What has a lower environmental impact? Digital versus traditional reading: a comparative LCA

LCA - Report

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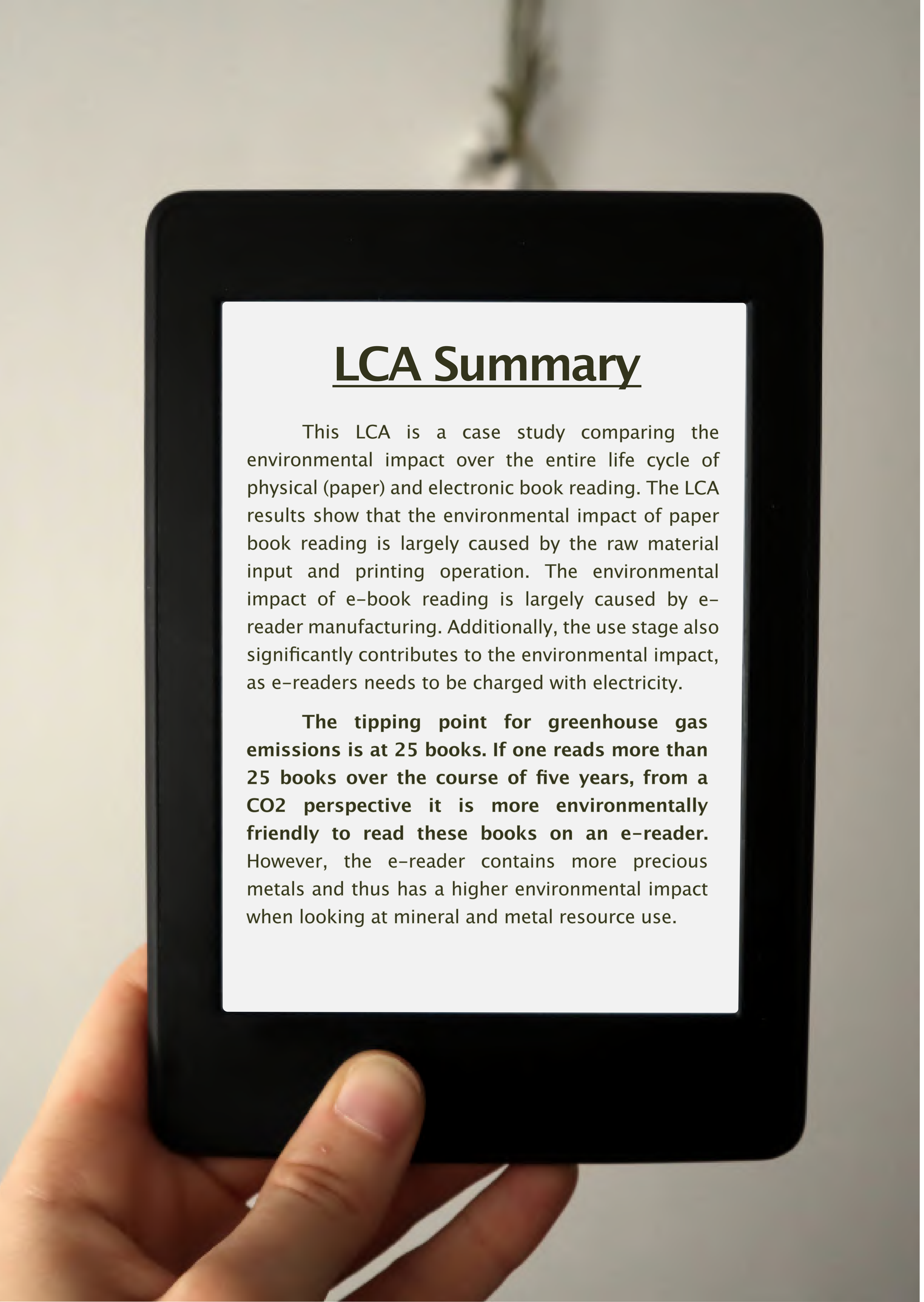

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Introduction

This LCA study was carried out on behalf of the Hedgehog Company and was drawn up by Saro Campisano, Rik Wessels and Joost Walterbos of Hedgehog Company. This report was written on 16-07-2021 and meets the requirements of NEN-EN ISO 14040 [1] and NEN-EN ISO 14044 [2]. For the LCA calculations Mobius version 0.8.638 is used, a LCA software developed by Ecochain Technologies. Results of LCA studies measuring other reading options and the resulting Environmental Product Declarations (EPDs) are only comparable if they comply with the same calculation method used in this LCA.

Goal and Scope Definiton

2.1 Goal

The aim of this study is to generate a reliable and accurate overview of two alternative reading options. This study measures the direct environmental impact of the production, the use and the end-of-life stage of these two reading methods. Thus, the overall objective of this study is:

- Quantifying and comparing the environmental impact of the production, use and end-of-life of reading books by making use of physical books and an electronic reader (i.e. e-reader)

The results of this study can be used to support environmental conscious consumers in their decision between reading books or e-books on an e-reader. Hence, the target audience consists of those interested in life cycle assessment and the environmental impact of reading. It must be noted that the data in this research is not supplier specific and is based on general databases and desk research. It gives an average view in the comparison between books and e-readers, but results can differ when comparing specific suppliers of both products.

2.2 Scope

The following section describes the scope of this study. This contains, but is not limited to, identifying the different product systems, the product function and functional unit, the system boundaries, allocation procedures and cut-off criteria.

2.2.1 Functional unit

In order to compare reading physical books with its electronic alternative it is important to identify the appropriate functional unit. The function studied in this LCA is that of reading a book. With one e-reader however, one can read more than one book. The impact of production and use of the e-reader should thus be divided over the amount of books that are read over the course of its lifetime.

In this case study, it is assumed that the average reader reads approximately two books of 300 pages per month. This adds up to 24 books over one single year. On the other hand, an e-reader device has a lifetime of approximately five years. In these five years, one person could then read a total of 120 books. Hence in order to take into account the lifetime of the e-reader, the functional unit used in this study is: reading 120 physical books and reading 120 books with an e-reader over the course of five years.

2.2.2 System boundaries

In order to accurately compare the two alternatives, the environmental impact needs to be quantified over the whole life cycle. Thus, the processes that are covered in this study are all life cycle stages from cradle to grave: the production, use and disposal of the two reading alternatives (see figure 1 and 2).

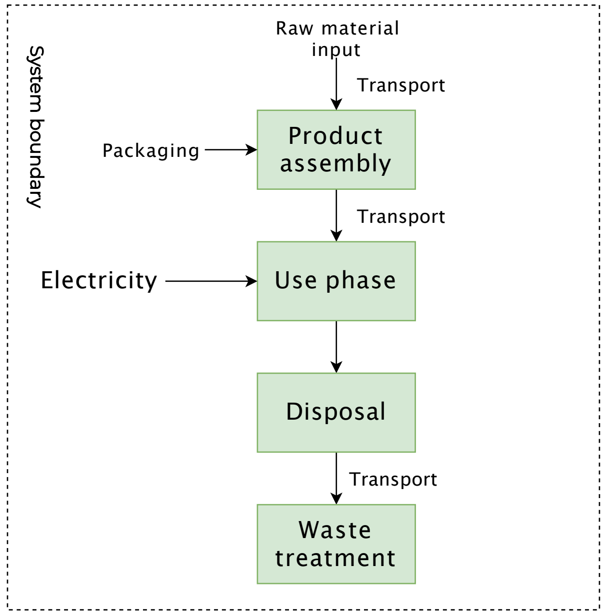


Figure 1: Flow chart e-reader life cycle

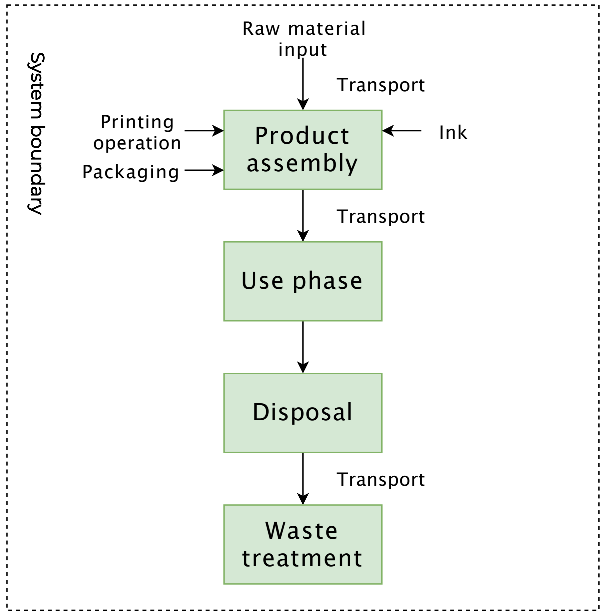


Figure 2: Flow chart book life cycle

The geographical coverage of this study comprises China and Europe. E-readers are generally manufactured in China and transported by ship to end-markets (Kozlowski, 2020). On the other hand, physical books are printed in any country. For the sake of this study, the final end-user is Dutch, and thus European and country specific data are collected where possible.

The coverage starts from the production of the initial raw material input. When collected, the materials are manufactured into either physical books, or into an e-reader. Afterwards, both products are transported to a distribution center in the Netherlands. From there, the reading alternatives are directly transported to the end-user.

For the physical books, the use phase does not result in any environmental impact, as reading in itself does not require any material or energy input into the book.

For the e-reader, the use phase consists of electricity use in the form of charging the device, and downloading e-books to read.

When disposed of, the material components of both the physical books and the e-reader are separated and treated according to the standard waste treatment procedures of the Netherlands, based on the SBK Bepalingsmethode[1]. The SBK Bepalingsmethode is aimed at conducting LCAs for the Dutch construction sector, however its waste scenarios are considered relevant for this study.

2.2.3 Impact assessment method

This study uses the impact categories from the EF Impact Assessment Method. This impact assessment method is the result of the Product Environmental Footprint (PEF) Initiative and offers a standard for impact assessment, so it is easier and more meaningful to compare products.

[1] https://milieudatabase.nl/milieuprestatie/bepalingsmethode/

Life Cycle Inventory

3.1 Data collection method

As this LCA is conducted as a comparative LCA without specific supplier data, the data is collected through desk research only. No e-reader manufacturers or printing offices were asked to provide data. This study aims to demonstrate the average difference between the environmental impact of reading physical books compared to making use of an e-reader. Data from literature serves as the basic input for defining the system boundaries and getting an overview of the required inputs in both product systems. Based on this information, relevant processes of the Nationale Milieu Database (v3.1) and Ecoinvent (v3.6) are selected. The selected processes are described in detail in section 4.2.

3.2 Inventory and allocation

3.2.1 E-reader

3.2.1.1 Production stage

The product composition of an e-reader is based on Babbitt et al. (2020). In addition to an e-reader, one needs a charger in order to make use of the device. Therefore, the material composition of a charger is based on data from research of Sangprasert & Pharino (2013), that includes mobile phone charger data. It is assumed that e-reader chargers are produced from similar materials. Due to limited data availability, energy inputs for processes other than material preparation are not considered in this study. It is assumed most of the environmental impact is stemming from the materials and the production of these materials, whereas the environmental impact of assembling an e-reader is neglectable.

Table 1: Bill of materials for an average e-reader device and complementary charger.

Material	Charger	E-reader
Plastic (PVC)	10,63	103,68
Steel	2,09	14,86
Carbon	0,41	-
Rubber	0,56	-
Copper	0,02	1,29
Iron	1,48	-
LCD	4,23	-
Aluminium	5,88	19,70
Integrated Circuit Board	1,41	-
Inductor	1,78	-
PWB	13,45	39,08
Li-ion battery	-	66,86
Flat panel glass	-	52,33
Other glass	-	17,12
Zinc	-	7,11
Totaal	**41,93**	**322,03**
Cardboard packaging weight (g)		200
Total distribution weight (g)		**563,96**

3.2.1.2 Transport

After production, the e-reader and complementary charger are shipped by ship from China to Rotterdam. In this study it is assumed that the total shipping distance for the average e-reader is approximately 19.500 km. This is the sea distance between Shanghai and Rotterdam (sea-distances.org, 2021). From the port of Rotterdam, the e-readers are transported with lorries to a distribution center covering an average distance of 100 km. From this distribution center, it is assumed that the e-reader is directly shipped to the end-user by making use of a light commercial vehicle, over an average distance of 2 km. This distance is the assumed average distance per package per driving route of the commercial vehicle. In order to protect the products during distribution, the e-readers and chargers are placed in cardboard boxes with a weight of 200 grams.

3.2.1.3 Use

The use phase of an e-reader consists of charging the device and downloading e-books to read on the device, using the Dutch electricity mix. An average 1.500 mAh battery of an e-reader uses approximately 345 Wh for a full charge. In this defined system, it is assumed that a full charge lasts for two weeks. Thus, in order to read two books per month, one needs to charge their device twice. The electricity used to download the e-books is covered by the energy use of the modem (Moberg, Borggren & Finnveden, 2010). The energy consumption related to the data server is outside the scope of this research. It is assumed that the average time it takes to download the e-book is 5 minutes. Over five years this accounts to a total energy consumption for downloading of 0,09 kWh.

3.2.1.4 End-of-Life

The end-of-life phase consists of the disposal - the waste processing - and the loads and benefits the recycling and incineration of the product have outside the system boundary. Electronic devices often contain valuable materials that can be recovered. In reality however, these devices are not always disposed of properly. On several occasions, these devices 'collect dust in drawers' or are directly thrown out in municipal waste bins at the end-of-life stage. Therefore, we assume that approximately 75% of the e-readers and complementary chargers are disposed of in the correct way, so that valuable materials can be recovered. We assume that the metals are fully recovered, and that the battery and electronic circuit boards are treated according to the representative treatment processes for these materials. By making use of the SBK Bepalingsmethode, we can then calculate the amount of metals that are saved due to end-of-life treatment. These recycled materials thus prevent the use of virgin materials in the next lifecycle.

Other materials, as well as the 25% that is not correctly disposed are assumed to be incinerated with energy recovery. The avoided energy inputs are accounted for by applying a 85-15 split for avoided fossil and renewable energy production respectively, as this is representative of the Dutch energy mix (EBN, 2019). The transport distance to the appropriate treatment facilities is assumed to be 50 km.

3.2.2 Physical book

3.2.2.1 Production stage

An average book of 300 pages weighs approximately 440 grams (Reference.com, 2020). If we assume that the pages of this book are in A5-format, and printed on regular 80 g/m2 paper, we can determine the weight of the pages that are printed (Table 2).

The paper that goes into the books is printed with ink. A 7ml ink cartridge can print approximately 800 pages, thus a total of 2,625 ml ink is required for each book (HP, 2021). The electricity consumption of Scandinavian advanced industrial printers is 2.100 kWh per tonne of product (Nordic Ecolabel, 2021). It is assumed that this technology is representative for the Dutch printing industry. Due to data availability, this study only considers the electricity use during printing. All other energy inputs in the book manufacturing process are excluded from this LCA.

3.2.2.2 Transport

It is assumed that the books are manufactured in the Netherlands. Thus, the transport distance from the producer to the book store is set at 100 km. From there, the books are transported by light commercial vehicles to the end-users over a distance of 2 km. In order to protect the products during distribution, the books are placed in cardboard boxes with a weight of 200 grams.

The use phase of reading a physical book is free from emissions in the defined product system. Potential energy consumption of a night light could be included, however this is cut-off in this analysis since this energy consumption is assumed insignificant. Hence, no material or energy inputs are required in this stage.

3.2.2.4 End-of-Life

The end-of-life phase consists of the disposal - the waste processing - and the loads and benefits the recycling and incineration of the product have outside the system boundary. After the book is read, it is assumed that it is disposed of. After disposal, the books as well as packaging are transported to the appropriate treatment facilities over a distance of 50 km. In the Netherlands, approximately 90% of the paper waste is recycled (PRN, 2021).

Based on literature study it is assumed recycled paper replaces wood chips in the production process of virgin paper. Therefore the amount of wood chips that are saved due to end-of-life treatment is calculated, as wood chips are one of the base materials for pulp in paper production. The other 10% is incinerated in a waste-to-energy plant. The avoided energy inputs are accounted for by applying a 85-15 split for avoided fossil and renewable energy production respectively, as this is representative of the Dutch energy mix (EBN, 2019). The transport distance to the appropriate treatment facilities is assumed to be 50 km.

Table 2: Dimensions and weight distribution of an average reading book. Based on assumptions.

Variable	Amount	Unit
Amount of pages	300	pages
Weight of book	440	g
Size of book	A5 (148 x 210 mm)	standard
Weight of printed paper in reading books	80	g/m2
Weight of paper	372,96	g
Weight of cover	67,04	g

Data validation

4.1 Data quality

4.1.1 Representativeness

The used database references for the e-reader are representative for the geographical area of Asia, as the devices are mainly produced in China. Further downstream processes take place in the Netherlands and are covered by European and Dutch references. The used references for the physical books are representative for the geographical area of the Netherlands. All processes are covered by European or Dutch references.

4.1.2 Consistency check

The quantitative data and process descriptions as described in this study are presented in such a way that they are fully reproducible and adaptable to more specific cases. Used references are selected based on the production location and adequate transport distances are estimated to match the defined system boundaries for this case study.

4.2 Qualitative and quantitative description of processes, scenarios and sources

This paragraph describes all background processes that are used to perform this LCA. Table 3 describes which references are selected for each emission source, from which database this reference is collected and why this reference is selected. All references are selected from the Nationale Milieudatabase v3.1 and Ecoinvent v3.6.

Table 3: Selected references for all emissions sources of both product systems.

Emission source	Reference	Database	Argumentation
	Physical book		
Paper, virgin material	paper production, woodfree, uncoated, at non-integrated mill | paper, woodfree, uncoated [RER]	Ecoinvent v3.6	Most representative reference, accounted for EoL recycling as described in 3.2.2.4.
Ink	market for printing ink, offset, without solvent, in 47.5% solution state | printing ink, offset, without solvent, in 47.5% solution state [RER]	Ecoinvent v3.6	Most representative reference
Printing operations	market for electricity, low voltage | electricity, low voltage [NL]	Ecoinvent v3.6	Most representative reference
Packaging	containerboard production, fluting medium, recycled | containerboard, fluting medium [RER]	Ecoinvent v3.6	Most representative reference
Transport to bookstore	transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 [RER]	Ecoinvent v3.6	Most representative reference
Transport to end-user	market for transport, freight, light commercial vehicle | transport, freight, light commercial vehicle [RER]	Ecoinvent v3.6	Most representative reference
Transport to treatment facilities	market for transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 [RER]	Ecoinvent v3.6	Most representative reference, accounted for EoL recycling as described in 3.2.2.4.
Treatment of waste paper	market for waste graphical paper | waste graphical paper [RER]	Ecoinvent v3.6	Most representative reference, accounted for EoL recycling as described in 3.2.2.4.
Avoided energy production renewable	0267-avD&Vermeden energieproductie AVI, o.b.v. FOSSIELE grondstoffen, 18% elektrisch en 31% thermisch (per MJ LHV)	Nationale Milieudatabase v3.1	Most representative reference, accounted for EoL treatment as described in 3.2.2.4.
Avoided energy production fossil	0268-avD&Vermeden energieproductie AVI, o.b.v. HERNIEUWBARE grondstoffen, 18% elektrisch en 31% thermisch (per MJ LHV)	Nationale Milieudatabase v3.1	Most representative reference, accounted for EoL treatment as described in 3.2.2.4.
Avoided wood chip production	0276-reD&Module D, houtspaanders, per kg NETTO geleverd (o.b.v. Wood chips, dry, measured as dry mass {RER}| three layered laminated board production | Cut-off) [NL]	Nationale Milieudatabase v3.1	Most representative reference, accounted for EoL treatment as described in 3.2.2.4.
	E-reader		
Aluminium, primary	market for aluminium, cast alloy | aluminium, cast alloy [GLO]	Ecoinvent v3.6	Most representative reference
Flat panel glass	section bar extrusion, aluminium | section bar extrusion, aluminium [RoW]	Ecoinvent v3.6	Most representative reference for aluminium extrusion
Battery Li-ion	battery production, Li-ion, rechargeable, prismatic | battery, Li-ion, rechargeable, prismatic [GLO]	Ecoinvent v3.6	Most representative reference
Flat panel glass	market for flat glass, uncoated | flat glass, uncoated [RoW]	Ecoinvent v3.6	Most representative reference
Glass (other)	flat glass production, coated | flat glass, coated [RoW]	Ecoinvent v3.6	Most representative reference
Copper	copper production, primary | copper [Asia]	Ecoinvent v3.6	Most representative reference
Carbon black	carbon black production | carbon black [GLO]	Ecoinvent v3.6	Most representative reference
Iron	pig iron production | pig iron [RoW]	Ecoinvent v3.6	Most representative reference
Inductor	inductor production, low value multilayer chip | inductor, low value multilayer chip [GLO]	Ecoinvent v3.6	Most representative reference
Integrated Circuit board	integrated circuit production, logic type | integrated circuit, logic type [GLO]	Ecoinvent v3.6	Most representative reference
LCD	liquid crystal display production, minor components, auxilliaries and assembly effort | liquid crystal display, minor components, auxilliaries and assembly effort [GLO]	Ecoinvent v3.6	Most representative reference
Printed Wiring Board	printed wiring board production, mounted mainboard, laptop computer, Pb free | printed wiring board, mounted mainboard, laptop computer, Pb free [GLO]	Ecoinvent v3.6	Most representative reference
PVC	polyvinylchloride production, emulsion polymerisation | polyvinylchloride, emulsion polymerised [RoW]	Ecoinvent v3.6	Most representative reference
	injection moulding | injection moulding [RoW]	Ecoinvent v3.6	Most representative reference, for injection moulding of plastics
Rubber	synthetic rubber production | synthetic rubber [RoW]	Ecoinvent v3.6	Most representative reference
Steel	steel production, converter, unalloyed | steel, unalloyed [RoW]	Ecoinvent v3.6	Most representative reference
Transport China to NL (ship)	hot rolling, steel | hot rolling, steel [RoW]	Ecoinvent v3.6	Most representative reference for steel rolling
Zinc	primary zinc production from concentrate | zinc [RoW]	Ecoinvent v3.6	Most representative reference
Transport China to NL (ship)	transport, freight, sea, transoceanic tanker | transport, freight, sea, transoceanic tanker [GLO]	Ecoinvent v3.6	Most representative reference
Transport from port to store	transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 [RER]	Ecoinvent v3.6	Most representative reference
Packaging, recycled	containerboard production, fluting medium, recycled | containerboard, fluting medium [RER]	Ecoinvent v3.6	Most representative reference
Electricity, for downloading and charging	market for electricity, low voltage | electricity, low voltage [NL]	Ecoinvent v3.6	Most representative reference
Transport to end-user	market for transport, freight, light commercial vehicle | transport, freight, light commercial vehicle [RER]	Ecoinvent v3.6	Most representative reference
Incorrect disposal, for incineration	treatment of municipal solid waste, incineration | municipal solid waste [NL]	Ecoinvent v3.6	Most representative reference
Net loss aluminium	market for aluminium, primary, ingot | aluminium, primary, ingot [EU27 and EFTA]	Ecoinvent v3.6	Most representative reference
Transport to waste treatment facility	transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 [RER]	Ecoinvent v3.6	Most representative reference
Avoided energy production renewable	0267-avD&Vermeden energieproductie AVI, o.b.v. FOSSIELE grondstoffen, 18% elektrisch en 31% thermisch (per MJ LHV)	Nationale Milieudatabase v3.1	Most representative reference, accounted for EoL treatment as described in 3.2.1.4.
Avoided energy production fossil	0268-avD&Vermeden energieproductie AVI, o.b.v. HERNIEUWBARE grondstoffen, 18% elektrisch en 31% thermisch (per MJ LHV)	Nationale Milieudatabase v3.1	Most representative reference, accounted for EoL treatment as described in 3.2.1.4.
Avoided iron/steel production	0282-reD&Module D, staal, per kg NETTO geleverd schroot (vermeden: Pig iron {GLO}| production | Cut-off, U)	Nationale Milieudatabase v3.1	Most representative reference, accounted for EoL treatment as described in 3.2.1.4.
Avoided copper production	0277-reD&Module D, koper, per kg NETTO geleverd schroot (vermeden: Copper {RER}| production, primary | Cut-off, U)	Nationale Milieudatabase v3.1	Most representative reference, accounted for EoL treatment as described in 3.2.1.4.

Life Cycle Impact Assessment

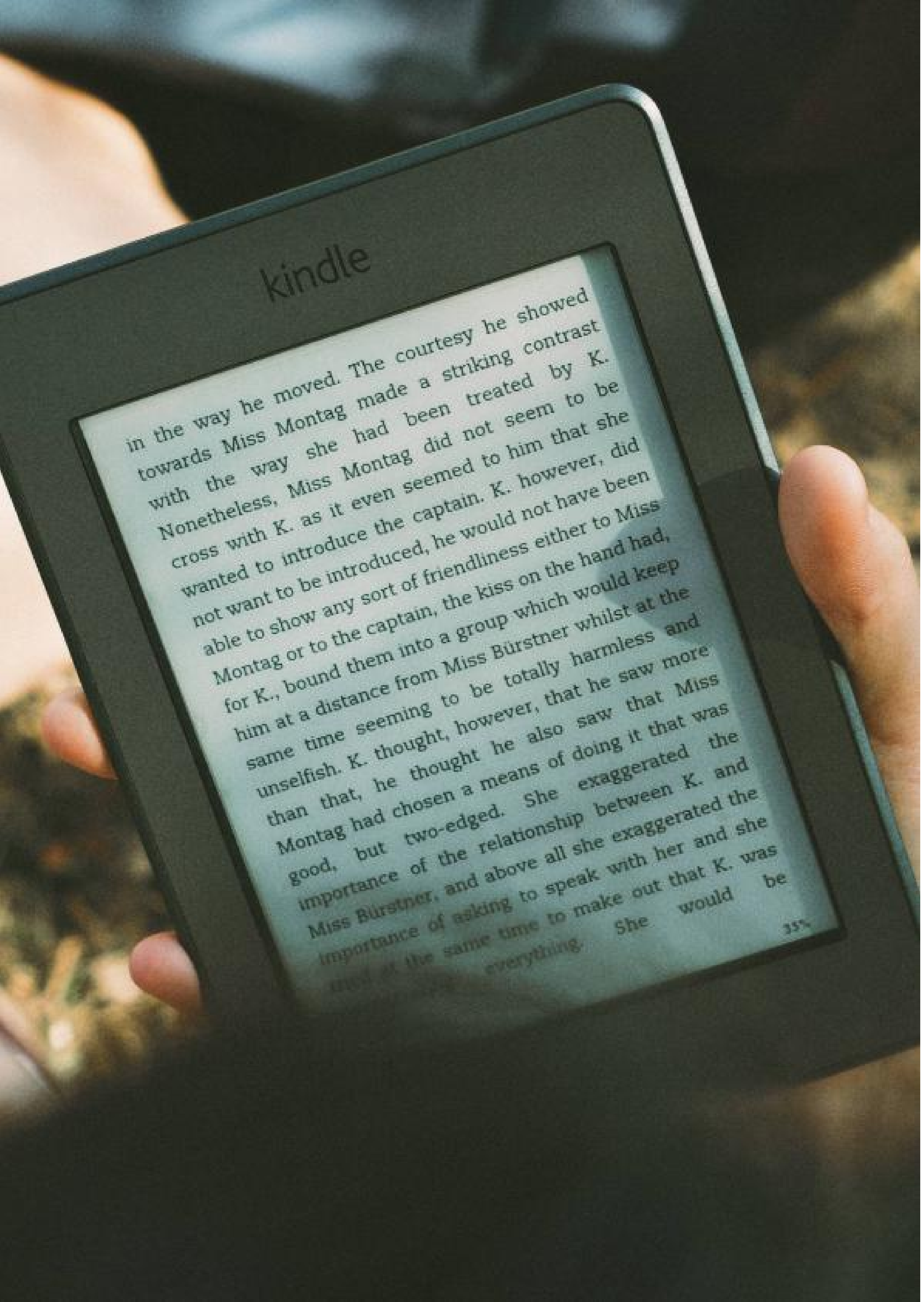
This chapter shows the results of the LCA calculation. The used EF Impact Assessment Method consists of several impact categories. The results of the calculations are presented in section 5.1. The results are divided over three life cycle stages: production, use and end-of-life. Transport emissions from manufacturing all the way to the point that the final products are delivered at the electrical hardware- or bookstore are classified under the production stage. The use phase consists of both the use and the transport from the store to the end-consumer. End-of-Life includes all emissions due to transportation, treatment of waste materials and the saved environmental impact of recycling the materials. The latter explains the negative value under End-of-Life for several indicators since with recycling the extraction of raw materials for a new life cycle is avoided.

Table 4: Characterisation results of one functional unit of the e-reader product alternative: reading 120 e-books in five years.

Impact category name	Reference unit	Production	Use	End Of Life	Total
Climate change	kg CO2 eq	2,50E+01	2,70E+01	1,72E-01	5,23E+01
Climate change - Fossil	kg CO2 eq	2,49E+01	2,70E+01	1,72E-01	5,21E+01
Climate change - Biogenic	kg CO2 eq	7,68E-02	7,24E-02	1,92E-04	1,49E-01
Climate change - Land use and LU change	kg CO2 eq	4,36E-02	7,96E-03	2,56E-04	5,18E-02
Ozone depletion	kg CFC11 eq	2,23E-06	1,31E-06	1,19E-08	3,55E-06
Human toxicity, cancer	CTUh	2,08E-08	6,17E-09	1,27E-09	2,83E-08
Human toxicity, cancer - metals	CTUh	1,57E-08	3,99E-09	3,09E-11	1,98E-08
Human toxicity, cancer - organics	CTUh	5,07E-09	2,18E-09	1,24E-09	8,49E-09
Human toxicity, cancer - inorganics	CTUh	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Human toxicity, non-cancer	CTUh	1,11E-06	2,01E-07	-2,55E-09	1,31E-06
Human toxicity, non-cancer - metals	CTUh	9,81E-07	1,80E-07	-2,61E-09	1,16E-06
Human toxicity, non-cancer - organics	CTUh	5,87E-08	6,66E-09	-2,41E-10	6,51E-08
Human toxicity, non-cancer - inorganics	CTUh	7,82E-08	1,73E-08	2,96E-10	9,57E-08
Particulate matter	disease inc.	1,24E-06	2,07E-07	3,47E-09	1,45E-06
Ionising radiation	kBq U-235 eq	1,26E+00	7,31E-01	3,91E-03	1,99E+00
Photochemical ozone formation	kg NMVOC eq	9,78E-02	4,10E-02	6,05E-05	1,39E-01
Acidification	mol H+ eq	1,91E-01	6,30E-02	7,72E-05	2,55E-01
Eutrophication, terrestrial	mol N eq	3,78E-01	1,66E-01	3,44E-04	5,44E-01
Eutrophication, freshwater	kg P eq	4,90E-03	1,54E-03	-1,11E-05	6,43E-03
Eutrophication, marine	kg N eq	3,30E-02	1,35E-02	2,04E-05	4,65E-02
Ecotoxicity, freshwater	CTUe	2,36E+03	3,59E+02	-2,73E+00	2,72E+03
Ecotoxicity, freshwater - metals	CTUe	2,04E+03	3,34E+02	-4,14E+00	2,37E+03
Ecotoxicity, freshwater - organics	CTUe	4,28E+00	1,05E+00	8,85E-03	5,33E+00
Ecotoxicity, freshwater - inorganics	CTUe	3,17E+02	2,38E+01	1,40E+00	3,43E+02
Land use	Pt	1,21E+02	7,27E+01	3,30E-01	1,94E+02
Water use	m3 depriv.	5,80E+00	2,72E+00	3,84E-02	8,56E+00
Resource use, fossils	MJ	3,15E+02	3,54E+02	7,09E-02	6,69E+02
Rescource use, minerals and metals	kg Sb eq	1,20E-02	1,09E-04	-3,71E-05	1,21E-02

Table 5: Characterisation results of one functional unit of the physical book product alternative: reading 120 physical books over five years.

Impact category name	Reference unit	Production	Use	End Of Life	Total
Climate change	kg CO2 eq	1,52E+02	2,87E-01	-1,08E-01	1,53E+02
Climate change - Fossil	kg CO2 eq	1,50E+02	2,86E-01	-1,45E+00	1,49E+02
Climate change - Biogenic	kg CO2 eq	1,63E+00	2,68E-04	1,36E+00	2,99E+00
Climate change - Land use and LU change	kg CO2 eq	1,12E+00	1,74E-04	-2,00E-02	1,11E+00
Ozone depletion	kg CFC11 eq	1,46E-05	5,97E-08	-2,05E-07	1,45E-05
Human toxicity, cancer	CTUh	7,42E-08	4,57E-10	1,16E-09	7,58E-08
Human toxicity, cancer - metals	CTUh	3,97E-08	9,25E-11	1,05E-09	4,08E-08
Human toxicity, cancer - organics	CTUh	3,45E-08	3,65E-10	1,05E-10	3,50E-08
Human toxicity, cancer - inorganics	CTUh	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Human toxicity, non-cancer	CTUh	1,78E-06	5,82E-09	-5,76E-11	1,78E-06
Human toxicity, non-cancer - metals	CTUh	1,38E-06	3,30E-09	1,38E-08	1,40E-06
Human toxicity, non-cancer - organics	CTUh	6,73E-08	1,81E-10	1,09E-09	6,85E-08
Human toxicity, non-cancer - inorganics	CTUh	3,40E-07	2,35E-09	-1,52E-08	3,27E-07
Particulate matter	disease inc.	8,20E-06	2,87E-08	-4,44E-07	7,78E-06
Ionising radiation	kBq U-235 eq	6,63E+00	1,94E-02	-1,93E-01	6,46E+00
Photochemical ozone formation	kg NMVOC eq	4,22E-01	1,74E-03	1,83E-03	4,25E-01
Acidification	mol H+ eq	6,67E-01	1,62E-03	-8,33E-03	6,61E-01
Eutrophication, terrestrial	mol N eq	1,87E+00	5,38E-03	-1,42E-02	1,86E+00
Eutrophication, freshwater	kg P eq	1,06E-02	4,84E-06	-1,88E-04	1,05E-02
Eutrophication, marine	kg N eq	1,79E-01	4,80E-04	6,01E-04	1,80E-01
Ecotoxicity, freshwater	CTUe	6,59E+03	4,65E+00	-6,88E-01	6,59E+03
Ecotoxicity, freshwater - metals	CTUe	6,11E+03	3,52E+00	-9,30E+00	6,10E+03
Ecotoxicity, freshwater - organics	CTUe	1,70E+02	2,34E-01	2,44E-01	1,71E+02
Ecotoxicity, freshwater - inorganics	CTUe	3,14E+02	8,96E-01	8,25E+00	3,23E+02
Land use	Pt	1,04E+04	2,00E+00	-4,26E+01	1,03E+04
Water use	m3 depriv.	1,65E+02	1,79E-02	-1,31E+00	1,64E+02
Resource use, fossils	MJ	2,17E+03	4,25E+00	-5,41E+01	2,12E+03
Rescource use, minerals and metals	kg Sb eq	2,08E-03	6,51E-06	1,28E-04	2,22E-03



5.2 Relative impact

For comparison purposes, Figure 3 visualizes the relative impact of the studied alternatives on the used impact categories. When 120 physical books are compared with reading 120 books on an e-reader, it can be observed that reading physical books comes with higher environmental impact for most impact categories. The e-reader has a higher impact on mineral and metal resource use and freshwater ecotoxicity from inorganics.

If we zoom in on the climate change impact category specifically, the impact of reading 120 physical books is approximately three times as high as for the e-reader alternative. If you directly compare the two systems, you should also account for the fact that the e-reader needs to be charged less, which results in lower CO2 emissions. When someone reads more than 25 books in five years, it is more environmentally friendly from a CO2 emission perspective to read these books on an e-reader. When someone reads less than these 25 books, one can better choose the physical alternative.

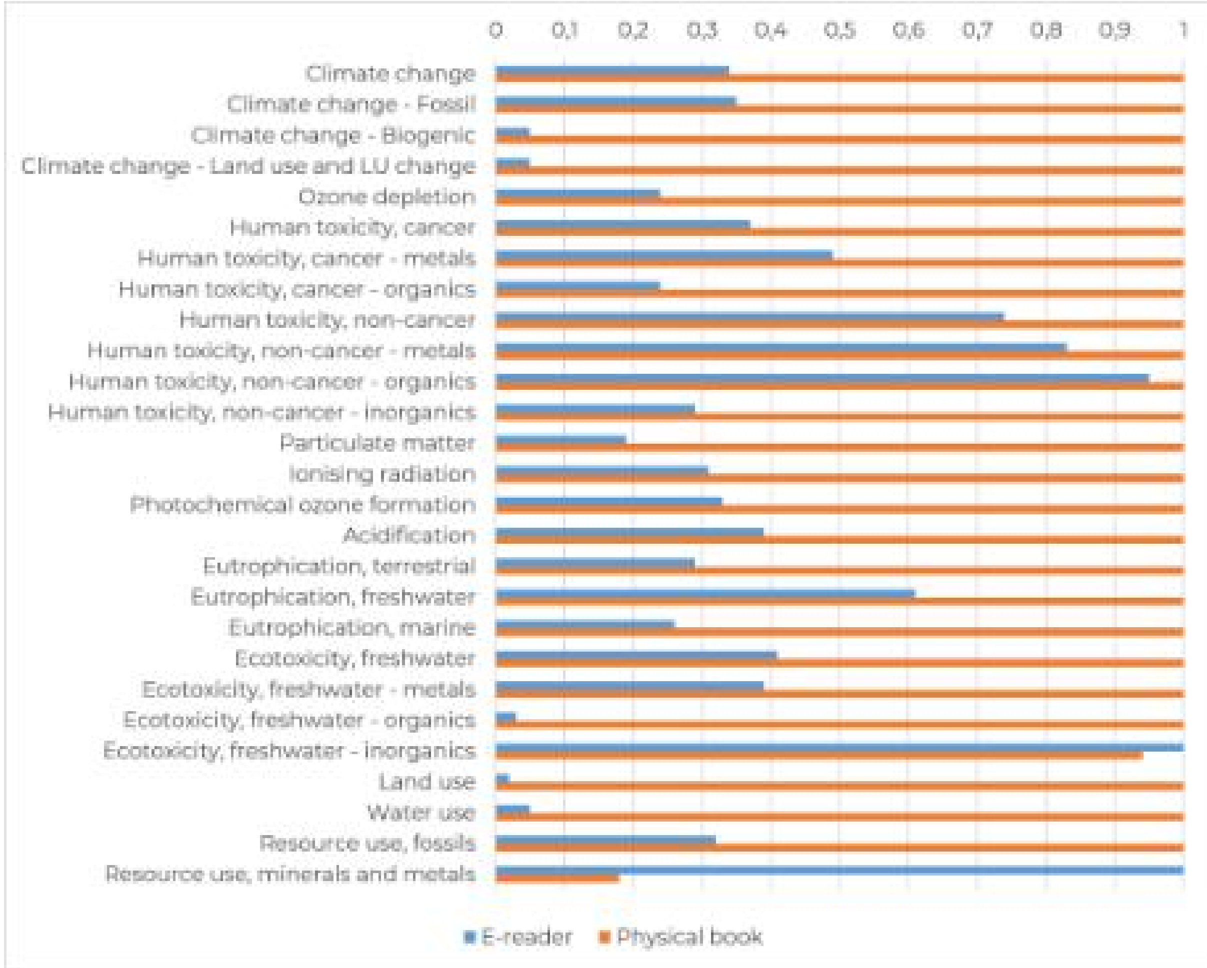


Figure 3: Relative impact of the studied alternatives.

Interpretation

In this chapter the results of the LCA are further analysed with a contribution analysis in section 6.1. Additionally in section 6.2, a sensitivity analysis is performed.

6.1 Contribution analysis

In order to get a better understanding of which processes cause the environmental emissions for both product alternatives, a contribution analysis is made. By tracing the emissions back to the emissions source we can get a better understanding of the hot-spots in the production process of both alternatives.

Figure 4 shows the contribution analysis of the e-reader alternative. Concludingly, the production stage is the highest contributor to almost all environmental impact categories. Only for the 'climate change', 'climate change – fossil' and 'resource use, fossil' impact categories the use stage is a higher contributor. This is likely due to the fact that the use stage comprises the electricity used for charging, using the Dutch electricity mix. The current Dutch electricity mix is based on fossil fuels to a large extent.

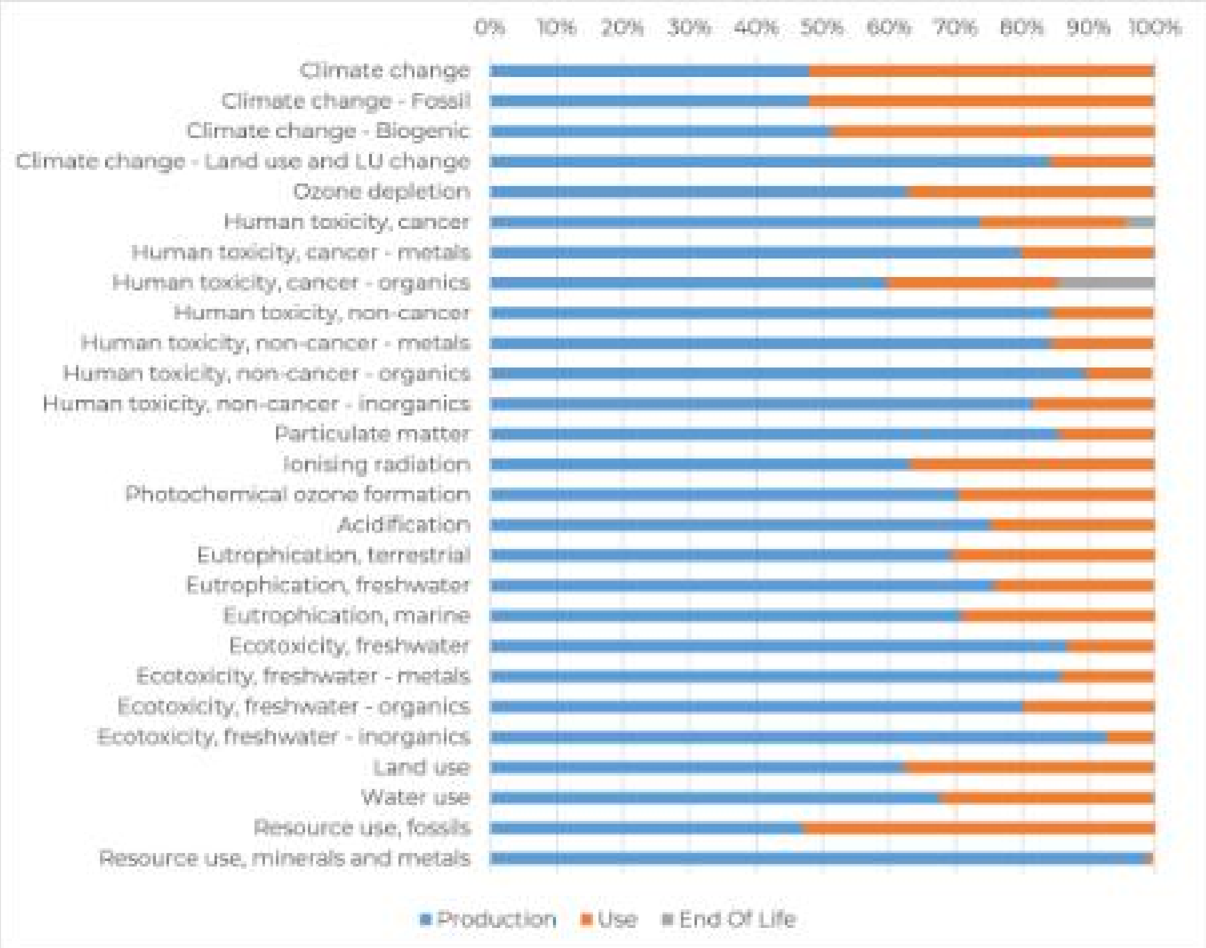


Figure 4: Contribution analysis of the environmental emissions of the e-reader life cycle.

For the physical book alternative, there are no emissions caused by the use phase. Therefore, to get a better overview of the sources for the environmental impact of the physical book alternative, we zoom in into all the material and process inputs. From Figure 5 can be observed that the emissions are largely caused by the virgin material input for paper. Additionally, the cardboard boxes used for packaging and printing operations take up a large share in the emissions for most impact categories.

Since the paper is recycled at the end-of-life, new pulp paper can be produced from this material. Thus, as pulp is generally produced from wood chips, the environmental benefits from avoiding the future use of wood chips are allocated to the end-of-life stage in this system. In Figure 5 this results in a negative contribution for the process 'Avoided wood chip production'.

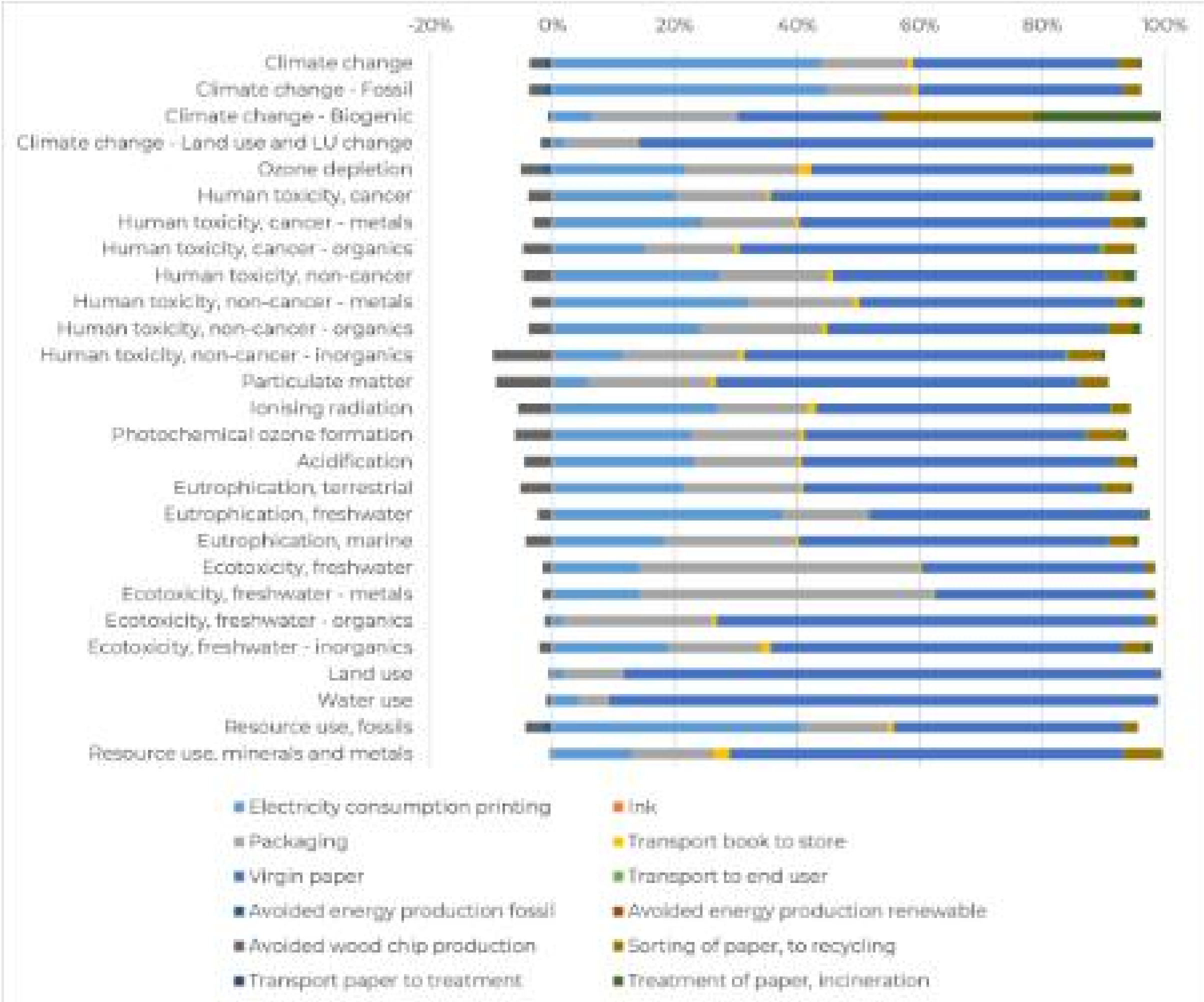


Figure 5: Contribution analysis of the environmental emissions of the life cycle of physical books.

6.2 Sensitivity analysis

6.2.1 Electricity consumption of printing operations

For the physical books, results show that the electricity used for printing the pages of the book accounts for a large share of the emissions. The current Dutch electricity grid still relies for a large part on fossil fuels. In order to see what our environmental impact would be on a fully solar powered printing process or a completely renewable grid, a sensitivity analysis is performed in which the electricity source is replaced from the current Dutch electricity mix with electricity from a photovoltaic slanted rooftop installation.

If we look at the climate change impact category, switching to renewable energy would lead to a CO2 emission reduction of approximately 40.63%. Overall impact of the life cycle of 120 physical books would then be 90.8 kg CO2-eq emissions.

Thus, when printing operations shift their energy supply to fully renewable, the environmental impact of the life cycle of a book would significantly reduce. When you directly compare this scenario with the e-reader alternative, one can read up to 48 books in five years to achieve similar CO2 emissions as the e-reader alternative.

6.2.2 Electricity consumption of e-reader use

Similar to section 6.2.1, a sensitivity analysis is performed regarding the use phase of the e-reader life cycle. If Dutch households switch to a fully renewable energy supply, by making use of photovoltaic panels, the life cycle of an e-reader would significantly reduce its environmental impact for most impact categories. If we look at the climate change impact category, switching to renewable energy for charging the e-reader and downloading e-books, would lead to a CO2 emission reduction of approximately 44.28%.

When we directly compare the CO2 emissions resulting from this scenario with the scenario from the previous section we can see a shift in the amount of books that can be read to achieve similar CO2 emissions. When both the physical book production and the use phase of the e-reader make use of renewable energy, one can read up to 35 physical books in five years to achieve similar CO2 emissions.

6.2.3 Overall results of the sensitivity analysis

Table 6 shows the overall results of both sensitivity analyses for all impact categories. Additionally, the percentual difference is calculated by comparing the baseline scenario with the sensitivity results.

6.3 Discussion

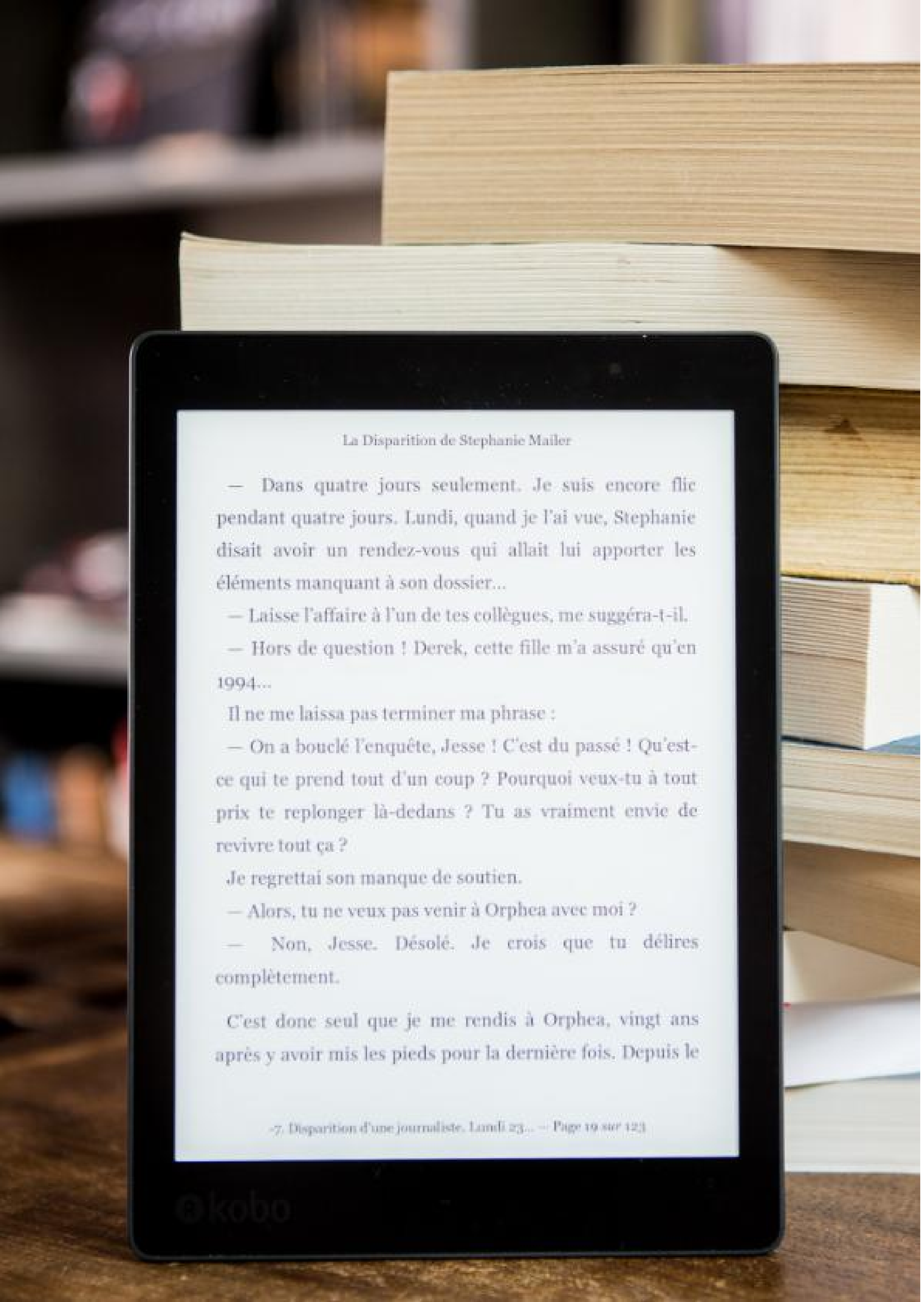
The results of the LCA have shown that physical reading comes with a higher environmental impact in most impact categories, compared to reading with an e-reader when reading more than 25 books in five years. However, in order to make this comparison, several assumptions were made. One of those assumptions was that physical books are only read once and are disposed afterwards. In reality, this may not be the case as books can get passed on to other readers. It would be interesting to see how the environmental impacts would change if this effect is also accounted for. This would then also mean that the environmental impact of reading one book is divided over multiple readers, which leads to a lower environmental impact of the used functional unit in this study.

6.4 Conclusion

This comparative LCA is a case study comparing the environmental impact over the entire life cycle of physical and electronic book reading. Within the determined system boundaries it is concluded that for an equivalent of 120 books read, the physical books result in higher overall environmental emissions. The tipping point for greenhouse gas emissions is at 25 books. Thus, if one reads more than 25 books over the course of five years, from a CO2 perspective it is more environmentally friendly to read these books on an e-reader. However, since the e-reader contains more precious metals, the e-reader has a higher impact when looking at the Resource Use indicator.

Table 6: Percentual differences between the baseline scenario and the sensitivity results.

Impact category name	E-reader			Physical book		
	Baseline emissions	Sensitivity results	Percentual decrease	Baseline emissions	Sensitivity results	Percentual decrease
Climate change	5,23E+01	2,91E+01	**-44,28%**	1,53E+02	9,08E+01	**-40,63%**
Climate change - Fossil	5,21E+01	2,90E+01	**-44,34%**	1,49E+02	8,69E+01	**-41,68%**
Climate change - Biogenic	1,49E-01	9,43E-02	**-36,72%**	2,99E+00	2,84E+00	**-4,95%**
Climate change - Land use and LU change	5,18E-02	5,08E-02	**-1,84%**	1,11E+00	1,10E+00	**-0,67%**
Ozone depletion	3,55E-06	2,64E-06	**-25,68%**	1,45E-05	1,20E-05	**-17,16%**
Human toxicity, cancer	2,83E-08	2,73E-08	**-3,42%**	7,58E-08	7,33E-08	**-3,35%**
Human toxicity, cancer - metals	1,98E-08	1,92E-08	**-2,97%**	4,08E-08	3,93E-08	**-3,71%**
Human toxicity, cancer - organics	8,49E-09	8,12E-09	**-4,37%**	3,50E-08	3,40E-08	**-2,93%**
Human toxicity, non-cancer	1,31E-06	1,36E-06	**3,68%**	1,78E-06	1,90E-06	**7,00%**
Human toxicity, non-cancer - metals	1,16E-06	1,20E-06	**3,31%**	1,40E-06	1,51E-06	**7,88%**
Human toxicity, non-cancer - organics	6,51E-08	6,75E-08	**3,71%**	6,85E-08	7,50E-08	**9,50%**
Human toxicity, non-cancer - inorganics	9,57E-08	9,57E-08	**0,01%**	3,27E-07	3,27E-07	**0,04%**
Particulate matter	1,45E-06	1,51E-06	**3,92%**	7,78E-06	7,92E-06	**1,85%**
Ionising radiation	1,99E+00	1,41E+00	**-29,23%**	6,46E+00	4,90E+00	**-24,13%**
Photochemical ozone formation	1,39E-01	1,15E-01	**-17,57%**	4,25E-01	3,60E-01	**-15,31%**
Acidification	2,55E-01	2,24E-01	**-12,32%**	6,61E-01	5,78E-01	**-12,59%**
Eutrophication, terrestrial	5,44E-01	4,28E-01	**-21,30%**	1,86E+00	1,55E+00	**-16,64%**
Eutrophication, freshwater	6,43E-03	5,22E-03	**-18,88%**	1,05E-02	7,21E-03	**-31,30%**
Eutrophication, marine	4,65E-02	3,75E-02	**-19,32%**	1,80E-01	1,56E-01	**-13,15%**
Ecotoxicity, freshwater	2,72E+03	2,58E+03	**-4,97%**	6,59E+03	6,23E+03	**-5,43%**
Ecotoxicity, freshwater - metals	2,37E+03	2,24E+03	**-5,58%**	6,10E+03	5,74E+03	**-5,86%**
Ecotoxicity, freshwater - organics	5,33E+00	5,18E+00	**-2,78%**	1,71E+02	1,70E+02	**-0,44%**
Ecotoxicity, freshwater - inorganics	3,43E+02	3,41E+02	**-0,45%**	3,23E+02	3,20E+02	**-1,03%**
Land use	1,94E+02	1,38E+02	**-29,11%**	1,03E+04	1,02E+04	**-1,38%**
Water use	8,56E+00	9,55E+00	**11,58%**	1,64E+02	1,67E+02	**1,60%**
Resource use, fossils	6,69E+02	3,64E+02	**-45,58%**	2,12E+03	1,30E+03	**-38,56%**
Resource use, minerals and metals	1,21E-02	1,25E-02	**3,60%**	2,22E-03	3,36E-03	**51,24%**



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