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Life Cycle Assessment of Reading Physical Books Compared To Reading Ebooks on Popular Ereaders

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Introduction

The rapid progress of technology has significantly transformed the way in which people engage with texts, pushing wide research on the differences between digital reading and reading the traditional physical book. In light of the accelerated digital transformation observed globally. During the Covid-19 pandemic, reading habits have suffered significant changes. The dichotomy of digital reading against physics includes variances in understanding, in the involvement of users and in evolution educational tendencies, all significant topics within contemporary literacy studies.

Digital reading

Digital reading is characterized by the use of devices such as electronic readers, tablets and smartphones, has distinct advantages. The transition from traditional print to digital formats has introduced new opportunities for improving reading experiences. It improves accessibility and fosters diverse cognitive skills. This shift is not only transforming individual reading habits but also influencing broader societal communication patterns. Digital reading materials are easily accessible and available 24/7, allowing readers to access a vast array of texts from anywhere with an internet connection. The portability of digital devices means that readers can carry entire libraries with them, facilitating reading on-the-go (Nedeljkov, 2016)

- . E-books and digital texts are often more cost-effective than their print counterparts, reducing financial barriers to accessing information (Pae, 2020)
- . Digital platforms allow for the customization of reading experiences, such as adjusting font size, background color, and screen brightness, which can enhance readability and comfort. E-texts can be tailored to individual learning needs, offering features like multimedia glossaries, bilingual translations, and interactive elements that support diverse learning styles (Dalton, 2014)
- . The searchability of digital texts allows readers to quickly locate specific information, making research and information retrieval more efficient. Digital reading platforms often include features that facilitate note-taking, highlighting, and bookmarking, which can aid in organizing and synthesizing information (Staiger, 2012)
- . While digital reading offers numerous advantages, it is important to consider the potential challenges and limitations associated with this format. For instance, some studies suggest that

digital reading may lead to superficial processing of information, as readers are more likely to scan texts rather than engage in deep reading (Pae, 2020)

- . On the other hand, reading physical books offers a range of advantages that extend beyond the mere acquisition of information. Physical books require a different kind of cognitive engagement compared to digital formats. The act of turning pages and the physical presence of a book can enhance focus and retention, reducing the cognitive load associated with digital reading (Jabr, 2013)
- . Physical books provide a multisensory experience that includes the feel of the pages, the weight of the book, and the distinctive smell, especially of older volumes. These sensory elements can evoke nostalgia and enhance the reading experience, making it more memorable and enjoyable (Spence, 2020)
- . The act of physically turning pages and the tactile feedback from handling a book contribute to a more immersive reading experience. This physical interaction is often cited as a reason why some readers prefer paper books over digital formats (Watanabe & Fujimoto, 2020)
- . While there are arguments to be made on both sides of the debate, one thing that cannot be argued is that digital reading is here to stay and is gaining popularity.

Sustainability benefits of digital reading

Digital reading offers several sustainability benefits, primarily through its potential to reduce environmental impacts, enhance educational processes, and support sustainable development goals. The transition from print to digital formats can lead to significant reductions in resource consumption and waste, while also providing opportunities for more inclusive and accessible education. However, the sustainability of digital reading is contingent upon various factors, including usage rates and technological infrastructure. Digital reading reduces the need for paper, which can significantly lower deforestation rates and the environmental impact associated with paper production and disposal. This dematerialization is seen as a way to mitigate the environmental implications of traditional printing (Piterou& Steward, 2016)

- . While digital reading devices have their own environmental impacts, such as energy consumption during production and use, they can be more sustainable if used extensively. High usage rates of e-readers can offset the initial environmental costs, making them a more sustainable option compared to printed books (Jeswani&Azapagic, 2015)
- (Gensch et al., 2017)
- . While digital reading offers numerous sustainability benefits, it is important to consider the associated challenges. The environmental sustainability of digital reading is not guaranteed and depends on factors such as the frequency of device use and the energy efficiency of digital infrastructure (Jeswani&Azapagic, 2015)
- (Gensch et al., 2017)
- . This study aims to explore the benefit of digital reading compared to reading physical books using published life cycle assessments.

Life cycle assessment

Life Cycle Assessment (LCA) is a comprehensive methodology used to evaluate the environmental impacts associated with all stages of a product's life, from raw material extraction to disposal. This paper uses LCA to compare the carbon footprint of digital and physical reading. LCA is a scientific technique that can quantify the environmental, human health, and natural resource impacts of products and services across all the stages of a product's life, from raw material extraction to manufacturing and product disposal or recycling. For digital reading, these phases include the manufacturing of the device, transporting the device to the customer, the electricity required to download each e-book, the electricity required to use the device, and the impact of disposing of the device. For physical books, these impacts include manufacturing the book, transporting it to the customer, and disposing of it.

A functional unit is a reference unit for quantifying the performance or functionality of a product or service's life cycle environmental effects. The purpose of the functional unit is to provide a reference to which input and output data are normalized. It allows decision-makers to compare across systems-of-interest based on their core performance characteristics. It is a core concept in LCA methodology. Each LCA requires a functional unit based on the service provided. In this analysis, the functional unit was defined as the set of books read by an e-book customer in one year. The environmental impact of reading these e-books was compared to the impact that would have occurred if each e-book had been replaced by a physical book. This functional unit was based on scientific and industry literature that analyzes and/or compares the environmental impact of digital and physical reading.

The literature review informed the development of a general mathematical model that calculates the device carbon payback, or the number of books a customer must read digitally before the associated carbon footprint for digital reading is smaller than that for physical books. Data from the most appropriate literature was adapted to estimate the environmental impacts and parameters for the model where primary data was lacking. The carbon payback varies for each customer and type of device due to differences in the environmental impacts associated with producing, transporting, and using digital and physical reading platforms. For digital reading, device usage data influences how manufacturing impacts are allocated to specific digital applications. All manufacturing impacts for an e-reader are allocated to reading because it is the sole function of the device. When using a tablet, smartphone, or computer, however, only a portion of impacts are allocated to reading, as these devices are also used for activities such as watching videos, browsing the internet, and shopping. For physical books, factors such as the number of pages, words per page, number of illustrations, and type of binding (softcover vs. hardcover) influence the total greenhouse gas emissions from production.

Review of Scientific Literature Comparing Digital and Physical Reading

Several LCA studies have compared e-book reading to physical books. Some of these studies disassembled eReaders to estimate the materials and the impacts of producing them. Table 1 summarizes the findings of previous and relevant LCA studies.

Table 1. Key findings from literature and reports on the environmental impact of physical and digital reading

Article/Report	Technologies assessed	Key findings
(Borggren et al., 2011)	physical books	0.6 kg CO2 equivalent (CO2e) per kg book (hardcover) Transportation makes up ~50% of life-cycle CO2e
(Moberg et al., 2011)	dedicated e-reader, physical books	Using an e-book reader had 33% less CO2e associated with it than a physical book.

		Assumed 30 books read over e-reader lifetime
(Wells et al., 2012)	Physical books produced in North America De-inked Market Pulp (DMP) Average virgin and recycled paper	Virgin and average recycled pulp were lower impact than DMP, due to energy consumed in de-inking plant and local power mix.

How a Digital versus Physical Media LCA Model Works

1. This image shows the impacts of reading e-books. The vast majority of carbon emissions from reading an e-book are from manufacturing the device(s) on which the book is read. The environmental impact of reading each book is relatively small. We reviewed the academic literature to get the device manufacturing impact for all of the devices on which our customers read e-books. Then we used the reading data, and percentage of time spent interacting with the device but not reading for multi-use to allocate the impact of manufacturing the device across all of its uses to arrive at what percentage of the impact we will allocate to e-books (the intercept of the y-axis). Then we need to calculate the marginal impact of reading a book.
2. This image shows the impacts of buying physical books. Approximately half of the environmental impact was transporting the book to the end customer. This impact is one of the reasons that you see a step function change in impact for every additional book read.
3. This image shows how we solve for the cross over, or point at which reading e-books has a lower carbon impact than purchasing physical books. This allows us to solve for the percentage of customers that have crossed the carbon payback, and the expected reduction in carbon a customer can expect from reading e-books.
4. This image shows how the environmental impact of reading increases when a customer begins reading on a new device. Recall from Image 1 that the largest impact for e-book customers is the manufacturing of the device.

Modeling physical books

The life-cycle greenhouse gas (GHG) emissions of physical books ordered and shipped within the US were modeled. Because each book read by e-book customers is different, the production and end-of-life stages of books were modeled on a per-page basis. The life cycle of a book includes producing pulp and paper from virgin and recycled sources, printing the book, transportation to the customer, usage, and end of life (EoL). To estimate the impacts of equivalent physical books to those read digitally, data from the most appropriate literature sources on book production were adapted and combined with logistics data on the impacts of shipping a typical package to customers. The GHG emissions from producing, using, and disposing of a physical book were adapted from (Wells et al., 2012)
, which quantified the life-cycle impacts of typical recycled and virgin paper books in North America. To ensure the analysis was defensible and conservative, the lowest reasonable impact estimate for paper books was used. A key parameter in determining the impact of a paper product over its life cycle is its

EoL, specifically how long the book stores carbon in the form of paper. The PAS 2050 standard employed by Wells provides a method for accounting for reductions in emissions from carbon sequestration during use or EoL (books are approximately 45% carbon by mass). Wells assumes that all books are disposed of after 30 years, with 50% going to landfill and 50% being recycled.

This assumption resulted in a high estimate of the physical book's impacts, as Wells also notes that approximately 60% of books are likely to be archived indefinitely, which decreases their EoL emissions. To be more conservative and provide physical books with the benefit of the doubt, it was assumed that 60% of books were kept indefinitely, while the remaining 40% were disposed of after 30 years, with equal proportions sent to landfill and recycling. This resulted in a lower impact for physical books compared to the estimates presented by Wells, although it remains higher than some other estimates in the literature. Table 2 shows the calculated GHG emissions for a paper book by life-cycle stage, as adapted from (Wells et al., 2012)

Additionally, logistics data on the average carbon footprint of shipping an item to a customer from 2019 was incorporated. This includes both inbound shipping (from the printer to the logistics center) and outbound shipping (from the logistics center to the customer).

Table 2. Paper book impact results extracted and adapted from Wells study

Life cycle Stage	**kg CO2e per book**	**kg CO2e per page**	**Explanation**
Upstream emissions	1.209	0.004	Derived from Figures 4 and 6 of Wells. We used the average recycled paper, which is 17.2% lower than the DMP case study
Paper Production	0.720	0.002	Same as DMP case study
Transport from Paper Mills to Printer	0.090	0.000	Same as DMP case study
Printing Process	0.230	0.001	Same as DMP case study
Distribution	0.060	0.000	Same as DMP case study
End of Life and Carbon Storage During Use	-1.375	-0.0043	Assumed carbon in paper stored for 100+ years
Total Excluding Distribution to Customer	0.934	0.00273	
Shipping	1.48	1.48	(Frischknecht&Rebitzer, 2005)
Total including shipping		2.36	Assuming a 320 page book

Modeling the eReader devices

eReader impacts for 2 popular eReaders were averaged from the studies done by (Jeswani&Azapagic, 2015)

(Glasson, 2016)

(Amasawa et al., 2018)

and the outcome is listed here:

	eReader #1	eReader #2
Life Cycle Stage	Carbon Emissions [kgCO2e]	Carbon Emissions [kgCO2e]
Materials production and manufacturing	28.09	33.83
Product use	0.1	0.1
Transportation	2.06	2.06
End of life	0.05	0.05
Total	30.3	36.04

Mathematical Model for Carbon Payback calculations

The Mathematical Model

The environmental impact of any product I can be broken down into different phases of its life cycle:

$$I\{I_E, I_B\} = I_M + I_T + I_F + I_P + I_U + I_{EOL} \quad (1)$$

We use this equation to break down the impact of reading a book on an e-reading device (I_E) and a physical book (I_B). I_M (manufacturing) includes all the cradle-to-gate impacts of a product from the extraction of raw materials (i.e. "cradle") through its manufacturing stage (i.e. "gate"). Other stages include transportation (I_T), facilities (I_F),packaging (I_P), product usage (I_U) and product end of life (I_{EOL}). For this type of analysis, upstream transportation should be included as part of I_M, and I_T is limited to only the downstream transportation.

The impacts of reading books materialize quite differently for the alternative systems analyzed here: (1) physical book, (2) e-book on a dedicated reader, and (3) e-book on a tablet or phone.

Physical book

Let $I_B$be the life-cycle impact of a given book or set of books b. A physical book has no use-phase impacts: $I_U = 0$. I_T is the impact of transporting the books to the consumer. For simplicity, we combine the impacts of use, manufacturing, facilities, packaging and EOL into "per page" impact factored: e_{pp} is the life-cycle impact of paper, printing, binding and ink per page. $p_{b,tot}$ is the total number of pages read,$p_{b,len}$ is the total number of pages in the book,rr_b is the number of times each book is read (i.e. the re-reading rate), $e_{b,T}$ is the impact intensity of delivering a package and$k$ is the number of books read.

$$I_B = I_M + I_T \quad (2)$$

$$= I_M + I_T = (e_{pp})\frac{1}{rr_b} \cdot \sum_{b=1}^{k} (p_{b,tot}) + (e_{b,T})\frac{1}{rr_b} \cdot \sum_{b=1}^{k} \frac{p_{b,tot}}{p_{b,len}} \quad (3)$$

Here we take the impact of using a physical book to be zero, and for simplicity we ignore the end-of-life impacts of the physical book. We assume that the impact of the binding is included in the per page impact factor. The impact of transportation is also not dependent on book size or weight.

e-book

Let $I_E$be the impact of reading a book on an e-reading device (or devices). e-books can be read on dedicated device(s), devices with multiple uses such as a tablet or phone, or a combination thereof.

$$I_E = I_M + I_U = I_{device} + I_{use} \quad (4)$$

Where I_{device} is the embodied impact of the e-reader device (d) that is allocated to all the pages read on the device. f_d is the fraction of a dedicated, tablet or phone (d) attributable to reading, and e_d is the embodied impact per device, where there are$d$=1 to n devices on which customers read.

$$I_{device} = \sum_{d=1}^{n} f_{b,d} \cdot e_d \quad (5)$$

The impact of use (I_{use}) of the device for reading a particular page is dependent on the electric power of the device w_d, and the time spent reading that page or set of pages(t_b).

$$I_{use} = \sum_{d=1}^{n} e_{elec} \cdot w_d \cdot t_{b,d} \quad (6)$$

The fraction of a device, $f_{b,d}$, attributable to reading a given book merits further discussion, due to the device production's large contribution to the life cycle impacts of devices. This fraction should be allocated based on time (hours) spent using the device for e-reading (t_b) versus the total time (hours) that the device is used over its lifetime (T_d). The time spent reading (t_b) is also related to a customer's reading rate in pages per hour (r), and the total number of pages consumed(c_b).cf is the correction factor that is used to account for customers that start/stop reading in the middle of the dataset. (M_d) is the total number of active months by device type, and (D_l) is the total device life (by type).

$$f_{b,d} = cf \cdot \frac{t_{b,d}}{T_d} = \left(\frac{\frac{\sum_{d=1}^{n} M_d}{n}}{D_l} \right) \cdot \frac{c_{b,d} r^{-1}}{T_d} \quad (7)$$

To calculate T_d on a device basis we have to aggregate across all the e-reading across the device, and then multiply this by the calculated device lifetime:

$$T_d = T_{reading,d} + T_{other,d} = \sum_{b=1}^{n} t_{b,d} + T_{other,d} \quad (8)$$

The impact of reading a page or set of pages$b$ using an e-reader, as a function of the time spent reading on each device, is thus:

$$I_E = \sum_{d=1}^{n} \left(\frac{t_{b,d}}{T_d} e_d + e_{elec} w_d t_{b,d} \right) \quad (9)$$

Carbon payback (CAP)

We are interested in finding the number of books,k^*, where the environmental impacts of reading e-books is equivalent to that of reading the same number of physical books. The quantity of books is defined as the Carbon payback (CAP). This holds only for e-books that were read up to the point where the customer is likely to have purchased a physical copy of the book.

First, we modify equation (3) and extract the number of books read by averaging across the books read by a customer:

$$I_B = \left(ke_{pp}p_{av} + ke_{b,cov} + e_{b,T} \cdot k\right)\frac{1}{rr_b} \tag{10}$$

$$= \frac{k}{rr_b}\left(e_{pp}p_{av} + e_{b,cov} + e_{b,T}\right) \tag{11}$$

Similarly, we must modify equation (9) to extract the number of books read from the e-book impact equation:

$$I_E = \sum_{d=1}^{n}\sum_{b=1}^{k}\left(\frac{t_{b,d}}{T_d}\, e_d + e_{elec}w_d t_{b,d}\right) = \sum_{d=1}^{n}\left(\frac{t_{b,d}}{T_d}\, e_d + e_{elec}w_d t_{b,d}\right) \tag{12}$$

Because T_d and $t_{b,d}$ are both dependent on the number of books read, we must modify these terms. p_{avr} is the average number of pages per book read by a particular customer.

$$I_E = \sum_{d=1}^{n}\left(\frac{k_d\frac{p_{avr}}{r}}{k_d\frac{p_{avr}}{r} + T_{other,d}}\, e_d + e_{elec}w_d k_d\frac{p_{avr}}{r}\right) \tag{13}$$

k_d is the number of books (or fraction of a book) that is read on a particular device, and ϕ_d is the fraction of reading done by a customer on a particular device.

$$k_d = k\,\phi_d \tag{14}$$

Thus, equation 14 becomes:

$$I_E = \sum_{d=1}^{n} k\left(\frac{\phi_d\frac{p_{avr}}{r}}{\phi_d k\frac{p_{avr}}{r} + T_{other,d}}\, e_d + e_{elec}w_d\phi_d\frac{p_{avr}}{r}\right) \tag{15}$$

To find the CAP (k^*), we set the impacts of the e-books and physical books equal to each other, and solve for k^*:

$$\frac{k^*}{rr_b}\left(e_{pp} \cdot p_{av} + e_{b,cov} + m_{b,T}\right) = \sum_{d=1}^{n} k^*\left(\frac{\phi_d\frac{p_{avr}}{r}}{\phi_d k^*\frac{p_{avr}}{r} + T_{other,d}}\, e_d + e_{elec}w_d\phi_d\frac{p_{avr}}{r}\right) \tag{16}$$

This equation does not have an analytical solution, but can be solved numerically for a given set of parameters.

If a customer uses only one device, as must customers do, then equation 16 becomes simpler:

$$\frac{k^*}{rr_b}\left(e_{pp} \cdot p_{av} + e_{b,cov} + m_{b,T}\right) = k^*\left(\frac{\frac{p_{avr}}{r}}{k^*\frac{p_{avr}}{r} + T_{other,d}}\, e_d + e_{elec}w_d\frac{p_{avr}}{r}\right) \tag{17}$$

solving for k^* we get:

$$k^* = \frac{e_d}{rr_b^{-1}(e_{pp} \cdot p_{av} + e_{b,cov} + m_{b,T}) - e_{elec} w_d \frac{p_{avr}}{r}} - \frac{T_{other,d}}{\frac{p_{avr}}{r}} \quad (18)$$

Results

The results show that for the two eReaders compared, it takes an average of 14.5 books to completely mitigate the impact of reading eBooks on a digital eReader.

Assumptions and Raw Data			Source
Number of book re-reads	1	time	assumption
Number of pages in book	320	pages	assumption
Impact per page of book	0.002732	kgCO2e/page	Wells study
Transportation impact of a book	1.48	kgCO2e	Ecoinvent
Total book impact	2.36	kgCO2e	
eReader#1 Manufacturing+Transport+EOL Impact	30	kgCO2e	
eReader#2 Manufacturing+Transport+EOL Impact	36	kgCO2e	
eReader Power Consumption	0.0003942	kW	
Average time taken to read a book	6.4	hours	assumption
Average US grid emissions	0.444	kgCO2e/kWh	eGrid
Use phase impact of eReader per book	0.00112	kgCO2e	
eReader #1 Base Carbon Payback	13	books	
eReader #2 Premium Carbon Payback	16	books	

The results show that digital reading offers several sustainability benefits compared to reading physical books, primarily through the the reduction of material consumption and associated environmental impact of producing and transporting physical books. This study shows how the transition from printed to digital text is often seen as a way to dematerialize the consumption of books, thereby reducing the environmental implications associated with the production and distribution of physical books.

Conclusion

In conclusion, this study provides a comprehensive life cycle assessment comparing the environmental impacts of reading physical books to reading eBooks on popular eReaders. The findings highlight the sustainability benefits of digital reading, particularly in terms of reducing material consumption and associated greenhouse gas emissions from the production and transportation of printed books. While both formats have their unique advantages and challenges, the analysis indicates that digital reading can offer a more environmentally friendly alternative, especially when usage rates of eReaders are high enough to offset their initial carbon footprint. As reading habits continue to evolve in the digital age, understanding the environmental implications of our choices becomes increasingly important. This research contributes to the ongoing discourse on the sustainability of reading practices and underscores the need for further exploration into the long-term impacts of digital versus physical reading.

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