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TOPICAL REVIEW

Digitalisation of goods: a systematic review of the determinants and magnitude of the impacts on energy consumption

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Abstract

Background. The contribution of information and communication technologies (ICTs) to a low carbon economy is unclear. Previous reviews emphasise the need to assess the specific factors that determine the environmental impacts of ICTs, but none of them link those factors to the magnitude of the impacts on energy consumption and carbon emissions. Our study aims to fill this evidence gap.
Methods/Design. We restrict our analysis to a single application domain, namely e-materialisation, defined as the partial or complete substitution of material products with electronic equivalents. We conduct the first systematic literature review of the direct and higher order impacts of the digitalisation of goods on energy consumption.
Results/Synthesis. We identify 31 relevant studies that we sort into five categories, namely: 'e-publications' (e-books, e-magazines and e-journals); 'e-news'; 'e-business'; 'e-music'; and 'e-videos and games'. All but one of the 31 studies use life-cycle analysis and employ a range of product-system configurations, functional units, system boundaries and allocation rules. Confining attention to direct and substitution effects, the studies suggest potential energy savings from e-publications, e-news and e-music, and less potential from e-business and e-videos/games. However, different assumptions for key variables (such as the lifetime and energy efficiency of user devices, the extent to which personal transport is displaced and the number of users of material and digital products) lead to very different estimates—including many where lifecycle energy consumption increases. Most of the studies assume that digital goods substitute for material goods and all of them neglect rebound effects—which suggests that they overestimate energy savings.
Discussion. Given the diversity and context-specificity of the available evidence, the optimistic assumptions that are frequently used (e.g. perfect substitution) and the neglect of rebound effects, we cannot conclude that e-materialisation has delivered significant energy savings to date or is likely to do so in the future.

1. Introduction

1.1. Background

The potential contribution of information and communication technologies (ICTs) to low-carbon economies is unclear. While it has been argued that the ICT revolution is net energy-saving (Kander *et al* 2013, pp 329–31) and can form the basis of a new surge of green growth (Perez 2013), this claim is contested (Williams 2011). On the one hand, ICTs offer many benefits for reducing energy demand and carbon emissions. For example, e-commerce can displace personal transport demand and improve logistics efficiency, digital monitoring and control can optimise in-use energy consumption (e.g. building energy management systems, smart homes, industrial process control), and teleworking can displace commuting and business travel. On the other hand, the digital economy has a large and rapidly growing energy and carbon footprint, and the continuing improvements in the energy and material efficiency of individual devices are being more than offset by the continuing increases in the number, power, complexity and range of applications of those devices (Galvin 2015). Digital technologies can stimulate demand for existing and new services (e.g. mobile GPS) that require complex, energy-intensive systems to provide (e.g. 4 G networks, satellites, data centres). Depending on systems boundaries and assumptions, the ICT sector was estimated to account for 3.5%–7% of global electricity consumption in 2015 and 1.5%–3% of global greenhouse gases (GHG) emissions (Belkhir and Elmeligi 2018, Malmodin and Lundén 2018, The Shift Project 2019). ICT energy use is currently increasing at 5%–10% per year, which means that its share in the total carbon footprint of societies is likely to increase.

The complexity of ICT systems, the rapidity of technical change and the variety of impact mechanisms (e.g. the emergence of entirely new services) all make the quantification of the historical impacts of ICTs on energy consumption very challenging, as well as creating uncertainty over their future impacts. To understand and address this challenge, a first step is to develop a classification of ICT end-uses and impact mechanisms.

1.2. A classification of ICT end-uses

ICTs provide a multitude of services, but these may be grouped into two broad categories:

- *Virtualisation*: where ICTs provide a complete or partial substitute for previously existing goods (e.g. books, music, videos) or services (e.g. healthcare), or provide entirely new goods or services (e.g. online video games, or 'e-games')[5].
- *Optimisation*: where ICTs improve the design or operation of various technologies, systems and processes (e.g. buildings, logistics, industrial processes).

Building upon Horner *et al* (2016), we may subdivide these two categories into several application domains. Here, we subdivide virtualisation into three application domains, namely *e-services*, *e-materialisation*, and *e-mobility*[6]; and we subdivide optimisation into two application domains, namely *e-design*, and *e-monitoring and control*.

Each application domain encompasses a variety of different services and technologies. For example, e-materialisation includes print versus electronic newspapers (e-news), traditional versus electronic books (e-books) and DVDs versus streaming video (e-video) amongst others. Similarly, 'e-monitoring and control' includes electronic control of industrial processes, and electronic control of heating, ventilation and air-conditioning in buildings amongst others. There are also overlaps and interdependencies between different services and domains: for example, e-books are dependent upon e-payment mechanisms, such as electronic bank transfers. Each of these different services may, in turn, have higher order impacts on energy consumption in several different economic sectors—such as transport, buildings and agriculture. Figure 1 summarizes this proposed classification scheme and provides some illustrative examples.

[5] ICTs frequently complement material goods rather than substitute for them. Subscription to both paper and digitalized versions of a journal is an example. We will return to this point in section 4.

[6] All material goods provide services, and all services require material goods. Our subdivision simply reflects whether the material good or 'immaterial' service is dominant. We classify mobility separately owing to its importance for energy consumption.

1.3. A typology of mechanisms influencing the energy impacts of ICTs

Different authors classify the energy impacts of ICTs in different ways (e.g. Börjesson Rivera *et al* 2014, Hilty and Aebischer 2015, Horner *et al* 2016, Pohl *et al* 2019), but all share the idea that ICTs have both direct and higher-order impacts on energy consumption. The direct impacts include the energy used in the manufacture, operation and disposal of ICTs, along with the energy used for the associated data transmission networks. The higher order impacts include the influence of ICTs on the energy consumption of other systems. For example, digital systems may improve the efficiency of energy use in appliances, networks, buildings, industrial processes and transport systems; and may substitute for more energy-intensive services —such as working from home rather than commuting. But there is no guarantee that the substituted ICT service will be less energy-intensive than the conventional service it replaces. Moreover, if the ICT service is cheaper and offers more utility, the consumption of that service may increase. The net impact on energy consumption will depend upon the balance between these different types of direct and higher order impacts —which can be challenging to evaluate, even in simple situations. Table 1 illustrates the complexity of these effects for a particular ICT application (e-books). In practice, we may expect the magnitude and sign of these different impacts to vary widely from one ICT application to another and also to change over time.

1.4. Objective and structure of the article

There is a large literature on the energy and environmental impacts of ICTs, but studies vary in their empirical focus, methodology and range of impacts included. Five reviews of this literature are worth mentioning. Arushanyan *et al* (2014a) review life cycle analyses (LCAs) of ICT products and services and find that: first, relatively few compare digital and non-digital products and services; and second, those that do typically neglect rebound effects. Horner *et al* (2016) provide an insightful review of the energy

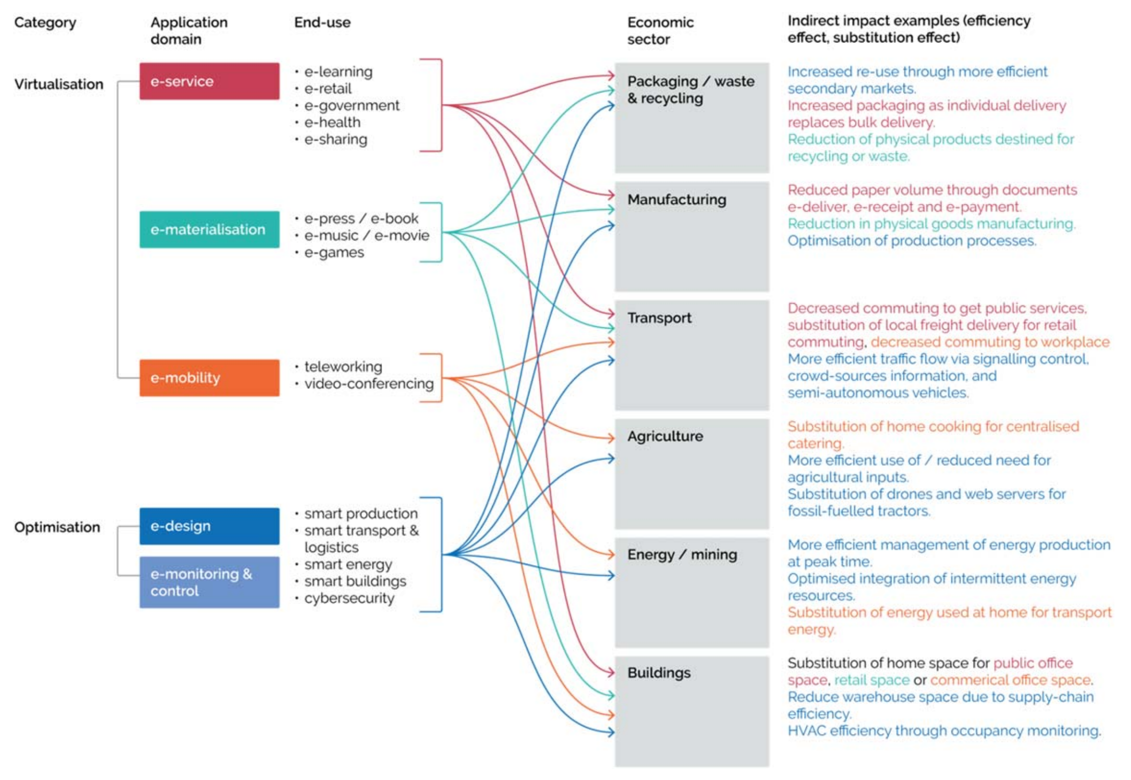

Figure 1. Classifying ICT end-uses based upon their application domain and relationship with economic sectors. *Source*: Based on Horner *et al* (2016).

Table 1. Classifying the mechanisms influencing the impact of ICTs on energy consumption.

Pohl *et al* (2019) aggregate categories		Horner *et al* (2016) aggregate categories	Impact mechanism	E-books example
Direct impacts	Technology perspective	Direct	Embodied energy (+)	Energy used to manufacture the technologies and infrastructure needed to produce, deliver, store, download and read e-books (e.g. data centers, networks e-readers)
			Operational energy (+)	Energy used to operate an e-reader
			Disposal energy (+)	Energy used to dispose of an e-reader
Higher order impacts	User perspective	Indirect: single-service	Efficiency/Optimisation (−)	(Does not apply in this example)
			Substitution (+ or −)	Life-cycle energy use saved by e-books substituting for traditional paper books
			Direct rebound (+)	Energy consumed in additional book reading, stimulated by lower cost and improved utility of e-books
		Indirect: complementary services	Indirect rebound (+ or −)	Energy used in manufacturing and consuming goods, whose demand has increased because of the cost savings from substituting paper books with e-books
	System perspective	Indirect: economy-wide	Economy-wide rebound (+ or −)	Energy used and saved in multiple markets because of economy-wide adjustments in prices and quantities following the introduction of e-books. (e.g. investments previously made in the paper industry are now redirected towards sectors with different energy intensities)
		Indirect: society-wide	Transformational change (+ or −)	Energy used and saved because of far-reaching changes in industrial and organisational structures and social practices following the introduction of e-books.

Source. Based on Horner *et al* (2016) and Pohl *et al* (2019).

impacts of selected ICT applications, focusing in particular upon comparing quantitative estimates. However, they do not employ a systematic review methodology and do not systematically examine the factors determining those impacts in different contexts. Bieser and Hilty (2018) conduct a systematic review of studies assessing the indirect environmental effects of ICTs, but (unlike Horner *et al*) their aim is solely to identify the research methods employed. Hankel *et al* (2018) conduct a systematic literature review of the factors influencing the environmental impact of ICTs, but do not assess the impact of these factors on the environmental outcomes. Finally, Pohl *et al* (2019) assess whether and how LCA studies take into account indirect (higher-order) impacts, but do not compare the resulting quantitative estimates. All these reviews—and especially the last three which employ systematic approaches—emphasise the need to assess the specific factors that determine the environmental impacts of ICTs in particular applications. However, none of them link those factors to the magnitude of the impacts of ICTs in those applications. Our study aims to fill this gap.

Since the evidence on the impact of ICTs on energy consumption is very large and is likely to prove unmanageable in a single study, we chose to restrict our review to one of the application domains illustrated in figure 1. Our selection criteria were: (a) the application should be economically and/or environmentally significant, or expected to become significant in the future; (b) there is evidence on the higher-order energy impacts of this application; and (c) there is reason to believe those impacts are significant, but there is controversy over their sign and magnitude. Based upon these criteria, we chose to focus on *e-materialisation*, defined as the partial or complete substitution of material products with electronic equivalents. Popular examples of e-materialisation include e-books, e-news, e-music and e-videos. In two 'sister' articles (in submission), we investigate the environmental impacts of e-working (or teleworking) and e-sharing (the sharing of material goods via digital platforms).

In what follows we examine the current state of knowledge of the direct and higher-order impacts of e-materialisation on economy-wide energy consumption. In addition to comparing quantitative estimates of energy impacts, we identify the drivers, mechanisms and determinants of those impacts and the conditions under which they are likely to be positive or negative, and larger or smaller.

The remainder of this article is organised as follows. section 2 details the systematic review methodology, including the research questions, search terms and criteria for inclusion. section 3 presents and compares the detailed results from the 31 empirical studies identified by the review and discusses the findings for each category of e-materialisation in turn. section 4 summarises the overall lessons, while section 5 concludes.

2. Methods

2.1. Systematic literature review approach

To review the evidence on the environmental impacts of e-materialisation, we employ the methodology of systematic reviews. These offer several advantages over traditional literature reviews (Petticrew and McCartney 2011, Haddaway *et al* 2015), including:

- A focused research question that avoids excessively wide-ranging discussion and inconclusive results.
- Precise search terms and strict criteria that avoid the selective and opportunistic use of evidence, including unintentional bias (e.g. people citing their own work or that of colleagues and friends).
- Assessment of the methodological quality of studies, with greater weight placed upon the more rigorous studies; and
- Transparency, to ensure replicability and to minimise subjectivity and bias.

To formulate our search and screening protocols, we follow the guidelines of the Collaboration for Environmental Evidence (2018), and use the free online platform CADIMA to perform the screening phase (Kohl *et al* 2018).

2.2. Research questions

The first stage of a systematic review consists of defining the main research question and relevant sub-questions. Our research question is as follows:

RQ. What are the determinants and magnitude of the direct and higher order impacts of e-materialisation on energy consumption?

We further specify six sub-questions:

RSQ1. What are the full range of impacts identified in the literature?

RSQ2. What are the key socio-technical determinants of those impacts?

RSQ3. How sensitive are the estimated impacts to the identified determinants?

RSQ4. What is the level and quality of evidence on the mechanisms contributing to those impacts?

RSQ5. To what extent is there a consensus on the sign and magnitude of impacts?

RSQ6. What potential do different goods and services offer for energy saving through e-materialisation?

2.3. Sources/databases

The second step is to choose the type of studies to investigate and where they will be found. We choose to include peer-reviewed academic journals, conference proceedings, working papers, books, and technical reports. We give priority to studies providing quantitative estimates, but also examine qualitative evidence—both in the final sample of studies and more broadly—to obtain a deeper understanding of

Table 2. Inclusion and exclusion criteria used to screen the preliminary sample.

	Description	Rationale
	Inclusion criteria (IC)	
IR1	The study relates to, or incorporates, one or more ICT end-uses that are within the scope of the study	This is to exclude studies that focus on ICTs related to applications other than e-materialisation
IR2	The study contains primary research results	This is to exclude studies that only report quantitative and qualitative evidence from other primary sources
IR3	The study measures or models one or more higher-order impacts of an e-dematerializing process on energy use or the environment (e.g. greenhouse gas emissions)	This is to include only those studies from which we can extract quantitative estimates of one or more higher-order impacts (most commonly substitution), rather than solely direct impacts
	Exclusion criteria (EC)	
EC1	The main topic of the study is unrelated to ICT	This is to exclude studies from completely different areas (e.g. chemistry or physics) that were caught by the search query but are not relevant to the research question
EC2	The topic of the study is related to ICT, but no particular ICT application is discussed qualitatively or quantitatively	This is to exclude studies from the ICT research field that were caught by the search query but are not relevant to our research question (e.g. article detailing a research agenda without studying a particular ICT end-use)
EC3	The study is not accessible	This is to exclude studies for which the full-text version is not accessible at the time of review (e.g. pre-publication)

Source. Based upon Hankel *et al* (2018).

the relevant mechanisms and determinants. Given the pace of technical change in this area, we confine the review to studies published after 2000—although this still encompasses a period of transformational change. We apply our search protocol to Scopus and Web of Science and identify additional grey literature (e.g. reports, working papers) through a combination of internet searches, checking the profiles of key researchers and checking the bibliography of key studies.

2.4. Search terms and their combination

The third stage involves choosing search terms that are relevant to the topic and combining these into one or more search queries for scholarly databases. This process is iterative, since small changes in the search terms can have a large influence on the number of identified sources. The queries should allow all relevant studies to be identified.

We combine four types of keyword in our search query, namely a synonym for 'ICT' or equivalent; a second for 'energy' or equivalent; a third for 'consumption' or equivalent; and a fourth for 'dematerialised goods' or equivalent. We investigate exhaustive variations around these terms (especially the last one) with the Boolean OR operator, and combinations of them with the Boolean AND operator, and also ensure that the terms catch the studies identified by other reviews (e.g. Horner *et al* 2016). This leads to a very long search string that we split into eight different queries to accommodate the uploading capacity of CADIMA (see supplementary material 1 available online at stacks.iop.org/ERL/15/043001/mmedia).

2.5. Inclusion/exclusion criteria

After merging the results from the searches performed on Scopus and Web of Science, we remove duplicates to obtain our 'initial sample'. We then screen this initial sample to discard irrelevant studies. This involves applying the inclusion and exclusion criteria of table 2, first to the title and abstract of the study and then to the entire text if necessary, to decide whether or not to include them. This gives our 'preliminary sample'. We then review the bibliography of the selected studies to identify additional grey literature, which we add manually to generate our 'final sample'. Following this, we extract information from each study in a consistent way and store this in an Excel file.

2.6. Data synthesis

The final step is to synthesise the data extracted from the final sample of relevant studies. In some cases, quantitative estimates can be combined and synthesised using meta-analysis techniques, but if the evidence is variable, largely qualitative and/or context-dependent, a narrative analysis is more appropriate. Combining a systematic search for evidence with a narrative synthesis of the results has the benefit of providing a clear audit trail from research evidence to policy-relevant insights (Snilstveit *et al* 2012, Dicks *et al* 2014). In the following section, we first report the main quantitative results for each category of good or service, and then discuss these results more qualitatively—focusing in particular on the determinants of these results.

3. Results

3.1. Search and screening phases

As indicated in figure 2, the search phase generated an initial sample of 5649 references from Scopus and

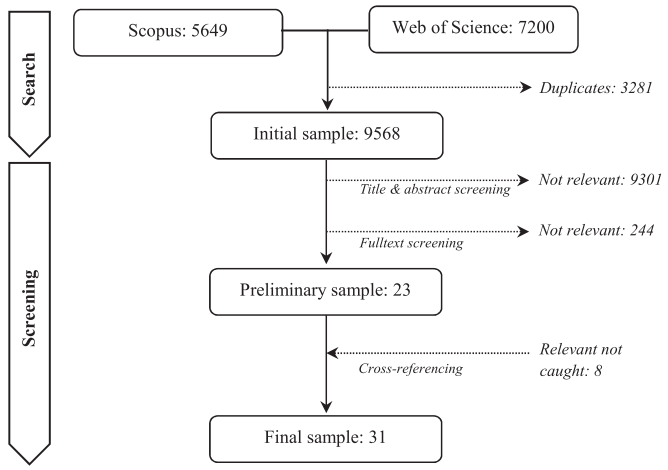

Figure 2. Samples' results after the search and screening phases.

7200 from Web of Science, making a total of 12 849 references. This number is much larger than for other systematic reviews because we were exhaustive in designing our search strings (see supplementary material 1). Adopting such a 'large nest' approach minimizes the risk of missing relevant studies but leads to the inclusion of many irrelevant studies that need to be screened out.

After removing 3281 duplicates, our initial sample comprised 9568 references. Screening the titles and abstract led to the removal of 9301 irrelevant references, while full text screening led to the removal of an additional 244 studies. Hence, our preliminary sample consisted of only 23 studies. From the bibliographies of these studies, we identified 8 additional relevant studies that were not caught by our search protocol since they were largely grey literature. This led to a final sample of 31 relevant studies, of which 74% came directly from our search and 26% from cross-referencing.

The final sample includes studies of the digitalisation of five categories of good or service, namely: 'e-publications' (books, magazines and journals); 'e-news'; 'e-business'; 'e-music'; and 'e-videos and games'. We initially included an additional category of e-mail, but this was dropped since we found only two poor-quality studies of this topic, one of which was obsolete. Table 3 summarizes the type of source (peer-reviewed article, conference paper, or technical report) for each category. Among the 21 peer-reviewed articles, the three most frequent journals were the *Journal of Industrial Ecology* (8 articles), the *International Journal of Life cycle Assessment* (2 articles), and the *Journal of Cleaner Production* (2 articles).

3.2. Data extraction and key features of the identified studies

Tables 4–9 summarize the key features and findings of the 31 studies in our final sample, grouped according to the category of good or service that is digitalised (see supplementary material for extracted data). Each table has nine columns that correspond to: (i) the main author's name and the year of publication; (ii) the region to which the study refers; (iii) the methodology employed (e.g. LCA, scenario analysis); (iv) the metric used to assess impacts (e.g. energy consumption, carbon emissions); (v) the functional unit investigated (see section 3.3); (vi) the impact mechanisms taken into account (see table 1); (vii) the key determinants of the magnitude and sign of impacts; (viii) our appraisal of the methodological quality of the study; and (ix) the percentage change in impacts when comparing digital and traditional goods, or different digital options (typically expressed as a range).

3.3. Methodological features of the identified studies

We first make some general observations about the methodological challenges of comparing the energy intensity of material and digital goods and then summarise the available evidence for each category.

All but one of the 31 studies conduct comparative LCAs of material goods and their digital substitutes (e.g. paper books and e-books), although to differing levels of detail. LCA is a well-established technique for assessing the cumulative environmental impacts of a product over all stages of its life-cycle, including material extraction, processing, manufacture, distribution, use and disposal, and including the intervening transport stages. Most of the reviewed studies investigate multiple categories of environmental impact, but our primary interest is life-cycle energy consumption. Where studies do not report this, we take estimates of carbon or GHG emissions where available (which depend upon fuel mix, disposal routes and other variables) and estimates of total environmental impact where not. The relative environmental performance of digital and material goods can vary widely depending upon the metric used.

A key variable for the LCA studies is their choice of functional unit—or the service that the material

Table 3. Classifying the final sample by the category of good or service and the type of source.

	Peer-reviewed article	Conference paper	Technical report	Total
e-publications	9	1	0	10
e-news	5	2	1	8
e-business	2	2	1	5
e-music	2	0	1	3
e-videos and games	3	2	0	5
Total	21	7	3	31

product and its digital alternative fulfils. So for example, a functional unit could be one reader's use of one copy of a magazine that is supplied in either digital or print form (Achachlouei *et al* 2015). However, alternative choices for functional unit are available, such as reading the magazine for one hour, or producing and using one copy of the magazine (which could have multiple readers). This choice can have a major influence on the LCA results. Also, many digital products provide only *partial substitutes* for material products (e.g. e-news consumers may still buy newspapers), and/or provide *qualitatively different functions* to those products (e.g. e-news includes links to other relevant articles) and/or provide *additional functions* (e.g. e-news includes both text and video). These differences can encourage far-reaching changes in user behaviour that are difficult to anticipate but nevertheless critical for their ultimate environmental impact.

Having defined the functional unit, the LCA studies elaborate the material and digital product-systems to be compared. For example, if the digital system is an electronic magazine, they define the system configuration (e.g. servers, routers, e-readers) and key variables such as the storage space per magazine; the number of downloads per issue; the lifetime, energy efficiency and average utilisation of the e-reader; the disposal route for the e-reader; and so on. It is common to assume more than one value for several of these variables (e.g. short and long device lifetimes) in order to assess the *sensitivity* of the results to key assumptions. The specified product-system reflects the technologies in use at the time, but assumptions regarding their configuration and performance can date very quickly (e.g. desktops are being replaced by laptops, tablets and smartphones).

The studies also define the boundary for each product-system, or the processes and activities that are included or excluded from the assessment. This involves decisions over geographical area, time horizon, the treatment of capital goods, the boundaries with other product-systems and other variables. The boundary should include processes that have a significant influence on total lifecycle impacts, but resource and time constraints, together with data limitations, necessarily lead to 'truncation bias' (Majeau-Bettez *et al* 2011). While it is possible to produce more comprehensive estimates by combining LCA with input-output techniques, this 'hybrid' approach is not widely used. Also, the complexity of ICT products and systems makes the choice of system boundary particularly challenging. For example, smartphones rely upon a complex, global infrastructure of cables, routers, servers, modems, data centres, transmitters and other elements, all containing multiple components supplied by hundreds of companies along global supply chains. The phone itself may contain as many as 60 chemical elements, including many high-purity rare-earths that require energy-intensive extraction and processing. The environmental impacts of these upstream stages are typically either overlooked by LCAs or only crudely estimated (e.g. by assuming 'average purity' raw materials) (Plepys 2002).

System boundaries invariably include infrastructures, facilities and technologies that serve multiple functions, so decisions are also required on how to allocate the associated environmental burdens to the relevant functional unit. For example, e-books may be read on a laptop that is also used for other purposes, so studies must allocate some fraction of the embodied emissions of the laptop to the reading of e-books. This partitioning may be guided by physical, monetary, temporal or other considerations (e.g. the fraction of use time devoted to reading e-books) and the results can be highly sensitive to the choices made. Most LCA assessments of ICT services include the electricity used in network technology and infrastructure (e.g. switches, routers, data centres) but frequently ignore the energy required to manufacture, install and dispose of that infrastructure (since the data used by the functional unit is a tiny fraction of the cumulative data flows over the network lifetime). But this risks overlooking a key component of ICT's environmental footprint.

In addition, LCA studies use data from life-cycle inventory databases and other sources, but this is often based upon uncertain assumptions, is generic rather than specific, is relevant to a different region or configuration to the one studied, and/or is out of date. Data limitations are particularly acute for complex systems that are undergoing rapid technical change, such as ICTs, leading to uncertain estimates that can rapidly become obsolete.

Table 4. Summary of e-publication studies (books, magazines and journals).

Study	Data location	Method	Metric(s)	Functional unit(s)	Mechanisms included	Key determinants of energy impacts	Methodological appraisal	Net savings interval
Moberg *et al* (2011)	Sweden (for edition and paper prod.), China (for e-reader prod.)	LCA	Multiple	Production and reading of one 360-pages hardcover book on paper or electronic format (1.5 MB)	Direct, substitution	Number of books read, number of readers per paper book, e-reader lifetime, electricity generation mix	Good *Strengths:* detailed specification of product-system (including dismantling of E-reader); Ecoinvent data supplemented with company- and site-specific data; key influencing variables identified *Weaknesses:* neglects data storage, tablet production and disposal	−71% to 0% (and even positive)
Part I, Achachlouei *et al* (2015); Part II, Achachlouei and Moberg (2015)	Sweden	LCA	Multiple	One reader's use of one copy of the Swedish magazine Sköna Hem read on a tablet or on paper in 2010 in two market scenarios, emerging and mature, differing by the market shares of paper and digital versions (0.17/99.83 versus 50/50) and the reading time per tablet copy (9 min and 41 min)	Direct, substitution	Number of e-copies per year (2212 or 653500), overall use of tablet per week (14 h or 1 h), magazine file size (163 MB/copy or 5 MB/copy), electricity mix (Swedish or European averages)	Good *Strengths:* detailed specification of product-system; use of context-specific data; inclusion of content production and network manufacture in LCA; comprehensive sensitivity analysis	−90% to +15% (and possibly higher)
Tahara *et al* (2018)	Japan	LCA + behavioural survey	GHG emissions (CO_2 eq.)	The provision and one-time reading of a 224-page paperback book (out of 3000 printed copies) or a 2.4 MB e-book in Japan	Direct, substitution	Type of electronic reading device (e-ink tablet, cell phone, smartphone, iPad, laptop or desktop computer), share of total use time of electronic device allocated to book reading, book weight (81.4 g or 61 g), transportation method for shopping (car, train, cycling, walking), number of readers	Good *Strengths:* includes survey of consumer behaviour; detailed specification of product-system; comprehensive system boundary; compares multiple reading devices; includes primary data for tablet; sensitivity analyses	−77% to 0% (and even positive)

Table 4. (Continued.)

Study	Data location	Method	Metric(s)	Functional unit(s)	Mechanisms included	Key determinants of energy impacts	Methodological appraisal	Net savings interval
Amasawa *et al* (2018)	Sweden (for technical data), USA (for behavioural data)	LCA + behavioural web survey + social experiment	GHG emissions (CO_2 eq.)	Book reading activities (production, delivery and use) per person and per person-book, either with a traditional 360-pages hard-cover paper book (with a mix of bookstore and internet retail) or a 1.5 MB e-book on e-reader (3rd gen. Amazon's Kindle or 1st gen. Apple's iPad)	Direct, substitution	Assumed embodied energy/emissions of e-reader, number of books read per year, reading time per day	Intermediate *Strengths:* combines LCA with web survey and natural experiment to identify buying and reading habits of different customer segments *Weaknesses:* difficult to extract comparative estimates	Not possible to derive meaningful estimates
Kozak and Keolelan (2003)	USA	LCA	Energy, material and water depletion; CO_2, CFC-11, and SO_2 emissions	40 scholarly textbooks read in print (500 pages per book, 8 trips to bookstore) versus an e-reader (1.4 MB per e-book)	Direct, substitution	Number of users per paper book, number of downloads per e-book, e-reading speed, grid efficiency	Intermediate *Strengths:* sensitivity tests *Weaknesses:* not peer-reviewed; limited information on data sources and assumptions; limited information on distribution of impacts between different categories	−81%

Note. 'Multiple' metrics mean: energy depletion, global warming potential, abiotic depletion, acidification potential, eutrophication potential, ozone depletion, human toxicity potential, freshwater and marine aquatic eco-toxicity potential, terrestrial eco-toxicity potential, photochemical ozone creation.

Table 5. Summary of e-publication studies (continued).

Study	Data location	Method	Metric(s)	Functional unit(s)	Mechanisms	Key determinants	Methodological appraisal	Net savings interval
Gard and Keoleian (2002)	USA	LCA	Energy use	12-pages scholarly article read in print (possibly photocopied) versus read online (possibly printed), both in a university library and at home in the digital case	Direct, substitution	Number of reads per article (1, 10 or 1000), article length (6, 12, 24 pages), number of paper journal copies (1,10 or 100), PC daily use duration; travel distance to library and vehicle efficiency, grid efficiency	Good *Strengths:* detailed specification of product-system (including mapping of network pathways); comprehensive system boundary (including built infrastructure); comprehensive sensitivity tests, allowing identification of critical variables; development of five scenarios with different assumptions for key variables such as laser printing and transport	−69% to +543%
Enroth (2009)	Norway	LCA	CO_2 emissions	Use of textbook online (1500 MB) or printed (0.8 kg) used 2 h/week, 40 weeks per year, by 5000 pupils per year for 5 years.	Direct, substitution	Printing process, computer and screens use (their production and disposal also to a lesser extent)	Intermediate *Weaknesses:* lack of detail and product-system; only one impact category; missing information (e.g. carbon intensity of electricity); few sensitivity tests	+808% to +3130%
Song *et al* (2016)	China	LCA + behavioural survey	Energy use, GHG emissions (CO_2 eq)	Review written by a postgraduate student of the Dalian University of Technology (DLUT, China) after searching, downloading and reading several scientific publications	Direct, substitution	Reading time per article, number of papers read, share of paper versus electronic desktop reading, computer power in active mode, number of writing days, computer lifespan	Intermediate *Strengths:* includes survey of user behaviour; careful estimation of direct emissions; Monte Carlo simulation of uncertainties *Weaknesses:* crude estimate of indirect emissions from published literature; excludes some elements of product-system (e.g. disposal); difficult to extract comparative estimates	Not possible to derive meaningful estimates
Naicker and Cohen (2016)	South Africa	LCA	Multiple	Reading the 21 books of (1.2 kg each) prescribed by the University of Cape Town Commerce degree over four years, on paper or digitally with an iPad	Direct, substitution	Electricity mix, number of readers per book, sizes of books	Intermediate *Strengths:* context-specific data and assumptions; sensitivity tests on generation mix and book re-use	−70% to 0% (and even positive)

Note. 'Multiple' metrics mean: energy depletion, global warming potential, abiotic depletion, acidification potential, eutrophication potential, ozone depletion, human toxicity potential, freshwater and marine aquatic ecotoxicity potential, terrestrial ecotoxicity potential, photochemical ozone creation.

Table 6. Summary of e-news studies.

Study	Data location	Method	Metric(s)	Functional unit(s)	Mechanisms	Key determinants	Methodological appraisal	Net savings interval
Reichart and Hischier (2002)	Switzerland	LCA	Ecopoints index	Reading or watching a single news item or an entire daily news set on paper, online, or on TV	Direct, substitution	Number of users per newspaper, number of users per TV set, electricity mix for online reading, time to open and read online news item	Good *Strengths:* detailed specification of product-system; comparison of four medias	−75% to +550%
Toffel and Horvath (2004)	USA	LCA	GHG emissions (CO_2 eq), NO_2, SO_2	Reading the New York Times for 1 year in California via a newspaper (printed in Concord, 62 km away) in a base and best-case scenario regarding paper recycling, or a personal digital assistant (PDA) with content uploaded through wireless or wired connection	Direct, substitution.	Amount of recycled fibres (50% or 100%) in paper journal, share of journal recycled (50% or 100%) or put to landfill, number of readers per journal (1 or 2.6)	Intermediate *Strengths:* context-specific data *Weaknesses:* simplified product-system; few sensitivity tests, old data	−1400% to −320%
Moberg *et al* (2010b)	Sweden	LCA	Multiple	30 min reading of 40-page traditional newspaper or tablet e-paper (assuming 2.6 reads of printed version)	Direct, substitution	Electricity mix (Swedish or European averages), tablet lifetime, internet energy intensity	Good *Strengths:* detailed specification product-system; comparison of Swedish and European contexts	−72% to −28%
Schien *et al* (2013)	UK	LCA	Energy use	10 min of content browsing on The Guardian website (video or text content) using different end-use device (smartphone, tablet, laptop, or desktop), access network (3 G, Wi-Fi or DSL if possible)	Direct, substitution	Content type (video or text content), end-user device, network accesses, geographical location, and browsing behaviour	Good *Strengths:* detailed specification of product-system; context-specific data; investigation of different allocation methods; investigation of multiple combinations of user device, access and service type; Monte Carlo simulations for each scenario *Weaknesses:* compares e-readers and networks rather than electronic versus traditional news	No comparison with a traditional newspaper
Arushanyan and Moberg (2012)	Finland	LCA	GHG emissions (CO_2 eq),	One user reading Finnish Iltalehti.fi online for one year, either on a computer (assuming a mix of	Direct	Electricity mix (Finish or European averages), reading time (2 h/week or 6 h/week)	Intermediate *Weaknesses:* not peer-reviewed; limited sensitivity tests; compares e-readers	No comparison with a traditional newspaper

Table 6. (Continued.)

Study	Data location	Method	Metric(s)	Functional unit(s)	Mechanisms	Key determinants	Methodological appraisal	Net savings interval
				55% desktop and 45% laptop) or on a tablet			rather than electronic versus traditional newspapers	
Arushanyan *et al* (2014b)	Finland	LCA	Multiple	Online or printed version of morning newspaper Aamulehti, evening newspaper Iltalehi, and financial newspaper Kauppa-lehti, considering either total burden per journal unit per year, per journal per reader per year, or per reading hour	Direct, substitution	Functional unit chosen, electricity mix, reading time	Intermediate *Strengths:* user-specific reader profiles; transparency over data and methodological limitations; highlights sensitivity of results to context, assumptions and user behaviours *Weaknesses:* not peer-reviewed; relies upon generic data	−85% to +50%
Wood *et al* (2014)	UK	LCA	GHG emissions (CO_2eq)	Total use of Guardian website during year 2012	Direct, substitution	Electricity provider, energy efficiency of third-party hosting provider, type of end-use device	Intermediate *Strength:* original investigation of the full GHG footprint of e-news provision, including both providers and users *Weaknesses:* no direct comparison with traditional newspaper	No comparison with a traditional newspaper

Note. 'Ecopoints index' in Reichart and Hischier (2002) aggregate air, water, and soil pollutants, wastes, and energy depletion. 'Multiple' metrics mean: energy depletion, global warming potential, abiotic depletion, acidification potential, eutrophication potential, ozone depletion, human toxicity potential, freshwater and marine aquatic ecotoxicity potential, terrestrial ecotoxicity potential, photochemical ozone creation.

Table 7. Summary of e-business studies.

Study	Data location	Method	Metric(s)	Functional unit(s)	Mechanisms	Key determinants	Methods appraisal	Net savings interval
Hoogeveen and Reijnders (2002)	Netherlands	LCA	Energy use	Electronic or paper-based information associated with e-retailing or traditional retailing of a personal computer (TakeitNow company)	Direct, substitution	Intensive online reading and/or printing of electronic information by the customer	Poor *Strengths:* identifies a range of factors that increase or decrease energy savings *Weaknesses:* not a full LCA; limited qualification; crude assumptions/estimates	− 60 MJ to +2 MJ per capita
Deetman and Odegard (2009)	Sweden	LCA	GHG emissions (CO_2 eq)	The service of one year of office paper use	Direct, substitution	Paper type (light-weight coated or wood-free uncoated), number of pages printed per year (2000 or 12480)	Intermediate *Strengths:* Comprehensive product systems; specific data from manufacturer *Weaknesses:* Not peer-reviewed; no sensitivity tests; neglect data storage	−75% to +130%
Moberg *et al* (2010a)	Sweden	LCA	Energy use, GHG emissions (CO_2 eq)	Distribution of 1.4 billion invoices in Sweden for one year, whereof 70% concern B2C, and 30% concern B2B either on paper or electronically	Direct, substitution	Number of pages (1 or 2 A4-sheet), paper invoice distribution (economy or first-class mail), B2C paper invoice handling (10 s or 1 min spend on the internet by consumer), B2B electronic invoice handling (0 or 5 min spend by business), proportion of e-invoices printed by user, paper invoice transported over short or long distance	Good	−1400 TJ eq/yr to −610 TJ eq/yr
Kim and Rohmer (2012)	USA	LCA	Multiple	4.5 g paper billing and payments versus electronic billing and payments (with 20% printing)	Direct, substitution	NA	Poor *weaknesses:* not peer-reviewed; limited information; unclear system boundary; no sensitivity tests; no information on size of invoice	Not possible to derive meaningful estimates
Karapetyan *et al* (2015)	USA	LCA	Multiple	Exchange between customers of 1.8 g paper-based business cards versus 10 kB digital business cards	Direct, substitution	Scale of application, i.e. number of card exchanges (1000 exchanges between customer's results in 2000 business cards, 33 000 exchanges result in 66 000 business cards)	Good *Strengths:* comprehensive product-systems; both screening and full LCA weaknesses: no sensitivity tests; old data	−91% to +179%

Note. 'Multiple' metrics mean: energy depletion, global warming potential, abiotic depletion, acidification potential, eutrophication potential, ozone depletion, human toxicity potential, freshwater and marine aquatic ecotoxicity potential, terrestrial ecotoxicity potential, photochemical ohzone creation.

Table 8. Summary of e-music studies.

Study	Data location	Method	Metric(s)	Functional unit(s)	Mechanisms	Key determinants	Methodological appraisal	Net savings interval
Türk *et al* (2003)	Netherlands	LCA	Material intensity	Provision of 56 min or 465.50 MB of music stored on one CD (bought via physical or online retail) or delivered digitally via the internet	Direct, substitution	CD-R capacity usage, downloading speed	Intermediate *Strengths:* comprehensive; specific information from manufacturer; detailed specification of product-system *Weaknesses:* not peer-reviewed	−63% to +235%
Hogg and Jackson (2009)	UK	Scenarios analysis	Total abiotic raw materials use	From 2005 to 2015, either 'pure music player' scenario (CDs still heavily used by 2015), or 'multifunctional device' scenario (CDs quickly disappear)	Direct, substitution	Multi-functionality of devices, flash-drive versus hard-disk storage	Intermediate *Strengths:* exploration of different scenarios *Weaknesses:* not original data (taken from Türk *et al*)	−53%
Weber *et al* (2010)	USA	LCA	Energy use, CO_2 emissions	Delivery of a music album by CD shop retail, CD e-retail by road or air (plane), digital download, digital download + CD burning, or digital download + CD burning + packaging	Direct, substitution	Driving distance from home to retail, car efficiency, type of jewel case production, last-mile truck efficiency, data centre efficiency	Good *Strengths:* detailed specification of product-system; comprehensive sensitivity tests; Monte Carlo simulation of uncertainty *Weaknesses:* excludes some elements from system boundary (e.g. digital music player)	−87% to −58%

Note. 'Material intensity' in Türk *et al* (2003) means total material input (abiotic and biotic raw materials, soil and water use, air pollutants) per service unit. 'Total abiotic raw materials use' in Hogg and Jackson (2009) aggregate minerals and fossil fuels flows, including excavation residues.

Table 9. Summary of e-video and e-game studies.

Study	Data location	Method	Metric(s)	Functional unit(s)	Mechanisms	Key determinants	Methodological appraisal	Net savings interval
Seetharam *et al* (2010)	USA	LCA	Energy use, GHG emissions (CO_2 eq)	8 GB movie delivery by online streaming versus traditional DVD mail (both from Netflix)	Direct, substitution	DVD lifetime, size of movie, data centre optimisation (particularly server utilisation and idle electricity consumption), multiple views of movie (no impact on DVD, but impact on online streaming), optimized shipping	Intermediate *Weaknesses:* not peer-reviewed; few sensitivity tests; some crude assumptions	−70% to +450%
Chandaria *et al* (2011)	UK	LCA	GHG emissions (CO_2 eq)	Watching one hour of the BBC's UK television programme via video-on-demand (VOD) over the Internet and viewed on a TV set, on desktop, or on a laptop versus broadcast digital terrestrial TV (DTT) viewed on a TV set	Direct, substitution	Number of viewers per display, type of channel watched, type of end-use watching device	Poor *Strengths:* highlights relative contribution of different system elements *Weaknesses:* not peer-reviewed;; not a full LCA - confined to direct emissions	−34% (VOD on laptop versus DTT on TV, or VOD on TV or desktop)
Shehabi *et al* (2014)	USA	LCA	Energy use, GHG emissions (CO_2 eq)	One-hour movie viewing from online streaming, mail-rented DVD, store-rented DVD, mail-purchased DVD, or store-purchased DVD	Direct, substitution	Electricity mix, average annual views per DVD, average DVD lifetime, warehouse shipping distance, mail delivery distance, consumer travel distance to store, vehicle efficiency, cloud server power and utilisation rate, data processing capacity of server (terabits/server), streaming rate per video (Mbps), viewing time by device (desktop computer, laptop computer, flat panel monitor, smart phone, DVD player, TV)	Good *Strengths:* detailed specification of product-system; comprehensive sensitivity tests; wide system boundary; context-specific data	−35% to +1.3%

Table 9. (Continued.)

Study	Data location	Method	Metric(s)	Functional unit(s)	Mechanisms	Key determinants	Methodological appraisal	Net savings interval
Hochschorner *et al* (2015)	Sweden	LCA	GHG emissions (CO_2 eq)	Distributing and watching a two-hour (3 GB) movie on television via peer-to-peer streaming (P2Ps) or peer-to-peer downloading (P2Pd), versus watching same movie on internet protocol television (IPTV) (latter is benchmark)	Direct, substitution	Uplink bandwidth, lifetime and utilisation of user devices, allocation rules for multifunctional devices, movie length	Good *strengths:* comprehensive sensitivity tests	+252% to 0%
Mayers *et al* (2015)	Austria (for development), UK (for use and disposal)	LCA	GHG emissions (CO_2 eq)	Development, distribution, use and disposal of a typical 8.8 GB PlayStation 3 game distributed online (downloaded) or through a Blu-ray disc (BD)	Direct, substitution	Internet energy intensity (0.5 or 1.5 kWh $G^{-1}B^{-1}$), file size (8.8 GB in reference scenario), number of other items shopped, travel mode used to shop, distance of shop to warehouse, CO_2 content of electricity	Good *Strengths:* detailed specification of product-system; product-specific and context-specific data; explicit treatment of uncertainty in electricity intensity of downloading; comprehensive sensitivity tests	+5% to +200% (and possibly above)

Finally, comparative LCA studies typically include only a subset of the higher order impacts on energy consumption (table 1). For example, they estimate the energy saved from substituting digital for material products effects but ignore the rebound effects associated with those products. As a result, they provide an incomplete picture of the environmental impacts of e-materialisation. We return to this important point in section 4.

The following subsections summarise the results of the reviewed studies in each category and highlight how these methodological challenges influence the results.

3.4. E-publications

Electronic publications are capturing an increasing share of global markets, driven by their flexibility and convenience, their low price compared to traditional paper publications and the technical improvements in reading devices. For example, e-books accounted for one quarter of global book sales in 2018, up from 12% in 2013.

Studies of the digitalisation of publications show clearly how estimates of energy savings depend upon key assumptions. For example, Moberg *et al* (2011) compare the impacts associated with producing, using and disposing of 48 hardback books of 360 pages each, with those associated with consuming the same number of e-books during a lifetime of an e-reader. The latter is energy efficient, so most of the energy use is associated with the production of the e-reader. Moberg *et al* estimate that the e-books require 71% less energy use per book, suggesting an energy break-even point of 20 books during the e-reader's lifetime. However, if the paper books are read twice, the break-even value increases to 40 books. The e-reader alternative can lead to more or less energy consumption depending upon the type of paper book (hardback or paperback), the number of people reading that book, the lifetime and utilisation of the e-reader, the mode of purchasing the paper book (e.g. online or travelling to a bookshop), the distance to the bookshop (assumed to be 2 km in the base case), and other variables.

In a particularly comprehensive study, Achachlouei *et al* (2015) and Achachlouei and Moberg (2015) compare the impacts of a print edition of a magazine to those of an electronic edition read on a tablet, and show how the estimated energy savings depend upon the choice of functional unit. Assuming 4.4 readers of the print edition, a large market for the electronic edition and equal reading time for both, they estimate that the electronic edition yields ~40% energy savings per reader, ~85% per copy and ~40% per reading hour. Energy savings increase with the number of readers of the electronic edition, the time spent reading that edition and the utilisation of the tablet; but decrease with the number of readers of the print edition.

Tahara *et al* (2018) shows how the impacts of dematerialising books are sensitive to the type of reading device and its intensity of use. Using typical values for the lifetimes of different devices and the reading patterns on those devices, they estimate that reading an e-book on a tablet produces 77% less GHG emissions than reading an equivalent paper edition, while reading on a desktop produces 18% less. Smartphones achieve the largest savings, followed by tablets, and laptops. Greater use of the reading device reduces the impacts per book, since this distributes the embodied emissions over more books. If the paper book is read twice, its lifetime emissions are comparable with an e-book read on a tablet. The emissions associated with paper books are particularly sensitive to the mode, duration and energy efficiency of travel to the bookstore.

Amasawa *et al* (2018) also compare paper books with e-readers and combine an LCA with a web survey and lab experiment to assess typical buying and reading habits. They estimate that the adoption of e-readers can reduce GHG emissions provided that more than 4.7 books are substituted by e-books annually and the e-reader is used less for than 10 h each day. This is significantly lower than the estimate by Moberg *et al* (2011) of 20–30 books per year, largely because the embodied emissions of the e-reader are assumed to be smaller—reflecting technical change in the intervening years. Comparable figures for reading on a tablet are 9 books per year and 1.6 h per day. The survey and experiments suggest that current users of e-readers achieve GHG savings while users of tablets do not, and that users of e-books read more books. However, this difference cannot be causally attributed to the e-reader.

Kozak and Keolelan (2003) compare the impact of purchasing, reading and retaining 40 textbooks over the course of a four-year degree (assuming 500 pages per book, and the purchase of 5 books on each trip to the bookshop) with consuming the equivalent number of books on an (early) e-reader. The environmental impacts for the paper book are dominated by paper production and printing, while those for the e-books are dominated by the electricity use for reading. Kozak and Keoleian estimate that the e-books require 81% less energy, but this depends upon the number of users accessing the books from the server, the e-reading speed and other variables. E-books require less energy than paper books if at least one other person accesses the former from the server—even if the personal transport to purchase the paper book is ignored. However, this result only applies if the paper books are not reused.

Enroth (2009) compares the CO_2 emissions associated with using an online schoolbook and a paper alternative, assuming two hours of reading per week for 40 weeks per year, by 5000 pupils over 5 years. Paper production accounts for half of the emissions for traditional books, while electricity use accounts for

44% of the emissions for the e-books—which is odd, since Norwegian electricity is low carbon (the assumed carbon intensity of electricity is not stated). Manufacturing the computer accounts for 38% of the emissions for e-books, but this number will be sensitive to the allocation rule assumed (3.7% of production emissions are allocated to reading e-books). Enroth estimates the online system would produce between 9 times and 32 times more carbon emissions, depending upon the printing process and the computer equipment used. Print books perform much better in this context because they have multiple users over an extended period of time.

Gard and Keoleian (2002) analyze the impact of reading an academic article in print or online. They estimate that on-line reading requires between 69% less and 543% more energy consumption, depending upon the number of reads per article, the number of paper journal copies, the daily usage of the reading device, and the mode, duration and energy efficiency of travel to the library. They estimate that digitalisation can achieve energy savings for journals/articles with low readership and when they displace lengthy car journeys to a library.

Song *et al* (2016) estimate that producing a review article at a Chinese university requires ~38 MJ of energy consumption, allowing for searching, downloading and reading several information sources. Reading accounts for 65% of the total, assuming one quarter is on a desktop and the remainder in print. They estimate that shifting to 50% or 100% electronic reading would *increase* energy consumption by 25% and 45% respectively, owing in part to the long reading time per article (3.4 h). But energy savings could be achieved by substituting laptops for desktops.

Finally, Naicker and Cohen (2016) estimate the impact of a student reading 21 textbooks for two hours per day over a four-year degree at the University of Cape Town, and compare this with reading the same books on an iPad. Assuming one reader per book, they estimate that the e-books reduce primary energy consumption by ~70%. Paper books are favoured if they are shared or resold—and if there are three or more readers per book, they have lower energy consumption.

Summary. Overall, the studies suggest that substituting digital for paper publications can reduce lifetime energy consumption, with several studies indicating potential savings of 70%–80%. However, the estimated savings are highly sensitive to assumptions and could easily be eliminated or reversed by different patterns of user behaviour for either the material or digital publications. Savings are more likely to be achieved if: (a) the electronic reading device is energy efficient and is used intensively over a relatively long lifetime (e.g. >3 years); (b) this device substitutes for rather than complements the use of material publications; (c) those publications would normally have only a single reader; and (c) the digital alternative allows the consumer to take fewer car trips to books or libraries. These conditions will not always hold, and there are likely to be situations where a switch to electronic publications will increase energy consumption (e.g. Enroth's schoolbook example). The energy savings from e-books are particularly sensitive to the energy efficiency of the reading device—and since this has dramatically improved over the last 20 years, the potential for energy savings has undoubtedly increased. At the same time, more of the remaining energy consumption is accounted for by the 'cloud', so is harder to estimate and to allocate to electronic publications. Also, the low cost and improved utility of e-publications is likely to encourage rebound effects, but these are ignored by all of the reviewed studies.

3.5. E-news

Digitalisation has transformed the structure and organisation of the news industry. For example, traditional weekly newspaper sales in the US fell from 62 million in 1990 to less than 28 million in 2018, and online news is now approaching TV news as the preferred news medium.

Reichart and Hischier (2002) compare the impacts of reading or watching either a single news item or the entire daily news on paper, a desktop computer or TV. Using an index of aggregate environmental impacts, they estimate that reading a news item online has ~5.5 times the impact of traditional newspapers (assuming 2.3 reads per paper), and approximately twice that of watching the item on TV. Online impacts derive primarily from the production and use of the computer and are sensitive to the speed of reading. In contrast, reading the entire daily news online has approximately one quarter of the impact of a traditional newspaper—although still more than watching the news on TV. This again illustrates the importance of the choice of functional unit. Key variables include the number of readers per newspaper, the number of viewers per TV set, the energy efficiency of the TV and computer and the intensity of use of the computer. When the assumed Swiss electricity generation mix is replaced with a European average electricity mix (in 2000), the impacts from reading the daily news online become comparable to those of a traditional newspaper—highlighting the importance of this variable. Since contemporary users are more likely to use smartphones or laptops, these results are now outdated and probably underestimate the potential environmental benefits from e-news.

Toffel and Horvath (2004) assess the GHG emissions associated with reading a newspaper for one year in California, with accessing the same news via a personal digital assistant (a precursor to a smartphone) using either a wired or wireless connection. The results consistently favour the digital system, with emission savings of between 320% (wire uploading, 2.6 readers per newspaper) and 1400% (wireless uploading, one reader per newspaper). However, the authors note that the PDA may complement rather than substitute traditional newspapers.

Moberg *et al* (2010b) analyze the environmental impacts associated with 30 min of reading the news on a printed newspaper and on a dedicated tablet. Their results suggest that the tablet is always preferred, with up to 72% energy savings—even after allowing for an average of 2.4 reads of the printed edition. The tablet performs better when it substitutes for larger newspapers with a small number of readers and when it is used intensively over a long lifetime.

Arushanyan *et al* (2014b) compare the aggregate environmental impacts of online and printed versions of three newspapers that vary in size and market share. Assuming the online version is read on a (European average) mix of desktop and laptop computers, they estimate that it has 60% smaller environmental impacts per year, and 85% smaller impacts per reader per year, but 50% larger impacts per reading hour. These estimates depend upon the lifetime and average utilisation of the computers, and also on the fuel mix for electricity generation. The authors highlight the difficulties of comparing traditional and electronic news, owing to differences in function and user behaviour and the lack of accurate data.

Three other studies in this category compare the impacts of different digital options and again highlight the importance of the choice of reading device. For example, Arushanyan and Moberg (2012) compare the GHG emissions associated with reading an online newspaper for one year on a computer (a mix of 55% desktop and 45% laptop) and on a dedicated tablet. They estimate the latter generates 33% less emissions.

Schien *et al* (2013) find that user devices and 3 G mobile networks contribute a much larger portion of the carbon footprint of an online newspaper than data centres. The former account for between 7% and 90% of the total footprint for articles and between 0.7% and 78% for video content. The analysis demonstrates the importance of allocation rules and shows how the distribution of carbon emissions varies with the specific configuration of user device, access method and service type. Using the same model, Wood *et al* (2014) estimate the GHG emissions associated with Guardian website were one third of those of the parent company and that three quarters of the online footprint derived from the electricity consumed by user devices. As a result, initiatives such as switching to zero-carbon energy, would have only a marginal impact (3%) on the total carbon footprint of the newspaper, while a shift of 10% of page views from desktops to e-readers would reduce that footprint by 9.7%.

Summary. Overall, these studies suggest that e-news has the potential to reduce energy use and emissions, largely because it displaces energy-intensive paper production and printing. As with e-publications, several of the studies suggest potential energy savings of 70% or more. But again, these estimates are highly sensitive to the choice of functional unit and to variables such as the number of pages of the newspaper, the number of readers of the newspaper, the lifetime and utilisation of the reading device and—most importantly—the energy efficiency of that device. Since e-news is commonly read on multifunctional devices (e.g. desktops, laptops, tablets, smartphones), its relative environmental performance is also sensitive to the allocation rules used. The study assumes full substitution of newspapers by e-news, but the continuing popularity of newspapers suggests a degree of complementarity The falling cost and improved utility of e-news (e.g. integration of videos, regular updates) is likely to encourage increased consumption (a rebound effect), but none of the studies consider this. Also, as e-news becomes more diverse and is produced for smaller target audiences, the environmental impacts related to production of news content are likely to form an increasing proportion of the total.

3.6. E-business

More than forty years ago, many commentators were anticipating the emergence of the paperless office (Bloomberg 1975). But despite the dominance of electronic communication, office paper consumption continues to increase—together with the associated energy consumption (Sellen and Harper 2003).

Studies of the substitution of business paper with electronic information suggest that potential savings vary widely from one application to another. For example, Hoogeveen and Reijnders (2002) compare traditional (shop-based) retailing of a personal computer with e-retailing and estimate the impact on paper and energy consumption. They find that paper use may be reduced by as much as 90% and that the associated energy savings could exceed those from other sources, such as reduced retail floor space. However, energy savings will be reduced if customers print the electronic information or spend longer searching online. They note that the cost savings from e-retailing could encourage large indirect rebound effects but provide only crude estimates of the size of those effects.

Deetman and Odegard (2009) estimate the GHG emissions associated with one year of office paper use. They estimate that substituting a dedicated digital reader for 2k pages of paper use could *increase* emissions by 45%–130%, depending upon the type of paper displaced. However, if 12.5k pages are displaced, the digital reader could reduce emissions by 60%–75%. This suggests a break-even point of 3–5k pages per year which is less than the average for an office worker (10k pages). However, they assume perfect substitution of the paper alternative and exclude some elements from their system boundary.

Moberg *et al* (2010a) estimate the energy savings from substituting the distribution of 1.4 billion paper invoices in Sweden (70% B2C and 30% B2B) with electronic distribution. Their results suggest a large potential for energy savings (1400 TJ yr^{-1}), but they do not indicate the baseline energy consumption. Variables such as economy or first-class mail, short or long-distance transport and the speed of invoice handling have only a marginal impact (<5%) on the estimated savings. Of much greater importance are the size of invoice (35% less savings for a one-page versus a two-page invoice) and whether the invoice is printed by the recipient (40% less savings).

Kim and Rohmer (2012) estimate the aggregate environmental impacts associated with a paper invoicing system (4.5 g per invoice) and compare these to an electronic alternative where 20% of the invoices are printed by the customer. They estimate that the electronic system has 74% lower GHG emissions. However, the systems boundary is poorly defined, the size of the electronic invoice is not stated, and no sensitivity tests are performed.

Karapetyan *et al* (2015) compare the exchange of 1.8 g paper business cards with 10 kB digital alternatives. For exchanges of 1000 cards, the digital system requires 179% more energy consumption, but for 33000 exchanges the digital system requires 91% less energy. In practice, the lower end of this range looks more plausible. No further sensitivity analysis is performed so it is not possible to estimate a break-even point.

Summary. As with e-publications and e-news, these studies suggest the potential for large energy savings from e-business, but only if it substitutes for rather than complements the paper alternative—for example, by avoiding the printing of electronic invoices. In addition, the e-business system must displace large volumes of paper, to offset the embodied emissions of that system, and must also avoid large rebound effects. These conditions appear more likely to hold for some applications than for others: for example, business cards are less likely to be printed than electronic invoices. However, recent experience suggests that large-scale substitution is unlikely. In their book, *The Myth of the Paperless Office*, Sellen and Harper (2003) show how various 'affordances' of paper (e.g. the ability to annotate, to juxtapose and to layout information in space) help explain its continued popularity, despite improvements in the quality of digital alternatives; while Mangen *et al* (2013) show how reading on paper ensures better comprehension than reading on a screen. More generally, ICTs facilitate access to large numbers of documents that can be easily printed, thereby encouraging increased paper consumption—a form of rebound effect. Hence, the energy-saving potential of e-business may not be realised in practice.

3.7. E-music

In less than 20 years, music delivery has evolved from CDs, through downloading MP3 files to streaming. Digital music formed 60% of revenues for the global music industry in 2018, compared to only 2% in 2004 (IFPI 2019, p 13). But analysis of the associated environmental impacts has not kept pace with these developments, and we found only three studies—all of which were published before 2010.

Türk *et al* (2003) investigate the material intensity of providing 56 min of music via CD (bought via physical or online retail) or digital download. They estimate the latter has 63% lower environmental impacts, which reduces to 59% if the downloaded music is compressed and burnt onto a CD and falls further to 17% if the full capacity of the disc is used. This 're-materialisation' is analogous to the printing of electronic documents, but (unlike the former) the burning of CDs is now obsolete. Faster downloading speeds increased the environmental benefits of the digital alternative.

Building upon Türk *et al's* estimates, Hogg and Jackson (2009) estimate raw material use in two scenarios to 2015: a 'pure music player' scenario where CDs are still heavily used, and a 'multifunctional device' scenario where they are replaced with technologies such as smartphones. Under their assumptions, the latter is only one half as material intensive owing to reductions in the number and size of user devices. These estimates exclude the use phase (listening to songs) and assume that the multifunctional device substitutes for several other devices—which may not always be the case. The authors also note that multi-functional devices may be relatively material intensive.

Weber *et al* (2010) compare six scenarios for delivering a music album, including buying CDs from shops, buying CDs online and downloading an MP3 file. In their reference scenario, they estimate that downloading requires 87% less energy consumption than a shop-bought CD. Energy savings fall to 58% if the consumer walks rather than drives to the shop and fall further if the downloaded music is compressed and burnt on a CD. However, the worst-case downloading scenario still uses 37% less energy than the best-case CD scenario. The logistics chain for CDs (including last-mile transport) uses more energy than the packaging, while data centres use more energy than user devices. Weber *et al* use Monte Carlo analysis to demonstrate that the energy savings from digital music are robust to key uncertainties.

Summary. Taken together, these studies suggest that downloading a single music album is significantly less energy-intensive than the CD alternative, even when using obsolete technology. The market has since shifted towards streaming, but the associated energy impacts have yet to be assessed. Rebound effects are again ignored, but this is another area where they could be large. Streaming is significantly cheaper than earlier modes and provides access to a much wider range of music, so could encourage increased music consumption. The associated upward pressure on energy consumption could offset the reduction in energy use per individual track. Also, the relative environmental impacts of different modes will depend upon the energy efficiency of the user device and number of times that a track is played—and the proportional increase in energy consumption from repeat playing will be greater for streaming than for CDs or downloading.

3.8. E-videos and e-games

Several studies compare the energy implications of different ways of watching videos and receiving and playing electronic games. As with e-music, this is an area of rapid technical change.

Seetharam et al (2010) compare the energy intensity of streaming an 8 GB movie with mailing a DVD to the consumer. Energy use for the former is estimated to be dominated by servers, and for the latter by manufacturing the DVD. The energy use for viewing is 3–5 times larger than that for delivery but is ignored since the viewing device is assumed to be the same for both modes. Seetharan *et al* estimate that streaming uses 22% less energy with current technology, and 70% less with 'energy-optimised' technology in data centres and networks. However, higher quality and more data intensive movies (e.g. 50 GB Blu-Ray) would make streaming significantly *more* energy-intensive (450%) than DVDs—as would viewing those movies multiple times.

Chandaria *et al* (2011) compare the GHG emissions from a one person watching a one-hour program on digital terrestrial TV (DTT) to those from watching the same program via video-on-demand (VOD) on either a TV set, a desktop or a laptop. They estimate that VOD requires between 2% and 65% less electricity consumption, with the consumer equipment accounting for between 37% and 76% of the total. However, this estimate ignores embodied emissions. With this functional unit, doubling the number of viewers per display decreases the carbon footprint of DTT + TV by 44% and VOD + TV by 39%. The trend towards larger displays may increase energy consumption, while efficiency improvements and the trend towards viewing on mobiles and tablets could reduce energy consumption. Also, the broadcast contribution to energy consumption is largely fixed for DTT but depends upon the size of audience for VOD, especially if investment is required for network expansion.

Shehabi *et al* (2014) compare the primary energy consumption associated with watching a one-hour movie delivered through online streaming, or via a DVD. They estimate that streaming consumes slightly (1.3%) more energy than mail-delivered DVDs (either rented or purchased), but 35% less energy than shop-rented or shop-purchased DVDs. Sensitivity analysis changes these results by 5% to 20%. Viewing devices account for the majority of energy use for all modes and energy savings can be achieved through eliminating DVD players. Driving to the shop is important for shop-rented/purchased DVDs and data transmission is important for streaming—with higher rates of data transmission leading to higher energy consumption. The authors note that technical change and the falling cost of streaming encourages more video consumption (not just movies but also other formats such as YouTube), but they do not quantify the energy implications.

Hochschorner *et al* (2015) compare the GHG emissions from distributing and watching a two-hour movie (3 GB) via internet protocol television (IPTV) against two different peer-to-peer solutions—namely streaming (P2Ps) and downloading (P2Pd)—that are often claimed to be more energy efficient. They estimate that with a uplink bandwidth of 50 kB s^{-1}, P2P (via streaming or downloading) emits 252% more GHGs than the IPTV system, but this difference disappears with a bandwidth of 1000 kB s^{-1}. Allocating half of the energy consumed by the laptop to downloading, the break-even bandwidth for P2P is 360 kB s^{-1}. The results are sensitive to assumptions about the electricity generation mix, the allocation rules for user devices, the lifetime of those devices, the movie length and the number of repeat views.

Finally, Mayers *et al* (2015) compare the life-cycle GHG emissions from distributing a PlayStation 3 game online (downloaded) or via a Blu-ray disc (BD). Game play accounts for the bulk of emissions, but this is excluded from the study as it is independent of the method of distribution. The carbon intensity of online distribution is sensitive to file size and the energy intensity of data transmission, while the carbon intensity of disc distribution is sensitive to consumer shopping behaviour. For an average file size (8.8 GB), online distribution is 5%–32% more GHG intensive, depending on the energy intensity of data transmission (which is uncertain). Online distribution is preferred for files smaller than 1.3 GB (over the full range of internet energy intensity), while disc distribution is preferred for files larger than 4.5 GB. The reference scenario assumes that consumers drive to retail outlets and purchase nine other items, along with the disc. But if consumers use public transport or buy more items per trip, emissions for the disc alternative are between one quarter and one third lower. Reductions in the energy intensity of data transmission favour online distribution, but increases in the file size of e-games favour disc distribution—and both are occurring at the same time

Summary. Overall, these studies present a rather mixed picture and suggest less potential for energy saving then the other categories. Streaming videos and games is data-intensive and hence can also be energy-intensive. As a result, there are likely to be circumstances where streaming videos requires more energy than earlier technologies such as DVDs. While the energy intensity of streaming a given volume of data is falling, the data intensity of videos and e-games is increasing, and therefore the net implications for energy consumption is unclear. In addition, the repeat streaming of a particular video is likely to involve proportionately more energy consumption than the repeat playing of a DVD, and streaming is likely to be more energy-intensive than broadcast television. On top of this, streaming has significantly increased overall video consumption as a result of the diversity of content available, the ability to use multiple devices and the rapid reduction in costs. Video streaming accounted for ~60% of global downstream data flows in 2017, and with global data flows growing at 5%–10% per year, both total and per capita video consumption is increasing (Cisco 2019, The Shift Project 2019, Efoui-Hess 2019). Overall, therefore, it is possible that e-materialisation has increased energy consumption in this area.

4. Discussion

As the section 3 has demonstrated, the evidence for energy savings from e-materialisation is limited, diverse and of varying quality. Our appraisals of the latter are necessarily broad-brush and subjective, but overall we judge 13 of the studies to be 'good', 15 to be 'intermediate' and 3 to be 'poor'. The reviewed studies vary widely in terms of their system configuration, supporting assumptions, functional units, environmental metrics and quantitative results. Some studies find large energy (or emission) savings from e-materialisation, others find significantly increased energy consumption, and many find that both outcomes are possible depending upon the functional unit chosen and assumptions used. The speed of technical change creates a major challenge, since many of the earlier studies are now obsolete. Taken together, these features make it difficult to compare the results and to draw overall conclusions.

Table 10 provides a summary, but this should be interpreted with caution. At the aggregate level, the results suggest considerable technical potential for e-materialisation to achieve energy savings by substituting for individual books, magazines, news items and musical tracks and rather less potential by substituting for business paper, videos and games. Whether those savings are realised in practice will depend upon the degree of substitution—which is frequently partial. For example, 34% of US consumers use e-books, but only 6% use them exclusively. Similar complementarity was observed in the early stages of market evolution for digital magazines, music, videos and games, but substitutability has increased as the technology has improved. At the same time, streaming videos and games can be more energy-intensive than earlier technologies.

Most of the studies test the sensitivity of results to key technical and behavioural variables, and typically find a wide range of possible outcomes. Only six of the studies unambiguously find energy/emission savings for all of the assumptions used. Indeed, the main lesson is that substituting digital for material products can have positive or negative impacts on energy consumption, depending on a range of plausible assumptions regarding technical configuration, allocation rules, and user behaviour. The more thorough studies that perform detailed sensitivity analyses (e.g. Gard and Keoleian) consistently point to inconclusive results[7].

Estimates of the energy savings from e-materialisation do not appear particularly sensitive to the assumed system boundary—largely because most studies include the dominant contributors to energy consumption (e.g. user devices) within their boundary. In contrast, differing assumptions for user behaviour and allocation rules have a very large impact on the estimated savings. Hence, further studies in this area should seek to base their assumptions upon empirical investigations of actual user behaviour.

Several studies find that end-use devices account for a large proportion of the life-cycle energy consumption of digital products. Hence, the benefits of e-materialisation should increase as those devices become more energy efficient. At the same time, life-cycle energy consumption may become more uncertain, since both the operational and embodied energy consumption of network infrastructure and the upstream energy consumption of raw material production are poorly understood, potentially underestimated and frequently overlooked. The benefits of more energy efficient devices are also offset by their short lifetimes and rapid obsolescence, since this necessitates energy use for manufacturing the replacement devices and changing the associated product-system (e.g. production lines).

One key lesson is the difficulty of estimating life-cycle energy consumption for digital products, and the context-specificity of the resulting estimates (Bull and Kozak 2014). Challenges include: the complexity and variability of ICT systems and the risk of truncation bias; the absence of accurate and up-to-date data for many system components; the uncertainty about key variables such as network energy consumption (Coroama and Hilty 2014); the prevalence of multi-functional technologies and infrastructures and the consequent sensitivity of results to allocation rules; the speed of technical change and the rapid obsolescence of environmental assessments; and the sensitivity of estimates to both the definition of the product-system (e.g. technology lifetimes) and assumptions about user behaviour (e.g. the number of times a publication is read). The last of these is particularly important, since

[7] Interestingly, cumulative energy consumption is typically expressed in terms of primary energy in LCAs. But no study discusses the different conventions that exist for estimating primary energy from final energy measures. This can have a major impact on results, especially if grid electricity contains a large share of nuclear and renewable electricity.

Table 10. Summary of available evidence on the energy savings from e-materialisation.

Application	Range of estimates of energy savings*	'Typical' estimate of energy savings*	Quality of evidence	Technical potential for energy savings	Vulnerability to rebound effects	Key determinants of energy savings (increase (↑), decrease (↓), and context-specific (∼))
E-publications	−90% to +3000	−70%	Medium	High	Medium	Choice of functional unit (∼) Lifetime, average utilisation and energy efficiency of e-reader (↑) Allocation rules for multifunctional devices (∼) Size of paper publication (↑) Number of readers of paper publication (↓) Extent of displacement of personal travel (∼)
E-news	−1400% to +550%	−70%	Medium	High	High	Choice of functional unit (∼) Size of newspaper (↑) Number of readers of newspaper (↓) Lifetime, utilisation and energy efficiency of e-reader (↑) Allocation rules for multifunctional devices (∼)
E-business	−91% to +179%	Insufficient evidence	Poor	Medium	High	Choice of functional unit (∼) Degree of substitution achieved (e.g. avoiding reprinting of docs.) (↑) Type of paper displaced (∼) Volume of paper displaced (↑)
E-music	−87% to +235%	−60%	Poor	High	High	Choice of functional unit (∼) Lifetime, average utilisation and energy efficiency of user device (↑) Extent of re-materialisation (↓) Extent to which multifunctional devices replace other devices (↑) Amount of repeat playing of music tracks (↓) Extent of displacement of personal travel (↑)
E-videos and e-games	−70% to +450%	0%	Medium	Low	High	Choice of functional unit (∼) Data intensity of video/game (↓) Network speed in processing capacity (↑) Amount of repeat viewing/playing (↓) Extent of displacement of personal transport (↑) Allocation rules for multifunctional devices (∼)

*Negative (respectively positive) sign indicates a decrease (resp. increase) in energy consumption for the digital alternative compared to the traditional material good.

very few studies empirically measure how the users of material and digital products actually behave. More generally, these difficulties highlight the limitations of LCA for assessing the environmental impact of digital technologies and systems (Bull and Kozak 2014). While sensitivity tests can help, there is clearly a need for alternative methodological approaches in this area.

Perhaps the biggest challenge is that digital substitutes are qualitatively different to the material products they substitute for. While these differences may limit their substitutability (e.g. it is easier to read on paper than on a screen), digital products more commonly provide greater utility and encourage increased consumption (e.g. people check their phones for regular news updates). This in turn leads to more energy consumption throughout the whole product-system (e.g. newsrooms must provide more news at more frequent intervals). In addition, digital products are often and increasingly cheaper than their material equivalents (e.g. the Guardian online is free) and/or have lower transaction costs—which again encourages increased consumption. This in turn can offset any reductions in energy use per unit of the relevant product or service. Such impacts may be labelled rebound effects, although this a rather loose use of that term.

The potential for rebound effects is largely ignored by the reviewed studies, which confine themselves to direct and substitution effects (table 1). A few studies acknowledge the importance of rebound effects, but none quantify them with any accuracy. While Pohl *et al* (2019) claim that Moberg *et al* (2010a), Weber *et al* (2010) and Amasawa *et al* (2018) include rebound effects, this is inaccurate. Practices such as 're-materialising' electronic music by burning CDs or printing copies of paper documents may be labelled as rebound effects, but they only form part of the story. Similarly, Amasawa *et al*'s (2018) finding that users of e-readers read more books does not demonstrate a direct rebound effect since it is also possible that book lovers are more likely to use e-readers.

If digital products provide a cheaper and better alternative, they will encourage increased consumption of the relevant service (a direct rebound), allow consumers to save money that they then can spend on other goods and services that also require energy to provide (an indirect rebound), trigger changes in the price and quantity of multiple goods in multiple markets (a general equilibrium rebound) and potentially facilitate far-reaching changes in industrial structures and social practices (a transformational rebound). Each of these effects could either amplify or offset the energy savings from e-materialisation and the net effect is highly uncertain. But at present, these effects are overlooked by LCA studies, not least because they are very difficult to quantify. As a result, the evidence base provides only a partial picture of the environmental impacts of digital products and neglects critical determinants of those impacts.

5. Conclusion

We performed the first systematic literature review of the determinants and magnitude of the direct and higher order impacts of e-materialisation on energy consumption. We found 31 relevant studies which we grouped into five categories—publications, news, business, music, videos and games. All but one of these use a common methodology (LCA) but employ a range of product-system configurations, supporting assumptions, functional units, systems boundaries and allocation rules. All the studies confine attention to direct and substitution effects and most employ sensitivity test for key variables. Referring to our research questions, our main findings are:

- The literature identifies impacts ranging from >90% reductions in life-cycle energy consumption to >2000% increases in energy consumption. Changes to key assumptions can lead to very different estimates within a single study.
- Key variables influencing energy savings that are common to several goods include the lifetime, utilisation and energy efficiency of user devices, the extent to which personal transport is displaced, the number of users of material and digital products and the choice of functional unit and allocation rules (table 10).
- The estimated impacts are highly sensitive to the technical features of the relevant systems and to the behaviour of users—which vary widely from one context to another, as well as over time. Some trends (e.g. more energy efficient user devices) are increasing the energy savings from e-materialisation while others (high-quality video) may be reducing those savings.
- The evidence-based is limited, patchy and variable in quality. While there are several high quality studies (e.g. Weber *et al* 2010), their results can rapidly become obsolete.
- If attention is confined to direct and substitution effects alone, most studies suggest a significant potential for energy savings in e-publications, e-news and e-music, but less so for e-business and e-videos/games. The extent to which those savings are realised depends upon the technical features of the relevant systems and the behaviour of users. Given the diversity of results, there is no consensus on the magnitude of potential energy savings and there are many circumstances where e-materialisation can increase energy consumption.

Most studies assume the substitutability of digital and material goods and neglect rebound effects—which suggests they overestimate the energy savings. As Mokhtarian and Gil (2013) observe, this is mainly because 'there is a natural tendency to think first of new technology as offering new ways to do (old) things, and only over time to realise that it also offers ways to do new things'. Despite this, very few studies unambiguously conclude that e-materialisation has reduced energy consumption owing to the context-specificity of the results. In practice, there are many examples of imperfect substitution, and the lower cost and higher utility of digital products creates the potential for large rebound effects—as evidenced, for example, by the rapid growth of video consumption since 2010. Allowing for this, we cannot conclude that e-materialisation has delivered energy savings to date or is likely to do so in the future. Neither is it likely that further LCA studies will resolve this question—due both to the unsuitability of this methodology for complex digital products and its inability to accommodate higher order effects. Hence, to gain a better understanding of how e-materialisation affects energy consumption, a broader range of methodological approaches will be required.

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Data statement

No new data were created or analysed in this study.

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