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Comparing Embodied Greenhouse Gas Emissions of Modern Computing and Electronics Products

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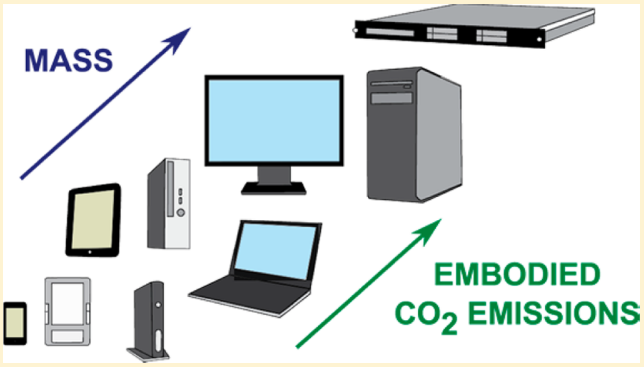
Supporting Information

ABSTRACT: Information and communications technology (ICT) contributes substantially to global greenhouse gas (GHG) pollutant emissions, but it is time-consuming to estimate the environmental impacts caused by the production of ICT devices, and the literature lacks coverage for newer products. Using a process-sum life cycle assessment (LCA) approach, we estimate and compare the embodied GHG emissions of 11 ICT products, including large- and small-form-factor desktop and laptop personal computers, a thin client device, an LCD monitor, newer mobile devices (an Apple iPad, an iPod Touch, and an Amazon Kindle), a rack server, and a network switch. Full bills of materials are provided via hand disassembly and weighing and are mapped to processes in the ecoinvent v2.2 database to produce impact estimates. Results are analyzed to develop simplified impact estimation models using linear regressions based on product characteristics. A simple and robust linear relationship between mass and embodied emissions is identified; a more sophisticated linear model using display mass, battery mass, and circuit board mass as inputs is slightly more accurate. Embodied GHG emissions for newer products are 50−60% lower than corresponding older products with similar functionality, largely due to decreased material usage, especially reductions in integrated circuit content.



1. INTRODUCTION

The global share of worldwide greenhouse gas (GHG) emissions from information and communications technology (ICT) is substantial and rising; computers and electronics are a significant source of household electricity consumption.[1] In the personal computing (PC) sector, operational impacts are estimated to account for roughly 60% of greenhouse gas emissions, with the remaining 40% due to manufacturing.[2] The latter, also referred to as embodied emissions, is difficult to estimate, and there is a need for both additional and improved estimates of embodied emissions of ICT products, and for heuristic methods to enable faster and easier first-order estimation.

Current literature examining the embodied impacts of ICT equipment suffers from three important shortcomings: disagreement across studies regarding the magnitude of impacts of ICT products;[3−5] lack of coverage for newer products; and lack of transparency in studies, particularly due to confidential input data, which hampers reproducibility and cross-study comparisons. Using primary data from hand disassembly and the ecoinvent v.2.2 database[6] for upstream process data, we quantify the embodied greenhouse gas (GHG) emissions of 11 ICT products, most of which were manufactured in 2009 or later. This work represents the first peer-reviewed examination of the embodied impacts of a small-form-factor desktop PC, netbook-style laptop, thin client device, Apple iPad, Apple iPod Touch, and Amazon Kindle. An additional study of three older ICT products from the ecoinvent database[7] was reformulated using our framework so that all 14 products could be compared. A full listing of the products analyzed and the results recorded is in Table 1. By using a consistent framework, we can compare product emissions estimates with some confidence, avoiding the problems of different modeling assumptions or different upstream data sources that arise when comparing results from independent studies. We use this framework to develop first-order linear models for estimating embodied emissions using a small set of product characteristics. We also compare our findings against a data set published by Apple (described in the Supporting Information (SI)) that provides life cycle assessments (LCAs) of its entire product line.[8]

The broad goal of this work is to make LCA results for ICT products easier to derive and more useful in supporting decisions, both by contributing a new primary data set of product inventories and impact estimates (provided in entirety in

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Table 1. Products Analyzed in This Study[a]

product analyzed (year of manufacture)	mass (kg)	GHG (kg CO_2-eq)
Desktop Computers, No Display		
[ei] typical desktop (2002)	11.1	322
Dell Optiplex 780 mini tower (2010)	10.7	164
Dell Optiplex 780 ultrasmall form factor (2010)	3.0	73.5
Dell FX-100 zero client (2009)	1.3	33.6
Laptop Computers		
[ei] 12.1" HP Omnibook with dock (2003)	3.3	256
HP 530 laptop, 16" (2009)	2.8	108
HP Mini 110−1030 CA Netbook, 10" (2009)	1.3	62.2
Displays − LCD		
[ei] Typical 17" (2004)	5.1	297
Samsung Syncmaster 2243 21" (2009)	5.1	168
Mobile Electronics		
Apple iPad 8gb Wi-Fi first gen (2009)	0.78	25.5
Apple iPod Touch 8gb third gen (2009)	0.20	7.5
Amazon Kindle Wi-Fi third gen (2010)	0.31	13.3
Server and Network		
Dell PowerEdge EMU3710P71 rack server (2005)	15.5	383
3Com 24-port Superstack 3 10/100 Ethernet switch (2003)	2.1	91.8

[a][ei] is the adjusted version of a study originally published in ecoinvent.[7] Mass includes power supplies. GHG: emissions due to material extraction and production phases only.

the SI), and by exploring linear regression-based models that could approximate impact assessment using a limited set of easily collected inputs. Similar linear regression-based methods being developed by the PAIA project[9] and by iNEMI[10] are aimed at enabling impact estimation using product characteristics (e.g., screen area, amount of RAM, hard drive size, etc.). Our data set could be adapted to use these tools and methods once they become publicly available.

2. MATERIALS AND METHODS

The process-LCA methods we apply have been used in many studies of ICT equipment, such as the original ecoinvent studies we adapted,[7] the EPIC-ICT project,[11] the EU energy-using-product studies,[12,13] and others. The ecoinvent database has been described as the "most complete and transparent process-LCA database"[14] and is used for upstream data in one LCA study of a desktop PC[15] and as the process component in several hybrid-LCA studies.[16,17] However, the limitations of this methodology must be stressed. Process-LCA accounts for only those impacts that are specified in product inventories and underlying process databases; truncation error due to activities not modeled in these databases can be significant. Large sectors of the economy, especially service sectors, are not modeled by the ecoinvent database at all.[14] Top-down methods, such as economic input-output LCA, do not suffer from truncation error, but have a limited ability to distinguish between similar products due to the coarseness of economic data. Hybrid-LCA methods attempt to achieve a balance by merging top-down economic data with process-LCA results. Two hybrid-LCA studies of a desktop PC[18] and laptop PC[16] found that the economic correction respectively accounts for 51%[18] and 40% to 56%[16] of total impacts in the production phase. Likewise, in a comparison of LCA methods for ICT products,[17] the original process-LCA estimate accounted for only 37% of the emissions estimated by a top-down input-output LCA. Accordingly, hybrid analysis is recommended by several researchers as the best means to produce accurate estimates of emissions in absolute terms.[14,17,19] Structural-path analysis is another promising approach.[20]

The scope of our study is limited to comparing the embodied impacts that can be identified using process-LCA methods with the ecoinvent database. This limitation is imposed because the strengths and weaknesses of this framework are relatively well understood, which allows for increased confidence that the relative differences in the product impacts that our analysis identifies are not methodological artifacts. The process-sum method introduces significant truncation error such that our results underestimate the absolute impact; the use of economic data to correct for truncation error would improve accuracy, but such a correction would require pricing data which is largely unavailable to us. Accordingly, our results should be interpreted as a comparison between products, and not as a calculation of product carbon footprints that could be used in contexts external to this study. Future work to produce product carbon footprints should address this truncation error, as well as the use phase and end-of-life phase which are not included in this study.

A number of standards for LCA of ICT equipment have recently been published or proposed by the ETSI,[21] ITU,[22] IEC,[23] and GHG Protocol,[24] coordinated in part by the European Commission's Information Society department.[25] Our study was conducted prior to the publication of these standards, and thus is not compliant with any of them, though compliance could be achieved with some additional effort. The use of standards, especially the ETSI standard which is the most thorough and rigorous of the above, would greatly improve transparency and comparability across compliant studies, and should be encouraged.

Our study focuses on embodied impacts, in terms of global warming potential, using the IPCC 100-year characterization;[24] primary energy demand is calculated as well in the SI. Raw material extraction, processing, final assembly, and transport are included. Modeling assumptions are equivalent to those used in previous ecoinvent studies.[7] In particular, we rely on the ecoinvent database for all electronic component manufacturing, processing, assembly, and transport data and assumptions, with the exception of silicon die, for which we use an updated study.[26]

Bills of materials were constructed via hand disassembly and weighing. Product packaging and extra parts, including manuals, software, and extra cables and adapters, are excluded, as this information is not available for all products and tends to represent a small share of the impacts for ICT products. Some other components, such as flame retardant coatings, are not detectable via weighing and were thus excluded.

The ecoinvent models for silicon die content in packaged integrated circuits (ICs) contain a calculation error (identified in other studies[3,27]) that leads to an underestimate of silicon die content. In order to develop more accurate estimates of silicon die content in packaged ICs, a selection of packaged ICs were X-rayed and their die areas measured. Silicon die content is modeled as a linear function of packaged IC area for large ICs and of mass for smaller ICs, which were weighed in bulk. An additional correction was made for stacked ICs in the Apple iPad and iPod Touch.

The SI contains full details regarding modeling assumptions; full bills of materials for all products; the mapping of bills of materials entries to ecoinvent processes; experimental data and calculations for the silicon die ratios; and a discussion of stacked ICs.

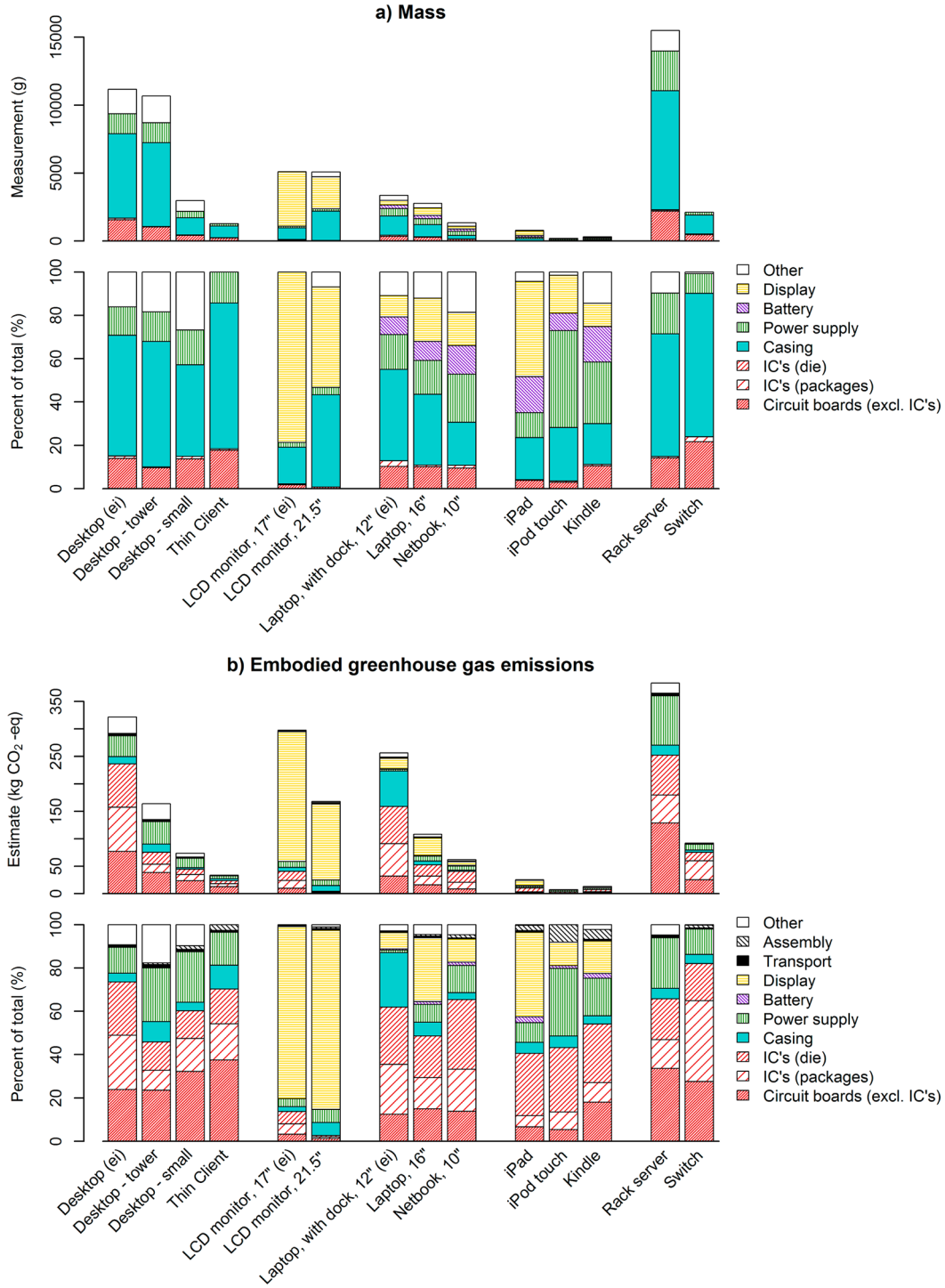

Figure 1. Results showing product mass (a) and embodied emissions (b). (ei) denotes adjusted studies from ecoinvent database.

3. RESULTS

Two sets of results are presented: the mass composition of each product as determined through hand disassembly (Figure 1a), and estimated embodied GHG emissions calculated with ecoinvent impact data (Figure 1b). Data tables for the graphs are available in the SI.

3.1. Product Composition by Mass. Circuit boards account for between 5% and 20% of product mass across most products. Casing, typically metal or plastic, represents roughly half of the mass in large desktop and rack servers, each of which weigh more than 10 kg. In mobile devices, casing is only about one-quarter of the mass due to the extra mass of batteries and displays.

The three studies adapted from the ecoinvent database model a desktop PC, manufactured in 2002; a 17" LCD monitor from 2004; and a 12.1" laptop (with dock) from 2003. Comparable products in this study, all manufactured in 2009 or 2010, are significantly lighter. The 21.5" monitor studied here is comparable in mass to the 17" monitor modeled in ecoinvent, despite the former's larger screen size, because the latter was significantly thicker and had a much heavier frame, likely because LCD technology was relatively new and less compact in 2004.

This information constitutes evidence that electronics products are becoming more materially efficient over time.

In terms of both IC mass and die area, modern devices show significantly less material usage for integrated circuits when compared to the older products modeled in ecoinvent. That is likely due to higher levels of miniaturization available in modern packaging technologies (as described in another study[28]), as well as reduced numbers of ICs per product due to increased integration of functionality.

3.2. Embodied Emissions. Circuit boards including ICs are responsible for the majority of embodied GHG emissions in most devices. Product casing in our study is modeled as aluminum, steel, or plastic, all of which have low emissions per unit mass, so the overall impact of casing is small. One exception is the laptop modeled in the ecoinvent database for which the casing includes a higher-emissions magnesium alloy. Integrated circuits have high impacts despite their very small mass; silicon dies alone are responsible for about 20% of product embodied emissions on average.

The results suggest a strong link between product mass and embodied emissions, with heavier or larger products having higher emissions; the following section explores this relationship in more detail. The older devices modeled in ecoinvent (desktop, laptop, monitor) have significantly higher emissions than modern devices with similar functionality. Since the modeling framework and data sources are identical in our study and in the ecoinvent study (including some adjustments we discuss in the SI), the difference can be ascribed to changes in the material composition of the products themselves: modern devices have fewer integrated circuits and circuit boards, certainly a consequence of higher levels of on-chip integration enabled by Moore's Law. When modern devices are compared to other modern devices from the same product category, smaller form factors have smaller impacts: the 10" netbook's embodied emissions are about 40% lower than a similar 16" laptop, while the small desktop's emissions are about 50% lower than a comparable minitower from the same product line. The impacts of mobile devices are very small compared to laptops, desktops, and monitors.

3.3. Comparison with Other Studies. Our results for the adjusted ecoinvent studies are very similar to those from the original ecoinvent studies, suggesting that the framework has been accurately reproduced; differences due to our adjustments are explained in the SI. We also compare our results to recent studies of similar equipment published within the last five years and find broadly similar results as well. Our emissions estimate for a rack server, 360 kg CO_2-eq, is comparable to a recent study's estimate of 380 kg CO_2-eq [27], while our result for the Dell Optiplex 780 tower desktop, 161 kg CO_2-eq, is comparable to Dell's estimate of 120−180 kg CO_2-eq for the same product.[29] Dell's study of a 14" laptop estimates emissions to be 160 kg CO_2-eq [30], larger than our estimate of 106 kg for a 16" HP laptop. In this case, differences occur primarily in casing (25 kg CO_2-eq in Dell's study vs 6 kg in ours), mainboard (72 kg vs 52 kg), and battery (9 kg vs 1.3 kg). The latter study is the only example from a manufacturer in which emissions are specified at a component level that allows a detailed comparison. A recent hybrid-LCA study of a 15" laptop manufactured in 2001 found GHG emissions from manufacturing to be between 227 and 270 kg CO_2-eq; of that amount, 93−136 kg CO_2-eq were accounted for via bottom-up process LCA, comparable to our estimate of 106 kg CO_2-eq for a 16" laptop using similar methods, with the remaining 134 kg CO_2-eq due to the top-down economic correction.

There is one study of an e-book reader, and it identifies 40 kg CO_2-eq for a 2007 Sony PRS 505,[31] higher than our estimate of 13 kg CO_2-eq for a 2010 Amazon Kindle. That study also uses the ecoinvent data set, but identifies 31 g of packaged ICs compared to 2 g in our study, implying that the difference is due to physical variation between products. Two studies of mobile phones report 20 kg CO_2-eq[32] and 30 kg CO_2-eq [33], higher than our estimate of 7 kg CO_2-eq for an iPod Touch. The mobile phone in the latter study had a mass of 250 g, which may or may not include an external charger, whereas the iPod Touch has a mass of 109 g, while its charger's mass is an additional 89 g. Given the tendency for the newer products in our study to use fewer integrated circuits compared to older products in the ecoinvent database, we speculate that the older mobile phones in those two studies likely contained more ICs, which could account for some of the difference between these results.

Apple's data set of 22 products[8] shows results that are considerably higher than our estimates for similar products. Our estimates of the manufacturing emissions of a laptop, netbook, iPad, and iPod touch are 106, 62, 22, and 6.7 kg CO_2-eq, respectively; comparable products in the Apple study, a 15" Macbook Pro, 11" Macbook Air, iPad 2, and iPod touch, are estimated to have embodied emissions of 290, 162, 25, and 15 kg CO_2-eq, respectively. The author of Apple's reports indicates that a different impact database, that is, not ecoinvent, was used by Apple, and notes that the casing materials were modeled in more detail and were not classified simply as aluminum or steel, but as rather more complex materials, though the methodologies are otherwise comparable (personal communication, 2011). A lack of transparency and access to the details of Apple's study prevents us from definitively identifying the source of the variation.

Overall, when compared against other studies, our results are roughly comparable for large products and lower for smaller mobile products. In some cases, the variation may be a consequence of the more recent vintage of products we analyzed relative to other studies, since newer products tend to have fewer integrated circuits. Additional variation may be caused by different underlying models for some parts (such as casing and battery) and/or different modeling assumptions. We stress that our study is replicating the modeling assumptions of the ecoinvent database. Agreement between our results and those of other studies is not a guarantee of accuracy, which is a function of the underlying source data and methods. Such agreement does, however, suggest that our methods and data are in-line with standard practices. To the extent that these practices are valid, the relative differences in our estimates of embodied emissions for different products arise due to differences in the products being analyzed, as intended.

3.4. Data Quality and Uncertainty. The ecoinvent database uses a semiquantitative uncertainty model based on 'pedigree' matrices in which each inventory item is assigned a probability distribution based entirely on the quality of the data as estimated by experts.[6] These scores are intended to account for mismatches between the ecoinvent technological processes and the physical real-world processes they model. We apply this method here in order to enable comparisons with other studies that use the ecoinvent database and uncertainty method, using Monte Carlo analysis with 100 trials per product. Details about the probability distributions used are discussed in the SI; results are shown in Figure 2. The distributions have standard deviations

ranging from 10% (several products) to 18% (LCD monitor) of their respective means.

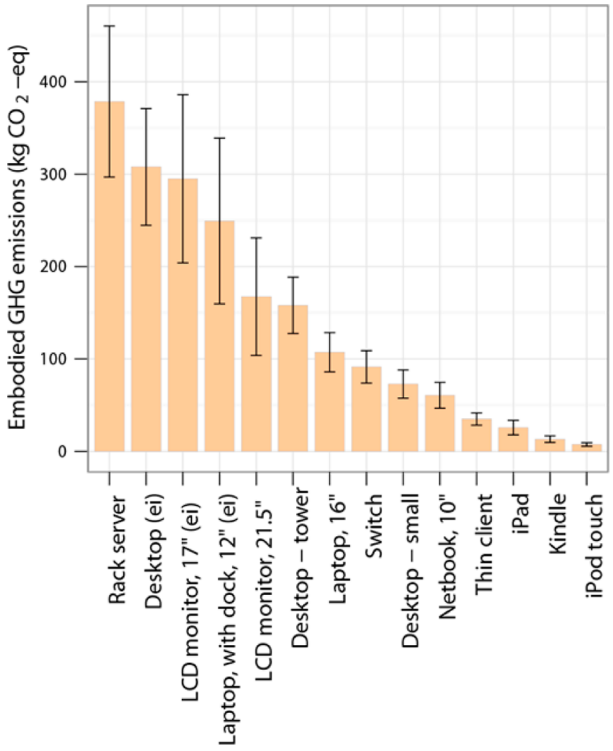

Figure 2. Monte Carlo results: mean embodied GHG emissions with error bars showing ± two standard deviations, using data quality pedigree matrix approach.

This uncertainty model has some advantages in that it is quantitative, consistent, and tractable, but it relies on expert judgment and is prone to errors related to that approach.[34] In particular, the pedigree approach produces artificial probability distributions that have no empirical basis and represent only expert judgments of data quality. Structural uncertainties due to cutoff errors are not included; neither are uncertainties in emissions characterization factors. The actual bounds on the results will be larger than those shown in Figure 2 and are not precisely quantifiable using this method.

4. ANALYSIS

The data in Figure 1 suggest the presence of a linear relationship between embodied emissions and product mass. This trend also appears in Apple's data set[8] (n = 22). These data sets could be used to estimate embodied emissions for ICT products based on easily measurable physical characteristics such as total mass and volume. Differences in the underlying modeling frameworks mean that our data set and Apple's cannot be combined in such an analysis. However, it is possible to develop a linear model that adequately describes both data sets, tuning the coefficients independently to produce one set of coefficients for each data set.

Apple provides a breakdown of the material composition of its products by mass. By arranging the data from our disassembly work into the same categories as Apple, six possible predictors of embodied GHG emissions are yielded: circuit board mass, display mass, battery mass, casing mass, power supply mass, and other mass. We also include two predictors that describe overall product characteristics: product mass and product volume. Using combinations of these eight predictors, we examined dozens of linear regression models, each of which was independently fit to both data sets to produce a set of coefficients that could be used to predict a product's emissions. We use leave-one-out cross-validation as a model selection criterion and compare the cross-validated residual sum of squares (cvss), which is intended to quantify how well the model can predict output values for data points not in the training set. Each candidate model is assigned two scores, $cvss_1$ and $cvss_2$, which are equal to the cvss for our data set and for Apple's data set, respectively. A combined score for both models is generated by summing $cvss_1^2+cvss_2^2$; the sum of squares is used to penalize models that fit one data set well and the other poorly, since our goal is to find a model that fits both data sets well. The linear model that has mass as its only predictor is used as a benchmark against which other scores are normalized.

Three of these models are shown below in detail; more model results are in the SI. The first, "mass only", which is the benchmark model, treats emissions as a linear function of product mass. The second model, "pcb+disp+batt", uses three internal predictors (i.e., emissions = $\alpha_1 \times \text{mass}_{\text{circuit board}} + \alpha_2 \times \text{mass}_{\text{display}} + \alpha_2 \times \text{mass}_{\text{battery}}$). The third, "all internal", uses all six internal predictors (circuit board, display, battery, casing, power supply, and other). All models are constrained to pass through the origin; adding an intercept does not improve the fit. For each model, the fitted results for both data sets are shown in Figure 3

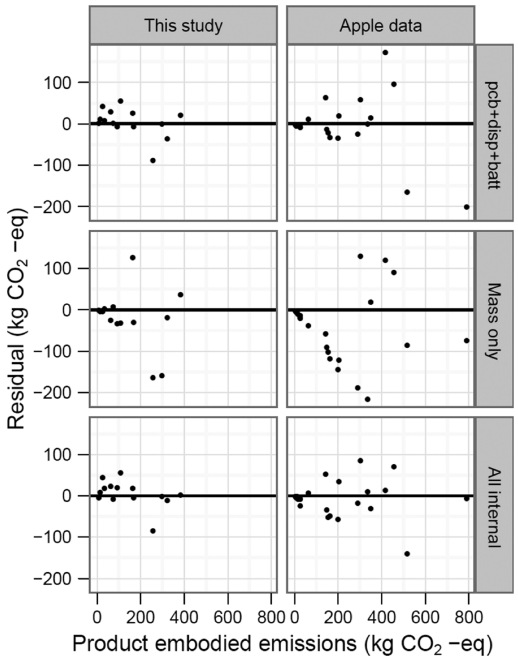

Figure 3. Residuals from model selection.

and the coefficients and diagnostics in Table 2. In the figure, the x-axis represents the actual estimate for embodied emissions for each product in the data set, while the y-axis shows the residual; a perfect model would have each point along the y = 0 line.

The mass-only model has the best cross-validated score of the dozens of models we compared, whereas the pcb+disp+batt model is only slightly worse. Figure 3 shows that the mass-only model systematically underestimates emissions for light products, especially in the Apple data set; that occurs because the masses of heavier products are dominated by casing, which has a much lower emissions-per-unit-mass than electronic components. A linear-mass model is not sufficiently sophisticated to account for the different composition of light and heavy

Table 2. Coefficients from Model Fitting, Measured in kg CO_2-eq per g

model	pcb+disp+batt		mass only		all internal	
study	this study	apple data	this study	apple data	this study	apple data
mass (*p*-val)			0.027 (<0.01)	0.039 (<0.01)		
pcb (*p*-val)	0.18 (<0.01)	0.37 (<0.01)			0.24 (<0.01)	0.48 (<0.01)
casing (*p*-val)					0.012 (0.49)	−0.1 (0.23)
batt (*p*-val)	0.30 (<0.01)	0.36 (<0.01)			0.36 (0.02)	0.41 (<0.01)
disp (*p*-val)	0.065 (<0.01)	0.052 (<0.01)			0.062 (<0.01)	0.066 (<0.01)
psu (*p*-val)					−0.079 (0.97)	0.53 (0.02)
other (*p*-val)					−0.012 (0.41)	0.1 (<0.01)
CVSS	0.42	1.4	1.0	1.0	0.45	2.8
combined CVSS	2.1	2.1	2.0	2.0	7.9	7.9
R^2	0.97	0.94	0.85	0.89	0.97	0.97
adj. R^2	0.96	0.93	0.84	0.88	0.95	0.96

products. The pcb+disp+batt model appears to be unbiased, and has a comparable cross-validation score, meaning it is a better fit overall, though it requires more data inputs than the mass-only model. The "all-internal" model illustrates the effect of including additional predictors: the residuals are smaller, but the model is overly tuned to the data set and does not accurately predict emissions, as shown by its poor cross-validation score. Some coefficients for this model are negative, indicating nonphysical results and double-counting from correlated predictors.

The two best models—mass only, and pcb+disp+batt—both produce good results and coefficients that are physically reasonable and fairly consistent numerically across the two data sets. Ideally, the analysis could be repeated with a wider data set, perhaps including multiple specimens from each product category, and should incorporate newer process data when available. Nevertheless, the strength of the linear relationships uncovered in both our data set and Apple's data set is encouraging, and suggests that linear models based on a limited number of product characteristics could reasonably approximate the results of using full process-sum LCA to estimate manufacturing emissions.

5. DISCUSSION

This work compares modern ICT products to those originally modeled almost a decade ago in the ecoinvent database. In all three cases, the newer products' embodied GHG emissions are an estimated 50−60% lower than those of the corresponding older products. This decrease is mainly caused by a reduction in total mass and a proportional decrease in integrated circuits and circuit boards, the result of systems becoming more highly integrated and thus using fewer ICs. These products were chosen to be roughly representative of typical products within their respective categories, so we can reasonably infer that over time ICT products are getting lighter, becoming more integrated, and having a reduced impact. However, efficiency trends in IT products are counteracted by increased growth in the installed base of existing products and the emergence of new complementary products; the overall impact of the IT industry, or of a consumer's personal collection of IT products, depends on the relative strength of these competing trends, which we have not analyzed here.

Embodied impacts identified in our study are linear with respect to mass, with a coefficient of 27 kg CO_2-eq per kg of product for our work and 39 kg CO_2-eq per kg of product for Apple's data set, but this model tends to underestimate impacts of lighter products. If the masses of printed circuit board (including ICs), battery, and display can be obtained, then emissions can be calculated as $0.18 \times \text{mass}_{\text{pcb}} + 0.30 \times \text{mass}_{\text{battery}} + 0.065 \times \text{mass}_{\text{display}}$ (our study), and as $0.37 \times \text{mass}_{\text{pcb}} + 0.36 \times \text{mass}_{\text{battery}} + 0.052 \times \text{mass}_{\text{display}}$ (Apple's data set), with masses in grams and coefficients in kg CO_2-eq per g. These results do not account for truncation error and exclude the use phase and end-of-life phase; they therefore should not be taken as product carbon footprint benchmarks. More sophisticated linear models can be constructed, but the benefits of doing so appear small.

The relatively good fit of these models suggests that linear regressions based on product characteristics may be a promising avenue of exploration for first-order life cycle assessments. Further investigation could determine the stability of these findings over a wider range of product categories, as well as over variation within a product category; for example, by assessing several monitors with different screen sizes, as in the PAIA project,[35] or by examining the effects of using alternative materials (e.g., for casing) that may have considerably higher impacts per unit mass than the materials used here. In addition, the effect of imposing a top-down economic correction on the results could be explored. Finally, the necessity to retune the model depending on the underlying framework and data is problematic; enforcing compliance with the aforementioned ETSI standard[21] (or others) could enable standardized models for simplified LCA, which would help achieve the broad goal of a more practical and useful methodology to support decisions.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information includes summary data tables for all graphs in the text; a summary of results from this study and Apple's study; a description of the adjustments made to the ecoinvent studies; justification for the probability distributions applied in the uncertainty calculation; experimental results that measure the integrated circuit content of the products; a discussion of our correction for stacked ICs; model selection results for the best 15 models from the linear regression analysis; full bills of materials for each product analyzed; and a description of how these bills of materials were mapped to ecoinvent processes, including a full listing of modeling assumptions. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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