

How to Improve the Sustainability of Digital Libraries and Information Services?

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Arguing that environmental sustainability is a growing concern for digital information systems and services, this article proposes a simple method for estimation of the energy and environmental costs of digital libraries and information services. It is shown that several factors contribute to the overall energy and environmental costs of information and communication technology (ICT) in general and digital information systems and services in particular. It is also shown that end-user energy costs play a key role in the overall environmental costs of a digital library or information service. It is argued that appropriate user research, transaction log analysis, user modeling, and better design and delivery of services can significantly reduce the user interaction time, and thus the environmental costs, of digital information systems and services, making them more sustainable.

Introduction

Terms such as *sustainability* and *sustainable development* have become very common in every international, national, and local policy document and action plan. Sustainability creates a harmony among the myriad activities that take place in fulfilling the social, economic, and other requirements of present and future generations (EPA, 2013). In other words, sustainability ensures that the actions taken today to ensure the economic and social wellbeing of the current generation should not compromise the life and wellbeing of future generations. There are three forms of sustainability, economic sustainability, social sustainability, and environmental sustainability, and they are interrelated (Chowdhury, 2013). In the context of a country, economic sustainability is associated with the sustained economic growth that can be measured in terms of gross domestic product (GDP), and, in the context of a business,

economic sustainability may mean sustained monetary profits, that is, a steady growth in revenues and profit margins (Soderbaum, 2008). Some other economic sustainability criteria such as innovativeness, competitiveness, and public debt or even terms such as *inflation* and *trade imbalance* are also used in the macroeconomic debate (Spangenberg, 2005). In the context of digital information systems and services, economic sustainability can be achieved through the provision of cheaper access to quality digital information through a sustainable business model, for profit or not for profit. The success can be measured by reducing both the (a) direct costs, for example, through improved production and distribution of information products and services, and (b) indirect costs, for example, through reduction of user time and efforts for accessing and using information. Impact of information services on a specific activity, businesses, or society is also a long-term measure of the economic sustainability of information systems and services.

Broadly speaking, social sustainability is defined as the maintenance and improvement of wellbeing of the current and future generations (Mak & Peacock, 2011). The concept of wellbeing is defined differently in different contexts, such as the equity of access to essential services, healthy life and wellbeing, civil society, democratic and informed citizenship, promotion and sharing of positive relations and culture, and so on. McKenzie (2004) defines social sustainability as a life-enhancing condition within communities and a process that can achieve that condition. Social sustainability of digital information systems and services can be achieved by ensuring easy and equitable access to information aligned with the users' specific contexts, such as their background, tasks, personal information behavior and preferences, etc. In other words, the focus should be on the users and context, and the objective should be to align the information services with the user's specific context—personal life, work, and social life, etc.—so that the information can be made available easily and readily to help users accomplish their tasks as effectively and efficiently as possible.

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Environmental sustainability is defined as a state in which the demands placed on the environment for an activity can be met without reducing its capacity to allow everyone in the current and future generations to live well (Financial Times Lexicon, 2013). In the context of digital information systems and services, the target for environmental sustainability is to reduce the energy and environmental costs throughout the life cycle of an information system or service (Chowdhury, 2013, 2014).

Digital libraries and information services make extensive use of information and communication technology (ICT) infrastructure and devices throughout the life cycle of information, for creation or digitization, management, and preservation of content, and for accessing, using, downloading, printing, and sharing content and data. ICT infrastructure and devices generate a significant amount of greenhouse gas (GHG) emissions and thus contribute to the environmental costs of digital libraries and information services. Some researchers have discussed the environmental costs of printed information resources (see, for example, Borggren, Moberg, & Finnveden, 2011; Chowdhury, 2012c; Enroth, 2009; Kozac, 2003; Lukovitz, 2009; Reed Elsevier, n.d.), whereas others have discussed the environmental sustainability aspects of library buildings (see, for example, Brodie, 2012; Edwards, 2011; Hawke, 2010; Linden, Reilly, & Herzog, 2012). However, sustainability, especially environmental sustainability, of digital information systems and services that form a major part of every business, and especially higher education and research has not been discussed or researched widely in the mainstream information science literature (Chowdhury, 2012a, 2012b, 2012c, 2013, 2014; Nolin, 2010). This article proposes a simple method for estimation of the energy and environmental costs of digital libraries and information services. It also argues that end-user energy costs play a key role in the overall environmental costs of a digital library or information service, so appropriate measures have to be taken to reduce the end-user search and access time, to reduce the overall environmental costs of digital information services.

Issues related to the environment and climate change debate, as discussed in various national and international platforms, are presented in the next section. The importance and extent of the environmental costs of ICT and information services are then discussed, especially in the context of research and scholarly activities in higher education institutions. The article then discusses how to measure the environmental costs of a digital library or information service and proposes a simple method for this. Factors contributing to the overall carbon footprint of digital information services, from both the server and the client sides, are then discussed. The article then discusses how user behavior and interactions contribute to the overall energy costs and what measures can be taken to reduce the energy and environmental costs of digital information services especially in the context of higher education institutions.

Overall, this article might stimulate some debate and further research on the environmental impact and sustain-

ability of digital libraries and information services. Reviews of research in different, related areas that shed light on this topic appear in earlier articles in this journal and elsewhere (Chowdhury, 2012a, 2012b, 2012c, 2013, 2014). The facts and the corresponding arguments for the environmental sustainability of digital information systems and services presented here have been drawn from a wide range of resources, some of which are research literature, whereas others are reports, commentaries, etc. Similarly, much of the discussion takes place within the context of higher education and research institutions simply because some data in this context are readily available. Some of the data used, especially with regard to the energy costs of a Google search or YouTube video viewing, are estimates made by others (which are referenced as appropriate); hence, it is not claimed that these are the most accurate figures. Nevertheless, together they show the importance of, as well as the underlying complexities associated with, the question of sustainability of digital information systems and services in general and environmental sustainability in particular. The arguments herein provide justifications for further research on the sustainability of digital information systems and services that form the foundation of the knowledge economy in general and academic, research and scholarly activities in higher education and research institutions in particular.

Background

To understand the importance of environmental sustainability, factors that contribute to the environmental impact of a system, product, or service, and more importantly how to control those factors and thus the overall carbon footprint, it is necessary to understand some basic concepts and policies related to the climate change debate. *Climate change* refers to a change “in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer” (IPCC, 2014, p.4). The 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) published in March, 2014, points out that climate change may be caused by man-made changes, natural internal processes, or external forces such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC, 2014). The man-made changes in the atmospheric conditions or in land use that are caused by some persistent human activities are of major concern for climate change researchers and policy makers. Article 1 of the United Nations Framework Convention on Climate Change (UNFCCC) points out that the natural climate variability observed over comparable time periods clearly indicates that climate change can be attributed directly or indirectly to a number of human activities that alter the composition of the global atmosphere (UNFCCC, 2014).

Different terms are used to denote the factors responsible for climate change, the most common ones being the carbon footprint or GHG emissions, the latter being defined as those

gaseous constituents of the atmosphere that absorb and re-emit infrared radiation (UNFCCC, 2014). GHG covers emission of carbon dioxide (CO₂) and other harmful gases such as methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphurhexafluoride (SF₆; Wiedmann & Minx, 2008). The IPCC (2007) report points out that, although human activities result in emissions of four long-lived GHG viz., CO₂, CH₄, N₂O, and halocarbons (a group of gases containing fluorine, chlorine or bromine), often GHG emission is measured and expressed in metric tonnes (1,000 kg) of CO₂ equivalent (mTCO₂e).

Although the concept of environmental sustainability has received a significant amount of attention over the past two decades, its origin can be traced back to over five decades. In the United States, a national policy for environmental sustainability was established in 1969 with the passage of the National Environmental Policy Act (NEPA), and the Environment Protection Agency (EPA) began its operations on December 2, 1970, as a national agency to protect and preserve the quality of the environment (U.S. Environmental Protection Agency, 2015). Another milestone in environmental sustainability was the UN Conference on Human Environment held in Stockholm, also known as the Stockholm conference, in which several countries expressed concerns about the impact of the increasing global developments on the environment. This gave rise to the United Nations Environment Programme (UNEP) with the mission to provide leadership and encourage partnership in caring for the environment by inspiring, informing, and enabling nations and people to improve their quality of life without compromising that of future generations (UNEP, 2013). In 1983, the UN Secretary General formed a special independent commission, called the *World Commission on Environment and Development* (WCED), under the chairmanship of the Prime Minister of Norway, Gro Harlem Brundtland, to re-examine the environmental problems and developmental problems around the world and to formulate specific proposals to address them. The Brundtland Commission concluded its work in 1987 and published its report as *Our Common Future* (also known as the *Brundtland Report*; Report of the World Commission on Environment and Development: Our Common Future, 1987). This canonical document defined the concept of sustainable development and emphasized an ecological balance. An important outcome of the *Brundtland Report* was the *Earth Summit* in Rio de Janeiro in June, 1992.

The Rio Declaration on Environment and Development (United Nations. General Assembly, 1992), also known as *Agenda 21*, was adopted at the United Nations Conference on Environment and Development held in Rio de Janeiro, Brazil, on June 3–14, 1992. This has subsequently given rise to several major international summits and conferences and has resulted in a major policy document, the *Kyoto Protocol*, which was adopted in Kyoto, Japan, on December 11, 1997, and entered into force on February 16, 2005, setting binding targets for 37 industrialized countries and the European

Community for reducing GHG emissions to an average of 5% against the 1990 levels over the 5-year period of 2008–2012 (UNFCCC, 2011; for details of the Kyoto Protocol see United Nations, 1998). Several more stringent measures have since been introduced by many countries for achieving the target of lower GHG emissions.

The IPCC was established jointly by the World Meteorological Organization and the United Nations Environment Programme in 1988 as the leading advisory body for the assessment of climate change, and it now has 194 countries as members (IPCC, 2011). The IPCC 2007 report on climate change warns that the continued GHG emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century (IPCC, 2007, p. 23). Seven years later, in the summary of the IPCC 5th Assessment Report, some of the major impacts of climate change were described as follows (IPCC, 2014):

- In recent decades, climate change has caused impacts on natural and human systems on all continents and across the oceans.
- In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources.
- Many terrestrial, freshwater, and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances, and species interactions in response to ongoing climate change.
- Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability.
- Climate-related hazards exacerbate other stressors, often with negative outcomes for livelihoods, especially for people living in poverty.

Most countries in the developed world, and some in the developing world, have now set specific targets for GHG reductions. For example, the U.K. government has set a target to reduce GHG emissions by 80% by 2050 (relative to 1990 levels) (Gov UK, 2014). To achieve this, the energy consumption in the U.K. has to be reduced by 26–43%. The EU Policy Framework has set a target for GHG emission reductions by 40% by 2030 (relative to 1990 levels; Europa, 2013a). In the United States, the EPA has set a target of reducing GHG emissions by 25% from the 2008 baseline (U.S. Environmental Protection Agency, 2012). The following sections address some important questions, such as: what are the environmental costs of ICT in general, what are the environmental costs of digital information systems and services, and how these can be reduced so that we can develop sustainable digital information systems and services to support education, scholarship, research and innovation?

Energy and Environmental Costs Information Services in Higher Education Institutions

As stated earlier, this article focuses on the energy and environmental costs of digital libraries and information

TABLE 1. ICT energy and environmental costs of U.K. HE and FE institutions.

Institutions	ICT energy/year	Cost/year
U.K. universities	770,000 MWh	£90 million
U.K. further education colleges	475,000 MWh	£57 million

services in the context of higher education institutions (HEIs). HEIs now make extensive use of digital libraries and information services in almost all research, scholarship, and management activities (Chowdhury, 2012a). In the context of a higher education or research institution, a digital information service may be based on a local system designed to provide access to specific type of content or data, such as an institutional repository or a research data management system; or systems specifically designed to support teaching and learning activities such as the institutional virtual learning environment (VLE) or various databases holding records for students, staff, finance, and research as well as various documents of regulations and policies, governance documents, minutes and communications, etc. All these systems are designed to provide information to support academic, research, and scholarly activities. There are also a number of external systems and services that can be accessed through subscription, such as proprietary databases and digital libraries; along with many external digital libraries and web resources that can be accessed free of cost.

To date we do not have any specific data for the energy costs of information services in HEIs, but some data for the overall ICT energy costs in HEIs are available. It is estimated that HEIs in the United States produce approximately 121 million tonnes of CO₂e in a year, which is equivalent to nearly 2% of total annual GHG emissions in the United States or about one fourth of the entire state of California's annual GHG emissions (Sinha, Schew, Sawant, Kolwaite, & Strode, 2010). Table 1 shows the breakdown of ICT energy costs in U.K. HEIs as found by the SusteIT project (James, 2012). It shows that for universities that use high-performance computing (HPC) facilities, the end-user costs from PCs can account for 37% of the total ICT energy costs, whereas such costs can be 33% of the total energy costs in other universities. The same study estimates that the total ICT energy costs in U.K. HEIs are £90 million/year. Thus the end-user PC energy costs in U.K. HEIs could be £29.7–33.3 million/year. The SusteIT study also shows that printing costs account for 3–18% of the total ICT energy costs, depending on how much printing and copying takes place. Thus overall, end-user PC and printing energy costs can range from one third to one half of the total ICT energy costs in U.K. HEIs.

Environmental Costs of ICT

Table 2 shows the estimated energy and environmental costs of global ICT (ACS News Service Weekly PressPac,

TABLE 2. Estimated energy and environmental costs of global ICT industry.

ICT costs	Estimates
Total energy	10% of global electricity generation (Clark, 2013)
Environmental	830 million tonnes of CO ₂ e (ACS News Service Weekly PressPac, 2013)

TABLE 3. Environmental costs of some Google activities.

Item	Emissions (CO ₂ e/year)
Google's total	1.67 million tonnes (Google's Business . . . , 2012)
Google's per user	1.46 kg (Clark, 2011)
Per Gmail user	1.2 kg (Clark, 2011)
YouTube user (for a 10-minute video watch)	1 g (Clark, 2011)

2013). To put this in perspective, all the 1,662 power stations in the United Kingdom taken together generate 174.6 million tonnes of CO₂ per annum (based on CARMA, 2013 statistics). In other words, worldwide ICT industry generates almost five times as much GHG emissions as produced by all the power stations in the United Kingdom taken together.

Let's look at some available data for the energy and environmental costs associated with information access on search engine services. As shown in Table 3, in 2011 Google's GHG emissions were equivalent to the annual emissions from nearly 14 typical power stations in Britain (estimates are based on the CARMA, 2013, statistics). With over 425 million Gmail users worldwide, the annual carbon footprint of Gmail use can be estimated to be 510,000 tonnes which is equivalent to the annual emissions from four average U.K. power stations (based on CARMA, 2013, statistics). These emission figures do not include the client-side ICT and energy usage figures. Let's assume that everyone uses a laptop to access Google or YouTube. The total carbon footprint of a Dell Latitude E6400 is approximately 320–370 kg CO₂e depending on the energy source used (Dell, 2010). With a typical replacement period of 4 years and assuming that a laptop is used for 10 hours/day, that is, 3,650 hours/year, for a typical 10-minute use of a laptop, for watching video on YouTube, the client-side embodied energy (energy used to manufacture a laptop, pro rata) cost would be about 4 g. At this rate, the carbon footprint for watching YouTube video will be 30 g ((1 + 4) × 6)) per hour. This is an estimate because not everyone uses a laptop to watch YouTube videos; many use PCs, and about half of the YouTube views are on mobile devices.

To date no reliable data are available for the carbon footprint of a digital library or digital information service. Some estimates of the carbon footprint of analogue content, such as printed books and newspapers, are available in the literature (see, for example, Borggren et al., 2011;

Chowdhury, 2012a, 2012c; Kozac, 2003; Moberg, Borggren, & Finnveden, 2011; Moberg, Johansson, & Finnveden, 2007). Similarly some researchers have studied the environmental costs of library buildings (for details see Brodie, 2012; Edwards, 2011; Hawke, 2010). Digital information systems and services make extensive use of ICT throughout their life cycle, from creation and management of digital content and data to their access and use, and each of these stages requires a significant amount of energy that generates GHG. At this stage, however, it is difficult to identify precisely the specific factors and their contributions to the overall environmental impact of digital information systems and services (Chowdhury 2010, 2012a, 2012b, 2012c, 2013). Thus a major research question in this regard is how to measure the carbon footprint, or the extent of the environmental impact, of digital information systems and services and what we can do to reduce this and thereby build sustainable information systems and services? The rest of this article aims to address these questions.

Measuring the Carbon Footprint of Digital Libraries

The digital library universe is a complex framework comprising three distinct systems (The Digital Library Reference Model, 2010):

1. A *digital library* that provides digital content to its users through a series of functionalities that are controlled by some quality and policy measures.
2. A *digital library system*, which is a software system that supports the functionalities of a *digital library*.
3. A *digital library management system*, which is a generic software system that provides the appropriate infrastructure for the functionalities of the *digital library system*.

The Digital Library Reference Model (2010) also identified three categories of actors that are fundamental to the operation of the digital library (DL) service.

1. The DL end users: content creators and content consumers.
2. The DL managers: DL designers and DL system administrators.
3. The DL software developers.

To study the environmental sustainability of DLs, it is necessary to identify the ICT and energy costs that are associated with all the three systems that form a DL as well as the activities and functions of all the actors. Furthermore, such a study should also consider the ICT and energy costs for the entire life cycle of information, from the creation of content and data to their management, use/re-use, and preservation. Life cycle analysis (LCA; also known as *life cycle assessment*) is a technique used to estimate the energy consumptions and environmental impact of a product or service throughout its life cycle, that is, from raw material acquisition, production, and use phases to waste management,

including disposal and recycling (ISO-14040, 2006; Finnveden et al., 2009). This is a resource-intensive process because it takes into account the energy inputs and emission outputs throughout the production chain from exploration and extraction of raw materials to different stages of processing, manufacturing, storage, transportation, use, and disposal. LCA is accredited by the ISO 14000 series standards that “reflect international consensus on good environmental and business practices that can be applied by organizations all over the world in their specific context” (ISO, 2009). There are four phases in an LCA study (Finnveden et al., 2009):

1. Goal and scope definition that includes the reasons for the study, the intended audience, applications, etc., and thus setting the boundaries and the functional units (a quantitative measure of the functions that the goods or service provide) of the analysis.
2. Life cycle inventory analysis (LCI), which produces a list of the inputs in terms of resources and outputs in terms of emissions for different stages of the life cycle of the product or service,
3. Life cycle impact assessment (LCIA), which helps in understanding and evaluating the potential environmental impacts of the system studied.
4. Interpretation, in which the findings are interpreted in the context of the goal and scope definition of the analysis (phase 1).

Using the LCA technique to measure the energy consumption of a digital library or information service, and assessing the corresponding carbon footprint or GHG emissions, is a complex process. The first challenge comes from the global dimension of a large DL or information service, and the arrays of people as well as equipment and tools used to build, manage, and access such digital information services. Furthermore, such LCA studies and the corresponding findings with regard to the carbon footprint of DLs will be very specific to a specific service because of the nature of the LCA method, which is very specific to a certain product or service being evaluated. In short, using the LCA technique to measure the carbon footprint of DL and information services is quite a resource-intensive process. The method proposed here, can be used to estimate the overall energy and environmental costs of a DL or information service.

A Simple Method for Measuring the Environmental Cost of Digital Information Services

A relatively simple approach to measure the overall energy and environmental costs of a DL or information system can be developed based on the computation of two major types of ICT costs, (a) server-side ICT energy costs and (b) client-side ICT energy costs. Such calculations should consider:

1. The types and number of devices involved in the life cycle of DLs on both the server and the client sides.

2. The number of users involved and the time spent by the users on a specific DL service over a period of time.
3. Proportion of the life of a typical computing device used specifically for accessing a DL as opposed to various other activities at the users' end.
4. Life of a typical computing device after which it is replaced, and the mode of destruction at both the client and the server sides.
5. Energy sources used for running the ICT infrastructure of the DL services as well as the end-user devices that may be spread over different parts of the world, for example, for a distributed DL.

Furthermore, one has to consider two forms of energy usage, embodied energy and socket energy (Raghavan & Ma, 2011). Embodied energy is the energy used to manufacture the myriad computing and network devices that are used to run and use the information services, and socket energy is used by the devices during a typical information search or use session. Some tools for measuring the socket energy costs and the resulting carbon footprint of various computing devices are available; see, for example, the Energy Star (2014) or the SusteIT toolkit (James, 2012; SusteIT, 2009). Such tools can be used for calculating the socket energy costs of specific computing devices used in a DL or information service at both the server and the client sides.

For estimating the overall energy costs of a DL or information service at the client and server sides one must take into account the following (Figure 1):

1. The computing time used for building and managing content held in a DL or information service.
2. The computing time spent by the users, recorded through transaction logs, on a given DL or information service.

3. The computing time required for using or downloading information on the client's device and the amount of time spent on the client computing devices to use such information.

It is also important to remember that some devices will always remain turned on—for example, servers or data centers—and they will consume energy irrespective of whether the DL is being used or not at a particular point in time. There are other factors as well; for example, the environmental costs of preservation of the digital content and data. Figure 1 shows the various factors that have to be considered for such calculations. As shown in Figure 1, energy consumption by the computing and network devices at different stages of the creation, processing, preservation, access, and use of information plays an important role in the overall carbon footprint or GHG emissions of a DL. Therefore, to estimate the carbon footprint of a DL, we have to estimate the embodied and socket energy costs for (a) the server side for all the DL activities and functions and (b) all the activities in relation to the end-user computing. Therefore, it is necessary to estimate (a) the embodied energy costs and (b) the socket energy costs for the computing devices required/used for:

1. Content and data creation, for the creation of born digital content as well as for digitization of analogue content. Estimation of the ICT energy costs for creation of content and data is a very complex process because of the diverse range of computing and network devices used by one or more creators of content in the same or different institutions and/or countries.
2. Content and data storage, acquisition/uploading, processing, and management. Estimation of the energy costs for storage and management of content and data should also

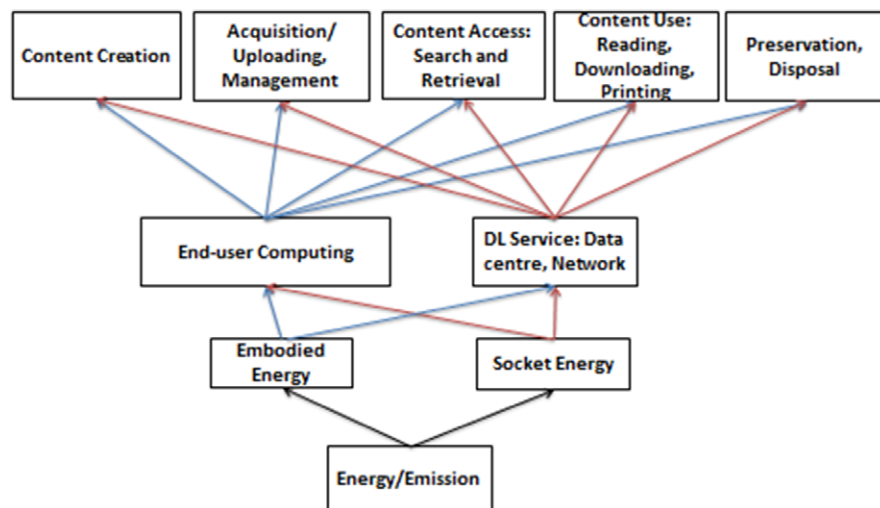


FIG. 1. Factors responsible for GHG emissions from a digital library. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

consider the architecture and policies of the digital information services concerned, for example, whether the content is stored locally or centrally, the maintenance and back-up schedules, and so on.

3. Software development for specific activities, for example, the IR software, interface, and various tools for transaction log management, report generation, etc. Estimation of the software costs should be based on the nature of the software, for example, whether it is built locally (custom-built) or purchased through a vendor. Some of the complexities associated with the estimation of the energy costs for software development have been discussed in the literature (Galster, 2010; WSRCC, 2011). A proportion of the energy costs of DL software such as DSpace, Fedora, Greenstone, etc. may be used as the pro rata software cost, but this energy cost may be negligible in comparison with the other energy costs mentioned in this section.
4. Content access (connect time, searching/viewing/reading; details are discussed later).
5. Content use (online use, downloading and offline use, printing, sharing, reuse; details are discussed later).
6. Content preservation and long-term storage (details are discussed later).

For each of these stages, we have to consider the following:

- Type of computing device, such as servers, desktops, laptops, tablets, mobile phones, etc., used for a given DL function or activity.
- Duration of the use of a specific computing device for a DL function or activity.
- Embodied and socket energy costs of every computing device used.

The total energy costs for a DL over a period, for example, in a year, can thus be estimated by adding the embodied energy and socket energy costs of the various functions and activities mentioned earlier. All of these might not have to be considered for every DL, for example, the energy costs of digital preservation may be considered separately from an operational DL, or the energy costs for software development may be very small compared with the overall energy costs of managing and accessing a DL or information service.

Factors Contributing to the Overall Carbon Footprint of Digital Information Services

To reduce the carbon footprint of digital information services, and thus make them more environmentally sustainable, it is necessary to identify the factors that contribute to this. A number of contributing factors and challenges are associated with the estimation and reduction of the energy and environmental costs of digital information services. A general estimate of the ICT costs of producing digital content—a research paper, a book, a book chapter, a course handbook, lecture slides, or research data sets—can be based on an average number of hours spent on computing

devices, their socket and embodied energy costs, and the number of hours spent on the Internet. This will vary quite significantly from one content type to another, from one discipline another, from one person to another, and so on. Empirical studies are needed to estimate the production costs of different types of content held in a DL database.

Content held in a DL or archive may be born digital or may be digitized. Energy costs for digitization vary depending on the nature and size of the analogue content, the devices used for digitization, time spent on each device, and the embedded and socket energy costs of each device. For large and/or complex analogue content collections, the ICT energy costs for digitization can be quite significant. Such energy and financial costs can be reduced by using the appropriate policies for digitization or creation of digital content and operation of a repository or an archive. Several institutions and research studies have developed specific guidelines for digitization programs that may be helpful for achieving sustainability. For example, the Blue Ribbon Task Force on Sustainable Digital Preservation and Access report (2010) provides the following specific guidelines:

- Articulate compelling value proposition, for example, who will be using the digital information, for what purpose, and what will be the benefits of such use?
- Provide clear incentives to preserve in the public interest, which can be achieved by building appropriate policy mechanisms such as financial incentives and other benefits to private owners who preserve digital materials for the benefit of the public, mandates to preserve when appropriate, and revision of the prevalent copyright laws to allow preservation of privately owned materials in the interest of the public.
- Define roles and responsibilities among stakeholders to identify clearly the activities and the associated workflow throughout the digital life cycle.

The Council of the European Union in its “Conclusions on the digitisation and online accessibility of cultural material and digital preservation,” of 20 April, 2012, invites the European member states (Council of the European Union, 2012):

- To consolidate their strategies and targets for the digitisation of cultural material,
- To improve the framework conditions for the online accessibility and use of cultural material,
- To contribute to the further development of Europeana, the Europeana Digital Library, and
- To ensure long-term digital preservation.

Such policies may help DL managers develop a sustainable digitization policy to guide the selection of content type and volume for digitization.

Server-Side Energy Costs

One of the major challenges comes from the rapid growth in the volume of digital information. Estimates show that the British Library’s digital collection will grow to 2 petabytes (2×10^{15} bytes) in 2018 (Knight, 2010). Research shows that

the energy and environmental costs of ICT can be brought down by one or more of the following measures (Baliga, Ayre, Hinton, & Tucker, 2011; Chowdhury, 2012a, 2012b; Jenkin, Webster, & McShane, 2010; Mell & Grance, 2011; Oliver & Knight, 2015):

1. Reducing the energy costs on the server side by developing and deploying more energy efficient computing devices, automatic scheduling, better cooling systems, and so on.
2. Using cloud computing and shared ICT infrastructure and thereby optimizing the use of computing and network resources, thus reducing the energy consumption figures.
3. Developing more sophisticated software and business systems that can help in the reduction of GHG emissions of businesses.

As discussed earlier, the server-side energy costs can be estimated by calculating the embodied and socket energy costs of the servers used to build and manage a DL. Server-side cooling cost is a major contributing factor too. A report in the *New York Times* points out that worldwide the digital warehouses use about 30 billion watts of electricity, which is equivalent to the output of 30 nuclear power plants (Glanz, 2012). Researchers estimate that for every £1 spent on running servers at the British Library, £1.20 is spent on cooling (Knight, 2010). Thus specific measures should be taken to reduce the server-side energy costs not only by optimizing the use of servers, for example, by using more energy-efficient servers or by automatic scheduling, etc., but also by using specific measures for reducing the cooling costs, by using more environmentally friendly energy sources, and so on.

Client-Side Energy Costs

The client-side energy costs of digital information services can also be quite high. Some estimates show that worldwide about 1.6 billion connected PCs and notebooks and 6 billion mobile devices are now used, and consequently their overall energy costs will be quite high (Renzenbrink, 2013). The SustelIT study discussed earlier estimates that the client-side energy costs can be more than one third of the overall ICT energy costs in U.K. HEIs. A significant proportion of the client-side energy costs arise from the creation and uploading of content and, more importantly, for accessing and using the digital content and data.

Content Creation and Uploading Costs. Often digital content—especially research content and data—is created by more than one person, using a variety of computing and network devices. Similarly, many tools and techniques are used for harvesting or uploading of content in a DL. Hence only a gross estimation can be made for apportioning and calculating the overall ICT energy costs for content preparation and uploading. Empirical research in different disciplines may produce the average energy cost of production of

different types of digital content, books, journals, conference papers, etc., in specific disciplines and subjects.

In the context of digital repositories, there is also some energy cost associated with the self-archiving of research publications. It is estimated that worldwide about 2 million peer-reviewed articles are published each year (Finch, 2012). Assuming that each of these 2 million papers is self-archived and that each self-archiving activity takes about 30 minutes—ranging from identifying the latest preprint version to filling in the form and metadata, checking, inclusion in the repository, and so on, this amounts to about 1 million hours' worth of online activities. Assuming that such activities take place in a typical work PC that requires 100 Wh energy, the overall energy cost just for manual uploading of content to a repository would be 100 MWh. Assuming that 125,000 of such papers are produced in a year in Britain (Finch, 2012), at this rate the total energy cost for self-archiving the annual journal output of Britain will be 6.25 MWh.

Access Costs. According to the statistics available at the Europeana DL site (Europeana Professional, 2012), in the second quarter of 2013 there were 1,274,109 visits to Europeana in 3 months, and an average visit lasted for 00:2:18. In other words, during these 3 months, users spent an equivalent of about 5.6 years' worth of time on the Europeana DL. Although people have used different devices ranging from PCs to laptops and handheld devices, assuming that everyone used a laptop that consumes 30 Wh energy, this would have cost nearly 1.5 MWh of electricity. This cost comes only from the time that people have spent on Europeana over a period of 3 months. For a year this could be about 6 MWh. This estimate is based on the assumption that everyone has used a laptop, but in fact a large proportion of the users still use PCs that consume at least three times more energy than a laptop. Furthermore, this estimate is based on the time people spent on the Europeana site. People might have already spent some time on search engines before arriving at the Europeana site. In fact, increasingly a large proportion of the Europeana traffic comes through search engine referrals. In the second quarter of 2013, there were 65.5% referrals from search engines and 12.5% from social networks. In other words, nearly 80% of the Europeana visitors have used a search engine or a social network service before visiting Europeana, so there are some energy costs for the use of Europeana that may have occurred even before people reached the Europeana DL site. Furthermore, it can be assumed that many people have spent some time online (but not on the Europeana site) with the information that they had retrieved from Europeana for which there is some ICT energy cost; and more energy and environmental costs would be involved if the users had printed the retrieved information.

Energy costs associated with the content access and content use, shown in Figure 1, can be divided as the energy costs associated with (a) the presearch activities, (b) the search activities, and (c) the postsearch activities. Often a

significant amount of end-user energy cost associated with a DL service might arise from what the users do before they reach a DL, that is, the search process associated with finding an appropriate DL service for a specific information need. As discussed in the previous section, often this involves use of search engine services. Once the user reaches a DL, there is the energy cost associated with (a) the time that he spends on the DL site and (b) the time he spends on the computers and networks after visiting a DL. By reducing the user interaction time, especially the search time, it is possible to reduce the end-user energy costs, which will improve environmental sustainability of digital information services.

User Behavior and Interactions

One of the ways to measure the success of a DL or information service is to count how many people use the service, but the efficiency of the service can be increased, and the resultant search time and the corresponding energy costs can be reduced, by introducing better design and usability features so that people must spend less time on the service looking for the required information. The following figures provide an idea of the ICT energy costs associated with searching, which, as stated earlier, is one of the factors contributing to the overall energy and environmental costs of a digital information service.

Google handled 1.2 trillion searches in 2012 (Google, 2013). If each of these had taken just 1 minute, this would mean end users have used their computing devices for 20 billion hours just in 1 year for conducting Google searches. As per the estimations shown earlier, the overall energy and the corresponding environmental costs for 20 billion hours' worth of computing time would be huge. Assuming that everyone has used a laptop to conduct the searches, 20 billion hours' worth of laptop usage would require 600,000 MWh of electricity. Of course, one may argue that a large number of those Google searches came from thin clients such as mobile devices that consume far less electricity, but at the same time it may be argued that many Google search activities are performed with PCs, and not every search session lasts for just 1 minute considering the various activities associated with a typical information access session—search formulation, search execution, viewing of results, and various activities with the retrieved results such as online reading, downloading, saving locally or printing, and so on.

As discussed in the previous section, energy cost estimates based simply on the amount of time spent by the users on the Europeana DL site could be as high as 6 MWh, and the overall client-side energy costs, depending on the time people spend on ICT before and after they have been to the Europeana site, can be quite high. In a survey of the institutional repositories in the United States, Burns, Lana, and Budd (2013) note that the average annual visits to a repository were just over 1.1 million, and on average 5,254 searches were conducted and 963,169 items were retrieved

or downloaded. This gives an indication of the end-user activities in institutional repositories, and it is evident that the end-user energy costs for accessing and using institutional repositories will be quite high.

Although not studied from the environmental sustainability perspectives per se, several researchers have pointed out that better design and user interactions can significantly improve the effectiveness and efficiency of DLs and information services. Toms (2012) points out that, although historically information services and information skills programme aimed at finding the right information, in today's world the challenge is not only to find the right information but to deliver it to the user in a humanly appropriate manner. She recommends that DLs should be integrated into the use environment of the target user community. Research and understanding of the user context and behavior are therefore of paramount importance, as pointed out by several DL researchers (see, for example, Clough, 2012; Duff, 2012; Nicholas & Clark, 2012; Osborne, 2012).

Deridder and Matheny (2014) point out that the gathering of digital data across multiple interfaces and platforms creates chaos for the research process, and even experienced researchers often struggle with this. Consequently, some new search systems have recently been developed to facilitate access to scholarly information; see, for example, *Odysci Academic Search System* by Bergamaschi, de Oliveira, Kumon, and Rezende (2014). Amolochitis, Christou, Tan, and Prasad (2013) recommend that link structure of the research literature as well as the properties of the corpus should be used to improve the retrieval accuracy in an academic environment.

Reducing ICT Energy Costs of Information Services in HEIs

A better understanding of user needs and context can lead to more sustainable design of digital information systems and services, but it may also call for the development of, and compliance with, appropriate policies. The Digital Agenda recommendation of the European Commission (Europa, 2011) points out that access to, and use of, digitized cultural material in the public domain must be improved. The British Library digitization strategy (2014) outlines some specific activities related to the understanding of the user needs and improving access to information. In short, these reports and the research studies mentioned earlier indicate that appropriate user-centered design and policies can improve the performance of DLs and information services. Although more empirical studies are needed to show how improved design and improved user interactions can contribute to the sustainability of digital information systems, Figure 2 and the following discussions show the different ways by which the ICT energy costs for information systems and services in HEIs can be reduced. The four major categories of ICT energy costs in HEIs, shown in Figure 2, have been identified from the SusteIT study (James, 2012).

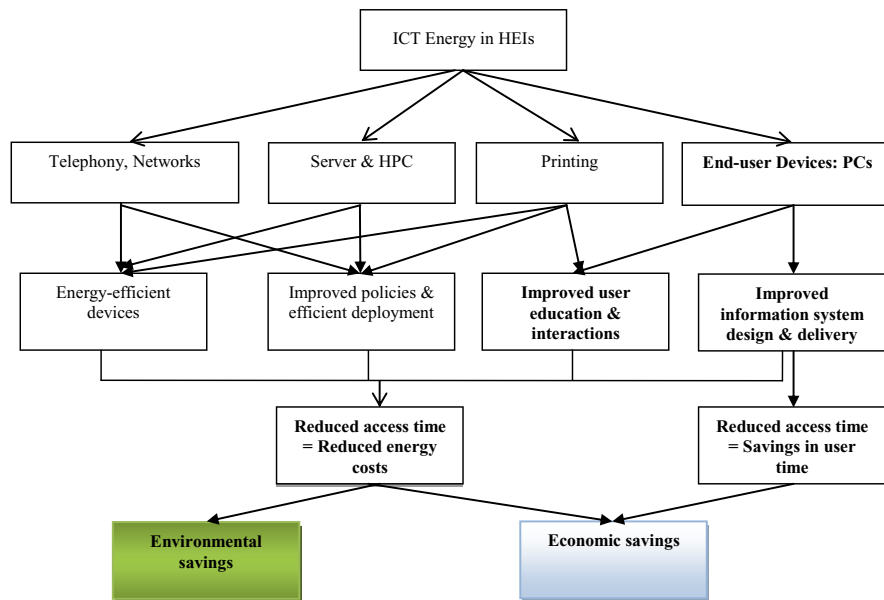


FIG. 2. ICT energy costs in HEIs. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

It may be noted that savings in emissions and economic costs can be achieved by using energy-efficient devices and efficient deployment of the devices and systems (as discussed by Chowdhury, 2012a, 2012b; Oliver and Knight, 2015) and also by introducing changes in the end-user behavior in terms of use of the computing devices and printing habits and also by improving user interactions through efficient design and delivery of information systems and services. End-user energy costs can be reduced by introducing specific policies and measures, for example, through:

- The use of more energy-efficient computing devices at the client ends (more efficient computers and printers, etc.; quick and periodic replacement of old computers).
- Better deployment of systems and services (e.g., automatic shutdown of computers and monitors that are not in use for a certain time; better control of printing facilities; running some software and applications on servers, rather than on user PCs, thereby supporting the use of thin clients for certain end-user activities; use of thin clients such as mobile devices can reduce the end-user energy costs of digital information services (Nicholas, Clark, Rowlands, & Jamali, 2013).

In addition, end-user energy and environmental costs can also be reduced through:

- Better design and delivery of information services through a better understanding of user behavior and usage patterns (designing information services aligned with the activities and workflow of specific category of users—students in specific programs and levels, researchers in specific disciplines, staff in different categories and with different roles, etc.; the nature of the university business does not change very often, and a lot of information about the user is already known—for example, it is possible to provide a more personalized interface and

service that is aligned with a specific user category or even an individual user, and this may significantly reduce the time that a user has to spend otherwise to trawl through a lot of information that is only remotely related to his interests or activities; developing specific applications for instant access to most frequently required information resources; many university libraries—for example, Northumbria University library, University of Nottingham library, University of York library, in the United Kingdom—now provide a service that automatically links to content items on the course reading lists and allows students to create and update a collection of reading materials online using a simple drag and drop function; such a service can significantly reduce the end-user search and interaction time—for example, the user can save information resources in one place from a variety of databases, including library catalogues, online databases, web and open access DLs/repositories—and thus the end-user doesn't have to spend time to locate and download a specific resource from the reading list every time he wants to read it; such a service can significantly reduce the energy costs as a result of the reduced interaction time; and it can also save user time and thus can help to improve the overall sustainability of digital information services).

- Better user education and environmental literacy training that will enable users to make informed decisions about the usage of computing devices for searching, downloading, and printing of information resources.
- Policies: Using energy and environmental considerations at every stage of the procurement, deployment, design, and delivery of ICT equipment, systems and services.

While studying the usage patterns of the Europeana DL, Nicholas et al. (2013) note that search engines, and predominantly Google, are the key drivers sending as much as 80% of Europeana's traffic. They also note that fixed and mobile users do not differ much in terms of their referral

patterns for the Europeana service. This study provides two important indications: first, more and more people are using mobile devices for accessing DL and information services, and, second, search engines are the first port of call for many mobile users, who are referred to the digital information services in response to a search query.

Overall, the less powerful the computing device is, and less time the user has to spend on a digital information system to find and access the required information, the more energy efficient will be the overall service. As stated earlier, there are many other contributing factors, too, but a variety of user intelligence-gathering techniques, such as transaction log analysis, can help us build better user profiles, and this can lead to more sustainable digital information services. Hienert, Sawitzki, and Mayr (2015) discuss a tool that can analyze user sessions, and the data can be used to answer specific questions such as “How has the search process evolved for a certain topic?” “Which documents have been finally viewed?” “How has a search process evolved over several sessions?” The authors recommend that such analyses can help us build a set of value-added services allowing personalization, recommendation, and awareness. For example, term suggestions can be generated based on the personal history of a user, or recommendations can be made based on an analysis of the documents viewed by other users who used the same search query (Hienert et al., 2015).

Log analysis studies can provide information only about what happens, that is, how much time users spend on a service, what would be the energy costs of the corresponding ICT devices, and so on. They do not provide an answer as to why the users spend a certain amount of time on a DL service, how efficiently they can find and access the required information, and so on. Thus, such quantitative studies should be supplemented with qualitative studies to understand the end-user information behavior vis-à-vis the design and usability of various DL systems and services. Such studies will not only provide information on what the end users usually do before, during, and after a DL search session but will also provide insight into the usability of specific digital information services and how that can be improved so that the users’ access time, and therefore the overall end-user energy costs, can be reduced.

Conclusions

Given the volume and growth rate of digital content and research data (Borgman, 2012, 2015; Eschenfelder & Johnson, 2014), the latter being several times greater in magnitude in terms of both volume and growth rate, the ICT energy costs associated with the management of research content and data will continue to increase rapidly. Digital information makes extensive use of ICT throughout the life cycle, so it is extremely important that appropriate measures are taken to make this more energy efficient and environmentally sustainable. The simple method proposed here can promote further research and empirical studies leading to an estimation of the overall energy and environmental costs of

a DL or information service. As discussed, the server-side energy and environmental costs of DLs and information services can be reduced in a number of ways, by using more energy-efficient machines and routines/systems, by developing appropriate policies for creating shared DL services and avoiding duplications, by using better cooling systems for servers, and so on.

The client-side energy consumption is also a major contributor to the overall energy and environmental costs of digital information systems and services, and more research is needed to study user information behavior and interactions as well as the usability of different DL systems and services. Regular and systematic analysis of transaction logs and information interactions research can help us understand user behavior and usage patterns, and this can be used for more efficient system and service design that can reduce users’ search and access time, especially for frequently used information sources. User studies should form an integral part of green information technology (IT) and green information system (IS) research, and this will help us reduce the environmental impact and thereby improve the sustainability of digital information systems and services.

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