# THE ENERGY AND CLIMATE CHANGE IMPACTS OF DIFFERENT MUSIC DELIVERY METHODS

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# EXECUTIVE SUMMARY

The impacts of information and communication technologies (ICT) on the environment have been a rich area for research in recent years. ICT has substantially affected commerce, enabling new methods for connecting producers and consumers (i.e., e-commerce) and creating new electronic products. A prime example is the continuing rise of digital music delivery, which has obvious potential for reducing the energy and environmental impacts of producing and delivering music to final consumers.

This study assesses the energy and $CO_2$ emissions associated with several alternative methods for delivering one album of music to a final customer, either via traditional retail or e-commerce sales of compact discs or via a digital download service. We analyze a set of six (3 compact disc and 3 digital download) scenarios of the delivery of one music album from the recording stage to the consumer's home in either CD or digital form. The scenarios were:

1) Album published on CD and delivered via traditional retail methods
2) Album published on CD and delivered by light-duty truck through an online e-tail provider
3) Album published on CD and delivered by express air through an online e-tail provider
4) Album downloaded as mp3/mp4 files from an online music service and used digitally
5) Album downloaded as mp3/mp4 files from an online music service and burned to CD-R for digital and CD use (no CD packaging)
6) Album downloaded as mp3/mp4 files from an online music service and burned to CD-R for digital and CD use, stored in individual CD packaging, i.e., slimline jewel cases

Because it is now common for listeners to convert between CD and digital formats, via burning digital files to disc or ripping CDs to digital format, we do not specifically consider the consumer's use of the music. To attempt to make the truest comparison possible, we include scenarios where the consumer burns the digital files to CD and stores the CD in a jewel case.

We find that despite the increased energy and emissions associated with Internet data flows, purchasing music digitally reduces the energy and carbon dioxide ($CO_2$) emissions associated with delivering music to customers by between 40 and 80% from the best-case physical CD delivery, depending on whether a customer then burns the files to CD or not (Figure ES-1). This reduction is due to the elimination of CDs, CD packaging, and the physical delivery of CDs to the household. Based on our assumptions, online delivery is clearly superior from an energy and $CO_2$ perspective when compared to traditional CD distribution.

However, despite the dominance of the digital music delivery method, there are scenarios by which digital music performs less well. For instance, the traditional retail delivery scenario is nearly equivalent to downloading and burning if the customer walks rather than drives to the retail store. Similarly, if the file transfer size is increased to 260 MB (from 60-100 MB) the download and burn option looks very similar to the e-commerce CD scenario due to increased Internet energy use for downloading. Thus, future work should examine new forms of online music delivery with potentially heavier network overhead, such as streaming audio systems and lossless audio files. However, 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.

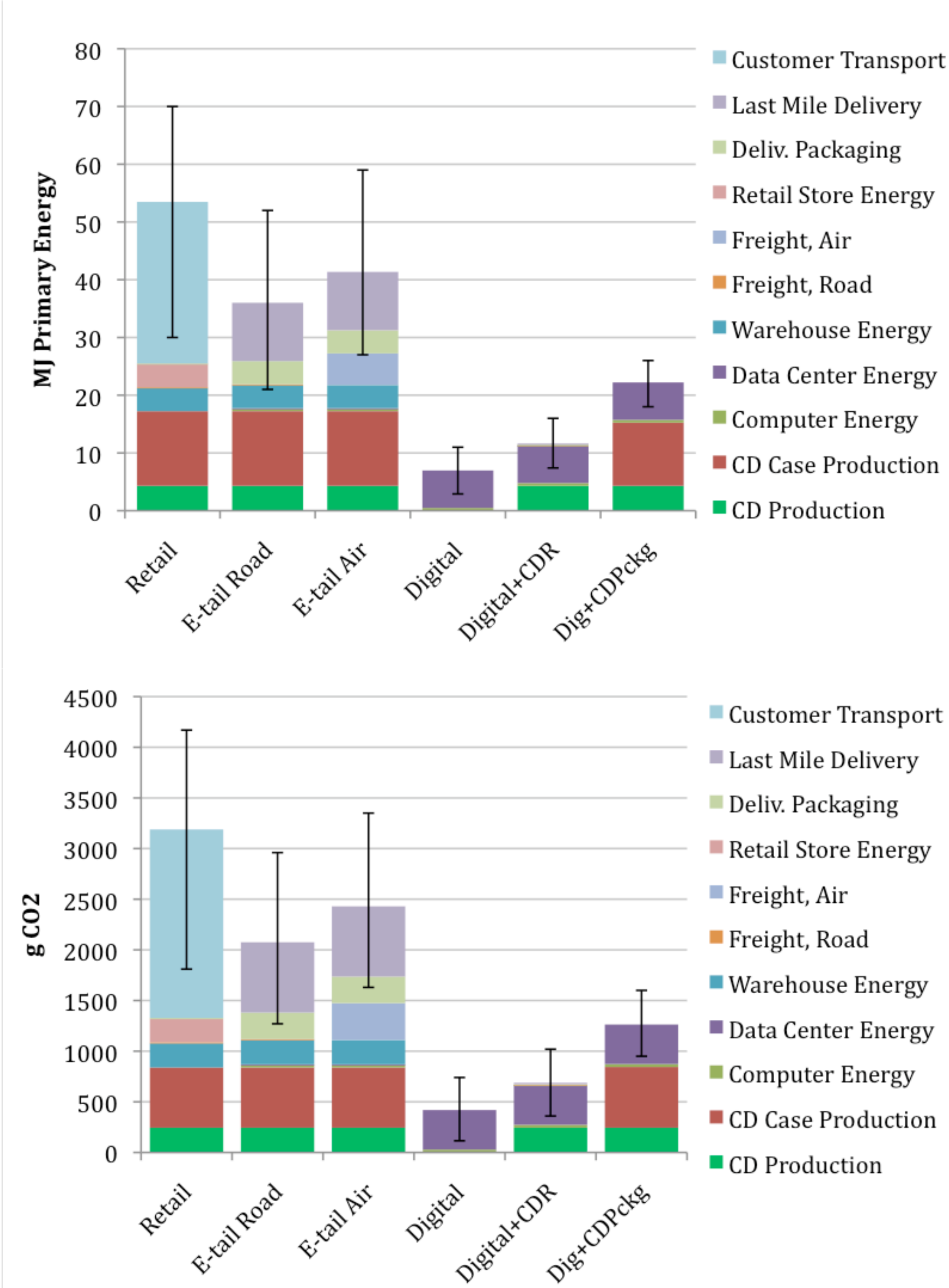


**Figure ES-1: Comparison of six album purchase scenarios in cumulative energy (MJ/album, top) and GHG emissions (g $CO_2$/album, bottom). Scenarios are ordered in numerical order (1, left to 6, right). Error bars represent 90% credible intervals from Monte Carlo analysis**

# THE ENERGY AND CLIMATE CHANGE IMPACTS OF DIFFERENT MUSIC DELIVERY METHODS

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## *1. INTRODUCTION*

Discussions about the environmental effects of information technology (IT) almost invariably focus on the direct electricity used by this equipment, which is easily measurable and has been growing over the past few decades (Harris et al., 1988; Kawamoto et al., 2002; Koomey et al., 1996; Roth et al., 2002; Roth et al., 2006).

The often-ignored indirect effects are also important, however. IT has at least three important indirect effects on resource use and environmental impacts:

- Dematerializing products and services: Moving bits instead of atoms is always less energy intensive and environmentally damaging (Atkyns et al., 2002; Matthews et al., 2000; Turk et al., 2003)
- Becoming smarter: Using IT to improve control of business and industrial processes reduces both costs and environmental impacts, while also improving productivity; and
- Becoming wealthier: IT increases economic growth (because it reduces costs and improves productivity) and makes the society wealthier than it would otherwise be.

The third effect is generally modest because energy use is only about 10% of GDP in highly developed countries like the US and so only 10% of an additional dollar of spending will on average be spent on energy, which is where the bulk of many types of environmental impacts occur (such as those related to climate change).

The size of the other two effects is rarely measured, in part because of the difficulty of doing so. To accurately assess environmental effects of dematerialization and becoming smarter requires a full life-cycle analysis for a well-defined business process or product.

Clean examples that allow for consistent comparisons are relatively rare, but in this analysis we characterize environmental impacts for dematerialization, focusing on delivering a music album via digital downloads vs. shipping a CD. This particular example allows an order of magnitude assessment of the benefits of moving bits instead of atoms.

## *2. BACKGROUND*

The past two decades have seen the emergence of new ways to sell and deliver products that are different from traditional retailing. These methods include "e-tail" (buying products on-line and shipping them directly to the customer), digital downloads (for information products like music), and subscription services for music and other digital products.

Assessing the environmental effects of IT has been an active topic of research for many years. Past work has discussed in general terms the energy and environmental benefits of telecommuting over traditional commuting (Atkyns et al., 2002). Several authors have compared the energy and environmental emissions associated with online retail (here forth, e-commerce) to traditional retail methods. Matthews (2001) reported a comparison of book purchasing via e-commerce and traditional retailing which was updated and summarized in Hendrickson (2005). Matthews (2002) completed an LCA study reviewing energy and cost impacts of logistics networks for the retail of books in Japan and the U.S. Abukhader (2004) proposed a methodology for assessing 'green supply chains' for e-commerce. Toffel and Horvath (2004) examined delivery of print products by digital means. Sivaraman et al. (2007) examined alternative logistics systems for DVD rental.

This paper differs from past studies of the e-tail/retail question by focusing on dematerializing products themselves instead of just analyzing the route a particular product takes from producer to consumer. While the general results for past studies have indicated that purchasing items online could lead to a slight improvement in energy efficiency over traditional retail methods (Matthews et al., 2001; Sivaraman et al., 2007), we focus here on a product only made possible in the last decade: the provision of music from recording process to digital music player or compact disc player. We also, however, consider potential consumer preferences for physical goods by including the possibility of burning digital files to CD.

Typical music supply chains have consisted of artists recording albums in studios, having these albums published onto the prevalent media of the time (currently compact discs), and moving this tangible good from production and publishing through to a final consumer in the home. While some previous work has been done on such dematerialized products, such as a study on the material intensity of digital music and another examining reading printed media online (Hogg and Jackson, 2008; Turk et al., 2003), to our knowledge this is the first study to directly compare the energy and greenhouse gas (GHG) impacts of downloading music vs. purchasing CDs by a retail or e-tail method.

There are clear potential energy and GHG savings from delivering music digitally as opposed to the typical supply chain of the past: the energy and emissions associated with producing the CD and packaging itself as well as the transportation chain to deliver this good. However, these savings are offset by the energy and emissions associated with network and data center usage to deliver the music digitally, as well as those of recordable media and media storage if the user burns music to a CD. Here we detail six scenarios of potential music delivery, three using traditional CD media and three using digital media. The next section describes these scenarios as well as data sources, assumptions, and methods. We then detail the results of delivering music by the six different scenarios, and finally discuss the implications and limitations of the study.

## *3. ASSUMPTIONS AND METHODS*

We define and analyze six scenarios by which a functional unit of one album of music could move from recording through distribution to a final consumer of music:

1) Album packaged on CD and delivered via traditional retail methods
2) Album published on CD and delivered by light-duty truck through an online e-tail provider
3) Album published on CD and delivered by express air through an online e-tail provider
4) Album downloaded as mp3/mp4 files from an online music service and used digitally
5) Album downloaded as mp3/mp4 files from an online music service and burned to CD-R for digital and CD use (no CD packaging)
6) Album downloaded as mp3/mp4 files from an online music service and burned to CD-R for digital and CD use, stored in individual CD packaging, i.e., slimline jewel cases

Each scenario is summarized further below.

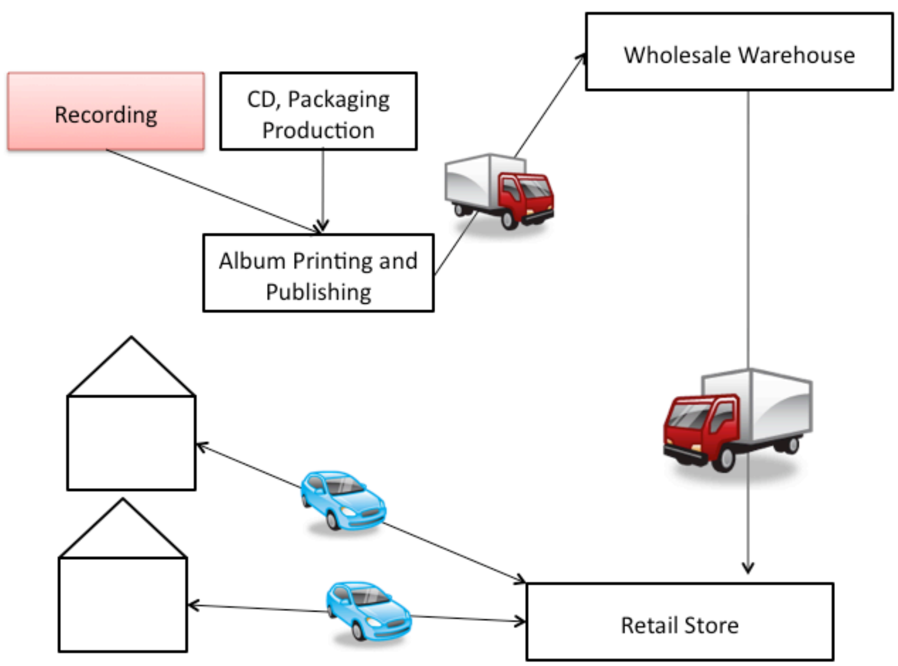



**Figure 1: Traditional Retail Product Flow Diagram**

Figure 1 shows a visual representation of the transportation chain for scenario 1, traditional retail. The product begins at the manufacturer from where it is assumed to be shipped by heavy-duty truck to the wholesale warehouse. The product sits in the warehouse (for simplicity we assume only one warehouse, owned by the retailer) for a certain amount of time until the product is in demand by the retail store, and we assume in the base case that it is then trucked directly to the store, packaged in bulk. While in some cases a shipment may go through a secondary warehouse belonging to the retailer (or an intermediate distribution warehousing facility) before it is shipped to the actual store, we assume direct delivery from the wholesale warehouse to the retail store. Individual consumers drive by car from their homes to the nearest retail store to pick up the product and then return home. Of course the consumer's trip to the retail store could include multiple stops or purposes, and this is discussed below in more detail. It should be noted that because the recording process itself (denoted in red in figures) was assumed to be similar between all 6 scenarios, it was not analyzed.

Figure 2 shows the transportation chain diagram for the e-tail or e-commerce model, scenarios 2 and 3. In this model, the product begins at a manufacturer and is delivered to a distributor warehouse, again by heavy-duty truck. While not shown as a part of the transportation flow in Figure 2, a customer shops for and buys a product on the e-commerce company website. After receiving information from the e-commerce company's data center that the product has been ordered and needs to be shipped, the distributor warehouse individually packages and sends the product to the collecting and sorting distribution center via a parcel service, either by truck (scenario 2) or airplane (scenario 3) depending on the online consumer's preferences for delivery time. The product, along with other products, is then taken to individual homes via a light-duty (we assume a 20,000 lb) delivery truck.

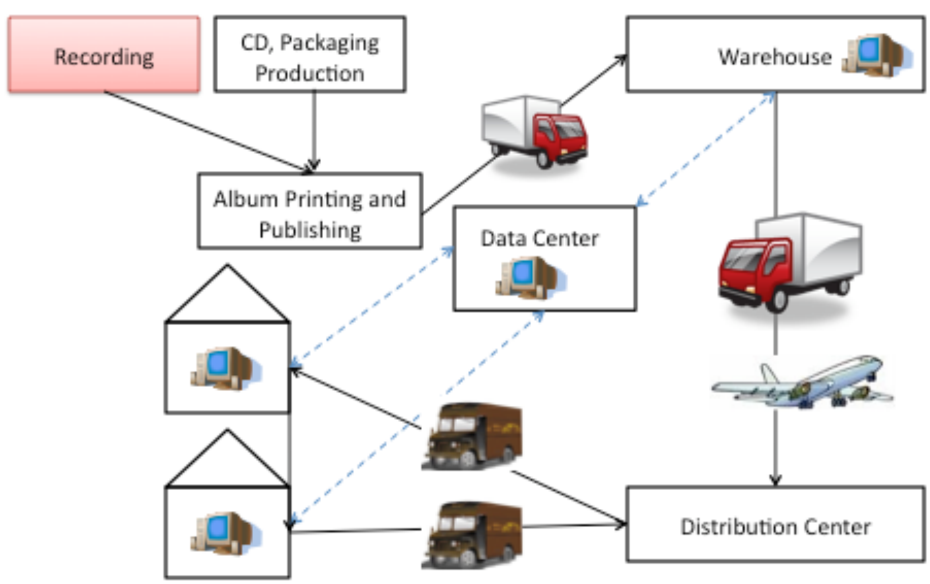



Figure 2: E-commerce Product Flow Diagram

As can be seen in Figure 1 and Figure 2, the initial stages in the product delivery (manufacturing, transport to first warehouse, and storage at first warehouse) are similar for both retail models. The time spent for a package in collecting and sorting distribution center after the wholesaler warehouse and before the distribution center were assumed to be small relative to the time spent in a wholesaler's warehouse. Thus, we assume the site energy use at the collection and sorting centers per package were relatively small compared to the warehouse energy use per package. The main differences in the transportation chains are from the warehouse to the retail store or distribution center and from the retail store or distribution center to the consumers. In addition, some potentially important non-transportation differences exist between the systems: energy usage in the data center to run the e-commerce web site, different uses of packaging (i.e., individual packaging vs. bulk packaging) from the wholesaler to the consumer, and energy use in the traditional retail store.

The possibility of downloading the album directly from an online music distributor changes the e-commerce/retail models considerably. This simpler chain is shown in Figure 3 and represents scenarios 4, 5, and 6. Here files from recording are sent directly to digital storage of the online music site and downloaded through data center communication when a customer shops online for the album, which comprises the complete logistics chain for scenario 4. However, one of the issues with analyzing online music systems is that online music customers can use their downloaded music in various ways—digitally on the computer used for downloading, on a digital music player such as Apple's iPod or Microsoft's Zune, or burned to a CD-R for use in a traditional CD player (Bottrill et al., 2008; Turk et al., 2003). To capture these different uses, we develop three scenarios, one where the customer buys bulk CD-R's (assumed to be in packs of 50) and burns the album to disc, and another where the customer does this and also purchases bulk CD-R packaging to protect the CD. We ignore any potential differences in lifetime between factory printed CDs and CD-Rs. To simplify this scenario, the packaging used by the customer was assumed to be similar to that used in the production of the physical CD from scenarios 1-3.

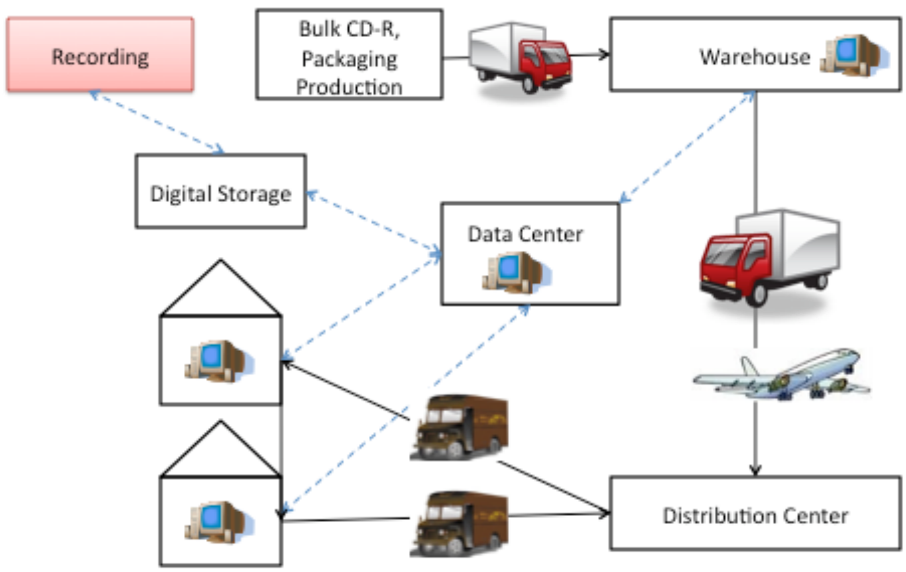



Figure 3: Download Flow Diagram

These different uses make exact comparison between the systems difficult, as downloading an album does not directly lead to the same type of music usage as purchasing a CD. However, purchasers of CDs are now able to easily convert music to digital format and purchasers of digital music can store it on CD media (albeit usually with lower fidelity). Thus we assert that including the production of a CD-R (scenarios 5 and 6) and individual CD-R packaging in cases (scenario 6) leads to full equivalence with the CD purchase, as scenarios 1, 2, 3, 5, and 6 can all lead to the same list of potential uses, including both CD and digital listening on various systems. Of course this is a simplistic representation of a complex system of consumer behavior—a customer is more likely to purchase digital music when he/she owns a digital music player, and is more likely to purchase a digital music player if he/she owns digital music. However, lacking data on how consumers use different music types differently, it is difficult to imagine any more complex assumptions about consumer behavior leading to more accurate results, and thus we focus here on consistency of functional unit.

The main remaining differences in these scenarios are (by assumption):

- Most online music consumers are unconcerned with the loss of fidelity associated with digitally downloaded music
- Online music consumers are more likely to buy CD-Rs and CD cases in bulk (i.e., assumed packages of 50 CD-Rs and cases) and online (similar to scenarios 2-3)

In summary, the systems under consideration included the following stages within the comparative study boundary:

- Warehouse Energy usage (scenarios 1-3)
- Electricity use at home computer to place e-commerce order (2-6)
- Transportation from the wholesale warehouse to the retail store, distribution center, or retail warehouse (1-3)
- Last mile transportation from local distribution center to customer home or from retail store to customer home (1-3)
- Data Center electricity usage to run e-commerce and online music sites (2-6)
- Individual vs. bulk cardboard packaging (1-3, 5-6)
- Energy use in traditional retail store (1)
- Internet network electricity usage for download (4-6)

In contrast, the following stages or parameters were assumed to be similar between the systems and were not included in this comparative study:

- Energy use of corporate headquarters of retail and e-commerce companies
- Non-cardboard packaging
- Production of listening systems (iPod/Zune, CD players, etc)
- Energy use of music listening

For summary purposes we include a table in Appendix A showing these assumed boundaries by scenario. Each process included within the system boundary required different data and assumptions. Thus we discuss each process individually in the following sections. In general, uncertainty was modeled using probabilistic analysis (Monte Carlo simulation) using triangular distributions where the most likely value was estimated from existing data and minimum and maximum likely values were estimated or taken as the largest and smallest available data point. We chose Monte Carlo simulation rather than simple uncertainty bounds because many of the variables utilized have considerable uncertainty ranges, and simple min/max ranges would be difficult to interpret. Simulation using simple assumed distributions such as is done here gives a more easily interpretable range of overall uncertainty by exploring interactions between the different variables' uncertainties. However, it should be stressed that most of the distributions utilized here were assumed, and thus probabilistic results should be taken as approximate.

## *4. DATA SOURCES*

For transparency, we show all assumed input parameters for the analysis in Appendix B. The origin of all values and all assumptions are documented in the following section.

### *4.1 Fuel Carbon and Energy Intensity*

Table 1 shows the assumed energy content and carbon content of different fuels. This data was used to estimate the $CO_2$ emissions associated with the energy consumption during the product flow stages of the retail models included in this study. In addition to the fuels listed in Table 1, electricity is used in various stages of the product flow. In the

U.S., the average fuel mix for electricity generation is consists of 50% coal, 20% natural gas, 3% petroleum, and 27% non-fossil sources (DOE, 2008). Using this average mix, the average emissions from electricity generation in the U.S. are estimated to be 650 g $CO_2$/kWh consumed on site, which includes transmission and distribution losses (Jaramillo et al., 2007). However, given the large variance in electricity emissions factors in different regions of the U.S. and different countries, we assume a distribution from 300-900 g $CO_2$/kWh with a mean of 650 g $CO_2$/kWh. This range represents both a reasonable range of variation within the U.S. (Weber et al., 2009b) as well as between country averages across the globe (World Resources Institute, 2007), so that all potential variability of production location was included. Electricity-based energy was converted to primary energy equivalents based on the IEA substitution method, which represents an adjustment for the initial amount of energy/fuels needed to generate electricity in electric power plants (IEA, 2008). In general we assume a 33% efficiency for converting primary energy to delivered site electricity, typical of governmental sources (EIA, 2008).

**Table 1: Carbon Content and Heat Content for Energy Fuels (EPA 2006)**

| Fuel | Carbon Content (Tg C/QBTU) | Heat Content (MMBTU/bbl or BTU/ft$^3$) | Oxidation Fraction |
|---|---|---|---|
| Finished Motor Gasoline | 19.3 | 5.25 | 0.99 |
| Finished Aviation Gasoline | 18.9 | 5.05 | 0.99 |
| Kerosene-Type Jet Fuel | 19.3 | 5.67 | 0.99 |
| Distillate Fuel Oil | 20.0 | 5.83 | 0.99 |
| Residual Fuel Oil | 21.5 | 6.29 | 0.99 |
| Liquefied Refinery Gases | 17.0 | 3.85 | 0.99 |
| Natural Gas | 14.5 | 1,030 | 0.995 |

### *4.2 Compact Disc and CD Packaging Production*

Data on the energy and $CO_2$ required to produce CDs and their packaging were taken from several sources, including two reports on GHG emissions associated with the UK music industry (Bottrill et al., 2008; Liverman, 2009), adjusted for different $CO_2$ emissions factors for electricity[1]. A second value for CDs was obtained using the Ecoinvent database for the production of the polycarbonate resin used in CD production, approximately 17 g/CD (Bottrill et al., 2008; Frischknecht and Rebitzer, 2005). A third value was obtained with the 2002 EIO-LCA model (magnetic and optical recording media sector), taking input value from 2002 export data for the United States (Green Design Institute, 2009; US Census, 2005). CDs used in the publishing industry were assumed to be similar to CD-Rs for lack of better data. These three data yielded average

[1] Numbers were adjusted to reflect the assumed distribution of electricity emissions factor used in this study, a triangular distribution with minimum of 300 g $CO_2$/kWh, mean 650 g $CO_2$/kWh, and max 900 g $CO_2$/kWh

production impacts of 4.3 MJ primary energy (range 3.6-5) and 240 g $CO_2$ (range 200-300) per CD produced.

A wide variety of CD packaging systems are in current use, and data were taken from a newly published study comparing the life cycle GHG impacts of these packaging types (Liverman, 2009). We thus assume a range of impacts for the different types of packaging to show the variation. The assumed range in the Liverman report (60 g $CO_2$/package to 1200 g $CO_2$/package) was used in scenarios 1-3, and a mean value was taken from Ecoinvent data for the production of an assumed mass of polystyrene plastic for a jewel case (~77 g (Bottrill et al., 2008)), yielding 380 g $CO_2$. Since no energy data were included in the packaging report, primary energy demand was estimated using Ecoinvent and the reported data for $CO_2$ emissions, assuming primary energy demand had a similar range to the GHG emissions range. This assumption yielded a distribution of 11 MJ/CD mean, ranging from 2-25. For scenario 6, we assume users purchasing their own CD-R packaging will choose slimline jewel cases, as opposed to the broad range of packaging options analyzed by Liverman (2009).

### *4.3 Shipping Packaging*

For packaging in scenarios 1, 2, and 3 we assumed that the main difference between systems was in the amount of cardboard used for shipping. Energy and emissions from plastic and paper packaging materials were assumed to be negligible compared to cardboard. The traditional bulk retail box was assumed to be a 36"x36"x24" box, which was estimated to hold approximately 1300 CDs or 250 50-pack CD-R spindles. The e-commerce shipping method was assumed to be flexible form corrugated foldable box with a surface area of 222 $in^2$ (8" x 10" x 1" with some overlap). Both standard box sizes and the average density of corrugated were taken from a commercial shipping box website.

Data on the energy and $CO_2$ intensities of corrugated cardboard were taken from the U.S. EPA's Waste Reduction Model (EPA, 2009), which specializes in providing estimates of the energy and greenhouse gas emissions of various types of materials that become municipal waste. For all energy and emissions associated with packaging, triangular distributions were used to express the uncertainty in life cycle energy and emissions of cardboard. The mean value of the distribution was taken to represent the case of source reduction in the usage of cardboard where reduction in demand for cardboard directly translates into reduced tree harvesting. Thus, forest carbon sequestration, one of the more difficult sources of emissions in paper products, is counted in the mean assumed value. For the maximum value of the distribution, forest carbon sequestration was included, but the reduction in demand was assumed to displace all virgin production as opposed to the average mix of virgin and recycled production as in the mean value. The low value of the distribution was taken to displace the average mix of cardboard, but forest carbon sequestration was not counted, under the assumption that reduction in demand for cardboard would not affect tree harvests on the margin. These values were also checked for consistency with EDF's Paper Calculator 2.0, which were in agreement to one significant figure (see Appendix 2) (Environmental Defense Fund, 2009).

### *4.4 Distribution and Final Delivery*

While the distance from warehouse to local distribution center or retail store was assumed to be similar given no better information, the distance is still relevant since the model energy intensity varies between road and air transport, as shown in Table 2 (Burnham et al., 2006; Facanha and Horvath, 2006). The distance was taken from a previous study of e-commerce logistics (Weber et al., 2009a), which reported 90$^{th}$ percentile and median distributions of (164 mi, 1,177 mi, 2,814 mi) for air delivery and (79 mi, 410 mi, 1270 mi) for ground shipping. The CD was assumed to weigh 1 lb (450 g) with packaging. For reference, Bottrill et al report CDs weighing 108 g (Bottrill et al., 2008). We took all modal energy intensities from the GREET 2.7 model from Argonne National Laboratory (Burnham et al., 2006).

**Table 2: Modal Energy Intensity (Burnham 2006)**

| Mode | Energy Intensity of Freight Modes (MJ/tonne-km) | Fuel Used |
|---|---|---|
| Heavy Duty Truck (25 ton cargo) | 0.74 | 100% Diesel |
| Medium Duty Truck (8 ton cargo) | 1.58 | 100% Diesel |
| Air Carrier | 9.93 | 100% Jet Fuel |

For the final delivery (last mile) portion of the logistics chain, data on total system energy per package was taken from a large commercial delivery company (UPS, 2007). The system-wide energy use per package was 28.1 MJ/package from this data set, but this represented all energy, not just last mile energy. We used the percentage of energy use from diesel to approximate the last mile energy intensity (10 MJ/package). To check this assumption, data was also gathered from local interviews of delivery truck drivers, who gave a distribution of packages delivered per day and miles driven from the local distribution center. This data (ranging from 0.1 to 1 miles/package delivered) was combined with the energy efficiency of a 20,000 lb delivery truck from Davis and Diegel (2007), given as 18 MJ/mile, which produced a per-package estimate range of 2-18 primary MJ/package, which was used as the assumed min-max range of the distribution.

### *4.5 Customer Transport to the Retail Store*

The energy and emissions associated with customer transport to the retail store was modeled using the equation shown below:

$$E/_{item} = \frac{(mi)\left(E/_{gal}\right)}{\left(mi/_{gal}\right)\left(p/_{veh}\right)\left(items/_{p}\right)}$$

**Equation 1**

Each of the parameters in equation 1 was treated parametrically or probabilistically. The distribution for miles driven was to have a minimum of 2 miles and a maximum of 20 miles, by assumption. The mean value was taken from the 2001 National Household

Travel Survey (NHTS), which gave a round trip of 14 miles for shopping purposes (DOT, 2002). The average on-road fuel economy of the US fleet was assumed to be 22 mi/gal (Davis and Diegel, 2007), with a minimum of 10 and a maximum of 30. The persons per vehicle was also taken from the NHTS, which gave a mean estimate of 1.5 person-trips/vehicle-trip for shopping purposes with a minimum of 1 and a maximum of 2. The same distribution was assumed for items/person on each trip, given no better data immediately available.

For the probabilistic analysis it was assumed that the number of different items purchased in a trip was correlated with the distance the customer had to drive to the store, with a linear correlation coefficient of 0.75. It was also assumed that the customer driving distance was correlated with the distance of the last mile delivery for e-commerce shipments (since those households living further from a retail store likely also live further from a distribution center). The correlation coefficient was assumed to be 0.65.

### *4.6 Warehouse Energy Usage*

Energy use in warehouses was again taken from a previous study of e-commerce logistics (Weber et al., 2009a), which utilized private data as well as public data from the Commercial Buildings Energy Consumption Survey (CBECS) (DOE, 2003). CBECS is a 5000+ building survey conducted by the Department of Energy that estimates energy intensities for various types of commercial businesses, including retail stores. These data sources summarize the average sales (in dollars) and size (in square feet) for many types of businesses.

### *4.7 Energy Usage in Retail Stores*

Data on energy use of retail stores came from HDL Companies and the Commercial Buildings Energy Consumption Survey. HDL Companies suggests the average retail sales are \$250 to \$900 per square foot (Bizstats 2008). For energy use, the Commercial Buildings Energy Consumption Survey (DOE, 2003) was used. From CBECS, the total energy use for retail (non-mall) stores ranges from 31 to 130 megajoules (site energy) per square foot (MJ/sf) ($25^{th}$ to $75^{th}$ percentile values). For retail stores in malls the energy use ranges from 60 to 153 MJ/sf. Given our data needs we allocate energy use instead by dollars of sales, resulting in an estimated energy use value in MJ/\$, which ranged from 0.03 to 0.14 MJ/\$ for non-mall stores (at \$900/sf) and 0.07 to 0.17 MJ/\$ for retails stores in malls (DOE, 2003). We assume a retail price of \$15 per CD to convert these intensities into MJ of energy uses in the retail phase.

### *4.8 Internet Energy Use for Download and Data Transfer*

To estimate the electricity intensity of data downloaded over the Internet, we use the methodology first presented in Koomey et al. (2004) and further developed in Taylor and Koomey (2008). Taylor and Koomey estimated the electricity intensity of information transfers in kWh per gigabyte for 2000 and 2006. We updated the 2006 estimate to 2008 by assuming total Internet data flows from 2006 to 2008 increased by 50% per year, as per the data at http://www.dtc.umn.edu/mints/home.php. We assumed also that telephone system data flows remained constant and that Internet electricity use grew at the same rate as did global data center electricity use from 2000 to 2005 (about 14%/year), as shown in Koomey (2008).

These assumptions resulted in an average electricity intensity of Internet data flows of about 7 kWh per gigabyte transferred for 2008 (taking the average of the low and high Internet data flow estimates from http://www.dtc.umn.edu/mints/home.php). This intensity is dropping about 30% per year, or halving every two years (see Figure 4). We assume a range of album size from 60 – 100 MB from inspection on a commonly used online music site (the iTunes store). We also assume 1-2 MB data transfer for online shopping and purchasing.

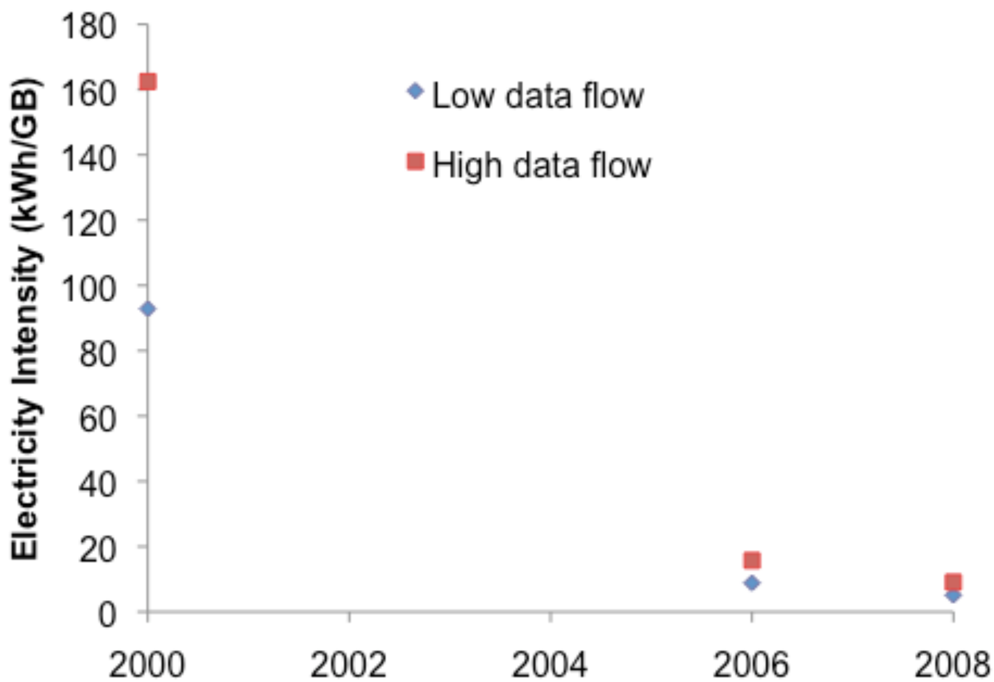



**Figure 4: Internet electricity intensity for transferring data (kWh/gigabyte transferred)**

### 4.9 Energy Usage in Homes for Placing E-commerce Orders

The consideration of home computer energy use in studies of e-commerce has varied over time (Sivaraman et al., 2007; Toffel and Horvath, 2004; Turk et al., 2003). Past work has included the energy of the computer and monitor (often desktop computers despite the high prevalence of laptops today), lighting and heating/cooling within the room, and the network energy overhead for the transaction. We assume a range of 40-200 W site energy for an average computer, representing reasonable values for current laptops and desktops with monitors in active mode. We further assume a person spends an average of 11-20 minutes shopping online for the album and that all energy use by the computer during this time can be allocated to the purpose of buying the album (Turk et al., 2003). This represents an upper bound estimate, though often computer users are performing multiple tasks at once. We also include an allocated share of the production energy of the computer (0.004 kWh/minute), using an assumed lifetime of 3 years, since previous work has shown the importance of the production phase for computers (Williams, 2004; Toffel, 2004). For the electricity used by online shopping, we take numbers from Taylor and Koomey (2008) which estimates average energy usage of Internet traffic of 7 kWh/GB of data, with a range of 5-9 kWh/GB. We assume an upper bound value of 1 MB data usage for the online shopping and purchasing. These ranges led to an estimate of 1-2 MJ of primary energy use from the consumer placing the order online.

## *5. RESULTS*

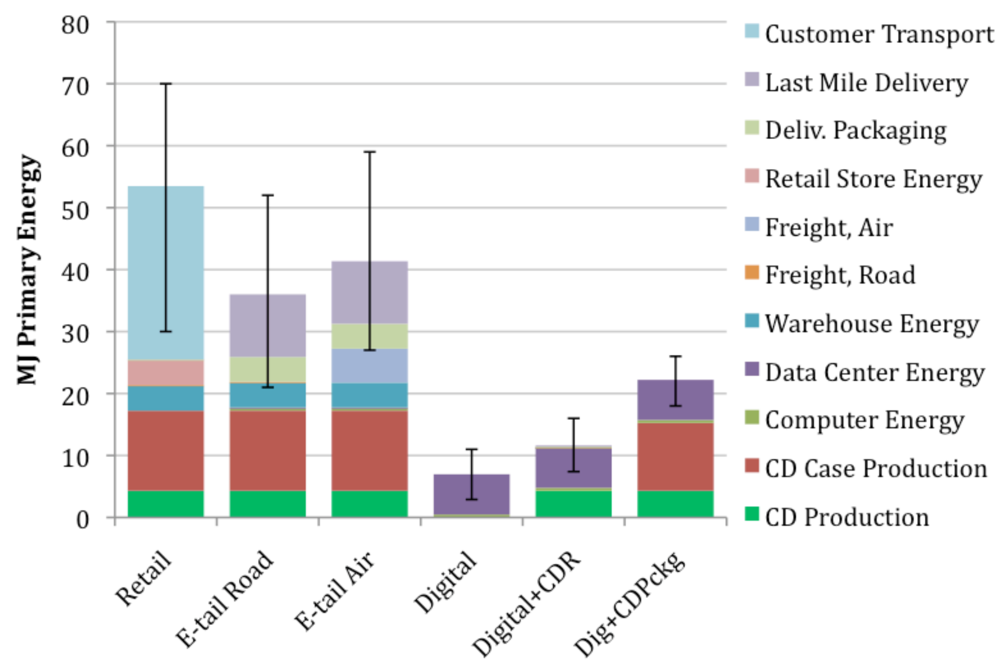
The main results for the six scenarios can be seen in Figure 5 below, for primary energy (MJ) per album, top, and $CO_2$ emissions (g $CO_2$) per album, below. Error bars represent the 90% credible intervals[2] (i.e., $5^{th}$ and $95^{th}$ percentiles of output distributions) from the Monte Carlo uncertainty analysis.

The graphs show that the mean rank order of scenarios was the same for primary energy and $CO_2$ emissions, with the retail method taking the most energy and emissions, followed by the two e-commerce scenarios, and with the three download scenarios using the least amount of energy and producing the least $CO_2$ emissions. We find a range from a high of 53 MJ/album and 3200 g $CO_2$/album for the retail scenario to 7 MJ/album and 400 g $CO_2$/album for the download with no CD burning scenario ("Dig" in figure). Thus, we find slightly less than an order of magnitude difference between the worst and best scenarios for artist to customer album delivery. It should be noted that the best physical CD option, scenario 2, still used 62% more energy and produced 64% more $CO_2$ emissions than the worst download option, scenario 6. Given the very similar results for energy and $CO_2$, we now focus purely on $CO_2$ emissions.

The production of CDs and CD packaging represent between 32% (scenario 1) and 69% (scenario 6, with very low logistics energy) of the album delivery. In 4 of 6 scenarios the logistics chain of getting the physical CD to the customer is even more important than the "dematerialization" of eliminating CD and CD packaging production. Similar to previous studies (Matthews et al., 2001; Matthews et al., 2002; Sivaraman et al., 2007), we find customer transport to the retail store and last mile delivery for e-commerce to be major contributors, 52% of scenario 1 and 24-28% of scenarios 2 and 3, respectively. In addition, warehouse energy use, retail store energy use, and individual shipping packaging for e-commerce contributed noticeable amounts to the physical CD delivery scenarios. Besides CD and slimline case production for scenarios 5 and 6, the energy and emissions associated with the download scenarios were almost completely due to upstream data center energy usage for data transfer—home computer usage was relatively unimportant, as was logistics of CD-R and CD case purchase. The impacts of producing CD packaging were smaller for scenario 6 than for scenarios 1-3 due to the

[2] The term credible intervals is used in Bayesian statistics to describe posterior probabilities of variables given Bayesian updating. While not strictly comparable to Monte Carlo simulated results as here, we use the term to describe the 90% probability bands for variables.

smaller mass of the slimline CD case. These requirements were minor regardless of whether CD-Rs and cases were purchased via retail or e-tail due to the assumed bulk delivery of 50 packs.



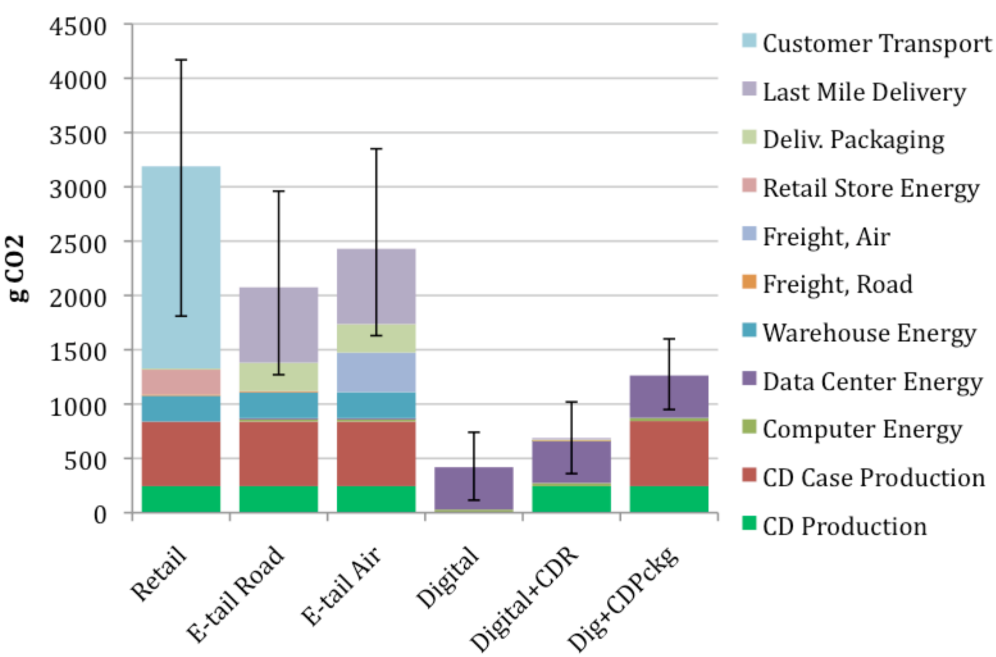




**Figure 5: Comparison of six album purchase scenarios in cumulative energy (MJ/album, top) and GHG emissions (g $CO_2$/album, bottom). Scenarios are ordered in numerical order (1, left to 6, right). Error bars represent 90% credible intervals from Monte Carlo analysis**

The results of the Monte Carlo analysis also provide insight to the relative importance of different parameters in the overall uncertainty of the album delivery scenario's emissions. Table 3 shows correlation coefficients of individual parameters with total delivery emissions, a rough measure of the importance of each parameter to the overall uncertainty and variability of the system. In summary, a large correlation coefficient means an uncertain variable is particularly important to the overall uncertainty of the total emissions associated with the delivery scenario. For the retail delivery system, as would be expected two of the most important parameters were found to be driving distance from home to retail store and fuel economy of the automobile taken, with minor importance from warehouse energy use and CD production. Jewel case production was also very important for uncertainty and variability due to the large range of different types of packaging assumed (Liverman, 2009). For the same reason, jewel case production dominated variability in e-commerce routes, with uncertainties in last mile delivery, shipping packaging, and warehouse energy use following. For the digital routes nearly all uncertainty and variability had to do with upstream data center energy, a combination of uncertainty due to energy per MB flow as well as the carbon intensity of electricity.

| | Retail | E-commerce Road | E-commerce Air | Dig | Dig+CDF | Dig+CD +Pckg |
|---|---|---|---|---|---|---|
| Driving Distance | 0.71 | | | | | |
| Fuel Economy | -0.33 | | | | | |
| Warehouse: electricity | 0.1 | 0.11 | 0.11 | | | |
| Retail: Gas | 0.04 | | | | | |
| Jewel Case Production | 0.59 | 0.85 | 0.81 | | | 0.06 |
| CD Production | 0.07 | 0.07 | 0.07 | | 0.23 | 0.23 |
| Last Mile Energy | | 0.49 | 0.47 | | | |
| Data Centers | | 0.07 | 0.06 | 0.99 | 0.96 | 0.95 |
| Computer Energy | | 0.07 | | 0.05 | 0.06 | 0.06 |
| E-tail packaging | | 0.13 | 0.12 | | | |
| E-tail Road Freight | | 0.05 | | | | |
| E-tail Air Freight | | | 0.29 | | | |

**Table 3: Correlation Coefficients of importance for uncertainty assessment in total GHG emissions from the six purchase scenarios**

Because the high end of the uncertainty range for the worst download scenario (6) overlaps with the low end of the uncertainty range for the best physical CD scenario (2), we also show the simulated difference between scenario 2 and 6 in a cumulative probability curve below in Figure 6. As seen in figure 6, less than 7% of simulations produced a negative difference (i.e., a simulation where scenario 6 produced more $CO_2$ emissions than scenario 2). Thus, despite the fact that the uncertainty ranges overlap, only in extreme cases of either scenario 2 or scenario 6 does the digital download scenario 6 produce more $CO_2$ emissions than the e-tail scenario 2.

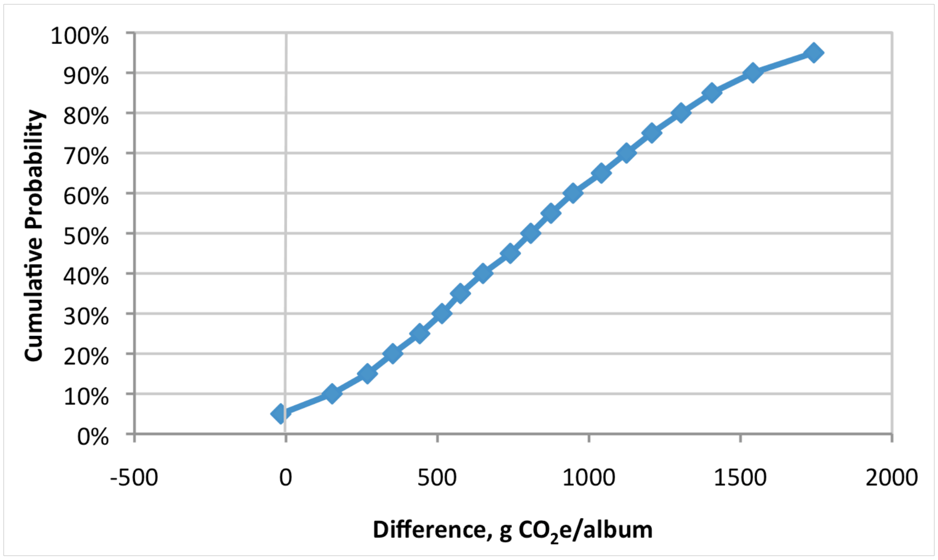



**Figure 6: Simulated cumulative distribution of difference between $CO_2$ emissions from e-tail scenario 2 and download scenario 6, g $CO_2$/album.**

## *6. DISCUSSION*

Given the assumptions of the analysis, the results are fairly clear—downloading albums uses less energy and produces fewer $CO_2$ emissions than purchasing a physical CD either via traditional retail or e-commerce methods. The difference between even the worst-case scenario (6) for downloading and the best-case scenario for physical CD purchase is large—around 65% more $CO_2$ emissions via e-tail compared to downloading an album, burning it to CD-R and storing the album in a slimline jewel case. Given the results of the Monte Carlo analysis, it would seem these results are robust.

However, it is relevant to ask what variable values would flip the result and make the download option more $CO_2$-intensive than e-tail purchase. Of course the six scenarios here do not describe all potential ways in which an album can be delivered from recording to a final consumer. We investigated several variables to see at what point their values would produce equivalent emissions between downloading and either e-tail or retail. The first and most obvious case is reducing consumer transportation to a retail store. In the extreme case, where the trip to the store produces no emissions (i.e., walking or biking with no assumed additional food requirements), the retail system produces a mean of 1330 g $CO_2$, still slightly higher than scenario 6 but given uncertainties basically the same. While walking to the store may be common in densely populated areas, it can be considered unlikely in suburban or rural areas where half of the US population lives (Census, 2007).

We also investigated how file size and time spent shopping online could increase emissions from the online purchase scenarios to the mean e-tail scenario 2 (an increase of around 800 g $CO_2$/album). Keeping file size constant, even the most energy-intensive computer assumed (200 W) would require over 5 hours of web browsing to increase scenario 6 by this amount. Thus it is unlikely this variable alone could change the result. For file size it was estimated that an album size of 260 MB would increase the emissions associated with scenario 6 to equivalence with scenario 2. Unlike the 5 hour browsing scenario, this data transfer is entirely plausible if online music stores were to move toward "lossless" digital audio formats in large number, such as Microsoft's WMA 9 lossless format. We assumed in this analysis that audio quality in the standard mp4 format, producing albums from 60-100 MB was good enough for most listeners, but as more homes get high fidelity home theater systems this may no longer be true. However, it is also critical to remember that the energy intensity of file transfers is dropping 30% per year currently (see above), and thus the equivalent file size is growing by approximately 30% per year concurrently. At the same time, though, CD manufacturing and logistics systems may also be getting more energy efficient with time, thus making the difference between the two systems a moving target.

## *7. FUTURE WORK*

A main limitation of this work is the assumption of equivalence between downloading an album and purchasing the album in CD form. While this assumption is convenient, in reality it is likely that customers use physical and digital albums somewhat differently and these differences may be critical for the analysis, as discussed previously (Turk et al., 2003). One issue is fidelity, as discussed above. Another is the importance of album artwork, which was not explored here. While many download services offer a digital version of the album artwork with the download, this may not be completely satisfactory for some customers. Further, we did not include any production impacts associated with digital music players, which could reasonably be attributed to the online music system (though users can of course rip CDs to digital music players as well). We also neglected emissions from the production of standard CD players, which are generally longer lived than MP3 players but still involve significant production emissions. Finally, it is likely that users may either purchase or store music in different units than albums; for instance either storing multiple albums per CD-R or downloading single tracks as opposed to whole albums (Hogg and Jackson, 2008). Future work assessing these behavioral variations would be extremely valuable.

Also, this study limited itself to one potential online music system, a purchase-for-download system as is currently common in Amazon's MP3 service and the iTunes store. However, many more systems exist, such as subscription systems where the user pays a fee per month for access to a catalog of albums that can then be streamed at will. Clearly this is an entirely different system, and future work should elucidate the energy and emissions associated with streaming audio. Further, streaming video is also a relatively unexplored area and one that is growing extremely quickly in Internet traffic. Extending previous studies on video rental (i.e., (Sivaraman et al., 2007)) to include both downloadable digital video rentals as well as streaming video systems would also be illuminating for tech-savvy customers.

## *8. CONCLUSIONS*

In this study we analyzed the energy and $CO_2$ emissions associated with delivering music from a recording studio to a final customer via traditional retail, e-tail, and download routes. Given our assumptions, our results indicate the superiority of downloadable online music, which even in the worst-case scenario produces on average 65% lower $CO_2$ emissions than the best-case e-tail delivery method. Significantly higher savings (nearly a factor of 5) can be seen if the customer forgoes CD-R burning in favor of fully digital use, thereby eliminating the energy it took to produce the CD and its packaging. However, the results are sensitive to both behavioral assumptions of how customers use digital music as well as several important parameters in the logistics chain of retail and e-tail delivery, such as customer transport to the store, CD packaging method, and final delivery to the customer's home for e-tail. In particular online music's superiority depends on the assumption of customer's driving automobiles to the retail store. Future work should focus on new methods for digital media acquisition such as subscription and streaming services, which may increase the energy requirements of downloading digital goods.

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**Appendix A**: Included and Excluded Variables in Scenarios

| | | 1<br>CD + traditional retail | 2<br>CD + land e-tail | 3<br>CD + air e-tail | 4<br>Digital | 5<br>Digital + burned CD | 6<br>Digital + burned CD + jewell case |
|---|---|---|---|---|---|---|---|
| Excluded overhead | Construction energy of production, transportation, and delivery systems (trucks, data centers, etc.) | - | - | - | - | - | - |
| | Energy use of corporate HQ for retail and e-commerce companies | - | - | - | - | - | - |
| | Non-cardboard packaging | - | - | - | - | - | - |
| Production | Recording | - | - | - | - | - | - |
| | CD production (music CD or CD-R) | X | X | X | - | X | X |
| | CD packaging (music CD or CD-R) | X | X | X | - | X | X |
| | Album printing + publishing | X | X | X | - | - | - |
| Distribution | Land transportation to warehouse (music CD or CD-R) | X | X | X | - | X | X |
| | Warehouse energy use | X | X | X | - | - | - |
| | Land transportation to retail store / distribution center | X | X | X | - | - | - |
| | Air transportation to retail store / distribution center | X | X | X | - | - | - |
| | Distribution center energy use | - | X | X | X | X | X |
| | Retail store energy use | X | - | - | - | - | - |
| Purchasing and delivery | Data center energy use for online purchasing | - | X | X | X | X | X |
| | Internet energy use for download | - | - | - | X | X | X |
| | Consumer transportation to/from retail store | X | - | - | - | - | - |
| | Delivery to customer at home | - | X | X | - | - | - |
| | Customer computer use shopping online | - | X | X | X | X | X |
| Excluded use-phase | Embodied energy of listening systems | - | - | - | - | - | - |
| | Use-phase energy of listening systems | - | - | - | - | - | - |

X = Included, - = Not included

**Appendix B**: Assumed input parameters and distributions for analysis

All distributions are shown as assumed distribution followed by parameters of the distribution. For example, Triang(10,15,20) denotes a triangular distribution with minimum value 10, maximum value 20, and maximum likelihood of 15. Where a range was available with no mean estimate the maximum likelihood was assumed to lie at the arithmetic mean of the range.

Data Center Energy Use: 0.005-0.009 kWh/MB

Album size: 60-100 MB

Internet data transfer to complete purchase: 1-2 MB

Assumed global electricity emissions factor: (300, 650, 900) g $CO_2$/kWh

CD mass: (14 - 33) mg polycarbonate/disc

CD jewel case mass: 77 g polycarbonate

Producer price of CD: ($0.53-$0.65) / CD 2002$

Life cycle primary energy of PC plastic: Triang(105, 107, 118) MJ/kg PC

Life cycle $CO_2$ of PC plastic: Triang(5.5, 5.6, 7.8) kg $CO_2$/kg PC

Warehouse gas usage per shipment: Triang(0.1, 0.2, 0.3) MJ/shipment

Warehouse electricity usage per shipment: Triang(2.2, 3.8, 5.5) MJ/shipment

Electricity usage of retail stores: 0.14 – 0.5 MJ/$

Gas usage of retail stores: 0.4 – 1.45 MJ/$

Packaging requirement area per CD, retail: 4.7 $in^2$

Packaging requirement area per CD, e-tail: 222 $in^2$

Mass to surface area ratio of corrugated cardboard: 0.0017 $lb/in^2$

Life cycle energy of corrugated cardboard: Triang(13, 22, 27) MJ/ton

Life cycle $CO_2$ of corrugated cardboard: Triang(0.2, 1.5, 2.2) ton $CO_2$/ton

Customer driving distance to retail store: Triang(2, 14, 20) miles round trip

Passengers per automobile shopping trip: Triang(1, 1.5, 2)

Items purchased per shopping trip per customer: Triang(1, 2, 3)

Correlation Coefficient, driving distance vs. items per trip: 0.75

Correlation coefficient, e-tail delivery distance vs. customer driving distance: 0.65

Energy intensity of 20,000 lb delivery truck: 18.5 MJ/mi

Distances from warehouse to retail store or etail delivery center, Ground: Triang(79, 410, 1270) miles

Distances from warehouse to retail store or etail delivery center, Air: Triang(160, 1200, 2800) miles

Last mile primary energy intensity, e-tail: Triang(2, 10, 19) MJ/item

Computer power use during active mode: Triang(40, 140, 200) W

Web shopping time: Triang(11, 15, 20) min

Download time for album (50% allocation): Triang(0.5, 1.5, 5) min