The Carbon Footprint of Games Distribution

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Keywords:

carbon footprint
climate change
distribution
entertainment
industrial ecology
life cycle assessment (LCA)

Supporting information is available on the *JIE* Web site

Summary

This research investigates the carbon footprint of the lifecycle of console games, using the example of PlayStation®3 distribution in the UK. We estimate total carbon equivalent emissions for an average 8.8-gigabyte (GB) game based on data for 2010. The bulk of emissions are accounted for by game play, followed by production and distribution. Two delivery scenarios are compared: The first examines Blu-ray discs (BDs) delivered by retail stores, and the second, games files downloaded over broadband Internet. Contrary to findings in previous research on music distribution, distribution of games by physical BDs results in lower greenhouse gas emissions than by Internet download. The estimated carbon emissions from downloading only fall definitively below that of BDs for games smaller than 1.3 GB. Sensitivity analysis indicates that as average game file sizes increase, and the energy intensity of the Internet falls, the file size at which BDs would result in lower emissions than downloads could shift either up- or downward over the next few years. Overall, the results appear to be broadly applicable to title games within the European Union (EU), and for larger-than-average sized games in the United States. Further research would be needed to confirm whether similar findings would apply in future years with changes in game size and Internet efficiency. The study findings serve to illustrate why it is not always true that digital distribution of media will have lower carbon emissions than distribution by physical means when file sizes are large.

Introduction

Calculating representative carbon footprints (CFs) for products is of increasing interest to help determine drivers of climate change (Hertwich and Peters 2009; Matthews et al. 2008). This article compares the CF of games distributed by Blu-ray discs (BDs) and by Internet, using the example of PlayStation®3 (PS3) in the UK.

Console-based gaming has undergone a rapid expansion since the original PlayStation® was launched in 1994. PlayStation® became the first console to hit the oft-quoted benchmark of 100 million cumulative sales worldwide toward the end of its life cycle in 2004.[1] By November 2013, cumulative sales of high-definition consoles (including Sony's PS3, Microsoft's XBOX360, and Nintendo's WiiU) were 165 million units worldwide, almost half of which were PS3 (VGChartz 2013). The story continues with the launch of Sony's PlayStation®4 (PS4) and Microsoft's Xbox One next-generation consoles in November 2013. As a consequence, the energy use of games consoles has attracted increasing attention from environmental groups (Horowitz et al. 2008), prompting various legislatures to consider specific energy efficiency measures (namely, the European Union [EU], United States, Australia, and New Zealand).

Little research is available examining the energy use of gaming (Webb et al. 2013). Available studies focus of the energy

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DOI: 10.1111/jiec.12181

Editor managing review: H. Scott Matthews

Volume 00, Number 0

use of games consoles, and not the games themselves. A number of CF studies have already examined the potential impacts of different entertainment media. Research to date has focused chiefly on music downloads (Bottrill et al. 2008, Digital Europe 2003, Weber et al. 2010), the film industry (TCFHE 2007), and film rental networks (Sivaraman et al. 2007). It is commonly argued that distribution of data over the Internet has a lower impact on climate change than by physical disc, as typified in a quote from Weber and colleagues (2009): "as file sizes and Internet energy use are increasing, Internet energy efficiency is also increasing, thus it is unlikely even in the case of large file transfers for digital downloads to use more energy or produce more CO_2 emissions than delivering music via CDs." Perhaps, contrary to current expectations, the same may not necessarily apply in the case of larger gaming or movie files distributed by digital video discs (DVDs) and BDs, as examined below.

Most major console game releases are now available either to download online or purchase on BDs from retailers (either by ordering online or buying in-store). At the time of this writing (October 2013), file sizes of the top ten selling games in Europe range between 1.3 and 24 gigabytes (GB) per game, with an average of 11 GB (Sony Network Entertainment 2013; VGChartz 2013).[2] This average is larger than the average for 2010 of 8.8 GB.

As it has conventionally been modeled to date, the energy attributed to downloading data over the Internet varies in proportion to file size. In contrast, the data capacity of optical discs has increased exponentially over the last two decades (figure 1), and the energy required to produce different types of optical discs with different capacities has remained approximately the same at any point in time (Sony DADC 2010).

The capacity of optical discs has increased exponentially over time (figure 1) Multilayer BDs are now available that can store up to 100 GB, and holographic technology that could store up to 1,000 GB per disc is currently in development (Barras 2009). Similar trends have been reported for data capacity of hard disk drives, where storage capacity growth has doubled each year (Grochowski and Halem 2003). Holographic discs have such high data capacity that eventually they may compete with the Internet itself as a cost-effective and -efficient means of mass data distribution. As a parallel example, data backups for many large companies are still stored on magnetic tape and transported by truck because it is not economic or feasible to move huge amounts of data over the Internet.

PS3 in the UK provides a useful example to investigate the relative carbon equivalent emissions of the life cycle of games production, distribution, use, and disposal as well as to examine the hypothesis that download of data should have lower carbon equivalent emissions than disc distribution.

Methodology

Life cycle assessment (LCA) can be used to determine the environmental impacts of a product from raw materials extraction, through to manufacturing, distribution, use, and end of life (EOL). CF studies use LCA methodology to assess the global warming potential of products. This study uses LCA International Organization for Standardization (ISO) 14040 methodology (ISO 2006) to compare the carbon equivalent emissions of the life cycle of PS3 game contrasting delivery by BDs and Internet download, as outlined below.

Process Description

Production and Distribution of Games Using Blu-Ray Disc

Most PS3 games are distributed by BD, rather than being downloaded, and all BDs distributed within Europe are manufactured in Salzburg, Austria. BD production involves both mastering and replication processes, as explained in more detail below (Sony DADC 2010). Once a game code is finalized, a master copy is transferred digitally from the games studio that produced it ready for manufacture. Each BD is composed of a combination of polycarbonate, silver, and a protective resin. Mastering involves the transformation and projection of an encrypted and certified digital data file onto a silicon wafer (figure 2a).

The BD mastering process happens only once per new game or film, from which thousands of replicated copies are made (figure 2b). The replicated discs are then transferred mechanically to the printing line for disc artwork and then transferred to the assembly packaging line. After the discs have been placed into a polypropylene molded box case with an inlay tray and a paper instruction booklet, they are packed into cardboard master cartons, stacked on wooden pallets, and secured with a polypropylene film wrap. Discs are then distributed by truck and shipped to a central warehouse in Northampton, UK and subsequently to retailers' warehouses ready for distribution to outlets and sold to consumers. Subsequent to use, domestic recycling options do not exist for BDs, and so at EOL they are collected and sent to either landfill or incineration.

Production and Distribution of Games Online

Games distributed online are downloaded through the PlayStation®Store directly by consumers. Copies of each game are transferred globally through content distribution networks by both core and edge networks, utilizing both central and regional Internet hubs according to demand, delivering game files data through local Internet access networks to each consumer's Internet router, and ultimately to their console to be saved onto the hard disk. Subsequent to use, consumers simply delete game files they no longer need to create space for more data.

Goal, Scope, and System Boundaries Definitions

Goal

The goal of this study is to calculate the carbon equivalent emissions of the life cycle of PS3 games and also determine whether downloading data had lower impact than distribution by BD in 2010.

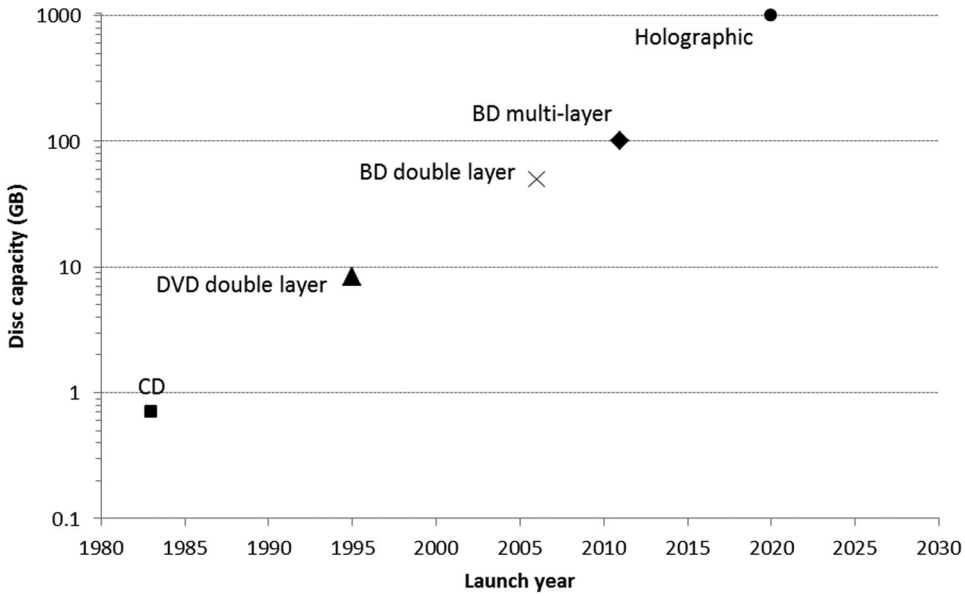

Figure 1 Increases in disc capacity. BD = Blu-ray disc; DVD = digital video disc; CD = compact disc; GB = gigabyte.

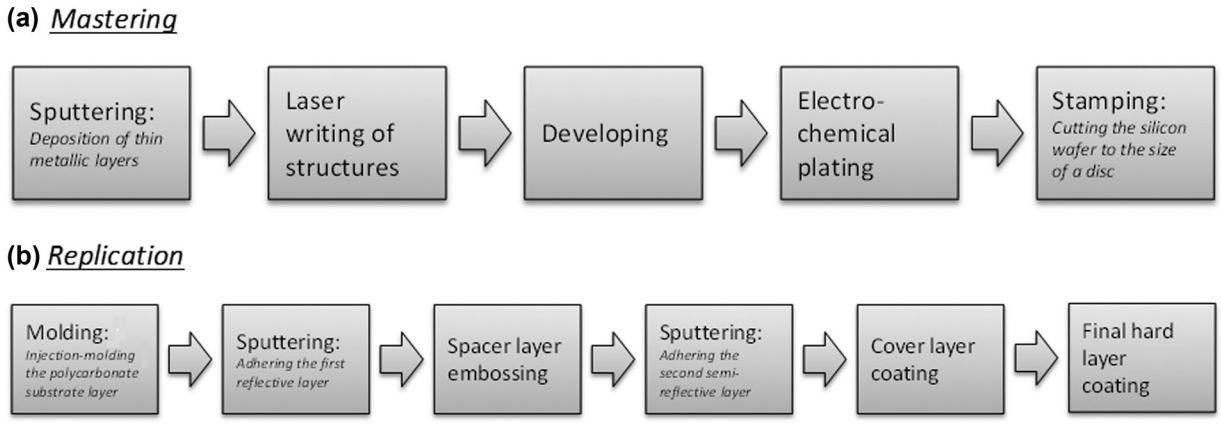

Figure 2 Blu-ray disc (BD) manufacture, including: (a) mastering and (b) replication.

Functional Unit

A number of functional units are considered in the analysis below in order to evaluate carbon emissions for a typical game in 2010 and also to estimate emissions with game files of different sizes:

- Development, distribution, use, and deletion of a typical 8.80-GB game file distributed online in 2010
- Development, production, distribution, use, and disposal of an individual BD used to distribute an 8.80-GB game file in 2010
- Delivery of game content by Internet (with file sizes varying between 0.001 and 100 GB at logarithmic intervals)
- Production and distribution of game content from individual dual-layer BDs (from one to two units holding up to 100 GB).

System Boundary and Scope

The study focuses on the carbon equivalent emissions arising from the raw materials production, manufacture, distribution, retail, use, and disposal of new PS3 game BDs and files produced for the UK. System boundaries for the BD delivery scenario are shown in figure 3a below, and for online delivery in figure 3b. The following are excluded from the study scope:

- The embedded emissions from the manufacture and distribution of PS3 consoles themselves are excluded because they are equivalent between scenarios. The focus of the study is on the games themselves.
- The study compares two methods of distribution (in-store retail and download). E-commerce was not investigated because retail distribution presents a "worst case" for physical distribution (Edwards et al. 2009) as a comparison to downloading.

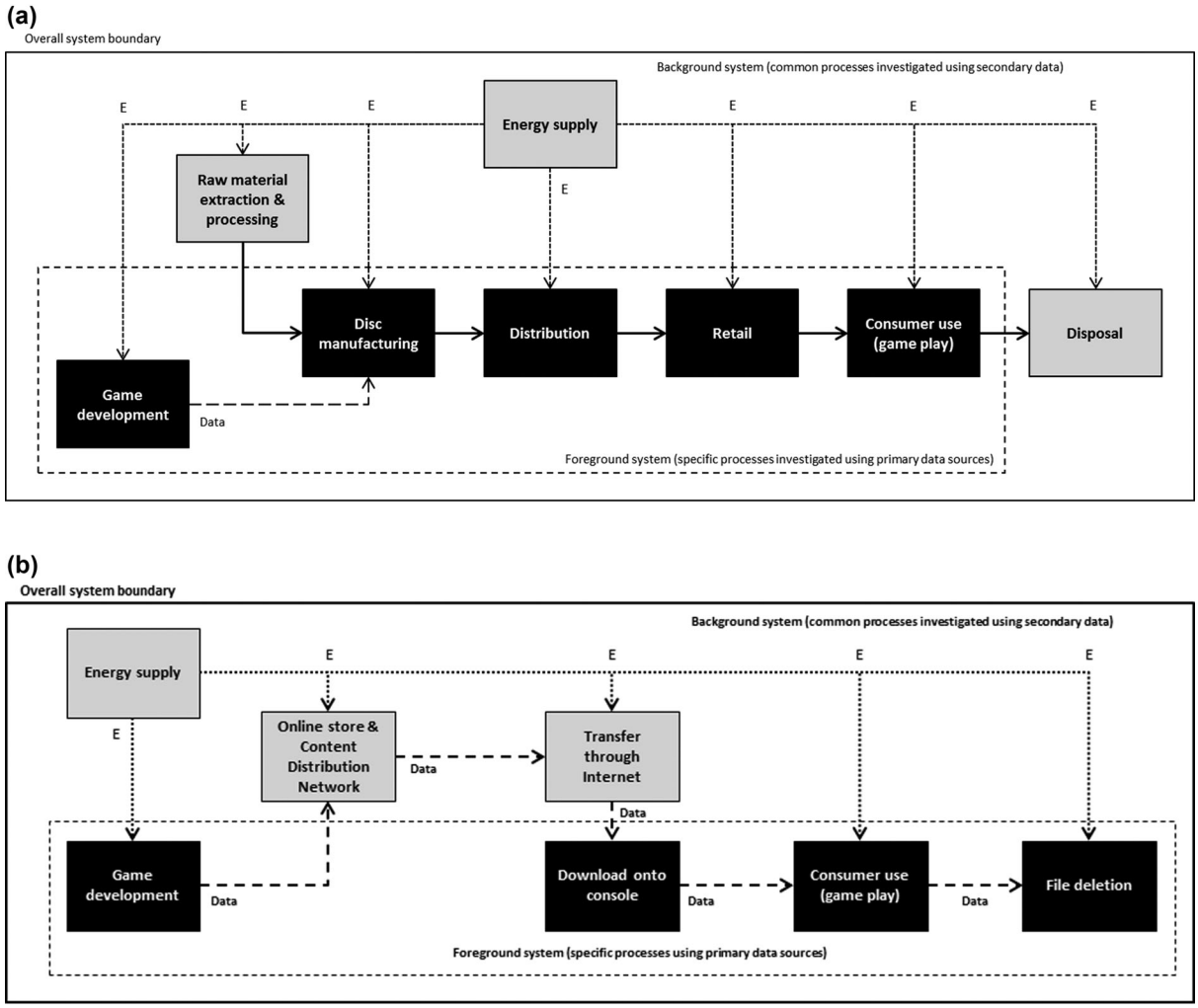

Figure 3 Systems boundaries for: (a) disc distribution scenario and (b) download scenario.

- As is standard practice in carbon footprinting, emissions from the manufacture of capital equipment, including vehicles for transport, the construction of facilities used in manufacturing and distribution, and energy used in running offices used for management and administration, are excluded from the study scope (BSI 2011).
- The consequential impact of reuse on carbon emissions is complex. Game reuse may occur informally between friends and family exchanging BD discs, through retail stores trading game discs, or by eBay or secondhand markets. In contrast, downloaded game software cannot be traded on because of copyright protection and restrictions. There are few data available on the relative flows of used games through secondhand markets. It should not be assumed, however, that reuse of a game disc will occur in place of the sale of a new game, because older games are less likely to be available for sale in the form of new BD or download, and also it may be that many users would not buy new versions of a game at full price if the cheaper reused games were unavailable. Resale and reuse scenarios are complex and out of scope of this particular study although certain assumptions are specified in the analysis. This study focuses on the usage of a game by one user only. The potential implications of reuse in respect to findings are examined further within the discussion.
- Cumulative lifetime carbon equivalent emissions of all games sold over time in the UK are not calculated as part of this study, because this would require more-extensive modeling of total energy consumption of different models of consoles in use each year, rather than the average comparisons made here.

Assumptions

A number of assumptions are used in the study (as described below).

General Assumptions

- Active power consumption of PS3 will be the same for downloaded and BD gameplay. Game data can be read from the spinning BD and often is, at least partially,

installed from BD to the hard disk. Online games are downloaded to, and then played from, the spinning hard disk. If games were to be played 100% from the BD drive (versus hard disk in the download scenario), then the differential power use of these hardware components would need to be considered. Even in a possible extreme case, for example, if the console hard disk used 3 watts (W) less power than the BD drive, this would only reduce carbon emissions for the download scenario by 1%, which is not substantial enough to affect the results of the study.

Blu-Ray Assumptions

- Carbon emissions arising from the electronic transfer of one master copy of each game from the studio for production are negligible, compared to the number of units of each game produced.
- Trucks are unlikely to be fully utilized on return journeys. It is assumed therefore that half of all returning transport will be empty (SCEE 2013).
- Transport distance from Austria to the UK is all by road (representing an extreme case for continental Europe).
- Wooden pallets and shipping boxes used for BD distribution will not be reused or recycled by retailers.[3]
- Consumers will buy discs from retail outlets along with only nine other items. In practice, they may purchase a single game (subsequent to the launch of a new game) or many more items (such as during a trip to a supermarket) in which case emissions are allocated across all of the purchases. There appears to be little reliable data on average numbers of items purchased by consumers during any shopping trip, and types of retail outlets differ widely. Ten items are assumed here and tested using sensitivity analysis below (assuming a minimum of one item and a maximum of 100 items).
- Shoppers will travel by car to retail outlets.

Download Assumptions

- Browsing the online store for a downloadable game will be at a data rate of 50 kilobytes per minute over 10 minutes (based on checks conducted browsing online retail websites by one of the authors).
- Consumers turn off their television (which is normally on when the console is in gameplay mode) while downloading a game.
- Games are usually downloaded in the background while the console is used primarily for other purposes. Because average on-time for each PS3 is 1.9 hours per day (Webb et al. 2013), files taking longer than this to download, on average, will result in consoles being left on until complete.
- Average distance from household to incineration or landfill is 50 kilometers (km; to reflect that landfill or incineration facilities usually are commissioned to serve local municipal geographies, such as county councils in the UK).
- To calculate game usage by first users (see *Data Collection* below), it is assumed that one half of disc games are reused once, that average gameplay time is representative of both first and subsequent use (reuse), and that, in 2010, 95% of games were distributed by disc (which are reasonable assumptions based on discussions with industry experts).

Sensitivities to uncertainties for a number of these assumptions are analyzed in the results below.

Data Collection

The data used in the study are available within the Supporting Information on the Web associated with the article. Sources of data used include:

Background Systems

Secondary energy production, transport, and waste recycling and disposal data on carbon equivalent emissions were taken from the published sources (DECC 2010) and the GABI LCA software database in 2010.

Game Data

Average game size in 2010 was approximately 8.80 GB.[4] Games development results in emissions of approximately 0.14 kilograms carbon dioxide equivalents (kg CO_2-eq) per unit sold, based on CO_2 emissions from annual gas and electricity use of two dedicated UK Sony games studios in 2010 (SCEE 2013). Based on empirical data on console usage and game ownership, each game is played, on average, for 232 hours over its lifetime including reuse:

- On-time includes any time spent inactive.
- Each console has more than one user.
- Games may be played over many years, including playing online or sports games, and games may be passed on or lent to friends and family for further play.
- The average is skewed upward by heavy users gaming for several hours per day.

First use of each game (excluding reuse) is estimated at 158 hours.[5]

PS3 Data

The average navigation mode power consumption of PS3 consoles (used to calculate energy used by consoles during downloading and use) is 96.6 W, and for average active gaming mode, 137 W (Webb 2014).

Disc Production

Primary raw materials and manufacturing data were obtained from the Sony DADC Austria BD production facility in Salzburg, where CFs have been completed and externally certified to the Publicly Available Specification (PAS) 2050 standard (Sony DADC 2010).

Disc Distribution

Primary data for distribution were collected directly from Sony's UK warehouse in Northampton. Statistics on retailer emissions were obtained from environmental and financial data published by a major UK music and game distributor (HMV 2009a, 2009b; Music Week 2005). Data on transport emissions between consumer households and stores were obtained from a published source (Edwards et al. 2009).[6]

Game Download

Estimating the electricity use associated with data flows over networks is a complicated business, and the existing literature reflects widely varying methods and results (Baliga et al. 2009; Coroama et al. 2013; Malmodin et al. 2012, 2014; Schien et al. 2012, 2013; Taylor and Koomey 2008; Weber et al. 2010; Williams and Tang 2011). The goal of such analysis is straightforward: to estimate the electricity use (kilowatt-hours; kWh) per GB of data downloaded. Unfortunately, the calculations are subject to a number of conceptual and practical constraints.

First, much of the data are proprietary, closely held, and owned by many different companies, so the practical difficulties of doing such analysis are substantial. Second, network devices show little marginal effect of changes in data flows on electricity use, so the average electricity intensity may be quite different from the short-run marginal intensity, and the medium- to long-run marginal intensity may be quite different from both of these (because network technology changes so rapidly). Third, because of the rapid changes in such networks over time (typically doubling their average energy efficiency for transmitting data every 2 years or so), the validity of any analysis of this type deteriorates rapidly as time passes from the actual data of estimation or measurement. Internet networks are continually upgraded to handle increased data rates and volumes, resulting in substantial changes to, and uncertainty over, their future electricity use.

In addition, the energy needed by data centers to deliver content into the networks is greatly uncertain, and it can be a much larger contributor to electricity intensity (measured in kWh per GB transferred) than the network electricity for landline broadband data delivery over the Internet. There is also complexity related to *allocation* of data center electricity use and data flows, because not all data flows from, and electricity use by, data centers are associated with the electricity intensity of the public Internet in a given country, because

1. some networks are privately owned by companies, so their data flows are unrelated to those on the public Internet,
2. many data center operations are computing related (like financial modeling) and result in little external information transfer over any networks,
3. some data center operations are devoted to data flows that exit the country or region being studied, and
4. data centers may be used to store, replicate, and transmit data through the Internet, but may also be used to process databases, or for computing, as part of the Internet service.

These allocation issues make it difficult to estimate the contribution of data center electricity use to the electricity intensity of a particular data download. Making things more complicated still is the use by many large companies of content distribution networks such as Akamai.

The actual process of creating data files for download using data center resources can vary greatly depending on the particular company, software, and purpose of the download, and there are very little data on how to handle variations in the associated electricity intensity at a high level. For example, specific data on the energy used by data centers and content distribution networks used for PS3 games are not available.

Two different philosophies pervade the literature on this topic leading to wide disparities in results. Top-down "attributional" models involve dividing total electricity use by total data flows for the entire network (or major parts of the network) to calculate average intensities in kWh of electricity use per GB of data transferred. Bottom-up "consequential" models tie their component parts (e.g., servers, data storage, and communications equipment) to a particular delivery of information services. Pure top-down models tend to overestimate electricity intensity (if not informed by bottom-up analysis), whereas pure bottom-up estimates tend to underestimate it (if not informed by top-down analysis). How accurate these approaches are in practice depends greatly on how carefully the data are collected, compiled, and analyzed.

The most suitable method of allocation depends on the specific research questions posed. Attributional allocation accounts for the average electricity use of the Internet for data transfer and allows different services to be compared, as in this study (just as for LCAs on electricity use). Consequential allocation estimates marginal changes in electricity use of a given network at different levels of activity, but disregards electricity used to maintain the fixed capacity of the Internet. Both allocation methods are useful depending on the specific research questions posed. The results of such studies vary widely and their context must be considered carefully before making any direct comparisons. This study estimates and compares the average carbon equivalent emissions of each game downloaded and purchased through retail outlets occurring in 2010. It does not try to evaluate the change in emissions that might have occurred with reducing or increasing download activity versus retail purchases.

Resolving these complicated issues is outside the scope of this analysis. Fortunately, a recent analysis for Sweden (Malmodin et al. 2014) gives enough detail and is comprehensive enough to create a range of plausible electricity intensities for Internet downloads in a developed European country for 2010. This analysis combines the intellectual discipline of having the electricity use and data flows add up to the correct top-line numbers and aggregating detailed data collected from the bottom up. Table 1 shows those numbers for low and high case scenarios used in this study.

To explain the low and high boundary scenarios: Whereas there is likely to be variability in the Internet energy intensity between developed (or a developing) countries, core network

Table 1 Components of Internet electricity intensity in 2010

	Average electric intensity		
	Lower bound scenario (kWh/GB transferred)	*Upper bound scenario (kWh/GB transferred)*	*Notes*
Customer premise equipment (modems/routers)	0.3	0.3	1
Access network (broadband)	0.08	0.08	2
Data transmission and core network	0.08	0.08	3
Data center/server rooms ("Internet" part)	0.0	1.0	4
Total	**0.46**	**1.46**	

Source: Malmodin and colleagues (2014), for Sweden in 2010.
(1) Customer premise equipment includes 1.5 modems/routers per household.
(2) Access network includes control and core nodes and dedicated transmission components.
(3) Core network traffic described in more detail in Malmodin and colleagues (2012).
(4) Data center energy use and data flows allocated to the parts associated with the public Internet, excluding private networks and energy use in data centers not associated with data flow over the public Internet.
kWh/GB = kilowatt hours per gigabyte.

and access networks energy intensity in developing countries, such as Sweden, will be similar to the UK and other developed countries. Energy used by customer premises equipment will also vary between users; 0.3 kWh/GB is simply used as an average value. In contrast, there is considerable uncertainty on how to allocate data center electricity intensity to different services and uses, such as for downloads versus other uses, such as financial transactions and databases. To tackle this, the low case includes the electricity intensity (in kWh/GB) for the customer premise equipment (e.g., the customer's wireless modem), the access network (e.g., broadband cable or digital subscriber line [DSL]), and the core network, but excludes electricity associated with data centers, which is why it is a lower bound. This lower bound total is 0.46 kWh/GB. The upper bound estimate also includes the electricity intensity of data centers from the Swedish study, which explicitly allocates data center electricity use and data flows to characterize the data flowing over the public Internet. The addition of the data center electricity brings the total in the high case to 1.46 kWh/GB. This range of electricity intensities reflects uncertainties in how to allocate data center energy use to the task of storing, replicating, and providing data for download. Most console users will play and download games during peak hours, when Internet access speeds average 19.47 megabits per second (Mbps) (EC 2012), with a download time of 0.11 hours per gigabyte (h/GB).[7] This affects how long a console will be used for if left on specifically to complete a download.

Results, Analysis, and Discussion

Overall carbon equivalent emissions for both downloaded and BD games are displayed in table 2, followed by a comparison of results for different file sizes in figure 4. Sensitivity analysis is performed to investigate the impact of any areas of uncertainty, for example, assuming faster data download speeds resulting in reduced energy used by consoles during game download in table 3.

Downloaded Compared to Blu-Ray Disc Games

The CF of the life cycle of a downloaded 8.80-GB game amounted to 21.9 to 27.5 kg CO_2-eq (for lower and upper bounds of Internet energy intensity), whereas the result for a BD game was 20.8 kg CO_2-eq. Gameplay (use phase) accounted for 19.5 kg CO_2-eq emissions in both scenarios.

Further results and analysis are presented in figure 4 to show trends with game files of different sizes and determine any differences in results. For ease of comparison, game development and gameplay (use phase) are excluded because they are equivalent between scenarios (as explained in the assumptions above). The carbon equivalent emissions of downloaded games are plotted at logarithmic intervals for both lower and upper bound Internet energy intensities. The CF of downloading games varies in proportion to file size. In comparison, there is no proportional relationship between carbon equivalent emissions of BD and file size. Each dual-layer BD can hold up to 50 GB, and so any game file larger than this would require more than one BD (unless multilayer BDs of 100 GB become commercially available for use in console gaming). Thus, results for BD follow a stepped progression.

Two thresholds can be clearly identified from these results: Game files of over 4.5 GB have lower carbon equivalent emissions if distributed by BD, compared to download for both lower and upper bound Internet energy intensity, and files of less than 1.3 GB have lower emissions, if downloaded in both cases. Between these ranges of file sizes, uncertainty on how to allocate data center energy use results in no clear "winner." Only one of the top ten selling games available in 2010 on PlayStation Network (Sony Network Entertainment 2013) for download reported by VGChartz (2013) was within this range (Need for Speed: Hot Pursuit at 4.5 GB).

Perhaps, contrary to current consensus that downloaded data will result in lower carbon emissions than distribution by disc, producing and distributing an average-sized game by BD in 2010 resulted in approximately 50% to 90% less emissions than downloading. The relative impact of uncertainties in the assumptions used in this study is examined further in the sensitivity analysis below.

Sensitivity Analysis

The impact of various uncertainties in the study assumptions are investigated below by changing input variables used, with results presented in table 3.

Table 2 The carbon footprint of an 8.80-GB game

		Lower bound (kg CO_2-eq)	*Upper bound (kg CO_2-eq)*	*Lower bound (% of total)*	*Upper bound (% of total)*
Digital downloads	Games development	0.14	0.14	0.6	0.5
	Product energy (download)	0.00	0.00	0.0	0.0
	Internet energy (download)	2.26	7.89	10.3	28.7
	Product energy (e-tail)	0.01	0.01	0.0	0.0
	Internet energy (e-tail)	0.00	0.00	0.0	0.0
	Game play (use)	19.48	19.48	89.0	70.8
	Product energy (file deletion)	0.00	0.00	0.0	0.0
	Total	**21.89**	**27.53**	**100.0**	**100.0**
	Total excluding gameplay and development	**2.27**	**7.91**	**10.4**	**28.7**
		Best estimate (kg CO_2-eq)	*% of total*		
Blu-ray discs	Games development	0.14	0.7		
	Raw materials production and transport	0.27	1.3		
	Manufacturing	0.01	0.0		
	Distribution	0.28	1.3		
	Retail	0.08	0.4		
	Transport home	0.43	2.1		
	Gameplay (use)	19.48	93.6		
	Disposal	0.13	0.6		
	Total	**20.82**	**100.0**		
	Total excluding gameplay and development	**1.20**	**5.7**		

Source data:
UK CO_2 from electricity: 5.41E-01 kg CO_2/kWh (DECC 2010).
UK gas use emissions: 1.84E-01 kg CO_2/kWh (DECC 2010).
CO_2 emission (Internet use): 0.46 to 1.46 kWh/GB (Malmodin et al. 2013).
Console gaming power: 137 W (Webb 2014).
Console downloading power: 96.6 W (Webb 2014).
Download speed: 0.11 h/GB.
Gameplay time: 232 hours.
Weight: 101 g per disc (Sony DADC 2010).
BD raw materials FY2010: 275 g CO_2-eq/disc (Sony DADC 2010).
BD raw materials FY2014: 247 g CO_2-eq/disc (Sony DADC 2010).
BD raw materials FY2019: 193 g CO_2-eq/disc (Sony DADC 2010).
BD manufacture FY2010: 9 g CO_2-eq/disc (Sony DADC 2010).
BD manufacture FY2014: 8 g CO_2-eq/disc (Sony DADC 2010).
BD manufacture FY2018: 7 g CO_2-eq/disc (Sony DADC 2010).
Store CO_2 for games sales (FY08–09): 651,931 kg CO_2-eq (HMV 2009a).
Store games sales per year: 8,806,500 units (HMV 2009b).
Car trip to home (1 item): 4,274 g CO_2/trip (Edwards et al. 2009).
For additional source data, see the Supporting Information on the Web.
kg CO_2-eq = kilograms carbon dioxide equivalents; kWh = kilowatt-hour; GB = gigabyte; W = watt; h/GB = hours per gigabyte; g = grams; BD = Blu-ray disc; FY = fiscal year; e-tail = online retail.

- Reducing the energy intensity of the Internet by half had a proportionate impact on carbon emissions of download. Although Weber and colleagues 2010 estimate that Internet energy efficiency is likely to double every 2 years, the historical rate of change may not continue. In addition, the capacity of BD discs has quadrupled between 2006 and 2013 (a doubling time of 3.5 years), allowing for larger game sizes, for example, new PS4 titles average 16 GB (Eurogamer 2013). Production efficiency of disc production is also expected to have improved by approximately 5% to 10% percent per year (Sony DADC 2010). Because of the uncertainty in these parameters, the future relationship between the carbon emissions of downloading games and that for producing and distributing BDs is difficult to predict with certainty.
- The carbon emissions of games distributed by BDs are highly sensitive to the energy used by consumers traveling to shops. If consumers purchase games along with many other items during a major shopping trip (e.g., 100 items), or use public transport to travel to the shops, the carbon emissions of BD production and distribution are between one quarter and one third lower. On the other hand, if consumers drive to the store specifically to buy a game (e.g., following a new game launch), then emissions

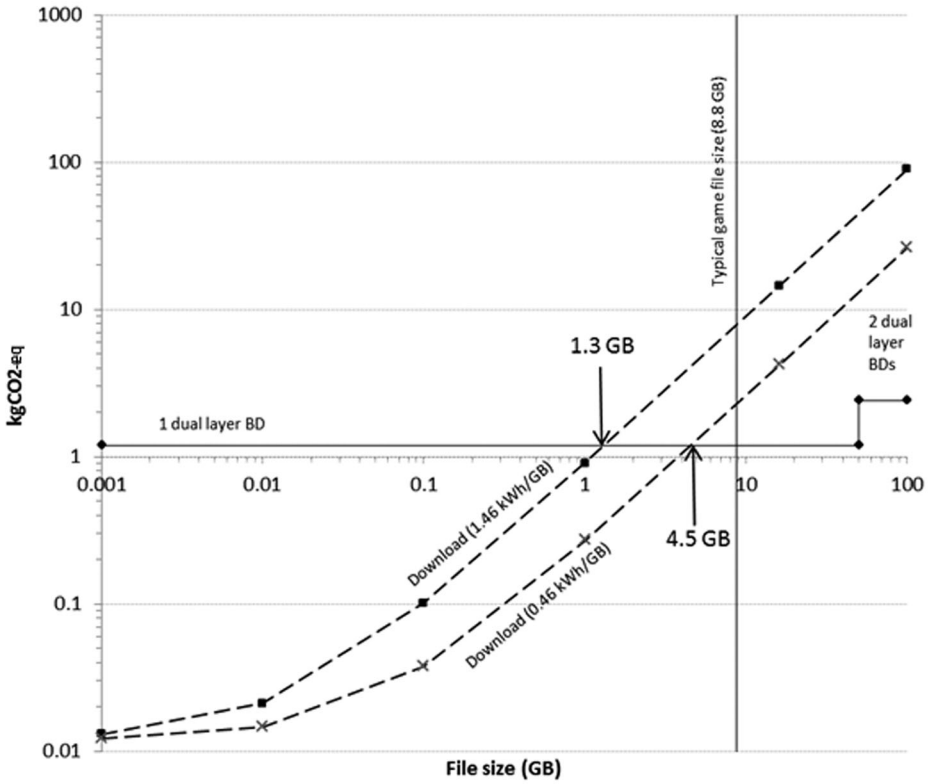

Figure 4 Overall comparison of game download and Blu-ray disc (BD) distribution. GB = gigabyte; kwh/GB = kilowatt-hours per gigabyte; kg CO_2-eq = kilograms carbon dioxide equivalents.

for BDs fall between lower and upper estimates for downloading. To put this in context, games of 5.40 to 19 GB (figure 5) purchased as the sole item during a shopping trip would have carbon emissions in the same range as that for a download (i.e., too close to call).

- Console electricity use during download only accounts for a small proportion of estimated emissions (e.g., less than 0.1% for a 25-GB file). Assuming average peak-time Internet speeds, users are only likely to leave their consoles on to complete a download for files of 17 GB or larger.
- For games production, distribution, and use in continental Europe, shops are likely to be closer to the production facility in Austria than in the UK (reduced from 2,250 to 500 km for the sensitivity analysis), and also carbon equivalent emissions of electricity generation are, on average, lower (DECC 2010). In this case for the EU, the life cycle carbon emissions of gaming would be reduced by approximately one third for all scenarios. The carbon impact of producing and distributing an average-sized game on a BD remains, as for the UK, below that of downloading.
- If reuse accounted for either half or double the total usage of each game over its lifetime, it would have a proportionate inverse impact on average gameplay usage time of "first use," which would not change the findings of the study.

Overall sensitivity analysis shows that results are most sensitive to reduced Internet energy intensity for downloads, increasing game file sizes, and also number of items purchased per shopping trip.

Weber and colleagues (2010) estimate that carbon equivalent emissions of compact disc (CD) production and distribution in the United States is almost 3 times[8] that of PS3 BD production in Europe. The higher emissions for optical disc production in the United States are mainly the result of the differences in transport and also differences in the carbon intensity of energy production and fuel use.[9] Assuming BD production would be similar to CDs, carbon equivalent emissions for BDs in 2010 would only fall categorically below downloading for files above 11 GB in the United States (based on lower bound intensity).

Based on the sensitivity analysis results above, the study findings can be considered broadly representative of PS3 games distributed within the EU (and for larger-than-average files in the United States) in 2010. Results will continue to have relevance because PS3 consoles and games sales are expected to continue over the next few years. Nevertheless, findings are also applicable to PS4 games, with increased games sizes, distribution by both BD and online, and with background downloading also possible. Care should be taken, however, in extrapolating these findings further beyond the study scope. The CF of gameplay in other regions of the world, or for other consoles or physical data media, may differ substantially. Results will vary

Table 3 Results of sensitivity analysis

	Results						*Inputs*									
	Download/distribution			*Total life cycle*			*Variables changed in sensitivity analysis*									
Scenario	*1 BD*	*96.6 GB download 0.46 kWh/GB*	*W GB download 1.46 kWh/GB*	*1 BD*	*96.6 GB download 0.46 kWh/GB*	*W GB download 1.46 kWh/GB*	*Background download*	*Efficiency improvement to Internet*	*TV left on for download*	*Connection speed*	*Gaming power consumption*	*Navigation power consumption*	*Number of items in shopping*	*Public transport use to shops*	*Distance to warehouse*	*CO_2 emissions from local electricity use*
Units	*(kg CO_2-eq)*			*(kg CO_2-eq)*			*(%)*	*(%)*	*(Y/N)*	*(Mbps)*	*(W)*	*(W)*	*units*	*(Y/N)*	*(km)*	*(kg CO_2/kWh)*
8.80-GB game (no change)	**1.20**	**2.27**	**7.91**	**20.8**	**21.9**	**27.5**	**100**	**0**	**N**	**19.47**	**137**	**96.6**	**0**	**N**	**4,274**	**0.541**
Inefficient download	1.20	2.65	8.28	20.8	22.3	27.9	10	—	Y	7.2	—	172.0	—	—	—	—
Efficient download	1.20	2.27	7.90	20.8	21.9	27.5	—	—	—	33.1	—	62.8	—	—	—	—
Internet energy intensity halves	1.20	1.14	3.96	20.8	20.8	23.6	—	50	—	—	—	—	—	—	—	—
100 items in shopping	0.810	2.27	7.91	20.4	21.9	27.5	—	—	—	—	—	—	100	—	—	—
1 item in shopping	5.04	2.27	7.91	24.7	21.9	27.5	—	—	—	—	—	—	1	—	—	—
Public transport to shops	0.895	2.27	7.91	20.5	21.9	27.5	—	—	—	—	—	—	—	Y	—	—
EU comparison	0.995	1.75	7.38	14.9	15.7	21.3	—	—	—	—	—	—	—	—	500	0.385
High gaming power	1.20	2.27	7.91	25.9	27.0	32.6	—	—	—	—	197	—	—	—	—	—
Low gaming power	1.20	2.27	7.91	15.8	16.9	22.5	—	—	—	—	78.1	—	—	—	—	—

Note: BD = Blu-ray disc; kg CO_2-eq = kilograms carbon dioxide equivalents; kWh/GB = kilowatt-hours per gigabyte; W = watt; TV = television; Y/N = yes/no; Mbps = megabits per second; km = kilometer; EU = European Union.

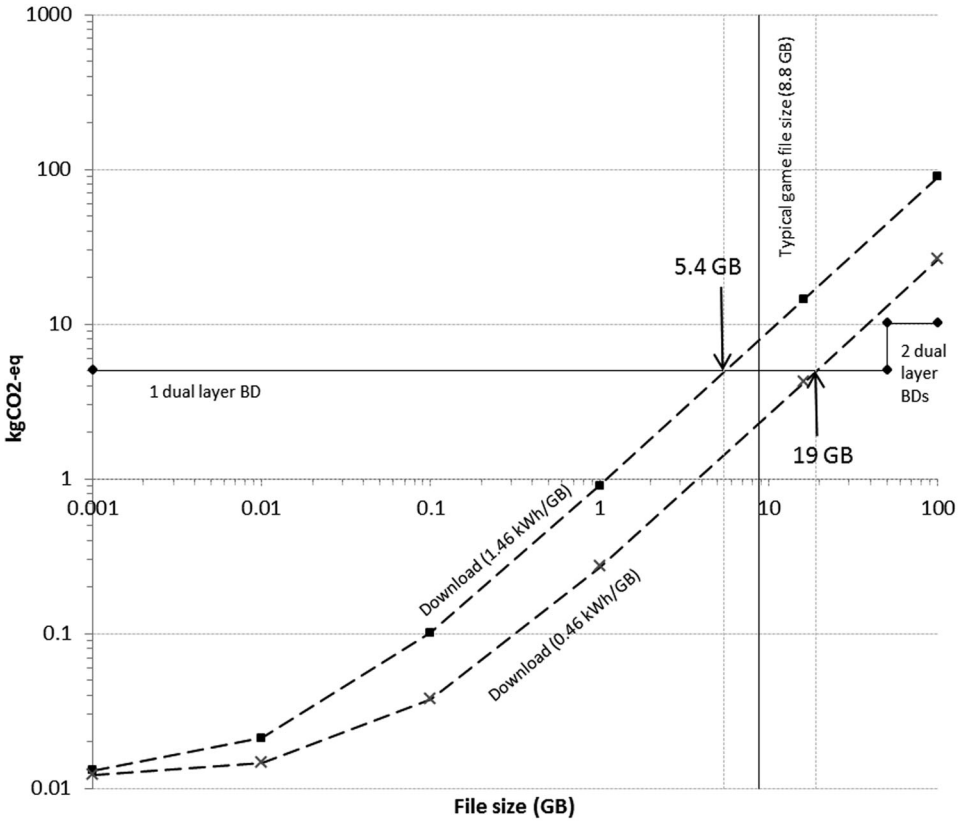

Figure 5 Comparison of game download and Blu-ray disc (BD) distribution (one item in shopping). GB = gigabyte; kwh/GB = kilowatt-hours per gigabyte; kg CO_2-eq = kilograms carbon dioxide equivalents.

depending on the carbon intensity of local energy used for BD production. For example, Austria, where BDs are produced for European distribution (Sony DADC 2010), uses 100% renewable electricity generation. Consequently, CO_2-eq emissions attributable to production are an order of magnitude higher for Sony's disc production facilities located outside of Europe (Sony DADC 2010). These differences are not substantial enough to impact the results of the study if disc production were to be located elsewhere in Europe. Overall, this study is intended to provide a "bounding case," demonstrating, for a substantial proportion of global console games, how downloading could have higher carbon equivalent emissions than distribution by BD.

For games that are reused, two scenarios can be considered. In the case that subsequent users purchase secondhand games in place of new discs, reuse is likely to have a lower impact than downloading an 8.8-GB game (because there will be no carbon impacts from manufacturing), although this will depend on method of transport used to deliver or collect the game (e.g., driving specifically to collect a game or post a game). Where subsequent users cannot or would not pay full price for a new game, but supplement their library games with secondhand games, the net effect is to extend the lifetime of disc games, resulting in more usage overall (making disc vs. download difficult to compare). Comparison of scenarios including reuse would therefore need to be compared based on average emissions per hour of gaming, rather than per game, or by modeling the total emissions of games by all users within a region.

Future Work

Future research could usefully examine games supply chains in other countries in greater depth, for example, Japan, Russia, Australia, and New Zealand, where the energy mix would be different. Additional research could examine other methods of game distribution for other platforms, such as by memory card. Research examining the emissions of gaming by cloud computing versus home-based console gaming would be particularly interesting, wherein games are not downloaded, but instead HD images and control signals exchanged over a rapid Internet connection to a "thin client" in the home with processing work undertaken at remote data centers. Ideally, analyses of the intensity of Internet downloads should rely on measurements of actual Internet equipment used to deliver data to the customer, so a consistent comparison using a well-defined system, including the exact servers and network equipment needed to accomplish that task, would be especially valuable to narrow down upper and lower bound estimates. In addition, a study of the sensitivity of these results to differing carbon emissions intensities of electricity generation (which can vary by orders of magnitude between regions and countries) would

be useful for extrapolating the results to places with different emissions intensities than those that prevail in the UK grid. Finally, investigation of the impact of reuse on the carbon emissions of gaming would be interesting, providing data were available of the relative flows or products and the behavior of consumers.

Conclusion

This research uses LCA methodology to evaluate and compare the CF of downloaded versus BD consoles games within the UK, based on data for 2010. For an average 8.80-GB game, carbon emissions varied depending on whether the game was downloaded (21.9 to 27.5 kg CO_2-eq) or distributed on a BD disc game (20.8 kg CO_2-eq). Gameplay accounted for the largest share of carbon emissions (19.5 kg CO_2-eq). Overall, the results indicate that the hypothesis—that downloading data will be more carbon efficient than distribution by disk—is not likely to have been correct in the case for PS3 console games sold within the EU since 2010 (except for games downloaded of less than 1.3 GB). Similar results can be expected for larger-than-average files in the United States, although by a smaller margin because carbon impacts of production and distribution of optical discs are estimated to be almost 3 times more than in the case of PS3 BDs within the EU.

Assuming Internet energy intensity halves every 2 years, the estimated carbon emissions of downloading will have reduced proportionately since 2010. Counter to this, average game file sizes have increased by one quarter for PS3 and doubled for PS4 by 2013, and disc production efficiency is expected to have improved by at least 15%. Though the carbon emissions of downloading could become much closer (but not below) to that for BDs during 2014–2015, it is uncertain how carbon emissions of BDs, compared to downloads, will balance out in the longer term, particularly for larger PS4 games over 40 GB in size.

Overall, practical and financial factors mean that consumers still purchase the overwhelming majority of larger headline title games on BD, perhaps to avoid waiting for download and to be able to sell their games secondhand after use. Smaller game files below 1.3 GB (such as rereleased previous-generation titles or minigames) have lower emissions when downloaded than if distributed by BD (and are only available to download anyway). This is particularly interesting because games increasingly combine disc-based and downloaded content (e.g., consumers may download additional characters, costumes, or levels). Because PS4 can be used to play games as they start to download, downloading may become more popular in the future. In parallel, as Internet efficiency and speeds increase, the carbon emissions of downloading versus BDs may indeed fall. This must, however, be considered against the trend for increasing game file sizes on next generation consoles.

Consumer behavior can have a significant impact. If consumers were to increasingly drive just to buy "must have" or new launch games and no other purchases (as with the case where stores open at midnight to sell new launch games), then file sizes between 5.50 and 19.9 GB would account for carbon equivalent emissions in the same range as that for downloading. If, however, consumers leave their consoles on especially to download games rather than use the "background download" feature (downloading while already watching a movie or playing a game), use public transport to purchase games from stores, or purchase games during shopping trips for other additional items, then the carbon emissions for BD would fair even better compared to downloading.

The results of this study are unlikely to change or influence consumer behaviors; the carbon emissions of production and distribution are not known to be factors consumers consider when buying electronic goods or entertainment media. Usage accounts for the largest share of the carbon emissions of games, which is far more relevant for consumers, and users would be well advised to consider their usage behavior, such as maintaining autopower down settings.

As interest in carbon footprinting increases as an analytical tool to support research, product development, and policy planning, appropriate methods and application will be vital to its future usefulness, success, and credibility. The general received wisdom is that "dematerialization" is preferable from an environmental policy standpoint, and consequently a shift to downloading data over physical distribution should be considered desirable. Although results of CF studies within the music industry support this view, results of this study for gaming did not. The balance of estimated carbon emissions favors distribution by physical BD for typical headline game titles, but for future comparisons, results are uncertain ("it depends"). Care should be taken to ensure that general principles taken from such research are relevant and applicable before being used to guide decision making on environmental policy.

Acknowledgments

The authors thank Claire Carter, Kennosuke Ido, Thomas Geruschkat, and Jens Malmodin for their valuable advice and support. Kieren Mayers is presently Head of Environment and Technology Compliance at Sony Computer Entertainment Europe. The article is written in his private capacity as a researcher at INSEAD. The research does not necessarily reflect the views of Sony, and no official endorsement should be inferred.

Notes

1. To place this in relative context, PlayStation® sales amounted to only 3.31 million units in 2003 (SCEI 2011).
2. Week ending 12 October 2013.
3. The actual percentage reused or recycled is unknown, so an extreme case is assumed. The related CO_2 equivalent emissions are relatively small and inconsequential to the results.
4. Based on top ten selling games available on both BD and to download online from PlayStation Network in 2010 (Sony Network

Entertainment 2013; VGChartz 2013). Titles include: Call of Duty: Black Ops; Red Dead Redemption; Assassin's Creed Brotherhood; Call of Duty: Modern Warfare; Need for Speed: Hot Pursuit; Battlefield: Bad Company; Medal of Honor; Sports Champions; Just Cause 2; Assassin's Creed II (average = 8.80 GB; minimum file size = 4.5 GB; maximum file size = 12.8 GB).

5. Average first usage of a game = average total lifetime usage / ratio of overall total usage to total "first usage," that is, (0.95/2) + 0.95 + 0.05 = 1.48; 232/1.48 = 157 h.
6. Based on average government emissions data for cars in the UK, and average travel distances for nonfood shopping of 6.4 miles from the UK Department of Transport.
7. Data from study completed in March 2012. Average Internet speeds are likely faster than in 2010, favoring the download scenario because consoles will be left on for shorter periods to complete downloads. This will only have very small impact on results because the energy used by console for download makes only a minor contribution to the carbon equivalent emissions of downloading (as explained in the discussion of sensitivity analysis results).
8. Approximately 3.20 kg CO_2-eq per disc.
9. Downloading an 8.80-GB game in the United States (using 0.640 kg CO_2/kWh for electricity production) would account for 2.61 to 8.24 kg CO_2-eq per game.

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