# Comparative LCA of Printed Books vs. E-Readers

## *Introduction, Background, and Literature Review*

While going paperless is often regarded as the most eco-friendly way to read, study, and conduct business, it is somewhat ambiguous as to which option (physical printed books or e-readers: hand-held tablet devices meant specifically for reading, like the Amazon Kindle) is actually more sustainable. Both options clearly have an environmental impact, from the use of trees for books, to the resource intensive nature of an electronic device. Past life cycle assessments have implied that the impact of each option can also vary with the degree of use, and it has been suggested that those who read many books per year can lessen their environmental impact by switching to an e-reader (Delgado 2022). Similarly, one LCA asserted that there is a threshold below which books cause more carbon emissions, and above this threshold, e-readers are the more sustainable choice, with the average cutoff sitting around 20 textbooks (Roy 2020). Yet another study, this time explaining that one would need to read 36 paperback books to break even with the environmental impact of an e-reader, speaks to the assertion that avid readers can greatly lessen their footprint by going paperless (Veltman 2024).

In general, the consensus seems to be that the issue of sustainability is not exactly clear and simple when comparing printed books to e-readers, but that the impact of an e-reader decreases with more use, while the impact of paper books increases. However, production of both items varies greatly, and the resource acquisition, transportation, and manufacturing process of e-readers has the potential to dwarf the production impact of a paper book (Towler 2022). The LCA that we will be conducting will examine the cradle-to-gate impact of the production of both books and e-readers.

*Goal*

The goal of this study is to conduct a comparative life cycle assessment to examine the difference in the environmental impacts of e-reader production and printed book production, focusing on the process from resource extraction to the point of distribution for a cradle-to-gate analysis. The intended application of this study is for an individual to determine the ecological and climate impacts of printed books and e-readers, and the audience will be the instructors and students of a college course. The findings of the study are not intended to be shared publicly to anyone except the aforementioned class participants.

- Product System: Hardcover printed books, and e-readers (Amazon Kindle Paperwhite)
- System Function: To convey information and entertainment through text
- System Boundary: Cradle to gate analysis of the life cycles of the aforementioned product systems from resource extraction through manufacturing
- Input Flows: Energy used for production (MJ), fossil fuels required (kg)
- Output Flows: Greenhouse gas emissions and water pollutants associated with manufacturing of both types of goods
- LCIA Method: TRACI
- Uncertainty Evaluation Method: Monte Carlo Simulation

*Scope and Functional Unit*

This study will conduct a cradle-to-gate analysis of the production process of printed books and e-readers. The function of these two items is to provide education and entertainment to the audience through written word. To be consistent across both platforms, the functional unit of this study will be 80,000 words of text, or the equivalent of about one novel (Reed 2022). The study will focus on the impacts of the methods of resource extraction, transportation, and the manufacturing process, which includes greenhouse gas emissions, water pollution, loss of biodiversity, and solid waste, though our study will specifically track GHG emissions, used to calculate global warming potential.

*Data Quality*

The data used should be the most recent data available: while data within the last 10 years is preferable, it is acceptable to utilize older resources if there is no other option available for the figures needed. The data will be obtained from existing literature, industry reports, government resources, and the 2012 USEEIOv2.0 model. Additionally, data will be analyzed using openLCA software to evaluate ecoinvent database information, using a TRACI impact assessment method. The data used will preferably be from the United States, but the main objective is to find reputable sources, U.S. based or otherwise.

*Process-Flow Diagrams*

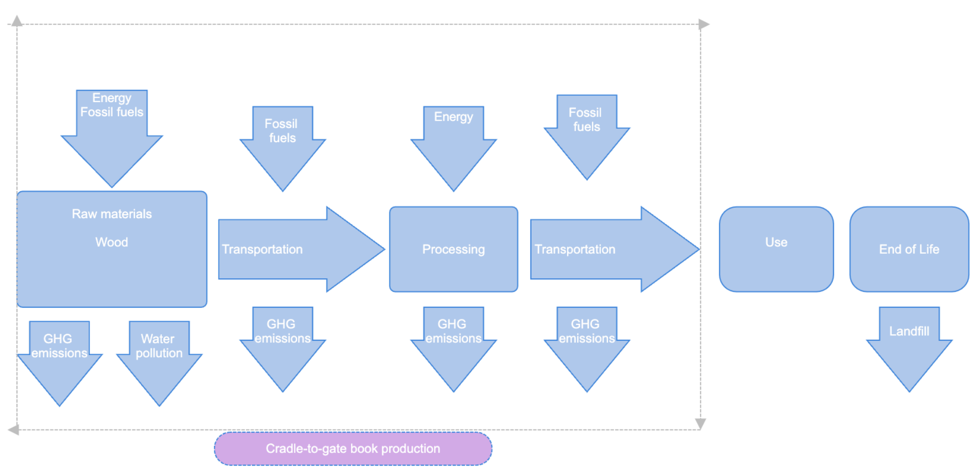


Figure 1 [printed book process-flow diagram]

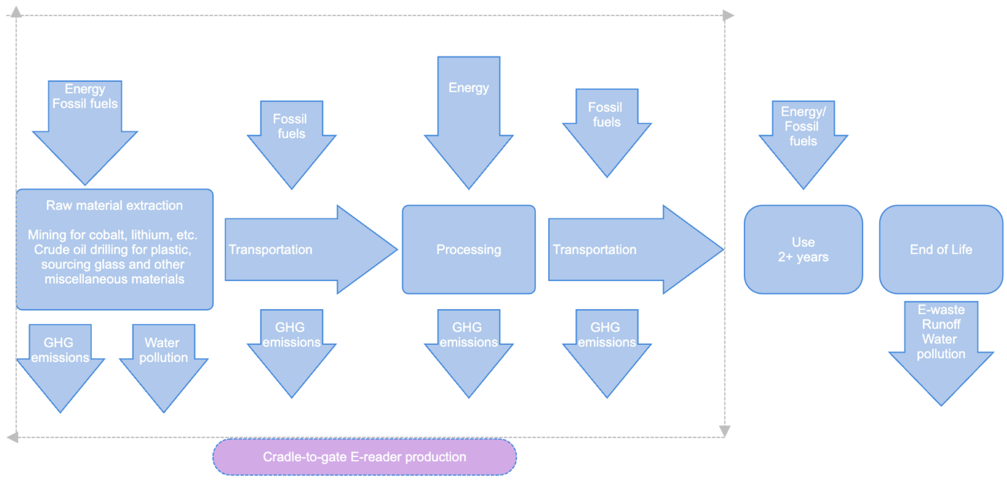


Figure 2 [e-reader process-flow diagram]

*Potential Environmental Impacts*

The production of both books and e-readers has many environmental implications. To begin, printed books require the use of trees, creating a cause for deforestation around the world. Forests, which serve to lessen the impact of greenhouse gasses in the atmosphere, are extremely important to the environment and surrounding ecosystems in terms of attempting to prevent climate change and preserve biodiversity. The average book requires about 4.5kWh of energy from raw material extraction to distribution, and produces about 7.5kg of carbon dioxide (Towler 2022). Fortunately, the use-phase of printed books is free of emissions, but we are not measuring this phase in our LCA.

The production of a single e-reader is energy, labor, and resource intensive. To begin, metals such as lithium, cobalt, and aluminum must be mined, which has extreme environmental impacts (as well as human rights implications in some parts of the world). Additionally, most e-readers are made largely from plastic, derived from crude oil, and they also require the use of glass. According to a previous study, the carbon footprint of an e-reader is 168kg $CO_2$, which clearly outweighs the footprint of a printed book by comparison, and they require 100kWh of fossil fuel energy during manufacturing (Towler 2022). Lithium is often mined using a method called brine-mining, an energy intensive process which also has an increased risk of polluting local water sources, and cobalt mining in Africa has similar impacts, with pollutants often leaching into rivers and streams, adding to the health effects of exposure to toxic chemicals and high levels of the radioactivity for the people working there (Zheng 2023). Mining also threatens habitats and biodiversity, disrupts soils, and produces air emissions (Parker et al., 2024). Our study will focus specifically on energy and fossil fuel inputs, and GHG emission and water pollutant outputs as we analyze the differences between these products.

*Functional Unit Economic Value*

While the functional unit for this study is 80,000 words of text, or about one novel, some considerations needed to be made when researching the cost of the functional unit for an e-reader. In order to be able to make use of one functional unit, the device needs to have already been produced, materials extracted and fully manufactured, ready for the consumer to dive into a novel. To determine the economic value of the functional unit for these product systems, I had to utilize cost analysis research from 2011 regarding an early model of the Amazon Kindle. Considering that today's low-end Kindle model (Paperwhite) costs the same as the 2011 version ($79), this is the model I am focusing on for this study. The research I found discussed the interesting fact that Amazon was selling its e-reader device for less than the production cost ($84.25). As such, the company was assumed to be making profits elsewhere, presumably during the use phase (Kindle 2011). However, because this is a cradle-to-gate study, I am using $84.25 as the economic value for my e-reader functional unit.

- NAICS Sector 511130 (Books)
- $84.25/80,000 words

For hardcover printed books, I approximated the page count for an 80,000 word novel to be about 300 pages. From here, I found a website that allows self-publishing of one's own literary works (https://www.48hrbooks.com/self-publishing-cost#/steps/quick-price). After entering my desired components (bound book, hardcover, page count), my cost to manufacture each book totaled $28.55 per functional unit.

- NAICS Sector 334112 (Computer storage device readers)
- $28.55/80,000 words

*LCI Methods*

To compare the two product systems, hardcover books and e-readers, my main focuses were inputs of energy (namely geothermal, hydroelectric, solar, wind, and crude oil for fuel), and outputs of some of the biggest (most harmful) greenhouse gasses, as well as pollutants to bodies of water. To draw these conclusions, I used the EPA's greenhouse gas information page to find keywords when searching through my main analysis tool, the USEEIOv2.0 spreadsheet model. Using this tool, I filtered different greenhouse gasses and environmental pollutants in order to track my desired inputs and outputs for each product. I used the NAICS sector 511130 for books, which was relatively easy to find. For the electronic reading devices, however, finding a sector was slightly more challenging, as many of the sectors that included computer manufacturing did not include any values in the USEEIOv2.0 spreadsheets. I finally settled on 334112 (Computer storage device readers), as it was the closest effective option to what I was searching for.

| Input/Output Item | Flow | Inventory for e-reader | Inventory for hardcover book |
|---|---|---|---|
| Energy, geothermal/resource/ground/MJ | Input | 8.139910524 | 4.567723718 |
| Energy, hydro/resource/water/MJ | Input | 20.37853926 | 11.46934839 |
| Energy, solar/resource/air/MJ | Input | 14.0802806 | 7.942093833 |
| Energy, wind/resource/air/MJ | Input | 49.33657048 | 27.68811526 |
| Crude oil/resource/water/MJ | Input | 430.7754217 | 293.4263646 |
| Carbon dioxide/emission/air/kg | Output | 72.2461177 | 4.40E+01 |
| Carbon tetrachloride/emission/air/kg | Output | 7.46E-06 | 4.63E-06 |
| Carbon tetrafluoride/emission/air/kg | Output | 9.88E-05 | 5.70E-05 |
| Chloromethane/emission/air/kg | Output | 1.70E-05 | 1.17E-05 |
| Dibromomethane/emission/air/kg | Output | 2.20E-08 | 1.21E-08 |
| Methane/emission/air/kg | Output | 3.43E-01 | 2.26E-01 |
| Nitrous oxide/emission/air/kg | Output | 8.00E-03 | 5.38E-03 |
| CFC-11/emission/air/kg | Output | 3.82E-07 | 2.53E-07 |
| CFC-113/emission/air/kg | Output | 2.16E-06 | 1.42E-06 |
| CFC-13/emission/air/kg | Output | 1.56E-08 | 1.04E-08 |
| HFC-125/emission/air/kg | Output | 1.47E-04 | 1.15E-04 |
| Perfluorocyclobutane/emission/air/kg | Output | 4.74E-06 | 2.74E-06 |
| Nitrogen trifluoride/emission/air/kg | Output | 1.58E-05 | 9.12E-06 |
| Chlorothalonil/emission/water/fresh water body/kg | Output | 7.24E-07 | 5.36E-07 |
| Fenpropathrin/emission/water/fresh water body/kg | Output | 3.07E-09 | 2.37E-09 |

Figure 3 [comparison between each input and output flow analyzed in this life cycle inventory]

*Comparison and Results*

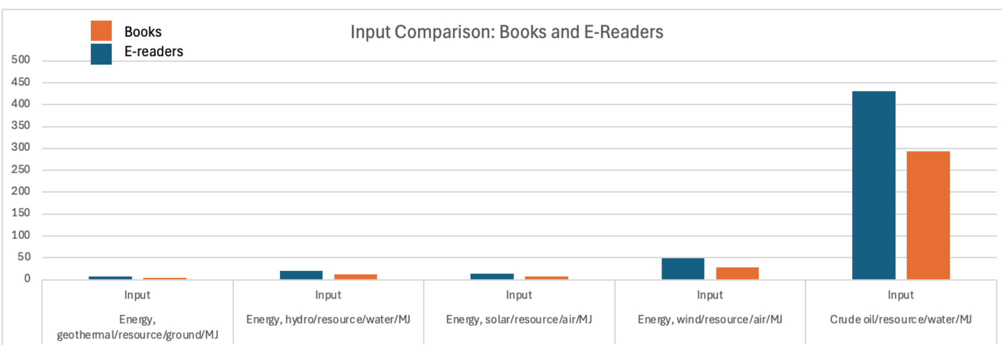


Figure 4 [Bar graph comparing inputs required for production between books and e-readers]

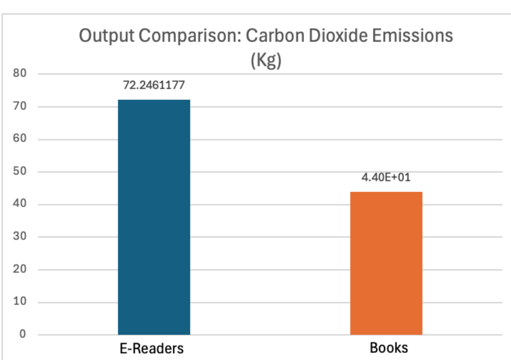


Figure 5 [Bar graph comparing carbon dioxide emissions between book and e-reader production]

In my analysis using the USEEIOv2.0 tool to compare the input and output life cycle inventories of hardcover paper books and electronic reading devices, it is clear that the cradle-to-gate process of manufacturing these two products varies greatly in terms of their energy intensiveness and amounts of air and water emissions from production. Figure 4 shows that in terms of inputs required for the production process, e-readers require slightly more in each energy category. Crude oil is the biggest input for both products, and the bar graph clearly shows the drastic difference in products: e-readers use far more oil in their production processes. However, there are limitations to the USEEIOv2.0 tool, as it is difficult to use the spreadsheets to quantify the inputs and outputs specifically from resource extraction (deforestation for books and the mining and sourcing processes for e-readers). Our study also does not account for the amount of carbon sequestration that will be lost by cutting down trees for book production, which adds another layer of nuance to this comparison. This study did find a different numerical result than that of the studies referenced in the literature review, which stated that e-reader production is responsible for 168kg CO2, where our study found the devices to cause only 72kg CO2 emissions. However, it is quite possible that the previous study used a different functional unit, or a different economic value, as e-readers come in a wide array of models, and I used a low-end model for my analysis. Based on this analysis, I believe it is fair to conclude that books are a more environmentally sustainable option, but this does come with a caveat: we did not analyze the use phase. We will touch on this more at the end, but the use phase determines a large portion of what might make an e-reader a more responsible choice for an environmentally conscious consumer.

*Comparative LCA Methods*

For this part of the study, OpenLCA software was used to analyze data provided within the ecoinvent database. To build product systems to analyze, specific input flows (indicated in figures 6-7 below) were chosen for both printed books and e-readers, and then the TRACI method was used to calculate global warming potential in a life cycle impact assessment. It is important to note that for e-reader production, the "computer production, laptop" flow was largely used as a basis for the e-reader product system, adding and subtracting input flows as necessary, and changing the unit (based on weight) to reflect, as accurately as possible, the differences between an e-reader and a laptop computer. From here, an additional LCIA was conducted using a Monte Carlo simulation in order to account for uncertainty in the analysis. Once the data had been configured adequately in the OpenLCA software, results were imported to Microsoft Excel to further reflect and interpret LCIA results.

| **Books Input Flows** |
| --- |
| Printed paper, offset |
| laminating service, foil, with acrylic binder |
| linerboard |
| textile, woven cotton |

Figure 6 [Input flows used for books system process in OpenLCA]

| e-readers Input Flows |
| --- |
| battery, Li-ion, rechargeable, prismatic |
| battery, NiMH, rechargeable, prismatic |
| copper |
| extrusion, plastic pipes |
| integrated circuit, memory type |
| liquid crystal display, unmounted |
| magnesium-alloy, AZ91 |
| magnesium-alloy, AZ91, diecast |
| photovoltaic cell factory |
| plug, inlet and outlet, for computer cable |
| polycarbonate |
| polypropylene, granulate |
| polystyrene, foam slab |
| polystyrene, high impact |
| printed wiring board, mounted mainboard, laptop computer, Pb containing |
| printed wiring board, surface mounted, unspecified, Pb containing |
| electricity, medium volatge |
| printed wiring board, surface mounted, unspecified, Pb containing |
| sheet rolling, copper |
| sheet rolling, steel |
| steel, chromium steel 18/8, hot rolled |
| tap water |

Figure 7 [Input flows used for e-readers system process in OpenLCA]

*LCA Results*

After evaluating the impacts of both books and e-readers using the TRACI impact assessment method, we found, as expected, that the global warming potential of e-reader manufacturing dramatically dwarfs that of book production and manufacturing. In the initial LCIA we conducted, it was found the mean global warming potential of the production process for books was about 27.317 kg CO2e/unit. In extreme contrast, the global warming potential for e-reader production was 760.47 kg CO2e for one unit.

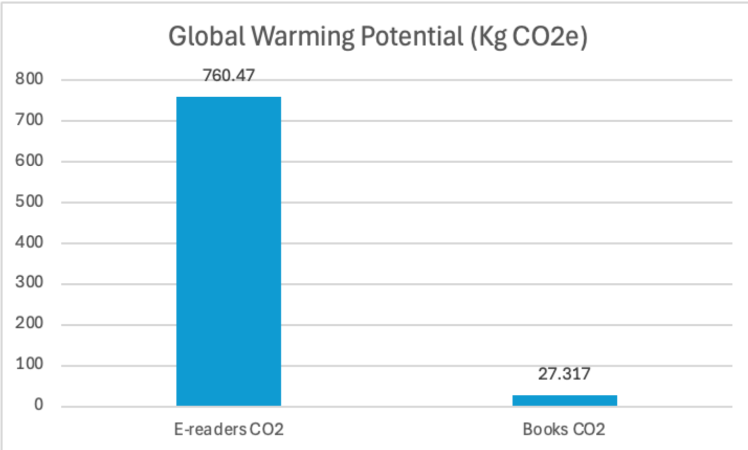

Figure 8 [GWP results without uncertainty shown as a bar graph]

After using a Monte Carlo simulation to adjust for uncertainty, these results were even more pronounced, with the simulation yielding 22.125 and 1009 kg CO2e per unit produced for books and e-readers, respectively. The results with uncertainty adjustments show that the environmental implications for e-reader production may be even more impactful than we previously thought, and highlight the relatively small impact of book manufacturing.

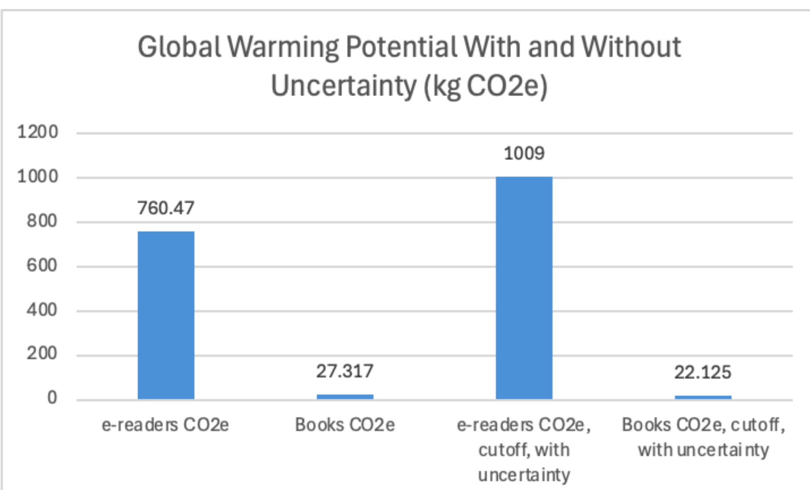

Figure 9 [GWP results with and without uncertainty calculated using Monte Carlo simulation]

| Mean Global Warming Potential | | | |
|---|---|---|---|
| **Item** | **GWP without uncertainty** | **GWP with uncertainty** | **Unit** |
| e-readers | 760.47 | 1009 | kg CO2e/item |
| Books | 27.317 | 22.125 | kg CO2e/item |

Figure 10 [uncertainty value table]

Below are the impact assessment Sankey diagrams following the production processes of both books and e-readers, highlighting which input flows contributed most significantly to global warming potential (GWP). For books, the largest GWP contributor was woven cotton, which is commonly used as an outer layer for hardcover books. The cotton textile production is tied into electricity, creating emissions by burning coal. Printed paper was another somewhat large source of GWP for books. For e-readers, the Sankey diagram looks different. The largest input source contributing to GWP in this case was production of the memory apparatus for the device, known in the ecoinvent database as “integrated circuit, memory type.” This input flow constitutes an enormous portion of the GWP for the e-reader category, tying into electricity as a main culprit.

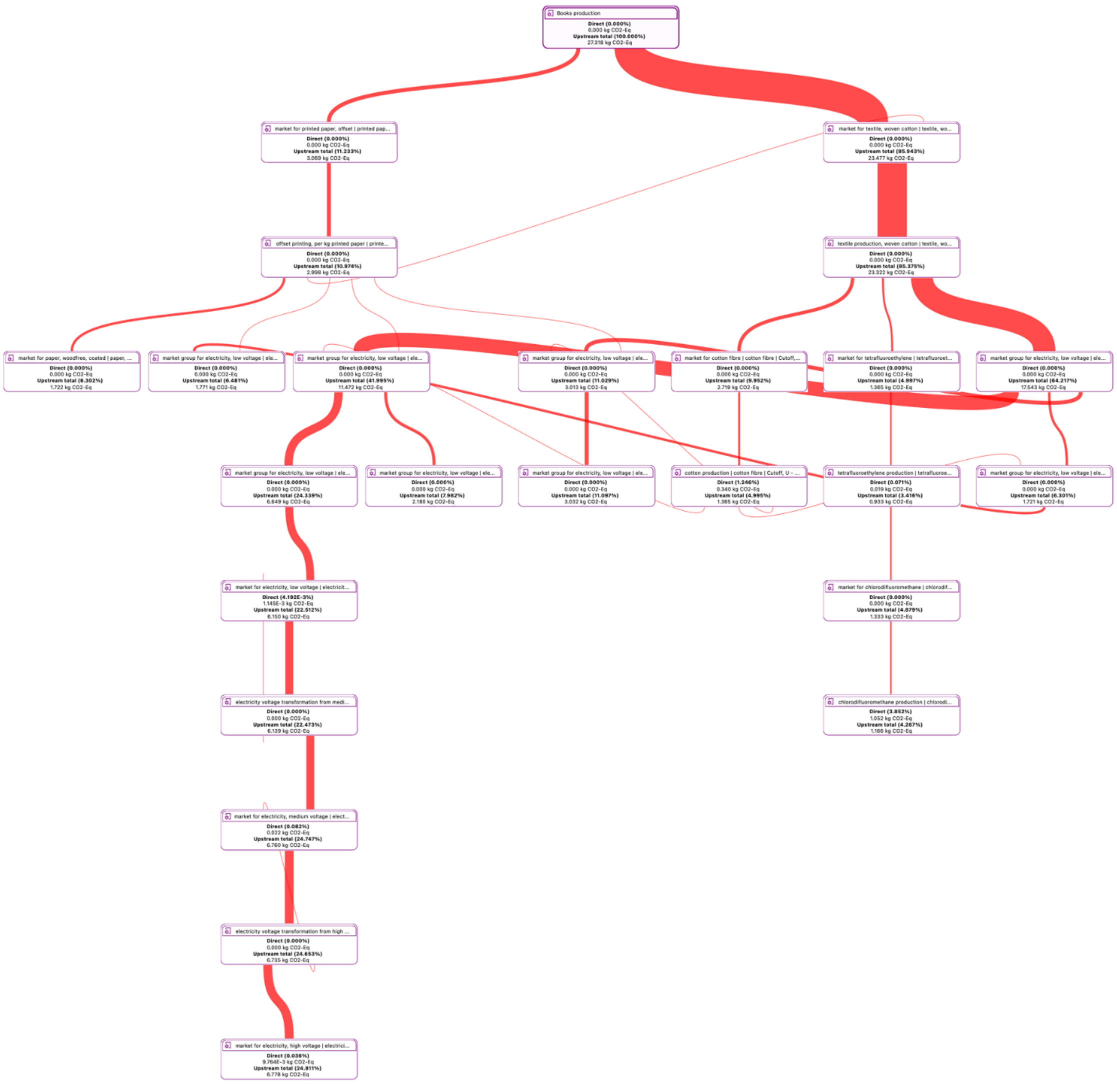

Figure 11 [Sankey diagram for books LCIA, showing woven cotton as main GWP source]

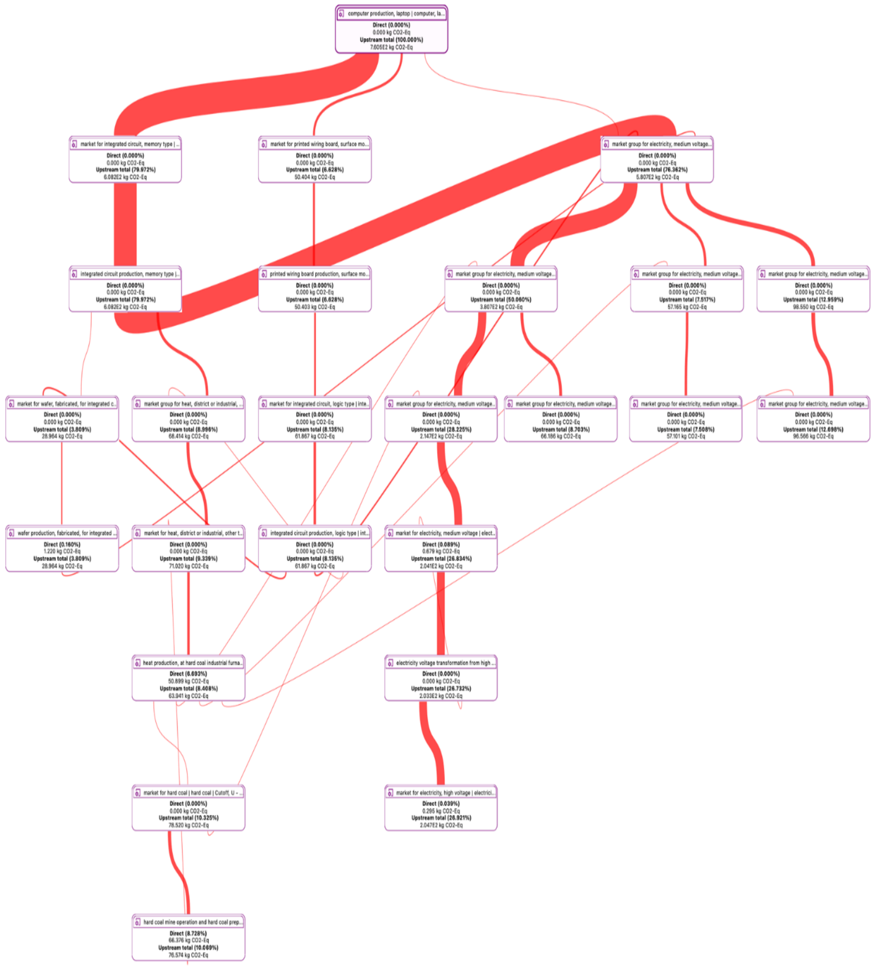

Figure 12 [Sankey diagram for e-reader LCIA, showing integrated circuit, memory type as main GWP source]

*Discussion*

In the comparative LCIA conducted with OpenLCA, similar to the results compiled from the previous analysis using the USEEIOv2.0 tool, it is clear that e-readers have a significantly larger environmental impact through the cradle-to-gate phase compared with the manufacturing of books. This was an expected result, but the difference, especially when taking uncertainty into consideration, was quite astounding. I feel relatively confident in the accuracy of the results because it is quite consistent with the findings from the research conducted before starting this comparative LCA study. In the literature review, we mentioned that one study found that one would have to read about 36 books to make an e-reader a smarter choice for the environment (Veltman 2024). According to our results without uncertainty, one would need to read about 28 books to make an e-reader the better choice, and the difference here could be attributed to differences in the functional unit used in each study. Corrected for uncertainty, our study found that reading 46 books would be necessary to make an e-reader the more environmentally-friendly choice. These similarities give me some confidence that my study has some merit. Even so, there are still things I would change about the way the analysis was conducted.

This comparative LCA assumed that all co-products were waste, so we did not use any type of allocation method. Conducting more extensive research would have been beneficial, because one of the areas where I lack the most confidence was building the system process for e-readers in OpenLCA, as it was difficult to determine which exact input flows to include. There are so many aspects of electronics manufacturing, and while my research was helpful in determining basic necessary components, types of plastic most likely used, and a surface-level understanding of how these devices work, I wish that I had found a bill of materials to help build the system process in the most accurate way possible. The study was based loosely on the Amazon Kindle Paperwhite, a device for which the bill of materials is not public. Had I known this earlier, I would definitely have done some more digging to find a comparable device with an accessible bill of materials. Because of my lack of expertise in this realm, I used the laptop computer process already in the ecoinvent database as a baseline for my e-reader system process, and while I refined it thoroughly to make it as close to accurate as I could with my understanding of the topic, I do think this could have been a significant source of error.

Another thing that makes me question the relevance of the study is that it was strictly focused on a cradle-to-gate analysis. I believe that the use and end-of-life phases would have an enormous impact on the results of the study– determining which is a more environmentally friendly option: books or e-readers. Considering cradle-to-gate only, we can conclude that books are undoubtedly the more environmentally responsible choice for consumers. However, given our calculations of the number of books one would have to read using an e-reader to offset the impact of manufacturing, we can safely assume that the use phase is *extremely* important in determining the true impact and GWP. To add even more uncertainty, the end-of-life phase is absolutely necessary to consider, as e-waste implications are becoming a very prevalent issue around the world, and more research is needed to determine how harmful end-of-life impacts are, and how they should be considered even if the consumer were to read thousands of books using the device. So, while a cradle-to-gate analysis shows that books are a clearly more environmentally conscious choice, more research is necessary to determine the true impacts of e-readers and to draw a conclusion on how this should influence consumer behavior.

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