario it is clear that increasing end of life GHG emissions for paper notes will not affect the overall conclusions from this study..

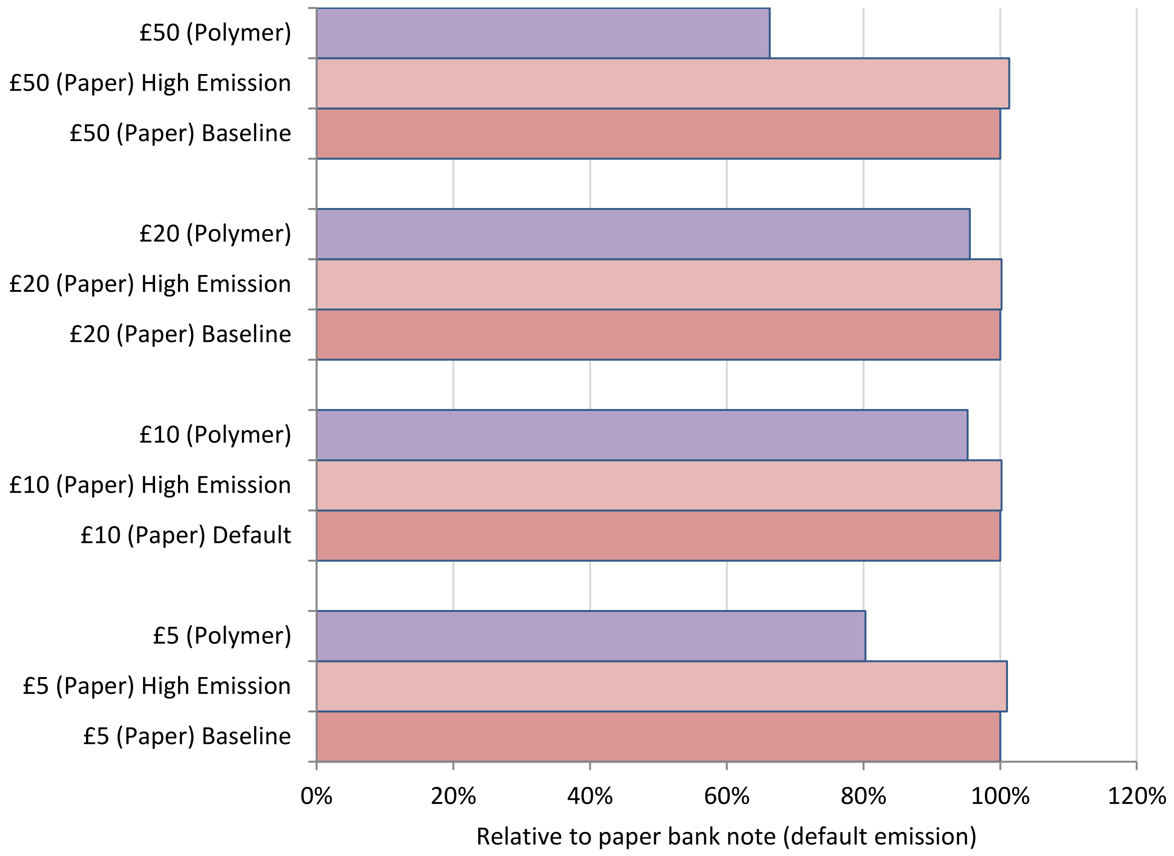


Figure 5-7: Influence of different composting emissions for paper bank notes (inc. ATM impacts)

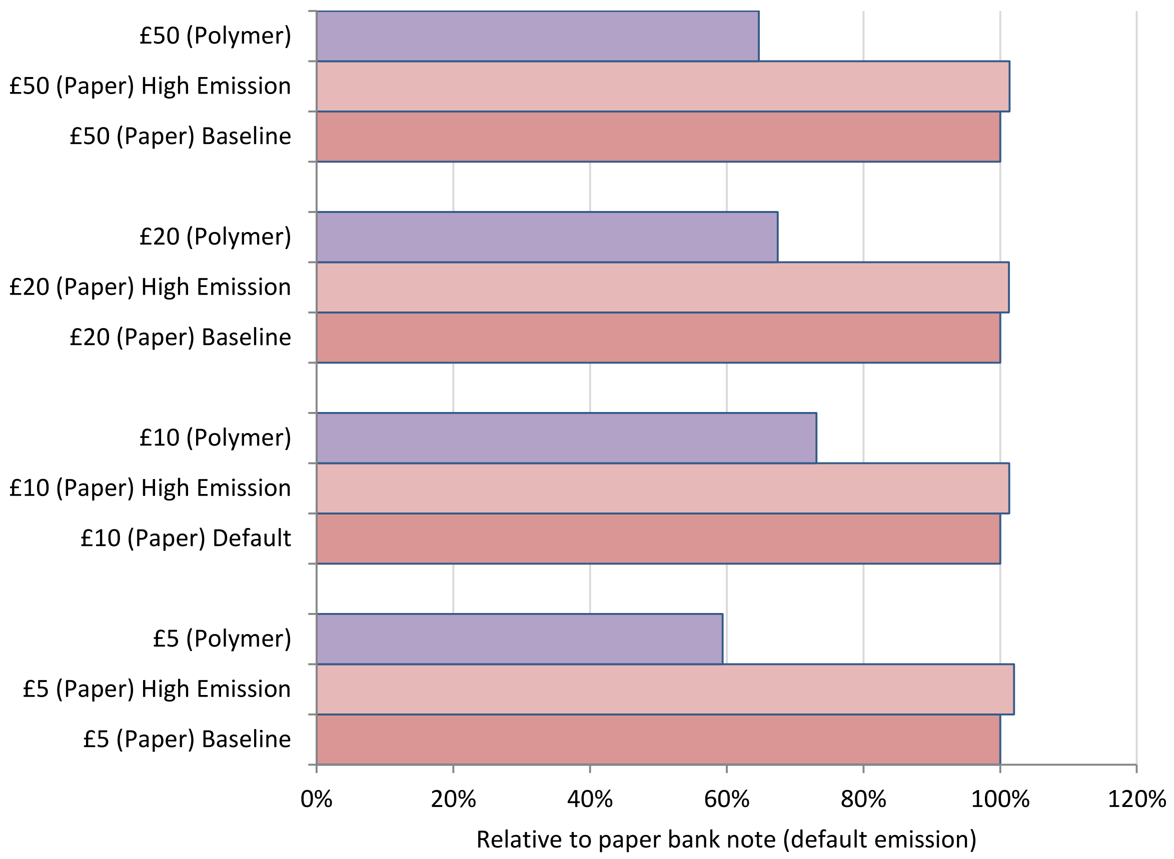


Figure 5-8: Influence of different composting emissions for paper bank notes (ex. ATM impacts)

5.4 END OF LIFE TREATMENT OPTIONS FOR POLYMER BANK NOTES

This sensitivity analysis considers the impact on the lifecycle GHG emissions of polymer bank notes when mechanical recycling instead of energy recovery is chosen as the treatment option for unfit bank notes at end of life.

Figures 5-9 and 5-10 show the results of this analysis both including and excluding the impacts of ATMs. These show that mechanical recycling is the preferred options when considering global warming potential. This is unsurprising as this avoids the significant carbon dioxide emissions from incinerating the notes and also results in a credit for offsetting primary polymer production. As for the previous sensitivity analyses Figure 6-9 shows the results including ATM impacts to put the changes in context with the full life cycle while figure 6-10 shows the results excluding ATM impacts.

As expected, the influence is seen most clearly for £5 and £50 denomination notes, where the results are not so dominated by use phase impacts from ATMs. The £50 note, with the lowest ATM usage shows the greatest improvement. For the £50 note recycling reduces impacts from GHG emissions by around 8% compared to energy recovery (this is true whether ATM impacts are included or not as these are very small for this denomination).

When ATM impacts are excluded from the assessment, the greatest improvement is seen for the £5 denomination, where recycling reduces impacts by 14% compared to the energy recovery option.

It should be reiterated that, due to lack of data on actual recycling impacts of polymer notes, the mechanical recycling process that has been modelled in this sensitivity analysis is idealised and represents a "best case" scenario to contrast with the energy from waste option. It assumes that 100% of the polymer is recycled (i.e. that inks, foil patches, etc. do not reduce the yield) and that the recyclate is of high quality and can substitute for primary granulate on a 1:1 basis.

When applied in practice, the actual benefits of recycling may be less than indicated in this assessment, but it serves to provide an indication of the scale of the improvements that may be achieved.

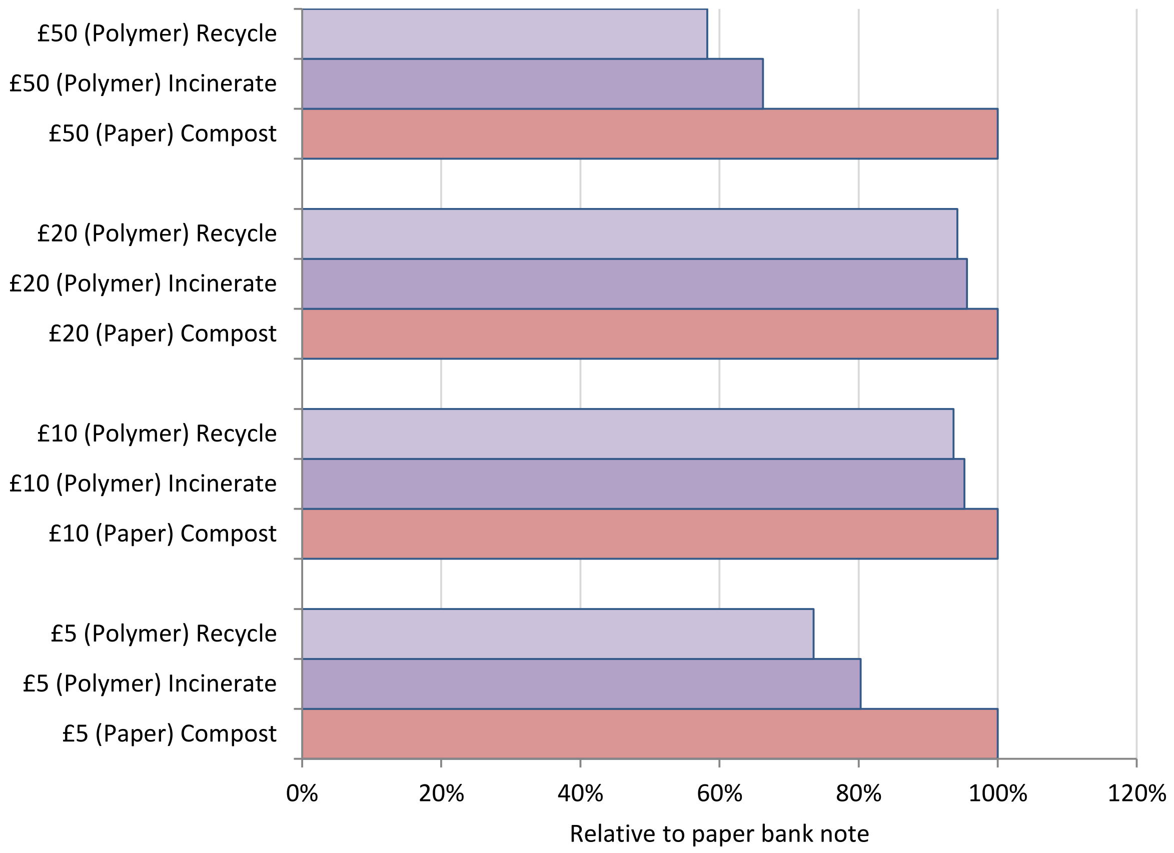


Figure 5-9: Influence of different end of life treatment options for polymer bank notes (inc. ATM impacts)

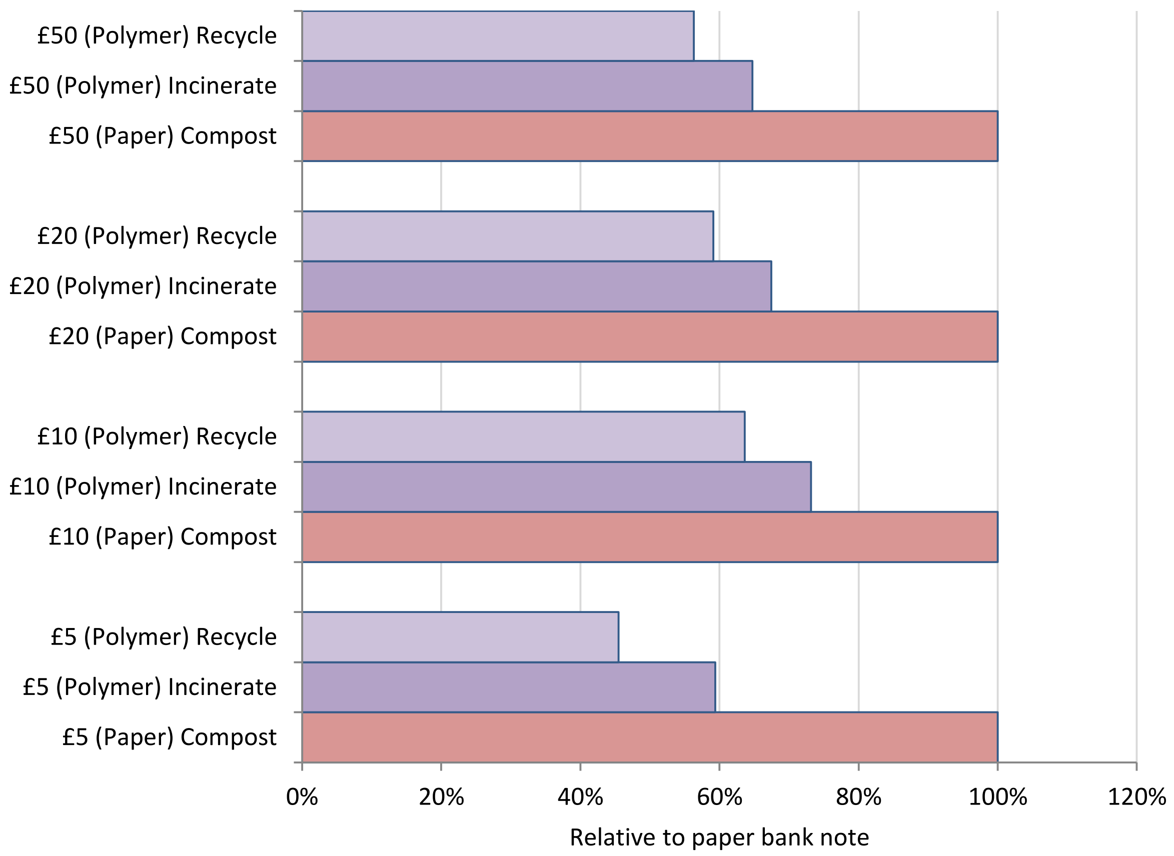


Figure 5-10: Influence of different end of life treatment options for polymer bank notes (ex. ATM impacts)

5.5 ATM ENERGY CONSUMPTION

Energy consumption by ATMs is seen to be a dominant contributor to many environmental indicators assessed in this study. The default electricity consumption data used in this study is based on “typical” through the wall and lobby style ATMs with what are considered to be reasonable usage scenarios for the number of notes vended in a single transaction, and the number of transactions per day. However, ATMs come in many different styles with differing energy consumption and differing cash carrying capacity. Furthermore ATMs in different locations will see different patterns of usage. Hence, there is a significant uncertainty in the electricity data for ATMs used in the default scenario. Figure 5-11 shows the influence on the results of a change in ATM electricity demand of ±20%.

It is immediately clear that the results for the £10 and £20 notes are very sensitive to changes in ATM energy consumption. For these denominations, a 20% change in ATM electricity demand corresponds to an 18% change in overall GHG emissions. This is as expected given the dominance of ATM impacts seen in the main results. The effect is less marked for the £5 note due to lower number that are sent to ATMs after sorting but still results in a noticeable 13% change in overall life cycle impact. In contrast, the results for the £50 note show very little sensitivity to variations in ATM electricity demand as only 1% of these notes are sent to ATMs after sorting.

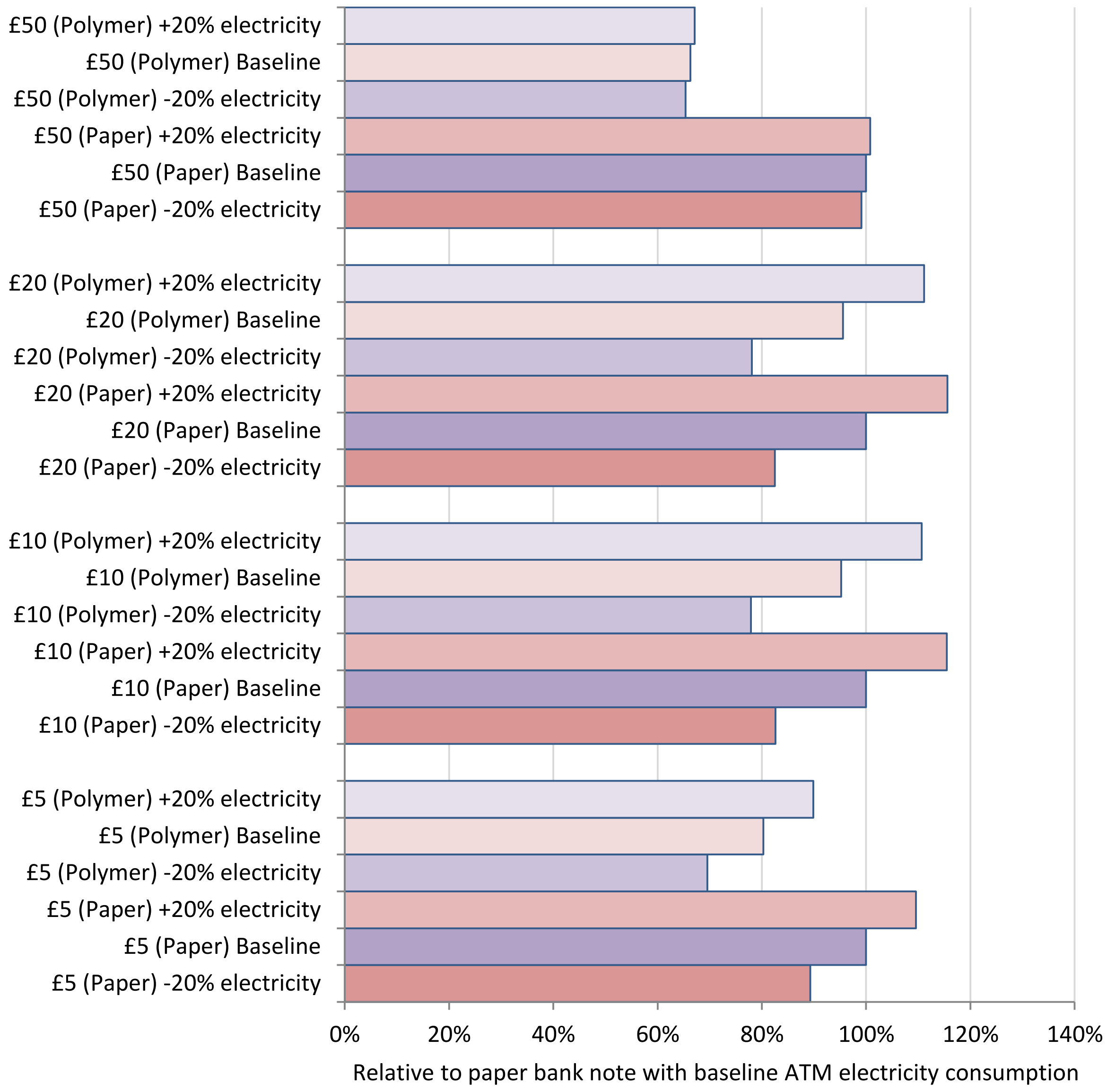


Figure 5-11: Influence of variation in ATM energy consumption

When discussing the GHG emissions associated with electricity use of ATMs it is worth considering the on-going decarbonisation of the UK electricity grid. The share of renewable energy in the UK grid mix is rising steadily and large reductions in carbon intensity per kWh are expected in the coming decades. It has been forecast that, by 2030, GHG emissions from electricity production will fall by around 60% compared to emissions from the UK grid mix in 1990 [POWER PERSPECTIVES 2012, EUROPEAN COMMISSION 2011]. Even if such large reductions are not realised it seems inevitable that there will be significant decarbonisation of the UK grid and, as such, in future, the contribution of ATMs to the total life cycle impact is likely to be reduced significantly.

6 INTERPRETATION

This section of the report summarises the overall results of the study considering the quality of the data used, discusses the key trends and conclusions, and provides recommendations on the best performing product along with suggestions for further work.

6.1 IDENTIFICATION OF SIGNIFICANT ISSUES

Using the criterion that a significant contribution is one that accounts for more than 20% of the total life cycle impact of a given indicator, the main findings of the LCA study can be summarised as follows.

6.1.1 Summary of Significant Issues for £5, £10 and £20 notes

- The results for most indicators are dominated by impacts associated with electricity generation required to operate ATMs. These are the same for both paper and polymer bank notes and have the effect of reducing the relative differences between the substrates that arise due to variations in production and end of life impacts. This effect is most marked for the £10 and £20 denominations where, respectively, 91% and 90% notes are sent to ATMs after sorting. For £5 notes the influence is slightly smaller as only 64% of these notes are distributed to ATMs.

  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 compared to 1990 levels [POWER PERSPECTIVES 2012, EUROPEAN COMMISSION 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 significantly in coming years and will make the impact of other life cycle stages more noticeable in contrast.

- 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 (although when considering fossil and biogenic GHG sources combined this stage is not a significant contributor);
  - eco-toxicity potential due to the use of pesticides during cotton cultivation;
  - freshwater consumption due to the use of irrigation water during cotton cultivation;
  - renewable primary energy due to the energy embodied within the cotton; and

- For paper £5 notes, where the influence of ATMs is not as dominant as for £10 and £20 denominations, other life cycle stages gain more significance:
  - in addition to the indicators listed above, raw material production is also a significant contributor to acidification potential and eutrophication potential;

    - the papermaking process is seen to have a significant contribution to eutrophication potential, global warming potential, photochemical ozone creation potential, human toxicity (cancer) potential, and non-renewable primary energy.

- For £5 polymer notes, substrate production has a significant contribution to the total life cycle impacts for:
    - acidification potential and global warming potential from fossil sources due to emissions associated with combustion of fossil energy sources
    - global warming potential from biogenic sources but in contrast to the paper notes this results in positive net GHG emissions; and
    - photochemical ozone creation potential due to VOC emissions during this opacification process.
- Impacts relating to other life cycle stages such as printing, transport and end of life are relatively small in comparison.

6.1.2 Summary of Significant Issues for £50 notes

- As only 1% of £50 notes are sent to ATMs their environmental profile is very different to those of other denominations. ATM usage is not a significant factor for this denomination.
- For paper notes, the cotton cultivation and papermaking have significant contributions to most impact categories. Note sorting at NCS cash centres during the use phase also contributes significantly to many impact categories.
- For polymer notes the note sorting process at NCS cash centres is usually responsible for the most significant contributions in its life cycle. The substrate production stage is also significant for a number of indicators.

6.1.3 Normalisation

When the results of the LCA are normalised against an external reference of an average EU citizen human toxicity (cancer) is clearly seen to be the most significant impact category, being about an order of magnitude greater than for most other impact categories[8].

This means that impacts associated with human toxicity (cancer) are relatively greater for the bank note life cycle when compared against the annual impacts of a typical EU citizen than are impacts from other categories.

The majority of this impact is from electricity generation associated with the use of ATMs. This reinforces the message that achieving energy efficiency savings during bank note circulation will be an effective way to tackle the most significant impacts associated with the bank note life cycle.

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[8] This does not necessarily imply that human toxicity (cancer) is the most *important* impact category as this cannot be determined without introducing the subjective weighting of different impact categories, which has not been carried out in this study

The result of this normalisation exercise also confirms the overall impression seen when considering the results for each impact category in isolation. On balance, the polymer bank notes have a better environmental performance than the paper bank notes.

6.1.4 Denomination Comparison

A comparison of the environmental performance of different denominations is also interesting and really highlights those aspects of the bank note life cycle that have the most influence on the results.

The aspects that turn out to be most important are:

- the mass of notes required to achieve the functional unit (shown as the “reference flow” in Table 2-3). This is determined by the denomination and lifetime of the bank note. Hence, it is seen that lower denomination notes with shorter lifetimes have greater reference flows than higher denomination notes;
- the circulation velocity, which determines the number of times a note is sorted and put back into circulation. Table 2-8 shows the number of sorting operations undergone by each denomination. The £10 note has the highest circulation velocity, so even though many fewer £10 notes than £5 notes are required per functional unit, the number of sorts undergone by £10 notes is much greater than for £5 notes;
- the proportion of notes sent to an ATM after each sort. This varies tremendously according to denomination, with £5 (64%), £10 (91%), £20 (90%) and £50 (1%). The higher the proportion of notes sent to ATMs after each sort, the greater the use phase impacts.

For some impact categories, including eutrophication potential, ecotoxicity potential, and freshwater use the impacts associated with production are most important and the mass of notes required determines the ranking of the denominations (£5 notes having the biggest impacts with progressive reductions as we move to higher denominations).

For other impact categories, including acidification potential, global warming potential, photochemical ozone creation potential, human toxicity potential (both cancer and non-cancer) and non-renewable primary energy, the impacts associated with the use phase outweigh those associated with the material production phase. Hence, even though the mass of £5 bank notes is almost three times greater per functional unit than the mass of £10 notes, for these indicators the £10 notes have the bigger life cycle impacts due to their very high use phase impacts, which are caused by a combination of high circulation velocity and a high proportion of notes sent to ATMs after each sort.

6.2 DATA QUALITY ASSESSMENT

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied on a study serving as a data source) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistent background LCA information from the GaBi LCI database were used. The LCI data sets from the GaBi LCI database are widely distributed and used with the GaBi 6 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.

6.2.1 Precision and completeness

- ✓ **Precision:** As the relevant foreground data are primary data or modelled based on primary information sources of the owner of the technology, no better precision is reachable within this project. Annual variations were balanced out by using yearly averages (for printing data at De La Rue a two year average was taken to balance annual variations). All background data are GaBi data with the documented precision.

- ✓ **Completeness:** Each unit process has been checked for mass balance and completeness of the emission inventory. No data were knowingly omitted except as described in Section 2.11.

6.2.2 Consistency and reproducibility

- ✓ **Consistency:** To ensure consistency, all primary data were collected with the same level of detail, while all background data were sourced from the GaBi databases. Allocation and other methodological choices were made consistently throughout the model.

- ✓ **Reproducibility:** Reproducibility is warranted as much as possible through the disclosure of input-output data, dataset choices, and modelling approaches in this report. Based on this information, any third party should be able to replicate the study and produce approximately equivalent results using the same data and modelling approaches.

6.2.3 Representativeness

- ✓ **Temporal:** The majority of primary data were collected for the year 2011, with the exception of papermaking and printing data which were collected over a two year period (financial years 2010-2012) and polymer film production which is based on data from 2009. All secondary data come from the GaBi 6 2012 databases and are representative of the years 2009-2011. As the study is intended to compare the product systems for the reference year 2011, temporal representativeness is considered to be high.

- ✓ **Geographical:** 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 high.

- ✓ **Technological:** 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. Technological representativeness is considered to be high.

6.3 COMPLETENESS, SENSITIVITY, AND CONSISTENCY

6.3.1 Completeness

All relevant process steps for each product system were considered and modelled to represent each specific situation. The process chain is considered sufficiently complete with regard to the goal and scope of this study.

6.3.2 Sensitivity

Sensitivity analyses were performed to test the robustness of the results towards uncertainty and the main assumptions. Detailed results can be found in Chapter 5.

The first sensitivity analysis focused on the lifetime of the polymer bank notes. This showed that, in the worst case (the £10 and £20 notes) the polymer bank notes need only have a lifetime 33% greater than that of the paper bank notes before they achieve a superior performance for the global warming potential impact category. In the best case (the £50 note), the polymer note need only have a lifetime 9% greater than that of the paper bank notes. Based on the current use of polymer bank notes in other countries it seems very likely that this minimum lifetime will be exceeded. We therefore consider the conclusion that the use of polymer bank notes will lead to a reduction in GHG emissions to be robust for the UK situation.

The second sensitivity analysis focused on the influence of uncertainties relating to the cultivation of cotton. For GHG emissions this step is shown not to be particularly significant, a change in the impacts of growing cotton of ±50% does not affect the relative ranking of paper and polymer bank notes.

The third sensitivity analysis focused on uncertainties relating to emissions from the composting process. Again, the results of study are seen to be relatively insensitive to these emissions as even when carbon dioxide emissions are doubled relative to the default scenario this is negligible compared to GHG emissions arising from other parts of the product life cycle.

The fourth sensitivity analysis considered how the results would be affected if the polymer bank notes were recycled at end of life instead of undergoing energy recovery. In this case the results of the change were more noticeable. Mechanical recycling and substitution for primary polymer results in a 12% reduction in GHG impacts for the £50 note. Reductions are also seen for other denominations but the relative benefit is lower.

The final sensitivity analysis considered the influence of uncertainty in electricity consumed by ATMs when notes are in circulation. £10 and £20 notes are very sensitive to changes in ATM energy consumption. For these denominations, a 20% change in ATM electricity demand results in an 18% change in overall GHG emissions. This is as expected given the dominance of ATM impacts seen in the main results. The effect is less marked for the £5 note due to lower number that are sent to ATMs after sorting but still results in a noticeable 13% change in overall life cycle impact. In contrast, the results for the £50 note show very little sensitivity to variations in ATM electricity demand as only 1% of these notes are sent to ATMs after sorting.

6.3.3 Consistency

All assumption, methods, and data were found to be consistent with the study’s goal and scope. Differences in background data quality were minimized by using LCI data from the GaBi 6 2012 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

6.4 CONCLUSIONS, LIMITATIONS, AND RECOMMENDATIONS

6.4.1 Conclusions

The results of this LCA study are summarised in Table 7-1 and show that, based on the assumption that the polymer bank note has a lifetime 2.5 times greater than that of a paper bank note, the polymer note will have the best environmental performance in all six impact categories considered. The toxicity-based impact categories are omitted from this table as, although they are useful for identifying substances of concern, they these are not considered sufficiently robust for making comparative assertions.

Table 6-1: Summary indicating the substrate with the best performance for each indicator and an indication of the robustness of the results

Impact Category	Paper Bank Notes	Polymer Bank Notes	Robustness of Result
Acidification Potential	-	✓	High
Eutrophication Potential	-	✓	High
Global Warming Potential	-	✓	High
Photochemical Ozone Creation Potential	✓	-	Poor
Primary Energy Demand (non-renewable)	-	✓	High
Primary Energy Demand (renewable)	-	✓	High
Water Consumption	-	✓	High

The results of the normalisation assessment shows that human toxicity (cancer) is the most significant issue relative to impacts caused by a typical EU citizen and the polymer note has the best performance in this category. The normalised results for other indicators were very similar, with the exception of eutrophication, which is negligible in comparison.

As such, the conclusions of this LCA study are clear cut: the environmental performance of polymer bank notes is better than that of paper bank notes if the polymer notes last 2.5 times longer. The sensitivity analysis carried on bank note lifetime shows that polymer bank notes only need to last 1.33 times longer than paper bank notes before they achieve a lower global warming potential.

The increased lifetime of polymer bank notes means that substantially fewer 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 polymer notes. This is the main reason for the improved performance of polymer bank notes compared to paper bank notes.

The polymer bank notes generally have higher end of life impacts based on disposal in an energy-from-waste plant. But this would be reversed if the polymer bank notes were recycled rather than incinerated.

An interesting outcome from the study is the finding that use phase impacts at the ATM dominate the environmental profiles of the £5, £10 and £20 notes. 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 6.1, 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.

6.4.2 Limitations & Assumptions

The main assumptions relating to the data used in the model are described in detail in Section 2.11. The quality of the foreground and background data used in this study are reported in Appendix C. Areas where data used were of lower quality or resulted in a data gaps, are summarised below.

- Motion thread – this is a security feature found on current £50 paper notes. No data were available for this thread so it was modelled as having the same impacts per kg as conventional security thread based on primary data supplied provided by De La Rue;

- Printing plates – no data were available on production of printing plates used for lithographic and intaglio printing. However, this omission will affect polymer and paper notes equally and the combined mass of plates amounts to less than 1% of the total inputs to the printing process so it is not considered likely that this will significantly affect the results;

- Printing on polymer substrate – this must take place more slowly than paper printing and results in a higher energy consumption. This has been crudely estimated at 10-20% increase by De La Rue (and a 15% increase has been assumed in the report). Uncertainty in this increased energy consumption may affect the reported impacts of the printing process. However, as printing is not a significant contributor to the indicators assessed in this study it is not anticipated that this will affect the overall conclusions of the study;

- Composting – the impacts of composting can vary significantly according to the composting conditions. However, sensitivity analysis of carbon dioxide emissions indicates that the results are not very sensitive to emissions in this life cycle stage;

- Note lifetime – a major uncertainty in this study has been the lifetime of the polymer bank note. However, as noted in the previous section, this has been addressed with a sensitivity analysis that shows that the polymer notes need only have a lifetime 33% longer than a paper note to have lower GHG emissions. A similar result is seen for other impact categories with the exception of photochemical ozone creation potential, which takes rather longer to reach parity with the paper note.

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. The comparison between the design and bank note lifetimes is given in Table 7-2.

Table 6-2: Comparison of design note lifetime with bank note lifetime

Denomination	Designs	Paper Bank Note Lifetime [years]	Polymer Bank Note Lifetime [years]
£5	Duke of Wellington – 1971-1991 (20 years) George Stephenson – 1990-2003 (13 years) Elizabeth Fry – 2002-current (11 years +)	2.00	4.80
£10	Florence Nightingale – 1975-1994 (19 years) Charles Dickens – 1992-2003 (11 years) Charles Darwin – 2000-current (13+ years)	3.09	7.51
£20	William Shakespeare – 1970-1993 (23 years) Michael Faraday – 1991-2001 (10 years) Edward Elgar – 1999-2010 (11 years) Adam Smith – 2007-current (6+ years)	9.43	23.8
£50	Sir Christopher Wren – 1981-1996 (15 years) Sir John Houblen – 1994-current (19+ years, but probably due to be withdrawn soon) Matthew Boulton/James Watt – 2011-current (1.5+ years)	41.4	103

From this, it can be seen the design lifetimes of the £5 and £10 denominations are significantly greater than the bank note lifetimes of both the paper and polymer notes. Hence, the environmental benefits of moving to polymer bank notes should be well described by the results in this study.

For £20 denominations the issue is less clear. For the last two design cycles the design lifetime has been only slightly longer than the lifetime of the paper note, and much shorter than the lifetime of the polymer note. Hence in this case it seems probable that the full benefit of the extended life of the polymer note would not be realised. However, given that the lifetime of the paper note is still slightly shorter than the design lifetime it would still be expected that two paper bank notes would be required for each polymer bank note, so it is probable that the polymer bank note would still have the better environmental performance.

For £50 denominations the lifetime of both the paper and polymer bank notes significantly exceed the design lifetime. Hence in this case the additional durability of the polymer bank note would not give any benefit since bank notes made of either substrate would be recalled before becoming unfit for use. In this case it may be expected that the £50 paper bank note would have slightly lower environmental impacts than the polymer bank note (as illustrated for global warming potential in the charts in Section 5.1 assessing the influence of note life on the environmental performance of polymer bank notes).

However, this analysis does give the full story. The main reason for changing the design of bank notes is to defend against counterfeiters. As counterfeiters have got more sophisticated, so paper bank notes have had to change design more frequently (which is why more recent designs tend to have shorter lifetimes than earlier designs). The use of a polymer substrate offers a step change in anti-counterfeiting robustness, so the pressure to change designs as frequently should lessen with the introduction of polymer banknotes (in Australia the oldest circulating bank note design is the AU$10, which was first issued in 1993).

Another factor to consider for the £50 bank note is that it is expected to become more commonly used in transactions in 10-20 years' time (and therefore less hoarded as a store of value). As such, its lifetime will fall accordingly; probably to become more in line with the current £20 should it be used more in ATMs.

Given these factors it may be reasonable to assume that for the £20 denomination and even for the £50 denomination, polymer bank notes will have a superior environmental performance to paper bank notes, although this conclusion is less clear cut than for £5 and £10 notes.

- Consequential effects of moving to polymer bank notes have not been addressed in this study. Clearly a move to polymer bank notes would reduce the demand for cotton noils 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 noils have other uses (such as in cotton wool for cosmetics).

- It should also be recognised that not all environmental impacts and issues can be addressed by LCA. Political and social pressure can drive decisions in the opposite direction to those recommended by LCA results. For example, a recent communication from the European Commission on a strategy for "Innovating for Sustainable Growth: A Bioeconomy for Europe" states that *"the partial replacement of non-renewable products by more sustainable bio-based ones should be pursued"* [EUROPEAN COMMISSION 2012]. A move from paper to polymer bank notes would run counter to this policy proposal.

6.4.3 Recommendations

The results of this study indicate that polymer bank notes have superior environmental performance to paper bank notes based on the impact categories considered and with consideration of the limitations noted above. On this basis it is recommended that the Bank of England should move from using paper bank notes to using polymer bank notes.

In addition, the Bank of England should work with ATM providers to assess opportunities for optimising the energy consumption of ATMs, as this is seen to be a key contributor to most impact categories.

The Bank of England should undertake further research with Veolia to identify the optimum waste management option for polymer bank notes. In addition to energy from waste and mechanical recycling considered in this study other options, such as pyrolysis, may also be beneficial. This may have a significant influence on the environmental performance of £50 notes, where the life cycle impacts are not dominated by ATM usage.

If the decision is made to move to polymer bank notes the Bank of England should investigate whether further environmental benefits could be achieved by locating polymer substrate production in the UK rather than importing substrate from Australia. Such benefits seem likely as:

- this would reduce transport impacts, and the
- UK grid mix has lower GHG impacts than electricity generation in Australia, which should lead to lower production impacts.

It would also be interesting to assess the impact of the average cash mix, accounting for the proportion of £5, £10, £20 and £50 notes in circulation, rather than considering each denomination in isolation.

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APPENDIX A: PROCESS FLOW DIAGRAMS

This section provides the detailed process flow diagrams that were used as the basis for the LCA model developed in GaBi software.

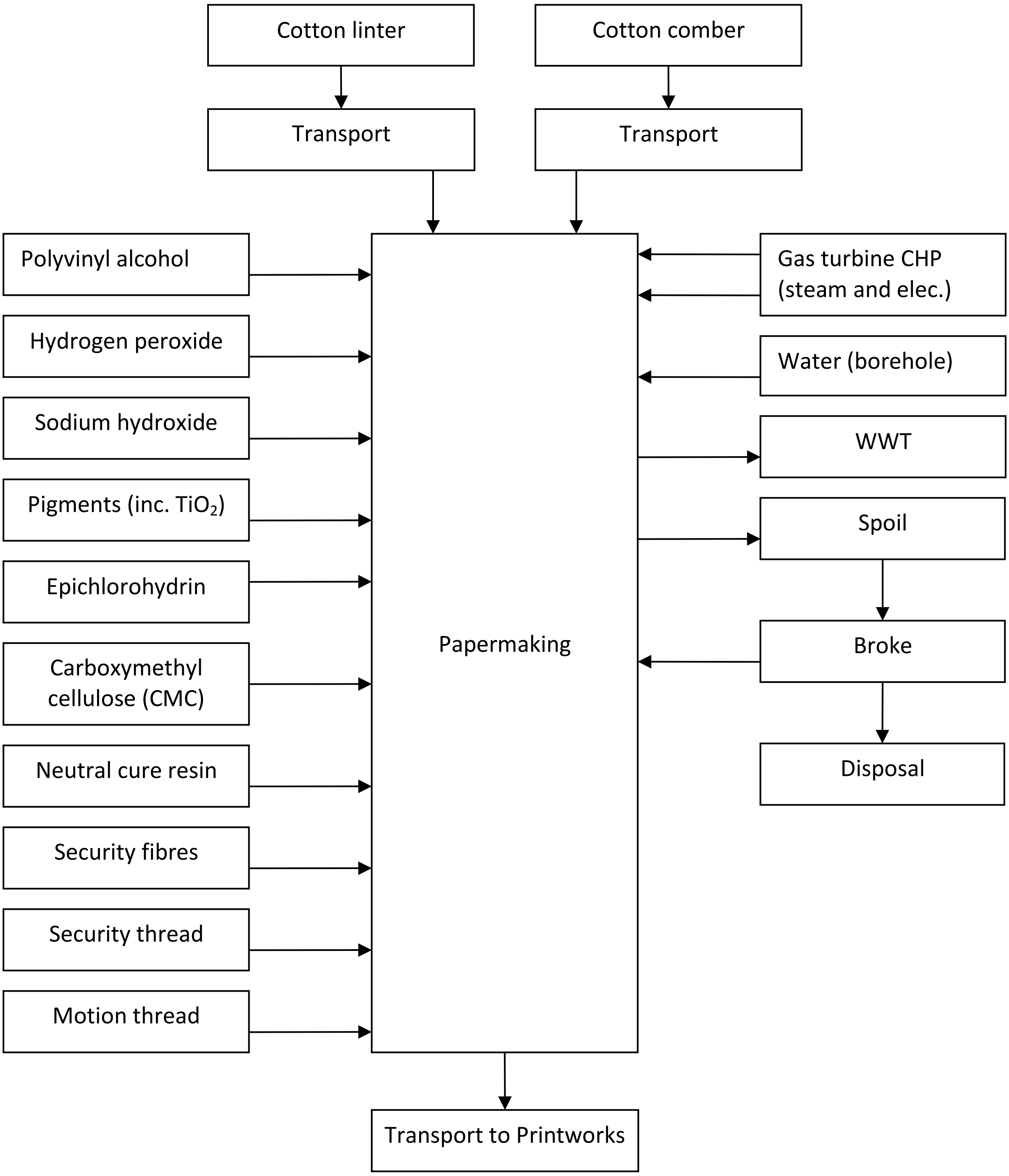

Figure A-1: Process flow diagram for the papermaking process

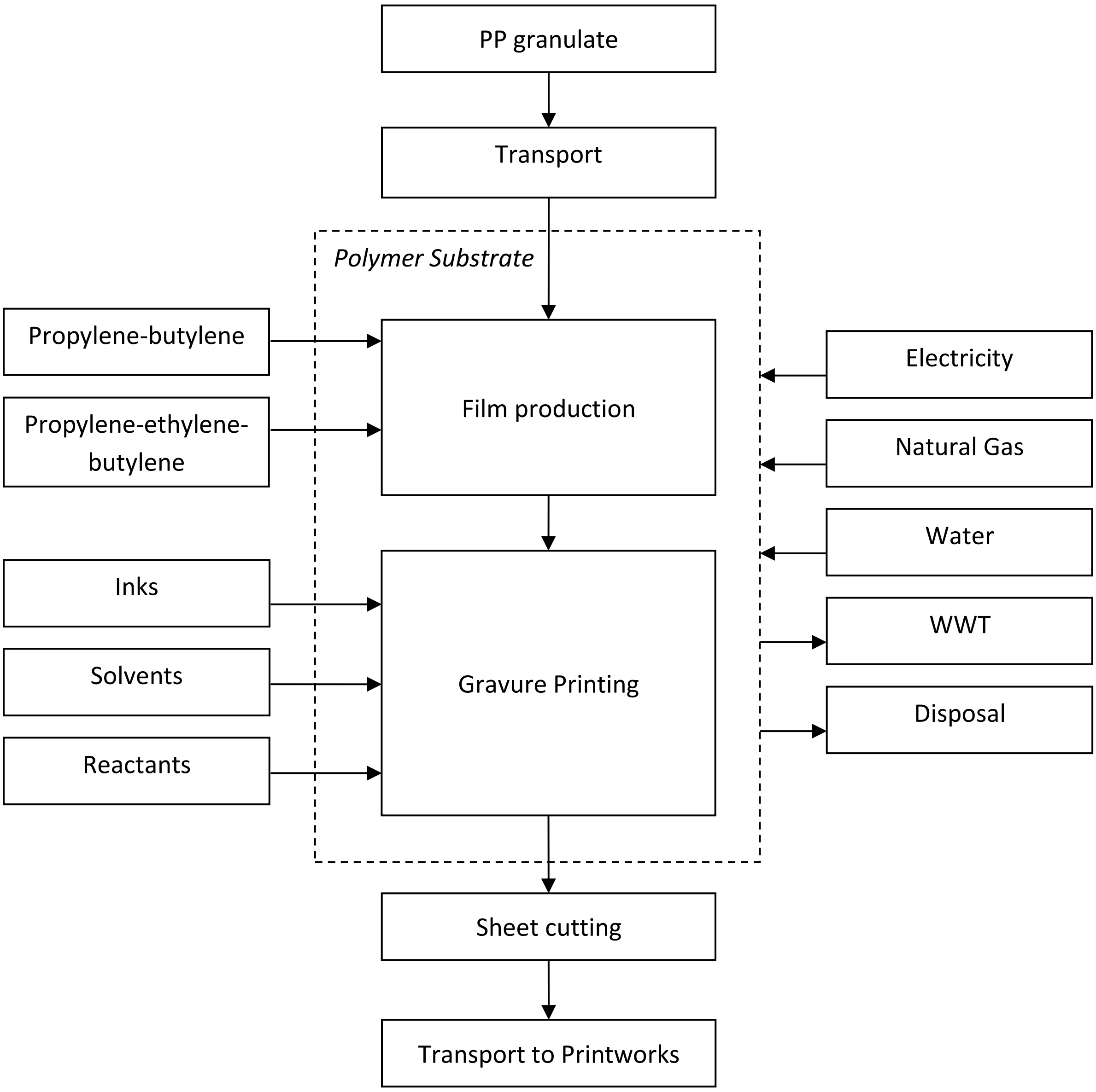

Figure A-2: Process flow diagram for the polymer substrate production process

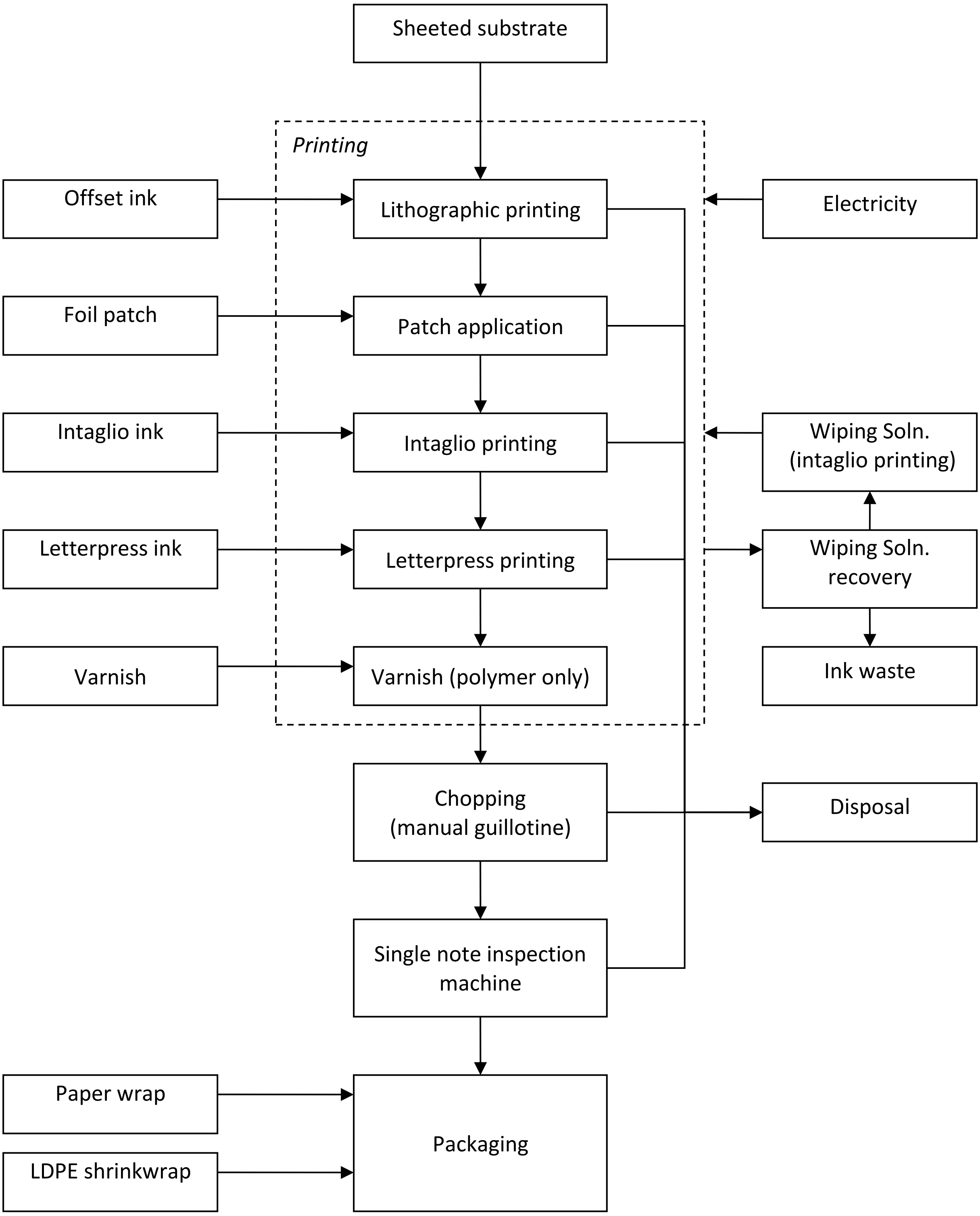

Figure A-3: Process flow diagram for the printing process

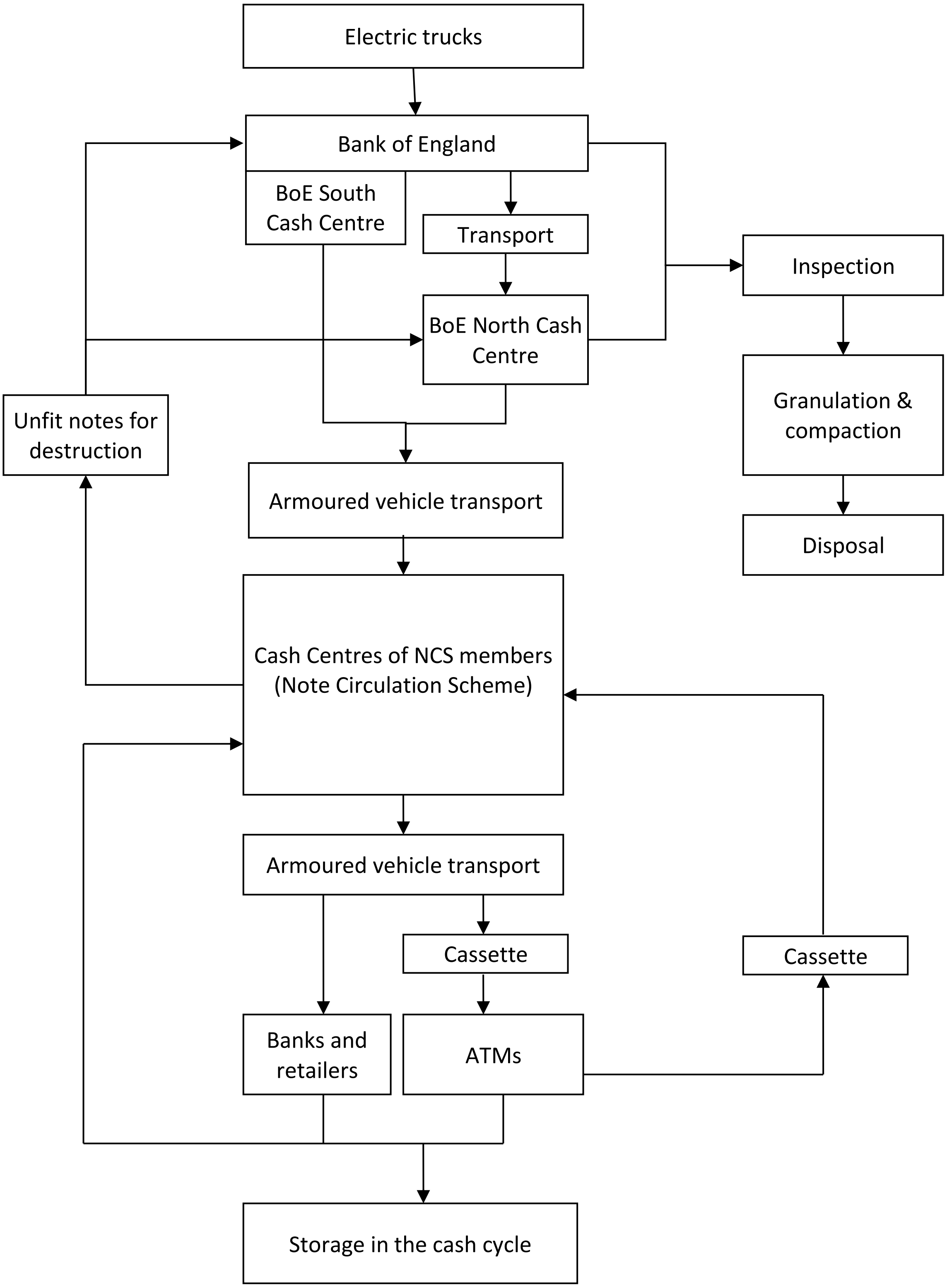

Figure A-4: Process flow diagram for notes in circulation

APPENDIX B: UNIT PROCESS DATA

The unit process data collected and applied in this assessment is reported in this section.

PAPER BANK NOTE PRODUCT SYSTEM

Description of Process Flow

The process diagram shown in Figure 2-1 provides an overview of the stages in the paper bank note life cycle. This is summarised again below:

- the paper substrate is manufactured using cotton linter and comber as fibre input;
- the paper then undergoes three separate printing process (lithographic, intaglio and letterpress) and additional features such as the foil patch are applied;
- the printed sheets are then cut into individual bank notes and packaged;
- the packaged bank notes are stored at the Bank of England South Cash Centre (located in Debden next to the printing site), other notes are transported to the North Cash Centre in Leeds;
- the bank notes are transported to regional cash centres operated by members of the Note Circulation Scheme;
- notes are distributed to end users (retailers, banks, ATMs);
- used notes are collected and sorted at the regional cash centres;
- unfit notes are returned to the Bank of England cash centres where they are checked for authenticity, before being granulated and then compacted;
- the compacted waste notes are collected by Veolia and composted.

Paper Making

Table B-1 gives the primary data used to model production of cotton paper, as received from De La Rue.

Table B-1: Primary data used to model production of cotton paper

<Table removed to preserve data confidentiality>

Paper Bank Note Printing

Table B-2 gives the primary data used to model printing of paper bank notes, as received from De La Rue.

Table B-2: Primary data used to model printing of paper bank notes

<Table removed to preserve data confidentiality>

Sorting

Data received from NCS members indicated that typical electricity consumption for sorting at regional cash centres equated to 374 kWh/million notes (0.000374 kWh/note).

ATMs

Table B-3 gives data provided by Diebold, a major manufacturer of ATMs for the UK market, on the daily electricity consumption of typical lobby and through-the-wall ATMs. Of more than 65,000 ATMs installed in the UK it is estimated that 37% are through the wall ATMs and 63% are lobby ATMs.

Table B-3: Primary data used to model ATM impacts

Mode	Time spent in each mode [hours/day]	Lobby ATM [kWh/day]	Through-the-wall ATM (no heater)[b] [kWh/day]	Through-the-wall ATM (heater on)[b] [kWh/day]
Standby	21.23	4.03	5.3	18.04
Transaction[a]	2.77	0.79	0.95	2.61

[a] based on assumption of 6 notes per transaction and 166 transactions per day
[b] when temperatures drop below freezing an internal heater activates

The results presented in this study assume that through-the-wall type ATMs are not operating with the heater on. Clearly, use of the heater would further increase the environmental impact of ATMs.

End-of-Life

When banks notes are judged unfit for recirculation at NCS cash centres they are sent back to Bank of England cash centres to be destroyed. On receipt at the Bank of England the notes are sorted again, to check for the presence of forgeries, before being granulated and compacted prior to being sent for composting.

Note sorting at the Bank of England uses a sorting machine with a nominal power consumption of 10.8 kW. Assuming that 30 notes are sorted per second in continuous mode (108,000 notes/hour) this equates to a power consumption of 0.0001 kWh/note.

The average power consumption of the granulating machine is 57 kW. With a throughput of 650 kg/hour this equates to an energy consumption of 0.0876 kWh/kg.

The average power consumption of the compacting machine is 32 kW. With a throughput of 550 kg/hour this equates to an energy consumption of 0.058 kWh/kg.

POLYMER BANK NOTE PRODUCT SYSTEM

Description of Process Flow

The process diagram shown in Figure 2-1 provides an overview of the stages in the paper bank note life cycle. This is summarised again below:

- the polymer film is manufactured from virgin polymer using a bubble process;
- the film is opacified using a gravure printing process;
- the polymer then undergoes three separate printing process (lithographic, intaglio and letterpress) and additional features such as the foil patch are attached and a final layer of varnish is applied;
- the printed sheets are then cut into individual bank notes and packaged;
- the packaged bank notes are stored at the Bank of England South Cash Centre (located in Debden next to the printing site), other notes are transported to the North Cash Centre in Leeds;
- the bank notes are transported to regional cash centres operated by members of the Note Circulation Scheme;
- notes are distributed to end users (retailers, banks, ATMs);
- used notes are collected and sorted at the regional cash centres;
- unfit notes are returned to the Bank of England cash centres where they are checked for authenticity before being granulated;
- the granulated waste notes are collected by Veolia and sent for recycling (or incinerated with energy recovery).

Polymer Film Production

Table B-4 gives the primary data used to model production of polymer film, as received from Innovia Films.

Table B-4: Primary data used to model production of polymer film

<Table removed to preserve data confidentiality>

Polymer Film Conversion (Opacification)

Table B-5: Primary data used to model polymer film conversion

<Table removed to preserve data confidentiality>

Polymer Bank Note Printing

Same as for paper bank notes although an additional varnishing process is required for polymer bank notes. The amount of varnish has been estimated based on previous data used for varnished £50 notes (61.11 kg varnish/million notes). For other denominations this varnish consumption has been scaled according to surface area.

The energy consumption for the varnishing processes is estimated as being similar to that for the foil application process.

Printing on polymer substrate cannot be carried out at the same rate as printing on paper. De La Rue estimates that this will raise the energy requirement for polymer printing by 10-20%. For this study an intermediate value of a 15% increase has been modelled.

Transport

Same as for paper bank notes.

Sorting

Same as for paper bank notes.

ATMs

Same as for paper bank notes.

End-of-Life

Polymer notes are granulated but, unlike paper notes, they are not compacted. The granulated notes are sent to an energy-from-waste facility.

APPENDIX 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.

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

Energy	Dataset name	Primary source	Year	Geography
Electricity	Electricity grid mix	PE	2009	UK
	Electricity grid mix	PE	2009	Australia
Technical heat	Thermal energy from natural gas	PE	2009	UK
	Thermal energy from natural gas	PE	2009	Australia
Fuels	Diesel mix at refinery	PE	2009	EU-27
	Heavy fuel oil at refinery (1.0wt.% S)	PE	2009	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	PE	2011	Europe
Alcohol	Ethanol	PE	2011	Germany
Carboxymethyl cellulose	Sodium Carboxy Methylcellulose from cotton/cellulose	PE	2011	Germany
Cotton Fibre	Cotton Fibre	Cotton Inc.	2010	US/China/India
Epichlorohydrin	Epichlorohydrin	PE	2011	Germany
Epoxy resin	Epoxy Resin (EP) Mix	PE	2011	Germany
Hazardous Waste Disposal	Hazardous waste (non-specific) (c rich, worst scenario)	PE	2011	Global
Hydrogen peroxide	Hydrogen peroxide (100%; H_2O_2) (Hydrogen from steam reforming)	PE	2011	Germany
K-fertiliser	Potassium chloride (agrarian)	PE	2011	Germany
Landfill	Landfill of paper waste	PE	2011	EU-27
Landfill	Landfill of plastic waste	PE	2011	EU-27
Landfill	Landfill (Commercial waste for municipal disposal; FR, UK, FI, NO)	PE	2011	UK
MEK	Methyl ethyl ketone (MEK)	PE	2011	US
Metal salts	Manganese sulphate (estimation)	PE	2011	Germany
MIBK	Methyl-isobutylketone (MIBK)	PE	2011	Germany
Modified alkyd resin	Phthalic anhydride	PE	2011	Germany
	Glycerine	PE	2011	Germany
Modified phenolic resin	Phenol formaldehyde-resin (Novolac)	PE	2011	Europe
N-fertiliser	Urea (agrarian)	PE	2010	Germany
Non-soluble mineral salt	Barium carbonate (estimation, barium sulphide and CO_2)	PE	2011	Germany
Organic coloured	Carbon black (furnace black; deep black	PE	2011	Germany

Material/ Process	Dataset name	Primary source	Year	Geography
pigments	pigment)			
PA fibres	Polyamide 6.6 fibres (PA 6.6)	PE	2011	EU-27
Paper	Kraft paper	PE	2011	Germany
PET fibres	Polyethylene terephthalate fibres (PET)	PE	2011	EU-27
PET film	Polyethylene terephthalate foil (PET) (without additives)	PE	2011	Germany
P-fertiliser	Triple superphosphate (TSP)	PE	2011	Netherlands
Photo-initiator	Benzoyl Peroxide	PE	2011	US
Polypropylene	Polypropylene granulate	PE	2011	Australia
Polyvinyl alcohol	Polyvinyl Alcohol Granulate (PVAL) Mix	PE	2011	Germany
PP Energy Recovery	Polypropylene (PP) in waste to energy plant (modified based on Veolia data)	PE	2011	Europe
Sea freight	Container ship (27500 DWT)	PE	2011	Global
Shrinkfilm	Polyethylene Film (PE-LD) without additives	PE	2011	Germany
Silica	Silica sand (flour)	PE	2011	Germany
Sodium hydroxide	Caustic soda mix	PE	2011	UK
Sulphonated castor oil	Sun flower oil production	PE	2011	France
Titanium dioxide	Titanium dioxide pigment	PE	2011	Europe
Truck freight	Truck (29-32 t gross weight, Euro V)	PE	2011	Global
Vegetable oil	Rapeseed oil	PE	2011	Germany
Waste plastic compounding	Pelletizing and compounding	PE	2011	Germany
Waste plastic granulation	Granulator	PE	2011	Germany
Waste plastic washing	Washing (plastic recycling)	PE	2011	Germany
Water	Process water	PE	2011	Europe

Material/ Process	Dataset name	Primary source	Year	Geography
Water	Water (desalinated; deionised)	PE	2011	Europe
Water	Tap water from surface water	PE	2011	Germany
Waxes & Mineral Oils	Wax / Paraffins at refinery	PE	2009	EU-27
White spirit	Naphtha at refinery	PE	2009	EU-27
WWT	Waste water treatment	PE	2011	EU-27

APPENDIX 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 C-4 and C-5 (based on that used in the GHG Protocol Product Life Cycle Accounting and Reporting Standard). This based on the scoring system presented in Table C-3 below.

Table C-1: Scoring system for pedigree matrix

Data Quality Indicator	Score			
	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 C-2: Pedigree matrix for foreground data used in this study

Data Point	Data Quality Indicator Reliability	Completeness	Temporal	Geographical	Technological
Papermaking	Very good	Very good	Very good	Very good	Very good
Polymer film production	Good	Good	Good	Good	Very good
Polymer film conversion	Very good	Good	Good	Very good	Very good
Inks production	Good	Very good	Very good	Very good	Very good
Printing	Very good	Very good	Very good	Very good	Very good
NCS note sorting and distribution	Good	Good	Very good	Very good	Very good
Bank of England note sorting and destruction	Very good	Very good	Very good	Very good	Very good

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

Data Point	Data Quality Indicator Reliability	Completeness	Temporal	Geographical	Technological
Cotton	Very good	Very good	Very good	Fair/good	Very good
Polymer granulate	Good	Fair	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	Fair	Very good	Very good	Good
Ship transport	Good	Fair	Very good	Very good	Good
Energy from waste	Good	Fair	Very good	Very good	Very good
Plastic recycling	Fair	Fair	Very good	Good	Good
Composting	Fair	Poor	Good	Good	Good

APPENDIX E: DETAILED RESULTS OF THE SENSITIVITY ANALYSES

This chapter provides tables containing the detailed results, covering all environmental indicators, for the sensitivity analyses that have been conducted as part of this study.

BANK NOTE LIFETIME

Table D-1: LCI results per functional unit assessing sensitivity of polymer note lifetime for £5 notes

Indicator	Unit	Paper (2 years)	Polymer (1.0 year)	Polymer (1.5 years)	Polymer (2.0 years)	Polymer (2.5 years)	Polymer (3.0 years)	Polymer (3.5 years)	Polymer (4.0 years)	Polymer (4.5 years)	Polymer (5.0 years)	Polymer (5.5 years)
Primary Energy Demand (non-renewable)	[MJ]	332	473	380	334	306	288	274	265	257	251	246
Primary Energy Demand (renewable)	[MJ]	52.6	20.0	17.1	15.7	14.8	14.2	13.8	13.5	13.2	13.0	12.9
Water Consumption	[litres]	1922	160	122	103	91.8	84.2	78.8	74.8	71.7	69.2	67.1

Table D-2: LCIA results per functional unit assessing sensitivity of polymer note lifetime for £5 notes

Indicator	Unit	Paper (2 years)	Polymer (1.0 year)	Polymer (1.5 years)	Polymer (2.0 years)	Polymer (2.5 years)	Polymer (3.0 years)	Polymer (3.5 years)	Polymer (4.0 years)	Polymer (4.5 years)	Polymer (5.0 years)	Polymer (5.5 years)
Acidification Potential	kg SO_2-eq.	8.72E-02	0.126	9.74E-02	8.31E-02	7.45E-02	6.87E-02	6.46E-02	6.16E-02	5.92E-02	5.73E-02	5.57E-02
Eutrophication Potential	kg PO_4^{3-} eq.	1.24E-02	1.19E-02	9.06E-03	7.67E-03	6.83E-03	6.27E-03	5.88E-03	5.58E-03	5.34E-03	5.16E-03	5.01E-03
Global Warming Potential (fossil)	kg CO_2-eq.	21.6	34.2	26.7	22.9	20.7	19.2	18.1	17.3	16.7	16.2	15.8
Global Warming Potential (biogenic)	kg CO_2-eq.	-1.11	0.105	7.41E-02	5.86E-02	4.93E-02	4.30E-02	3.86E-02	3.53E-02	3.27E-02	3.06E-02	2.89E-02
Photochem. Ozone Creation Potential	kg C_2H_4-eq.	4.22E-03	1.95E-02	1.37E-02	1.08E-02	9.07E-03	7.92E-03	7.09E-03	6.47E-03	5.99E-03	5.60E-03	5.28E-03
Ecotoxicity Potential	CTUeco	29.5	6.88	6.66	6.54	6.48	6.43	6.40	6.37	6.36	6.34	6.33
Human Toxicity Potential (cancer)	CTUh	1.10E-07	8.62E-08	7.48E-08	6.91E-08	6.57E-08	6.34E-08	6.18E-08	6.06E-08	5.96E-08	5.89E-08	5.83E-08
Human Toxicity Potential (non-cancer)	CTUh	1.98E-05	1.80E-05	1.68E-05	1.62E-05	1.58E-05	1.56E-05	1.54E-05	1.53E-05	1.52E-05	1.51E-05	1.50E-05

Table D-3: LCI results per functional unit assessing sensitivity of polymer note lifetime for £10 notes

Indicator	Unit	Paper (3.09 years)	Polymer (2.0 year)	Polymer (2.75 years)	Polymer (3.5 years)	Polymer (4.25 years)	Polymer (5.0 years)	Polymer (5.75 years)	Polymer (6.5 years)	Polymer (7.25 years)	Polymer (8.0 years)	Polymer (8.75 years)
Primary Energy Demand (non-renewable)	[MJ]	499	528	507	495	488	483	479	476	473	471	470
Primary Energy Demand (renewable)	[MJ]	40.4	28.5	27.9	27.6	27.3	27.2	27.0	26.9	26.9	26.8	26.8
Water Consumption	[litres]	754	139	130	126	122	120	119	118	117	116	115

Table D-4: LCIA results per functional unit assessing sensitivity of polymer note lifetime for £10 notes

Indicator	Unit	Paper (3.09 years)	Polymer (2.0 year)	Polymer (2.75 years)	Polymer (3.5 years)	Polymer (4.25 years)	Polymer (5.0 years)	Polymer (5.75 years)	Polymer (6.5 years)	Polymer (7.25 years)	Polymer (8.0 years)	Polymer (8.75 years)
Acidification Potential	kg SO_2-eq.	0.109	0.116	0.110	0.106	0.104	0.102	0.101	0.100	0.099	0.099	0.098
Eutrophication Potential	kg PO_4^{3-} eq.	1.11E-02	1.03E-02	9.70E-03	9.35E-03	9.12E-03	8.96E-03	8.84E-03	8.75E-03	8.68E-03	8.62E-03	8.57E-03
Global Warming Potential (fossil)	kg CO_2-eq.	30.5	33.3	31.6	30.6	30.0	29.6	29.3	29.0	28.8	28.7	28.6
Global Warming Potential (biogenic)	kg CO_2-eq.	-0.349	5.47E-02	4.73E-02	4.31E-02	4.04E-02	3.85E-02	3.70E-02	3.60E-02	3.51E-02	3.44E-02	3.38E-02
Photochem. Ozone Creation Potential	kg C_2H_4-eq.	5.72E-03	9.73E-03	8.44E-03	7.70E-03	7.22E-03	6.89E-03	6.64E-03	6.45E-03	6.30E-03	6.18E-03	6.08E-03
Ecotoxicity Potential	CTUeco	22.4	14.6	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
Human Toxicity Potential (cancer)	CTUh	1.41E-07	1.30E-07	1.27E-07	1.26E-07	1.25E-07	1.24E-07	1.24E-07	1.24E-07	1.23E-07	1.23E-07	1.23E-07
Human Toxicity Potential (non-cancer)	CTUh	3.53E-05	3.43E-05	3.41E-05	3.39E-05	3.38E-05	3.38E-05	3.37E-05	3.37E-05	3.37E-05	3.36E-05	3.36E-05

Table D-5: LCI results per functional unit assessing sensitivity of polymer note lifetime for £20 notes

Indicator	Unit	Paper (9.43 years)	Polymer (8 year)	Polymer (10 years)	Polymer (12 years)	Polymer (14 years)	Polymer (16 years)	Polymer (18 years)	Polymer (20 years)	Polymer (22 years)	Polymer (24 years)	Polymer (26 years)
Primary Energy Demand (non-renewable)	[MJ]	102	104	102	100	99.4	98.6	98.0	97.6	97.2	96.9	96.6
Primary Energy Demand (renewable)	[MJ]	7.85	5.77	5.70	5.65	5.61	5.59	5.57	5.55	5.54	5.53	5.52
Water Consumption	[litres]	133	27.1	26.2	25.5	25.0	24.7	24.4	24.2	24.0	23.9	23.8

Table D-6: LCIA results per functional unit assessing sensitivity of polymer note lifetime for £20 notes

Indicator	Unit	Paper (9.43 years)	Polymer (8 year)	Polymer (10 years)	Polymer (12 years)	Polymer (14 years)	Polymer (16 years)	Polymer (18 years)	Polymer (20 years)	Polymer (22 years)	Polymer (24 years)	Polymer (26 years)
Acidification Potential	kg SO_2-eq.	2.20E-02	2.25E-02	2.18E-02	2.14E-02	2.10E-02	2.08E-02	2.06E-02	2.05E-02	2.04E-02	2.03E-02	2.02E-02
Eutrophication Potential	kg PO_4^{3-} eq.	2.23E-03	2.00E-03	1.93E-03	1.89E-03	1.86E-03	1.83E-03	1.81E-03	1.80E-03	1.79E-03	1.78E-03	1.77E-03
Global Warming Potential (fossil)	kg CO_2-eq.	6.23	6.46	6.29	6.18	6.09	6.03	5.98	5.95	5.91	5.89	5.87
Global Warming Potential (biogenic)	kg CO_2-eq.	-6.71E-02	7.89E-03	7.45E-03	7.16E-03	6.95E-03	6.79E-03	6.67E-03	6.57E-03	6.50E-03	6.43E-03	6.37E-03
Photochem. Ozone Creation Potential	kg C_2H_4-eq.	1.15E-03	1.68E-03	1.55E-03	1.46E-03	1.40E-03	1.35E-03	1.31E-03	1.29E-03	1.26E-03	1.24E-03	1.22E-03
Ecotoxicity Potential	CTUeco	4.34	3.00	2.99	2.99	2.99	2.98	2.98	2.98	2.98	2.98	2.98
Human Toxicity Potential (cancer)	CTUh	2.87E-08	2.62E-08	2.60E-08	2.58E-08	2.57E-08	2.56E-08	2.55E-08	2.54E-08	2.54E-08	2.53E-08	2.53E-08
Human Toxicity Potential (non-cancer)	CTUh	7.25E-06	7.03E-06	7.00E-06	6.98E-06	6.97E-06	6.95E-06	6.95E-06	6.94E-06	6.93E-06	6.93E-06	6.93E-06

Table D-7: LCI results per functional unit assessing sensitivity of polymer note lifetime for £50 notes

Indicator	Unit	Paper (41.4 years)	Polymer (30 year)	Polymer (40 years)	Polymer (50 years)	Polymer (60 years)	Polymer (70 years)	Polymer (80 years)	Polymer (90 years)	Polymer (100 years)	Polymer (110 years)	Polymer (120 years)
Primary Energy Demand (non-renewable)	[MJ]	1.70	1.91	1.60	1.41	1.28	1.20	1.13	1.08	1.04	1.00	0.974
Primary Energy Demand (renewable)	[MJ]	0.309	7.19E-02	6.31E-02	5.78E-02	5.43E-02	5.17E-02	4.99E-02	4.84E-02	4.72E-02	4.63E-02	4.55E-02
Water Consumption	[litres]	12.7	0.505	0.414	0.359	0.323	0.296	0.277	0.262	0.249	0.239	0.231

Table D-8: LCIA results per functional unit assessing sensitivity of polymer note lifetime for £50 notes

Indicator	Unit	Paper (41.4 years)	Polymer (30 year)	Polymer (40 years)	Polymer (50 years)	Polymer (60 years)	Polymer (70 years)	Polymer (80 years)	Polymer (90 years)	Polymer (100 years)	Polymer (110 years)	Polymer (120 years)
Acidification Potential	kg SO_2-eq.	4.70E-04	5.22E-04	4.25E-04	3.67E-04	3.29E-04	3.01E-04	2.80E-04	2.64E-04	2.51E-04	2.41E-04	2.32E-04
Eutrophication Potential	kg PO_4^{3-} eq.	7.44E-05	4.70E-05	3.88E-05	3.38E-05	3.05E-05	2.81E-05	2.64E-05	2.50E-05	2.39E-05	2.30E-05	2.22E-05
Global Warming Potential (fossil)	kg CO_2-eq.	0.114	0.140	0.115	1.00E-01	9.03E-02	8.32E-02	7.79E-02	7.38E-02	7.06E-02	6.79E-02	6.56E-02
Global Warming Potential (biogenic)	kg CO_2-eq.	-7.85E-03	3.71E-04	2.89E-04	2.41E-04	2.08E-04	1.85E-04	1.67E-04	1.54E-04	1.43E-04	1.34E-04	1.26E-04
Photochem. Ozone Creation Potential	kg C_2H_4-eq.	1.62E-05	7.98E-05	6.02E-05	4.84E-05	4.06E-05	3.50E-05	3.08E-05	2.75E-05	2.49E-05	2.28E-05	2.10E-05
Ecotoxicity Potential	CTUeco	0.178	2.26E-02	2.17E-02	2.11E-02	2.08E-02	2.05E-02	2.03E-02	2.02E-02	2.00E-02	1.99E-02	1.98E-02
Human Toxicity Potential (cancer)	CTUh	5.91E-10	3.11E-10	2.72E-10	2.49E-10	2.33E-10	2.22E-10	2.14E-10	2.07E-10	2.02E-10	1.98E-10	1.94E-10
Human Toxicity Potential (non-cancer)	CTUh	8.47E-08	6.10E-08	5.66E-08	5.40E-08	5.23E-08	5.10E-08	5.01E-08	4.94E-08	4.88E-08	4.83E-08	4.79E-08

INFLUENCE OF CHOICE OF COTTON DATASET

Table D-9: LCI results per functional unit assessing sensitivity of cotton cultivation impacts (including ATM impacts)

Indicator	Unit	£5 Paper (low impact)	£5 Paper (default impact)	£5 Paper (high impact)	£5 Polymer	£10 Paper (low impact)	£10 Paper (default impact)	£10 Paper (high impact)	£10 Polymer
Primary Energy Demand (non-renewable)	[MJ]	326	332	338	253	497	499	501	471
Primary Energy Demand (renewable)	[MJ]	32.6	52.6	72.6	13.1	33.5	40.4	47.3	26.8
Water Consumption	[litres]	1042	1922	2801	70.1	451	754	1057	116

Indicator	Unit	£20 Paper (low impact)	£20 Paper (default impact)	£20 Paper (high impact)	£20 Polymer	£50 Paper (low impact)	£50 Paper (default impact)	£50 Paper (high impact)	£50 Polymer
Primary Energy Demand (non-renewable)	[MJ]	102	102	102	96.8	1.66	1.70	1.74	1.03
Primary Energy Demand (renewable)	[MJ]	6.68	7.85	9.02	5.52	0.175	0.309	0.443	4.71E-02
Water Consumption	[litres]	81.5	133	184	23.9	6.82	12.7	18.6	0.247

Table D-10: LCIA results per functional unit assessing sensitivity of cotton cultivation impacts (including ATM impacts)

Indicator	Unit	£5 Paper (low impact)	£5 Paper (default impact)	£5 Paper (high impact)	£5 Polymer	£10 Paper (low impact)	£10 Paper (default impact)	£10 Paper (high impact)	£10 Polymer
Acidification Potential	kg SO_2-eq.	7.95E-02	8.72E-02	9.50E-02	5.80E-02	0.106	0.109	0.112	9.89E-02
Eutrophication Potential	kg PO_4^{3-} eq.	1.08E-02	1.24E-02	1.40E-02	5.23E-03	1.06E-02	1.11E-02	1.17E-02	8.63E-03
Global Warming Potential (fossil)	kg CO_2-eq.	20.8	21.6	22.3	16.4	30.3	30.5	30.8	28.7
Global Warming Potential (biogenic)	kg CO_2-eq.	-1.11	-1.11	-1.11	3.14E-02	-0.349	-0.349	-0.349	3.47E-02
Photochem. Ozone Creation Potential	kg C_2H_4-eq.	4.05E-03	4.22E-03	4.39E-03	5.74E-03	5.66E-03	5.72E-03	5.78E-03	6.24E-03
Ecotoxicity Potential	CTUeco	19.0	29.5	40.1	6.35	18.8	22.4	26.1	14.4
Human Toxicity Potential (cancer)	CTUh	1.09E-07	1.10E-07	1.11E-07	5.92E-08	1.41E-07	1.41E-07	1.41E-07	1.23E-07
Human Toxicity Potential (non-cancer)	CTUh	1.97E-05	1.98E-05	1.99E-05	1.51E-05	3.53E-05	3.53E-05	3.53E-05	3.35E-05

Indicator	Unit	£20 Paper (low impact)	£20 Paper (default impact)	£20 Paper (high impact)	£20 Polymer	£50 Paper (low impact)	£50 Paper (default impact)	£50 Paper (high impact)	£50 Polymer
Acidification Potential	kg SO_2-eq.	2.16E-02	2.20E-02	2.25E-02	2.02E-02	4.18E-04	4.70E-04	5.22E-04	2.49E-04
Eutrophication Potential	kg PO_4^{3-} eq.	2.13E-03	2.23E-03	2.32E-03	1.78E-03	6.37E-05	7.44E-05	8.51E-05	2.37E-05
Global Warming Potential (fossil)	kg CO_2-eq.	6.19	6.23	6.27	5.88	0.109	0.114	0.119	6.99E-02
Global Warming Potential (biogenic)	kg CO_2-eq.	-6.71E-02	-6.71E-02	-6.71E-02	6.43E-03	-7.85E-03	-7.85E-03	-7.85E-03	1.40E-04
Photochem. Ozone Creation Potential	kg C_2H_4-eq.	1.14E-03	1.15E-03	1.16E-03	1.24E-03	1.51E-05	1.62E-05	1.74E-05	2.43E-05
Ecotoxicity Potential	CTUeco	3.73	4.34	4.96	2.97	0.107	0.178	0.248	2.01E-02
Human Toxicity Potential (cancer)	CTUh	2.86E-08	2.87E-08	2.87E-08	2.53E-08	5.86E-10	5.91E-10	5.96E-10	2.01E-10
Human Toxicity Potential (non-cancer)	CTUh	7.24E-06	7.25E-06	7.25E-06	6.92E-06	8.40E-08	8.47E-08	8.54E-08	4.88E-08

Table D-11: LCI results per functional unit assessing sensitivity of paper composting emissions (including ATM impacts)

Indicator	Unit	£5 (Paper) Default	£5 (Paper) High emission	£5 (Polymer)	£10 (Paper) Default	£10 (Paper) High emission	£10 (Polymer)	£20 (Paper) Default	£20 (Paper) High emission	£20 (Polymer)	£50 (Paper) Default	£50 (Paper) High emission	£50 (Polymer)
Primary Energy Demand (non-renewable)	[MJ]	332	332	253	499	499	471	102	102	96.8	1.70	1.70	1.03
Primary Energy Demand (renewable)	[MJ]	52.6	52.6	13.1	40.4	40.4	26.8	7.85	7.85	5.52	0.309	0.309	4.71E-02
Water Consumption	[litres]	1922	1922	70.1	754	754	116	133	133	23.9	12.7	12.7	0.247

Table D-12: LCIA results per functional unit assessing sensitivity of paper composting emissions (including ATM impacts)

Indicator	Unit	£5 (Paper) Default	£5 (Paper) High emission	£5 (Polymer)	£10 (Paper) Default	£10 (Paper) High emission	£10 (Polymer)	£20 (Paper) Default	£20 (Paper) High emission	£20 (Polymer)	£50 (Paper) Default	£50 (Paper) High emission	£50 (Polymer)
Acidification Potential	kg SO_2-eq.	8.72E-02	8.72E-02	5.80E-02	0.109	0.109	9.89E-02	2.20E-02	2.20E-02	2.02E-02	4.70E-04	4.70E-04	2.49E-04
Eutrophication Potential	kg PO_4^{3-} eq.	1.24E-02	1.24E-02	5.23E-03	1.11E-02	1.11E-02	8.63E-03	2.23E-03	2.23E-03	1.78E-03	7.44E-05	7.44E-05	2.37E-05
Global Warming Potential (fossil)	kg CO_2-eq.	21.6	21.6	16.4	30.5	30.5	28.7	6.23	6.23	5.88	0.114	0.114	6.99E-02
Global Warming Potential (biogenic)	kg CO_2-eq.	-1.11	-0.905	3.14E-02	-0.349	-0.281	3.47E-02	-6.71E-2	-5.42E-2	6.43E-03	-7.85E-3	-6.44E-3	1.40E-04
Photochem. Ozone Creation Potential	kg C_2H_4-eq.	4.22E-03	4.22E-03	5.74E-03	5.72E-03	5.72E-03	6.24E-03	1.15E-03	1.15E-03	1.24E-03	1.62E-05	1.62E-05	2.43E-05
Ecotoxicity Potential	CTUeco	29.5	29.5	6.35	22.4	22.4	14.4	4.34	4.34	2.97	0.178	0.178	2.01E-02
Human Toxicity Potential (cancer)	CTUh	1.10E-07	1.10E-07	5.92E-08	1.41E-07	1.41E-07	1.23E-07	2.87E-08	2.87E-08	2.53E-08	5.91E-10	5.91E-10	2.01E-10
Human Toxicity Potential (non-cancer)	CTUh	1.98E-05	1.98E-05	1.51E-05	3.53E-05	3.53E-05	3.35E-05	7.25E-06	7.25E-06	6.92E-06	8.47E-08	8.47E-08	4.88E-08

Table D-13: LCI results per functional unit assessing sensitivity of polymer end of life options (including ATM impacts)

Indicator	Unit	£5 (Paper)	£5 (Polymer) Incinerate	£5 (Polymer) Recycle	£10 (Paper)	£10 (Polymer) Incinerate	£10 (Polymer) Recycle	£20 (Paper)	£20 (Polymer) Incinerate	£20 (Polymer) Recycle	£50 (Paper)	£50 (Polymer) Incinerate	£50 (Polymer) Recycle
Primary Energy Demand (non-renewable)	[MJ]	332	253	235	499	471	465	102	96.8	95.7	1.70	1.03	0.918
Primary Energy Demand (renewable)	[MJ]	52.6	13.1	13.2	40.4	26.8	26.8	7.85	5.52	5.53	0.309	4.71E-02	4.76E-02
Water Consumption	[litres]	1922	70.1	65.5	754	116	114	133	23.9	23.6	12.7	0.247	0.219

Table D-14: LCIA results per functional unit assessing sensitivity of polymer end of life options (including ATM impacts)

Indicator	Unit	£5 (Paper)	£5 (Polymer) Incinerate	£5 (Polymer) Recycle	£10 (Paper)	£10 (Polymer) Incinerate	£10 (Polymer) Recycle	£20 (Paper)	£20 (Polymer) Incinerate	£20 (Polymer) Recycle	£50 (Paper)	£50 (Polymer) Incinerate	£50 (Polymer) Recycle
Acidification Potential	kg SO_2-eq.	8.72E-02	5.80E-02	5.73E-02	1.09E-01	9.89E-02	9.86E-02	2.20E-02	2.02E-02	2.02E-02	4.70E-04	2.49E-04	2.45E-04
Eutrophication Potential	kg PO_4^{3-} eq.	1.24E-02	5.23E-03	5.20E-03	1.11E-02	8.63E-03	8.62E-03	2.23E-03	1.78E-03	1.77E-03	7.44E-05	2.37E-05	2.35E-05
Global Warming Potential (fossil)	kg CO_2-eq.	21.6	16.4	15.0	30.5	28.7	28.2	6.23	5.88	5.80	0.114	6.99E-02	6.14E-02
Global Warming Potential (biogenic)	kg CO_2-eq.	-1.11	3.14E-02	3.16E-02	-0.349	3.47E-02	3.48E-02	-6.71E-2	6.43E-03	6.44E-03	-7.85E-3	1.40E-04	1.42E-04
Photochem. Ozone Creation Potential	kg C_2H_4-eq.	4.22E-03	5.74E-03	5.44E-03	5.72E-03	6.24E-03	6.14E-03	1.15E-03	1.24E-03	1.22E-03	1.62E-05	2.43E-05	2.25E-05
Ecotoxicity Potential	CTUeco	29.5	6.35	6.56	22.4	14.4	14.5	4.34	2.97	2.99	0.178	2.01E-02	2.14E-02
Human Toxicity Potential (cancer)	CTUh	1.10E-07	5.92E-08	6.12E-08	1.41E-07	1.23E-07	1.24E-07	2.87E-08	2.53E-08	2.54E-08	5.91E-10	2.01E-10	2.13E-10
Human Toxicity Potential (non-cancer)	CTUh	1.98E-05	1.51E-05	1.57E-05	3.53E-05	3.35E-05	3.37E-05	7.25E-06	6.92E-06	6.95E-06	8.47E-08	4.88E-08	5.22E-08

ATM ENERGY CONSUMPTION

Table D-15: LCI results per functional unit assessing sensitivity of ATM energy consumption

Indicator	Unit	£5 (Paper) (Low energy)	£5 (Paper) (Default energy)	£5 (Paper) (High energy)	£5 (Polymer) (Low energy)	£5 (Polymer) (Default energy)	£5 (Polymer) (High energy)	£10 (Paper) (Low energy)	£10 (Paper) (Default energy)	£10 (Paper) (High energy)	£10 (Polymer) (Low ATM)	£10 (Polymer) (Default energy)	£10 (Polymer) (High energy)
Primary Energy Demand (non-renewable)	[MJ]	295	332	364	216	253	286	412	499	577	384	471	549
Primary Energy Demand (renewable)	[MJ]	50.5	52.6	54.5	11.0	13.1	15.0	35.4	40.4	45.0	21.7	26.8	31.3
Water Consumption	[litres]	1913	1922	1929	61.2	70.1	78.0	733	754	773	94.9	116	135

Indicator	Unit	£5 (Paper) (Low energy)	£5 (Paper) (Default energy)	£5 (Paper) (High energy)	£5 (Polymer) (Low energy)	£5 (Polymer) (Default energy)	£5 (Polymer) (High energy)	£10 (Paper) (Low energy)	£10 (Paper) (Default energy)	£10 (Paper) (High energy)	£10 (Polymer) (Low ATM)	£10 (Polymer) (Default energy)	£10 (Polymer) (High energy)
Primary Energy Demand (non-renewable)	[MJ]	84.1	102	118	78.8	96.8	113	1.68	1.70	1.71	1.01	1.03	1.04
Primary Energy Demand (renewable)	[MJ]	6.80	7.85	8.78	4.47	5.52	6.45	0.308	0.309	0.310	4.61E-02	4.71E-02	4.79E-02
Water Consumption	[litres]	128	133	137	19.5	23.9	27.7	12.7	12.7	12.7	0.243	0.247	0.250

Table D-16: LCIA results per functional unit assessing sensitivity of ATM energy consumption

Indicator	Unit	£5 (Paper) (Low energy)	£5 (Paper) (Default energy)	£5 (Paper) (High energy)	£5 (Polymer) (Low energy)	£5 (Polymer) (Default energy)	£5 (Polymer) (High energy)	£10 (Paper) (Low energy)	£10 (Paper) (Default energy)	£10 (Paper) (High energy)	£10 (Polymer) (Low ATM)	£10 (Polymer) (Default energy)	£10 (Polymer) (High energy)
Acidification Potential	kg SO_2-eq.	7.97E-02	8.72E-02	9.39E-02	5.05E-02	5.80E-02	6.47E-02	9.10E-02	0.109	0.125	8.09E-02	9.89E-02	0.115
Eutrophication Potential	kg PO_4^{3-} eq.	1.18E-02	1.24E-02	1.30E-02	4.58E-03	5.23E-03	5.80E-03	9.59E-03	1.11E-02	1.25E-02	7.10E-03	8.63E-03	1.00E-02
Global Warming Potential (fossil)	kg CO_2-eq.	19.4	21.6	23.5	14.2	16.4	18.4	25.3	30.5	35.2	23.5	28.7	33.4
Global Warming Potential (biogenic)	kg CO_2-eq.	-1.11	-1.11	-1.11	2.92E-02	3.14E-02	3.33E-02	-0.355	-0.349	-0.345	2.95E-02	3.47E-02	3.95E-02
Photochem. Ozone Creation Potential	kg C_2H_4-eq.	3.79E-03	4.22E-03	4.61E-03	5.31E-03	5.74E-03	6.13E-03	4.69E-03	5.72E-03	6.63E-03	5.22E-03	6.24E-03	7.15E-03
Ecotoxicity Potential	CTUeco	28.3	29.5	30.6	5.17	6.35	7.39	19.6	22.4	24.9	11.6	14.4	16.9
Human Toxicity Potential (cancer)	CTUh	1.00E-07	1.10E-07	1.19E-07	4.93E-08	5.92E-08	6.80E-08	1.17E-07	1.41E-07	1.62E-07	9.94E-08	1.23E-07	1.44E-07
Human Toxicity Potential (non-cancer)	CTUh	1.71E-05	1.98E-05	2.23E-05	1.24E-05	1.51E-05	1.76E-05	2.88E-05	3.53E-05	4.11E-05	2.70E-05	3.35E-05	3.93E-05

Indicator	Unit	£20 (Paper) (Low energy)	£20 (Paper) (Default energy)	£20 (Paper) (High energy)	£20 (Polymer) (Low energy)	£20 (Polymer) (Default energy)	£20 (Polymer) (High energy)	£50 (Paper) (Low energy)	£50 (Paper) (Default energy)	£50 (Paper) (High energy)	£50 (Polymer) (Low ATM)	£50 (Polymer) (Default energy)	£50 (Polymer) (High energy)
Acidification Potential	kg SO_2-eq.	1.83E-02	2.20E-02	2.53E-02	1.65E-02	2.02E-02	2.35E-02	4.67E-04	4.70E-04	4.73E-04	2.45E-04	2.49E-04	2.52E-04
Eutrophication Potential	kg PO_4^{3-} eq.	1.91E-03	2.23E-03	2.51E-03	1.46E-03	1.78E-03	2.06E-03	7.41E-05	7.44E-05	7.46E-05	2.34E-05	2.37E-05	2.39E-05
Global Warming Potential (fossil)	kg CO_2-eq.	5.15	6.23	7.19	4.81	5.88	6.84	0.113	0.114	0.114	6.90E-02	6.99E-02	7.08E-02
Global Warming Potential (biogenic)	kg CO_2-eq.	-6.82E-2	-6.71E-2	-6.61E-2	5.34E-03	6.43E-03	7.40E-03	-7.85E-3	-7.85E-3	-7.85E-3	1.39E-04	1.40E-04	1.41E-04
Photochem. Ozone Creation Potential	kg C_2H_4-eq.	9.41E-04	1.15E-03	1.34E-03	1.03E-03	1.24E-03	1.43E-03	1.60E-05	1.62E-05	1.64E-05	2.42E-05	2.43E-05	2.45E-05
Ecotoxicity Potential	CTUeco	3.76	4.34	4.86	2.40	2.97	3.49	0.177	0.178	0.178	1.95E-02	2.01E-02	2.05E-02
Human Toxicity Potential (cancer)	CTUh	2.38E-08	2.87E-08	3.30E-08	2.05E-08	2.53E-08	2.96E-08	5.87E-10	5.91E-10	5.95E-10	1.97E-10	2.01E-10	2.05E-10
Human Toxicity Potential (non-cancer)	CTUh	5.90E-06	7.25E-06	8.44E-06	5.58E-06	6.92E-06	8.11E-06	8.35E-08	8.47E-08	8.58E-08	4.76E-08	4.88E-08	4.98E-08

APPENDIX F: DESCRIPTION OF IMPACT CATEGORIES

GLOBAL WARMING POTENTIAL

In the Earth's atmosphere "greenhouse gases" such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs) act as insulators; keeping the Earth warm by preventing heat from escaping into space. Human activities are resulting in increased emissions of these gases, causing an increase in global temperatures and resulting in climate change which is expected to lead to extremes of weather (floods and droughts) and rising ocean levels.

The contribution of atmospheric emissions to the greenhouse effect can be described in terms of Global Warming Potentials (GWP). The GWP of an emission is a parameter that indicates the extent to which a unit mass of that emission absorbs infrared radiation with respect to a unit mass of CO_2. Emissions to air can thus be converted to CO_2 emissions with an equivalent global warming potential.

ACIDIFICATION POTENTIAL

Emission of nitrogen oxides (NO_x), sulfur oxides (SO_x) and ammonia (NH_3) leads to acidification of the environment and changes in the chemical composition of soil and surface waters. This can lead to large scale damage to vegetation, buildings and human health. In addition to the direct effects on the environment of pH lowering, there may also be indirect effects. These include increasing the mobility of many metal ions in soil such that nourishing elements such as calcium, magnesium, sodium and potassium are leached out, and also leading to liberation of toxic aluminum and heavy metal ions into surface waters.

The contribution of atmospheric emissions to acidification effects in the environment can be described in terms of Acidification Potentials (AP). The AP of an emission is a parameter that indicates the extent to which a unit mass of that emission releases H^+ ions compared to sulfur dioxide. Emissions to air can thus be converted to sulfur dioxide emissions with an equivalent acidification potential.

EUTROPHICATION POTENTIAL

Eutrophication (sometimes called nutrification) is the enrichment of water or soil with nutritive elements. At natural levels, where mineral salts are made available by erosion, this is beneficial to aquatic life. However, over-nutrification, mostly due to phosphates and nitrates introduced by human activities, can result in algal blooms which deoxygenate the water and damage the aquatic ecosystem.

The contribution of various emissions to eutrophication effects can be described in terms of Eutrophication Potentials (EP). The EP of an emission is a parameter that indicates the potential of a unit mass of that emission to form biomass relative to an equivalent emission of phosphate. Emissions to air, water and soil are therefore converted to phosphate emissions with an equivalent eutrophication potential.

PHOTOCHEMICAL OZONE CREATION POTENTIAL

Under certain climatic conditions, air emissions from industry and transportation can be trapped at ground level, where they react with sunlight to produce photochemical smog. This can often be seen above towns and cities on sunny summer days. Ozone is a major component of smog and is produced by the reaction of volatile organic compounds (VOCs) and nitrogen oxides (NO_x). Increased levels of ozone in the troposphere can adversely affect human health and cause damage to plants and crops.

The contribution of atmospheric emissions to the formation of photochemical ozone can be described in terms of Photochemical Ozone Creation Potential (POCP). The POCP of an emission is a parameter that indicates the extent to which a unit mass of that emission forms ozone with respect to a unit mass of ethylene. Emissions to air can thus be converted to ethylene emissions with an equivalent photochemical ozone formation potential.

HUMAN/ECO-TOXICITY POTENTIAL

The emission of many chemicals into the environment can result in toxic effects that damage human and/or ecosystem health. The USEtox methodology has been followed to assess the contribution of toxic emissions to human and eco-toxicity.

Human effect factors in USEtox relate the quantity of a toxic chemical taken in by the population via ingestion and inhalation to the probability of adverse effects (or potential risk) of the chemical in humans. It is based on toxicity data for cancer and non-cancer effects derived from laboratory studies.

The characterisation factor for human toxicity (human toxicity potential) is expressed in comparative toxic units, providing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram). Results are reported separately for cancer and non-cancer causing toxic effects.

The characterisation factor for aquatic ecotoxicity (ecotoxicity potential) is expressed in comparative toxic units and provides an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m^3 day kg^{-1}).

PRIMARY ENERGY DEMAND

Primary energy demand is a measure of the amount of energy taken from nature that has not been subjected to any conversion or transformation process. It can be renewable (e.g. solar energy) or non-renewable (e.g. energy in coal or oil).

The total energy usage is quoted in terms of MJ (net calorific value). This assessment accounts for both feedstock energy (energy inherent in the material, such as plastics) and process fuel energy requirements (energy required to manufacture a product).

Energy use is not strictly an environmental impact—it is not a direct measure of environmental damage—but it correlates well with many environmental issues such as resource consumption and atmospheric pollution, and this makes it a useful indicator. For example fossil fuels are non-renewable resources and their combustion contributes to other impacts such as global warming, acidification and photochemical oxidant formation.

Care must be taken when selecting energy use as an environmental indicator because different energy sources can have very different environmental impacts, e.g. a wind turbine vs. a coal-fired power station. It is therefore advisable to consider whether the energy source is renewable or non-renewable.

WATER CONSUMPTION

Water is a renewable resource and in general (barring chemical reactions) it is neither created nor destroyed. However it may change from one form to another (liquid water, vapour/steam or ice) or change quality (i.e. become polluted).

In this assessment net water use is calculated in a simple fashion based on dissipative consumption. This is a measure of water taken from the environment that is not available for immediate reuse in the local watershed (i.e. water that is lost to atmosphere as steam or water vapour or that becomes embodied in the product).

In the nomenclature of water footprinting, all the water assessed in this study can be considered to be “blue” water, i.e. water sourced from rivers, lakes or aquifers.

Water quality has not been assessed.

APPENDIX G: CRITICAL REVIEW

REVIEW PROCESS

This LCA study has undergone critical review by a panel of external experts. This has comprised a two-part review as follows:

- Goal and Scope Definition document – at the start of the project the panel reviewed the Goal and Scope Definition document for the study. Comments regarding this document were reviewed with the project team in a telephone conference.
- Draft Final Study Report – at the end of the project the critical review panel reviewed the Final Study Report. Comments relating to this draft report were received by the author who prepared a detailed written response and made adjustments to the report as necessary. A final draft version of the report was then circulated and approved by the critical review panel.
- Critical Review Statement - the Chair of the Critical Review Panel prepared a critical review statement which assimilates the views of all the reviewers regarding the quality of the study. This can be found in the following section of this report.

The LCA model developed using GaBi 6 has not been reviewed by the panel but has undergone rigorous internal QA at PE by senior consultants who have had no previous involvement with the project.

BIOGRAPHIES OF CRITICAL REVIEWERS

Professor Adisa Azapagic (University of Manchester) (Panel Chair)

Adisa Azapagic *FREng FIChemE FRSC FRSA HonFSE* is professor of Sustainable Chemical Engineering at the University of Manchester. She obtained both her Dipl. Eng. and MSc degrees from University of Tuzla (Bosnia) and a PhD from University of Surrey (England). She leads the Sustainable Industrial Systems group, an internationally-leading research group applying the principles of sustainable development and life cycle thinking in industrial practice. Her research interests include life cycle sustainability assessment, carbon footprinting, sustainable production and consumption, and corporate sustainability.

This critical review has been carried out in a personal capacity and does not represent the views of the University of Manchester.

Erik Balodis (Bank of Canada)

Erik has been with the Bank of Canada for six years and holds a Master’s of Science in Physical Chemistry from the University of Guelph, in Ontario, Canada. As a Scientific Adviser at the Bank of Canada, Erik has worked on a number of projects in bank note technology research and development, security assessment, materials testing and bank note lifecycle topics.

Erik’s current responsibilities include:

- Development of new test methods for the evaluation of bank note durability
- Evaluation of note wear and root-cause analysis of wear mechanisms
- Development of security assessment methods and frameworks
- Analysis of counterfeit methods

In the past, he has worked on:

- The design and implementation of durability testing schemes for new note series
- Perception testing methods for the evaluation of bank note security and usability
- Dashboarding of various security-related topics for wider use

Erik's Master's work focussed on the analysis of biomolecules at high temperatures and pressures. He has been published in peer-reviewed scientific literature, and in bank-note industry publications and conference proceedings

Michael Sturges (Innventia)

Michael has over fifteen years of experience in providing life cycle assessment and related consultancy services to a variety of industry sectors, but with a specific emphasis on the paper, packaging, printing and publishing supply chains. During this time, Michael has delivered more than fifty major LCA and related studies, acting in all roles including life cycle practitioner, project manager, project director and critical reviewer. As well as LCA modelling, his experience includes data collection, data quality evaluation and developing and implementing new methodology approaches and impact assessment categories. This critical review was undertaken in his capacity as a consultant with the Innventia Group. Innventia AB is one of the world's leading R&D companies in the fields of pulp & paper, biorefining, packaging and graphics media. Michael is responsible for Innventia's environmental and sustainability activities in the UK, including LCA, carbon footprinting and corporate sustainability reporting.