Applied Energy 136 (2014) 636–648

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Carbon footprinting of electronic products

Arvind Vasan *, Bhanu Sood, Michael Pecht

Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, College Park, MD 20742, USA

HIGHLIGHTS

- Challenges in adopting existing CF standards for electronic products are discussed.
- Carbon footprint of electronic products is underestimated using existing standards.
- Multipronged approach is presented to overcome the identified challenges.
- Multipronged approach demonstrated on commercial and military grade DC–DC converter system.

ARTICLE INFO

Article history:
Received 2 May 2014
Received in revised form 11 September 2014
Accepted 22 September 2014
Available online 10 October 2014

Keywords:
Carbon footprinting of electronic products
DC–DC converter
Product-group standardization
Supply chain integration
Hybrid life cycle assessment

ABSTRACT

In order to mitigate the effects of global warming, companies are being compelled by governments, investors, and customers to control their greenhouse gas (GHG) emissions. Similar to the European Union's legislation on the airline industry, legislation is expected to require the electronics industry to assess their product's carbon footprint before sale or use, as the electronics industry's contribution to global GHG emissions is comparable to the airline industry's contribution. Thus, it is necessary for members of the electronics industry to assess their current GHG emission rates and identify methods to reduce environmental impacts. Organizations use Carbon Footprint (CF) analysis methods to identify and quantify the GHG emissions associated with the life cycle stages of their product or services. This paper discusses the prevailing methods used by organizations to estimate the CF of their electronics products and identifies the challenges faced by the electronics industry when adopting these methods in an environment of decreasing product development cycles with complex and diffuse supply chains. We find that, as a result of the inconsistencies arising from the system boundary selection methods and databases, the use of outdated LCA approaches, and the lack of supplier's emissions-related data, the CFs of electronic products are typically underestimated. To address these challenges, we present a comprehensive approach to the carbon footprinting of electronic products that involves the use of product-group-oriented standards, hybrid life cycle assessment techniques, and the integration of CF into products' supply chains. A case study on commercial- and military-grade DC–DC buck converters demonstrating the recommended approach is presented.

1. Introduction

Changes in climatic conditions have increased the concern about global warming among government organizations [1]. This concern has intensified due to the rapid growth in greenhouse gas (GHG) emissions since 2000 [2,3]. As a result, governments, investors, and customers are requiring companies to control their GHG emissions. For example, the US Environmental Protection Agency (EPA) issued the Mandatory Reporting of Greenhouse Gases Rule (74 FR 56260) in 2009, which requires facilities that emit 25,000 metric tons or more per year of GHGs to report their emissions data via annual reports to EPA [4]. The Carbon Disclosure Project's (CDP) Carbon Action program is an investor-driven initiative wherein 254 investors having control of $19 trillion worth of assets have called for the world's highest GHG emitting companies to publicly disclose their GHG data and their respective approaches to reducing their GHG emissions [5]. The United Kingdom has begun the Feed-in-Tariffs (FiTs) program to stimulate the use of renewable sources of energy (via photovoltaic and micro-wind technologies) among businesses in order to reduce dependence on non-renewable means of energy from 98% in 2009 to 85% in 2020 [6].

Electronics manufacturers are already required by the Waste from Electrical and Electronic Equipment (WEEE) Directive [7] to

* Corresponding author. Tel.: +1 301 405 5324.
E-mail addresses: arvind@calce.umd.edu (A. Vasan), bpsood@calce.umd.edu (B. Sood), pecht@calce.umd.edu (M. Pecht).

http://dx.doi.org/10.1016/j.apenergy.2014.09.074
0306-2619/

reduce their disposal waste of electronic products by reuse, recycling, and other forms of recovery. As a supplement to WEEE, the Restriction of the Use of Certain Hazardous Substances (RoHS) legislation further restricts electronic manufacturers from using materials that could negatively impact health (such as lead, cadmium, hexavalent chromium, PBBs, and PBDEs) [8]. In addition to these requirements, the electronics industry will also have to deal with additional directives associated with GHG emissions [4], because electronic components are classified as very high GHG emission-intensive materials (>5 kg CO_2e/kg [9]).

As of 2013, electronic manufacturers have only been subjected to taxes levied on the carbon content of the fuels used to support the activities under the control of an organization [10]. However, regulations on GHG emissions mandated by the European Union (EU) on the airline industry foreshadow GHG emission taxes for the electronics industry [11]. This is because the contribution by the electronic industry to global GHG emissions (2%) is comparable to the airline industry's contribution, which is estimated to be between 2% and 4%. Additionally, under the US EPA's "Mandatory Reporting of Greenhouse Gases" rule [4], many electricity generators and electronics and electrical product manufacturers are required to report direct GHG emissions from their facilities. The purpose of the rule is to collect accurate and timely GHG data to inform future policy decisions.

Furthermore, with the growth of electric vehicles (EVs) estimated to be 6% and 39% for hybrid EVs and plug-in EVs, respectively, between 2012 and 2020 [12], new legislation is expected for emissions resulting from processes related to the manufacturing of EVs [13,14]. Talks concerning carbon taxes on mining activities have also started in various countries, including Australia, India, and South Africa [15], indicating that electronic manufacturers may have to pay taxes for the processes involved in the extraction of raw materials. Thus, it is becoming time for members of the electronics industry to identify drivers of GHG emissions in their product or process life cycles and take measures to reduce emissions.

Carbon footprinting is the method used to quantify GHG emissions and identify emission drivers in a product or process life cycle [16,17]. This paper shows the need for CF in the electronics industry by discussing the effects of existing and possible future government legislation. We then review different methods used to calculate the CF of a product. Next, we identify the challenges that the electronics industry faces in adopting existing CF practices. Finally, we provide a comprehensive approach to address the challenges with existing CF methods in order to enable electronics manufacturers to adopt a more reliable carbon footprinting method.

2. The need for carbon footprinting in the electronics industry

The carbon footprinting method is used to quantify the life cycle GHG emissions caused directly or indirectly by a person, product, event, or organization. Peters [18] states that the "Carbon Footprint (CF) of a functional unit is the climate impact under a specified metric that considers all relevant emission sources, sinks, and storage in both consumption and production within the specified spatial and temporal boundary." The CF of a product is typically expressed in terms of carbon dioxide (CO_2) equivalent, and is calculated using the global warming potential (GWP) of a GHG. GWP, as defined in the Publicly Available Specifications (PAS) 2050, is the radiative forcing impact of one mass-based unit of a given GHG relative to an equivalent unit of CO_2 over a given time period [9]. For example, the GWP of methane (CH_4), a GHG, is 23 [19].

Life cycle in the context of CF is defined as the consecutive and interlinked stages of a product's development, from raw material extraction, manufacturing, distribution, and use up through final disposal. Typically, there are two boundary scenarios for a life cycle (Fig. 1): cradle-to-grave or cradle-to-gate [20]. In a cradle-to-grave scenario, GHG emissions are captured in all stages of the life cycle, from the extraction of raw materials for manufacturing until product disposal or recycling. In a cradle-to-gate scenario, the GHG emissions are only considered from raw material extraction up to the point at which the finished product leaves the organization. In most cases, organizations choose the cradle-to-gate scenario for CF analysis, as the stages involved are mostly under the control of the organization. However, the cradle-to-gate scenario significantly underestimates the total CF of a product when compared to the cradle-to-grave scenario, as it neglects the GHG emissions resulting from indirect energy (e.g., the electricity or cooling method purchased to support manufacturing facilities) consumed during the use phase of the product.

Fig. 1 shows the cradle-to-gate and cradle-to-grave scenarios for a mobile phone. Similar life cycle stages can be drawn for other electronic products. The components in a mobile phone include the plastic casing, liquid crystal display (LCD), microphone/speaker, printed circuit boards with the associated digital and analog components, antenna, battery, and adapter. In order to manufacture these components, a variety of minerals have to be mined and processed. For example, the PCB contains copper traces, gold wire bonds within the ICs, tin in the solder interconnects, silicon substrates within the IC packages, chromium and nickel in the surface finish, fiberglass, and plastic resins within the PCBs. The LCD might contain substances such as mercury. All the mining and material processing steps contribute to the emission of GHG gasses. Even though the extraction or recycling of raw materials and material processing steps might not fall directly within the control of a cell phone manufacturer (that is, they might fall within the control of a component or assembly supplier), it is generally considered the responsibility of the original equipment manufacturer (OEM) to identify emissions resulting from materials extraction and processing activities, and include them in the CF analysis of their product [21].

Once materials are extracted and processed, the next steps in the life cycle of a mobile phone are the manufacturing of the circuit boards and assembly processes, wherein the electronic components are placed onto the PCB, interconnects are soldered, and the PCB is coated with a protective surface finish. The manufacturing and assembly processes are carried out using machines that consume electricity, the production of which contributes to global warming. Since manufacturing and assembly are within the control of the OEM, it is easier for mobile phone manufacturers to perform a cradle-to-gate CF analysis. However, cell phone parts and their finished products need packaging and transportation to get them to customers. Transportation contributes to GHG emissions through the consumption of nonrenewable sources of energy (e.g., petrol and diesel). Furthermore, the materials used in packaging, such as paper, plastic, and aluminum, all require energy for production and can result in waste. In addition to packaging and transportation, the electricity consumed in charging a cell phone over its useful lifetime is also generated by consuming natural resources and transmitted through electric grids that contribute to global warming. If we consider OEMs such as Samsung and Apple that sell millions of smart phones each year, and calculate the electricity consumed by these millions of devices over their useful lifetimes, the resulting amount of GHG emissions during the product use phase cannot be neglected. Thus, the cradle-to-gate life cycle approach lacks the completeness in GHG emission estimation found in the cradle-to-grave scenario, especially for electronic products where significant GHG emissions continue to take place after the product has left the OEM [22].

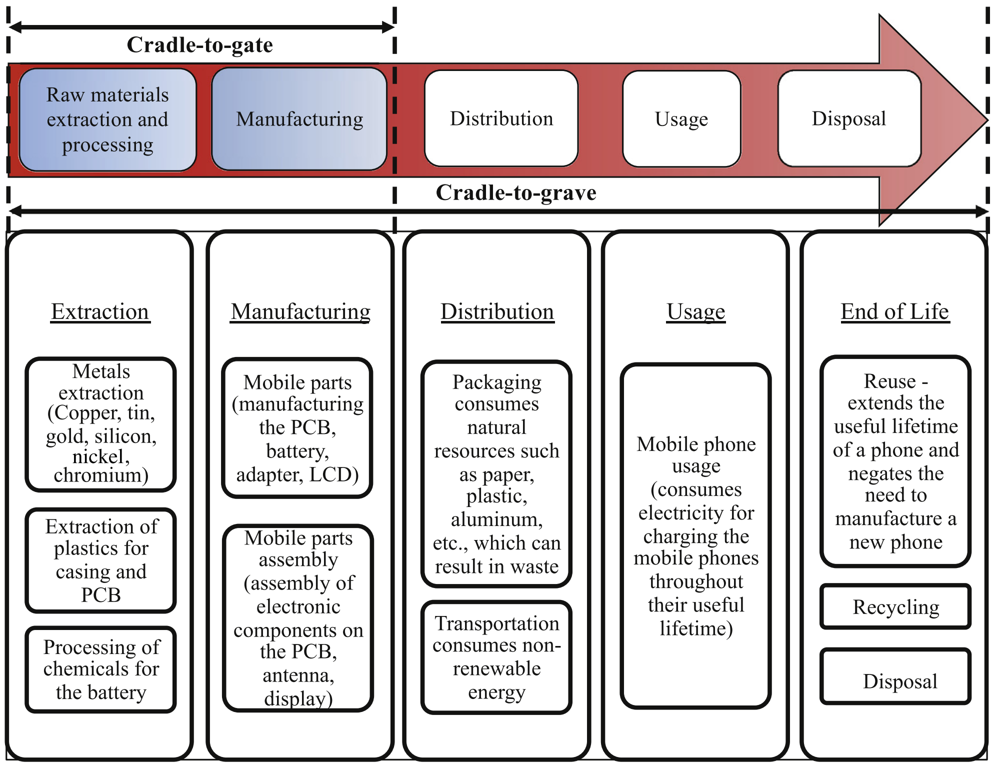

Fig. 1. Cradle-to-gate and cradle-to-grave life cycle stages of a mobile phone.

2.1. Legislation related to electronics products

While there is no current legislation regulating the GHG emissions for companies in the electronics industry, legislation regulating other industries will probably influence the regulations on the electronics industry. The EU has enacted legislation in 2008 that places a cap on the airline industry's allowable GHG emissions, as it is responsible for 2–4% of global GHG emissions [23,24]. EU temporarily suspended the legislation in April 2013, for flights operated from or to non-European countries, while continuing to apply the legislation to flights within and between countries in Europe to allow time for the International Civil Aviation Organization (ICAO) Assembly to reach a global agreement to tackle aviation emissions. In October 2013, ICAO Assembly agreed to develop by 2016, a global market-based mechanism addressing international aviation emissions and apply it by 2020. In April 2014, the Council of the EU and European Parliament decided to limit the aviation coverage of the legislation to emissions from any flights within the European economic area for the period from 2013 to 16.

It is predicted that airline regulations could reduce the global GHG emissions by 0.3 billion kg CO_2e/year [25]. The airline industry is meeting the additional cost (GHG emission taxes) by increasing its passenger airfares [26]. However, in the long run, it is expected that the airline industry will pressure the members of its supply chain to reduce their GHG emissions [27]. Since the electronics industry is one of the major suppliers to the airline industry, it will experience the effects of the airline GHG legislation. In fact, due to global competition, first-level suppliers will try to reduce their GHG emissions. As a result, the first-level suppliers may prefer to purchase their products from suppliers with low GHG emissions. This will extend to the end-level of upstream suppliers. An example of an end-level supplier is a company that performs mining to extract raw materials from the environment.

In 2011, the Australian government approved the Clean Energy Future Plan, which imposes carbon taxes (Australian $24.15 per each metric ton of CO_2e) on companies for their GHG emissions [28]. According to this plan, organizations are required to purchase permits from the Australian government up to the number of their emissions for the compliance year. Organizations with emissions above 25,000 tons CO_2e have to surrender their permits. One-fifth of the companies that were affected due to this plan belonged to the mining industry [15]. As in Australia, South Africa is also planning to impose carbon taxes that will directly affect the mining industry. This trend is expected to be adopted in countries that are motivated to drastically reduce their GHG emissions, suggesting that electronic manufacturers may have to pay taxes for the processes involved in the extraction of raw materials.

2.2. Future legislation related to the electronics industry

The electronics industry is estimated to contribute 2% of global GHG emissions [29–31], which is comparable to the GHG emissions of the airline industry. This suggests that there could be new legislation that will cap the allowable emissions for the electronics industry. In 2007, a survey conducted by McKinsey and Company [32] found that 82% of company executives are expecting regulations to be implemented in their respective countries for organizations contributing to global warming.

In a 2008 study titled "Policy options for reducing CO_2 emissions," the US Congressional Budget Office (CBO) stated [33] that the most efficient approach to reduce GHG emissions is to give organizations incentives (in the form of taxes) to curb activities that produce GHGs. In relation to this study, the US CBO conducted another study in 2008 [34] to estimate the cost required to implement legislation requiring the US EPA to conduct a study that identifies the major sources of carbon emissions in the United States, their contributions to global warming, and the most effective technologies for removing or reducing such emissions. Following this study, the 110th Congress passed an act [35] allowing the EPA to collect GHG emissions-related data from facilities in all sectors of the economy. Finally, in 2009, the US EPA issued the "Mandatory

Reporting of Greenhouse Gases" rule, according to which, facilities within the US that emit 25,000 metric tons or more of GHGs are required to disclose their facilities emission data through annual reports to the EPA [4]. Under this rule, electricity generators and electronics and electrical product manufacturing facilities are required to report annually the direct GHG emissions by their facilities to the EPA. The purpose of the rule is to collect accurate and timely GHG data and inform future policy decisions. Since 2010, EPA has been collecting direct emissions–related data from more than 7000 facilities across the US. Simultaneously, the US CBO has been conducting studies (as of 2013) on the "effects of carbon tax on the economy and the environment" [36]. The actions of the US CBO and EPA indicate that soon there might be legislation, regulating companies within the US for their GHG emissions. The electronics industry, which is known to be one of the leading emitters of GHGs, will be no exception.

Many countries have begun to implement legislation to limit activities that impact the environment [37]. For example, Mexico passed a law in 2012 that aims to reduce their GHG emissions by 30% by 2020. South Korea has passed a bill with a motive to set up an emission trading system by 2015. China, the world's largest GHG emitter, has also passed local legislation to manage GHG emissions from the industrial area of Shenzhen.

The EU is discussing the setting of an emission performance standard (called the 2020 Standard) to reduce GHG emissions from new passenger cars. The 2020 Standard proposes using 95 gm CO_2e/km as the maximum allowable emissions from a car [38]. Implementing a standard for allowable emissions from cars would allow the EU to reduce transportation GHG emissions to 60% of the 2013 GHG emissions level by 2050 [39]. Furthermore, a report by Cambridge Econometrics and Ricardo-AEA suggests that meeting the proposed 2020 standard will make the European vehicle fleet cheaper by €35 billion each year through fuel savings. In addition to EU car manufacturers, US car manufacturers are also facing a call from President Obama to reduce the GHG emissions of each car to 93 gm CO_2e/km by 2025 [38]. As in avionics, electronics companies that are in the upstream supply chain for the automobile industry could face pressure similar to that of the airline industry. Therefore, companies in the electronics supply chain that does not take steps to reduce their GHG emissions will lose their ability to compete.

In 2010, US investors filed 95 shareholder resolutions related to global warming with 82 US and Canadian companies, including coal companies, electric power and oil producers, homebuilders, and financial institutions, based on the belief that these countries were not disclosing and managing potential climate-related business impacts [40]. Some of these resolutions demanded that the companies report on regulatory, legal, and environmental risks, while the others sought to determine the companies' plans for adopting GHG reduction goals in anticipation of legislation relating to GHG emissions. These resolutions demonstrate that there is stakeholder interest in climate change-related policies. The resolutions also foreshadow the involvement of the government in implementing legislation to regulate the GHG emissions of the electronics industry.

2.3. Resource and cost savings through carbon footprinting

CF analysis allows organizations to identify the operations that have the greatest environmental impact. It gives organizations the ability to identify wasteful processes that can be optimized in order to save resources and lower costs, either by lowering their resource consumption or by selling their waste materials to other companies. A Consumer Electronics Association (CEA) survey demonstrated that CF analysis can lower costs and increase sustainability. The survey found that companies that performed CF analysis were able to reduce their electricity consumption by 5–25% per million dollars of revenue. For example, the reduction in electricity consumption by two of the participating companies was equivalent to 223,000 tons of CO_2 [41].

CF analysis gives a company insight into how a product's life cycle can be changed to increase sustainability. For example, Lenovo identified the value of reusing materials from their older products (when customers are done using them) after performing CF on their display monitors. Thus, Lenovo decided to acquire, recycle, and incorporate materials from end-of-life products into its new designs [41]; 25% of the materials in Lenovo's Gold monitors are recovered from end-of-life products. These materials include recycled plastic and metals such as gold and silver. MicroPro unveiled the world's first green and EU eco-labeled computer "IAMECO," which has a 70% smaller CF than a normal desktop, is 98% recyclable, and contains no lead, mercury, plastics, PVC, or flame retardants [42]. According to MicroPro, this was made possible through the use of CF analysis, which helped MicroPro assess and identify opportunities to reduce their environmental impact, compare their design and manufacturing processes with competing manufacturers, and review customer requirements [43]. Performing CF analysis preemptively will provide companies with opportunities to identify drivers of GHG emissions and take action before legislation is implemented [44].

Companies can also use CF as a marketing strategy. Apple's marketing campaign claims that their latest generation of devices has a significantly reduced life cycle CF compared to previous generations [45]. For example, Apple claims that the GHG emissions from the manufacturing of Mac mini 2012 have been reduced by 49% and that of MacBook Pro 2012 have gone down by 6% (both products compared to their 2007 model). Apple also claims that since 2008, the average power consumed by Apple products has been reduced by 40%. Similarly, Mitsubishi has touted the reduced CF of their home heating systems. Since there is increased awareness of CF among consumers, these marketing steps by manufacturers could give them an edge.

3. Carbon footprinting approaches

Life cycle assessment (LCA) approaches have been employed to estimate parameters, such as air pollutants or energy consumption that result from human actions. In the context of CF, LCA is used to estimate the GHGs emitted at each identified step in the product's life cycle [18,46]. Although the term carbon footprinting emerged in the public domain during the early 2000s, LCA strategies have been used for decades to assess ecological footprint (which expresses the impact of a product or process on the environment as a measure of the bio-productive land required to sustain its use of natural resources). There are two conventional LCA techniques: process-based LCA (PA) and input–output based LCA (IOA) [47]. The PA method is typically performed at the product or process level and uses a bottom–up approach to address the environmental impact of a product or process over its entire life cycle. The IOA method uses a top–down approach for evaluating the environmental interventions of a product based on an economic IO analysis [48]. Both of these methods have been used to assess the CF of a product or process. However, researchers have found limitations with each that hinder them from generating an accurate estimate of total GHG emissions.

The PA method is limited in terms of system boundary selection, as it is not feasible in practice to analyze every activity associated with the manufacturing of a product [47]. Therefore, activities to include in CF analysis are predetermined using a product's process flow (which refers to the simplified analysis of each process stage associated with the production, distribution, and disposal of a product or service). This "system cut-off" results in truncation errors, some of which have been reported to be as high as 50% [49]. This arbitrary boundary selection method can limit the robustness, transparency, and comparability of GHG emission estimates. In contrast, the IOA method is less time-consuming and is easy to implement using the requirement matrix published by the US Department of Commerce (which quantitatively summarizes the input–output relation between different commodity sectors of the economy) [50]. However, the IOA method is limited because it employs high-level aggregation of a product, which approximates a product's IO model by its corresponding commodity sector [51]. For example, in estimating the GHG emissions generated by the plastic encapsulants used in electronic packages, the IOA approach approximates the encapsulants by the industry sector "Plastic Materials and Resins." Typically, there are many materials and processes involved in the manufacturing of a product. Therefore, making such approximations could result in erroneous GHG emission estimates. Furthermore, IOA models are useful only for modeling GHG emissions during the cradle-to-gate stages of the life cycle. These limitations show that the CF estimates generated by IOA approaches are not accurate. Detailed reviews of the goal, scope, and framework of LCA can be found in Rebitzer et al. [52] and Pennington et al. [53]. A detailed review of the developments in LCA strategies can be found in Finnveden et al. [54].

Most of the existing standards for CF analysis prescribe an LCA-based approach. These standards are classified based on the level at which they are applied (i.e., product or organization level). Product-level standards include ISO 14040 [55], ISO 14044 [56], and PAS 2050 [9] by the British Standards Institute (BSI). The ISO 14040 and 14044 standards are not specific to GHG emissions, but they provide the principles, framework, and requirement guidelines for the LCA of a product. PAS 2050, on the other hand, specifies the requirements for the LCA of GHG emissions for goods and services. As of 2013–2014, ISO is developing a standard, ISO 14067, specifically for CF analysis [57]. Another standard, "Product life cycle accounting and reporting" [58], came from the GHG protocol initiative created by the World Resources Institute and World Business Council for Sustainable Development.

Organizational-level standards include ISO 14064 [59] and the GHG protocol's corporate accounting and reporting standards [60]. The ISO 14064 standard provides guidance for determining the process boundaries and quantifying GHG emissions and removal, while the GHG protocol's standard for corporate accounting and reporting specifically deals with the quantification of Scope 3 emissions (Scope 3 includes upstream emissions, which are indirect emissions resulting from the activities of the supplier, and downstream emissions, which are GHG emissions associated with the use and disposal phases of a product) using the IOA approach. While the GHG protocol's product standard can help an organization to identify GHG hotspots at the product level, the GHG protocol's corporate standard assists an organization in identifying GHG reduction opportunities and engaging suppliers at the corporate level. The GHG protocol's product standards require that all companies report the sources of uncertainty in the inventory results. However, this is only a recommendation in the GHG protocol's corporate standards.

The above mentioned standards follow a common framework for tracking the GHG emissions resulting from processes carried out by an organization or from the processes involved in the life cycle of a product [9,58,61]. In the framework's first step, the GHGs of concern for a particular product or process are selected. A number of gases contribute to global warming, and it is not possible to keep track of all of these gases. Therefore, the gases to be considered in a CF analysis are selected depending on the guideline followed and the type of activity. For example, in a thermal plant, CO_2 is the dominant gas, and the amount of other GHGs present is negligible. So, CO_2 emission measurements are sufficient for CF analysis. However, in cattle farms, CO_2, CH_4, and N_2O emissions are all significant.

Once the GHGs are selected, the activities that should be considered for CF analysis are identified. This step is known as the boundary setting or identification step. In CF analysis, two types of boundaries are set: organizational and operational. Organizational boundaries represent the organization based on legal, financial, or business control, while operational boundaries are the types (or sources) of emissions that will be accounted for while carrying out a CF analysis. These sources include either direct emissions from the operation of facilities that are within the organizational boundary or indirect emissions from facilities that fall within the organizational boundary (e.g., electricity consumption by a manufacturing facility). In addition, there are other emissions from the organization and its activities located outside the physical boundaries, such as those resulting from interactions with suppliers, raw material extractions by the supplier, and the purchase of food, air transportation, and hotel accommodation from employees traveling to customer locations.

After setting the boundaries, GHG emission data are collected through on-site measurements or estimations using emission factors and models. The choice of data collection method depends on the cost, feasibility, and credibility of the method. The estimation method is preferred because it utilizes data on the consumption of fuels, energy, and other inputs leading to emissions. Emission factors are available for a wide range of industrial processes in the PAS 2050 standard, the GHG protocol standard, and the Intergovernmental Panel on Climate Change (IPCC) guidelines.

The final step in CF analysis is the quantification step. During the quantification process, a historical base year is first identified for comparison. Next, a methodology to quantify GHG emissions is selected. A common practice is the use of emission factors with activity data. Emission factors quantify the emissions from individual processes and account for the contributions from different GHGs. They are calculated using the following equation:

$$\text{emission factor} = \sum \mathrm{GWP}_x \times g_x \tag{1}$$

where GWP_x is the GWP and g_x is the amount of GHGs produced by process x. GHG emissions are calculated for each process using the organization's activity data and relevant emission factors. Once the quantification method is selected and relevant data are aggregated, the CF of the product or organization is calculated using an appropriate LCA method.

3.1. Application of CF to electronic products

Fujitsu carried out CF analysis using ISO Standards 14040 and 14044 on their desktop PC (ESPRIMO E9900) and servers (PRIMERGY TX300/RX300 S5) [62,63]. The objective of their study was to determine the environmental impacts of these two products and achieve transparency along their supply chain in order to show customers their product's superiority through reduced environmental impacts. The CF analysis included LCAs for the mouse, keyboard, manuals, and packaging. A cradle-to-grave LCA (which included raw material extraction, assembly, distribution, use, and disposal) was performed. During the raw materials, assembly, and distribution phases, the organizational boundaries were defined according to the organization's ability to control operations (i.e., only emissions resulting from processes under the control of the organization were considered). However, during the use and disposal phases, certain assumptions were made. It was assumed that the desktop PCs and servers were used for 5 years with an average annual energy consumption of 114 kW h/year (corresponding to 30% load). For the disposal or recycling phase, it was assumed that the recovery rate was >90%, and all recovered products were recycled after their anticipated lifetime of 5 years. Furthermore, it was assumed that no recovered components were resold.

For this case study, activity data were available from within the organization for processes directly under the control of the organization. However, Fujitsu revealed that certain assumptions were made while considering activities from upstream suppliers. In addition to activity data, the emission factor data were determined by using life cycle assessment databases and considering all the relevant GHG emissions of the selected operations. By applying Eq. (1) to the processes within the system boundaries of the two products and summing the results, the impacts of the two products during their life cycles were quantified.

Fujitsu was expecting the use phase to dominate GHG emissions. This was true for servers, where the product use phase accounted for 85% of GHG emissions. However, this was not the case for desktop PCs, where the contribution of raw material extraction processes to GHG emissions was comparable to the emissions resulting from the use phase (the use and raw material extraction phases contributed 50% and 35% to GHG emissions, respectively).

A number of studies have assessed the GHG emissions for semiconductor electronics. Higgs et al. [64] studied the GHG emissions resulting from Intel semiconductor chips and concluded that the largest GHG emission contribution for Intel computer chips came from the use phase. Furthermore, while considering only the cradle-to-gate life cycle stages, the largest GHG emission contribution was the manufacturing of the chip, largely due to the consumption of electricity and water during the manufacturing of the silicon substrate (accounting for 80% of CO_2 emissions in the manufacturing phase).

Joyce et al. [31] found a linear dependence between the number of pins in an IC and the estimated equivalent CO_2 emitted (during the manufacturing, assembly, distribution, use, and disposal phases). A similar relationship was found to exist between the carbon content per unit area of a PCB and its number of layers. These findings complement the experiments of Andrae and Andersen [65], which found that the equivalent CO_2 emissions (CO_2e) from a 64-pin wafer chip scale package (WCSP) were less than the CO_2e from an 84-pin low-profile fine-pitch ball grid array (LFBGA) package. However, once mounted to a board, the emissions could increase, as the CSP miniaturization is paralleled with more PCB layers.

Members of the electronics industry use different CF quantification methods. Some companies use models to calculate their CF based on the type of product they manufacture. For example, Alcatel-Lucent uses a model that estimates their product's CF based on the parts that make up the device [31]. Other companies measure their emissions from the processes involved in manufacturing (e.g., Intel uses sensors to measure emissions from the fabrication of semiconductor devices [64]).

The direct environmental impact of a company's CF has been estimated based on the industry sector. For some industries, such as the electronics packaging industry, the development of processes that reduce material or energy consumption can affect CF [66]. Altering the raw materials used in the manufacturing processes can help companies become less reliant on diminishing global resources [67]. Using local suppliers can reduce a company's CF by reducing the emissions incurred by transportation [68]. Alcatel-Lucent uses a CF model in the design phase to determine which designs for future products should be pursued [31]. General Electric (GE) has days where employees are taken to a plant during its "sleep" state and are encouraged to examine the facility and provide recommendations for improvements [69]. Mitsubishi electric has been working on recovering the maximum amount of material from their air conditioning system for reuse. Additionally, Mitsubishi uses safe disposal of refrigerants from their obsolete air conditioning systems as a marketing strategy [70]. Some companies are looking beyond their direct environmental impact and have begun to examine how their upstream processes contribute to their CF. For example, after breaking down the contributors to CF, Fujitsu found that 40% of their product's CF was accounted for by the extraction of raw materials [71]. Mitsubishi determined that the end-of-life phase for electronics equipment is a key factor in the equipment's life cycle GHG emissions, and that recycling efforts could not only lower the CF, but also offer savings on raw materials [70]. Sony found that even changing their product packaging method could measurably decrease their CF [72].

Companies have found benefits in controlling the downstream impact of their products through CF. GE has attempted to reduce its downstream impact by emphasizing the cost savings available to customers who use energy-saving products. GE has an online calculator that allows customers to select the type and number of bulbs that they could replace with "energy smart" bulbs, and displays the potential estimated savings [73,74]. Similarly, Jenkins and Newborough [75] developed a simple spreadsheet based tool to estimate the energy savings in changing the specifications for office lighting based on available daylight. Mitsubishi has replaced their home heating systems with energy-efficient systems [76], and Fujitsu has developed eco-friendly servers that consume less energy than older models [77].

Companies have taken different steps to manage their environmental impact. Intel documents its emissions in a manner that is accessible to the public [64]. Toyota focuses on improving its internal practices, such as turning off unused lights during downtime, in order to reduce their CF. IBM stated that larger government involvement is necessary for successful management of industrial environmental impact.

4. Challenges with CF approaches for electronic products

This section presents the challenges with CF practices that affect the estimation of an electronic product's CF. As a result of these challenges, the CF of a product is generally underestimated, and the CF process might fail to identify the emission drivers in the product's life cycle. As the Society of Environmental Toxicology and Chemistry Europe (SETAC) LCA Steering Committee noted, "It is critical not to separate the intended use of CF analysis results from the guidance on how the emission numbers are to be calculated [82]." It is the responsibility of the electronic product manufacturers to identify challenges with GHG emission calculation method and take actions to overcome those challenges in order to make effective decisions based on the CF results.

4.1. Inconsistencies in CF methods and tools

Inconsistencies in the methods and tools adopted by companies make it difficult to compare the CF of a product or component of the same category from different manufacturers. This is a problem for customers who want to consider a product's CF when making a selection among competing manufacturers. Inconsistencies could arise due to differences in the system boundary selection methods, LCA approaches, and life cycle inventory (LCI) databases employed by the software used to compute the product's CF.

Andrae and Andersen [78] compared the results from different CF studies on laptop computers in order to examine the consistency between CF studies. The CF of a laptop from Taiwan computed using the SimaPro software tool was estimated to be 54 $kgCO_2e$. However, the CF from a laptop from Japan having a similar weight and share of PWBs and ICs was estimated to be

260 $kgCO_2e$, as computed with the NIRE-LCA software tool. In addition, the CF of a laptop calculated using data from the EcoInvent database was compared to the CF calculated with a database developed by the Swedish Institute of Production Engineering Research (IVF). According to the CF estimates from the EcoInvent database, the manufacturing phase of that laptop contributed to 93% of the total CO_2e emissions. However, CF results from the IVF database found that manufacturing contributes to only 26% of the total CO_2e emissions, and the leading contribution came from the use phase (>70%). This shows that the choice of LCI database and the system boundary selection affect the estimation of CF.

Additionally, companies using the same production methods but different suppliers will have different CFs. Since standards do not emphasize modeling the GHG emissions downstream (Scope 3), many companies fail to take into account the GHG emissions during the use phase. Furthermore, the LCI databases are several years old and could possibly be outdated. These issues cause CF estimates to vary widely within the industry, creating uncertainty about the validity of CF calculations.

4.2. Outdated practices in standards

Existing CF standards fail to consider the improvements suggested by the research community, leading to outdated practices. Most of the existing standards employ a PA or IOA-based LCA approach for CF analysis. For example, PAS 2050 [9] is primarily based on a PA method with a negligible focus on IOA, even though a methodological review of PAS 2050 concluded that "the method best suited to meet the needs of the various PAS applications is a fully integrated Hybrid LCA approach" and recommended that the "PAS development should be redirected from a PA approach towards a Hybrid LCA approach" [47].

Suh et al. [79] notes that these standards, which employ PA or IOA-based LCA approaches, impose practical difficulties for drawing a clear system boundary for a CF analysis problem. As explained in Section 3, unless a clear system boundary is established, it is not possible to obtain a reliable estimate of a product's CF.

Furthermore, the existing standards do not provide rules for monitoring and managing the GHG emissions from a product over time. The monitoring of GHG emissions over time enables an evaluation of the effectiveness of strategies implemented to reduce GHG emissions. This is important for electronic products, as the "use phase" of an electronic product serves as a significant contributor (often more than 50%) to the total CF of a product.

4.3. Limited availability of emission-related data from a supply chain

Most standards have difficulty handling out-of-house contributors to a product's CF. Estimation errors are also caused by the scopes of the existing standards, which suggest estimating only Scope 1 and Scope 2 emissions (where the Scope 1 emissions refer to direct emissions from sources that are owned or controlled by the organization, while the Scope 2 emissions refer to emissions from directly purchased energy), with little or no focus on Scope 3 emissions. For electronic products, Scope 1 and Scope 2 emissions account for only 25% of the total emissions [80,81]. Thus, the adoption of current standards for electronic products will decrease the accuracy of CF estimates.

Scope 3 emissions, which account for 75% of the total emissions in electronic products, include the indirect GHG emissions caused by processes in the supply chain, logistics (transportation and distribution, employee travel, end-of-life recycling, and disposal), and a product's use phase. While it is possible for electronic product manufacturers to calculate their product's use phase emissions through testing and customer feedback, the unavailability of emission data from the supply chain makes it difficult for manufacturers to estimate the upstream GHG emissions from their products.

5. A comprehensive CF approach for electronic products

To overcome the challenges with current CF practices, a multipronged approach is recommended for electronic product manufacturers. This comprehensive multipronged approach, involving the use of product group-oriented standards, hybrid LCA techniques, and the integration of CF into the supply chain, will lead to a more reliable method for estimating a product's CF and identifying GHG emission drivers in a product development cycle.

5.1. Product group-oriented standardization

A product group-oriented standard adopts a functional unit approach to enable comparisons between competing products that are intended to fulfill the same function (such as cell phones, laptops, desktops, routers, and network switches). A product group-oriented standardization approach will eliminate the risks of omitting important life cycle stages while calculating the CF of an electronic product, thereby ensuring a fair comparison between the GHG emissions from a product manufactured by different manufacturers. In a way, product group-oriented standardization has been proposed earlier by Scharnhorst [83] and Andrae and Andersen [78]. Scharnhorst [83] recognized the need for well-balanced LCIs for complex products (the example provided in [83] involved electronic products in the telecommunication industry) and insisted on the formulation of a clear goal and scope before performing LCA for a product in order to ensure the identification of critical life cycle stages. Scharnhorst did not specifically stress LCA for CF, but rather, general LCA for studying environmental impacts. Similarly, Andrae and Andersen [78] (as mentioned in Section 4.1) identified the inconsistencies resulting from the differences in LCIs and the lack of transparency in the life cycle stages assessed for calculating the CF of consumer electronic products (such as laptops, cell phones, and PCs). They suggested the use of product category rules as one means of avoiding inconsistencies.

Before developing product group-oriented standards, electronic product manufacturers must first define a base functional unit for the product group. This functional unit will serve as a reference product from which further rules and criteria are derived. Next, the CF assessment method should include all the life cycle stages of the functional unit and the GHSs emitted from a product group in order to ensure that no critical life cycle stages or GHG emission sources are omitted. There might be instances where a product (e.g., an iPhone) belonging to a broader product category (mobile phones) from a manufacturer (Apple), would have certain life cycle stages that are not common to the product category (or might not have a life cycle stage in a product category). In such instances, the manufacturer must identify and report the additional or missing life cycle stages and the product's CF assessment results.

In order to ensure the credibility of the approach used to calculate the CF of a product, a critical review must be conducted to verify that the necessary requirements for that product group in terms of the LCI data considered and the LCA approach followed are met. Organizations such as the National Science Foundation (NSF) and US EPA have started to provide CarbonFree [84] and Energy Star [85] certifications, respectively, which could be used by product manufacturers to prove to their customers and stakeholders that a review of their CF practice has been conducted and their products' CF results are verified. Such certifications pave the way for brand differentiation and prove that a manufacturer is socially responsible. For example, LEI Electronics Inc. obtained NSF

CarbonFree certification for their alkaline battery in order to differentiate their battery and provide sustainable solutions for their customers [86].

To enable CF comparison between competing products, it is necessary to ensure consistency in the data considered for carbon footprinting. As suggested by the SETAC steering committee [82] and Andrae and Andersen [78], this is possible only if product category-based criteria and rules are set. These rules and criteria should clearly identify the required level of detail in the data for different life cycle stages of the product group. It is essential to involve the relevant stakeholders while standardizing the rules for product groups. Standardizing the CF practice for a product group according to the needs of the concerned stakeholders will ensure consistency.

5.2. Hybrid LCA for improved CF practices

Existing standards that are based on a PA or IOA approach allow for subjective choices for system boundary selection; however, inconsistencies in an electronic product's CF results are largely due to these subjective choices. One way to alleviate this problem is to incorporate a hybrid LCA approach. A hybrid LCA approach combines elements of the PA and IOA approaches and allows for the integration of sector- and process-level data. In the life cycle of a product, IOA can provide information for processes that are well-represented by input–output categories, while the rest of the processes in the product's life cycle are modeled using a PA.

Suh et al. [79] categorized hybrid approaches into three types of analysis: tiered hybrid analysis, input–output-based hybrid analysis, and integrated hybrid analysis. In a tiered hybrid analysis, a detailed process-based analysis is carried out when environmental impact data are available for processes associated with the development of a product. The rest of the processes in the product development are covered by input–output analysis. Krishnan et al. [87] implemented a tiered hybrid LCA to study the environmental impacts of the high-purity specialty chemicals and materials used in semiconductor manufacturing. LCI data on such specialty chemicals are rare. Also, chemical manufacturers are reluctant to share the processes involved in chemical development due to proprietary concerns. Therefore, to address the scarcity in data, Krishnan et al. [87] used a process-based analysis for cases where data existed for the manufacturing of specialty chemicals. For the chemicals whose manufacturing process details were absent, an IO analysis was carried out.

In input–output hybrid analysis, if detailed process data are available for input–output sectors, these sectors are further disaggregated to improve the accuracy of the estimate. An example of such an analysis is the hybrid input–output approach implemented by Nakamura et al. [88] to study the impacts from scraps and byproducts during the production process of metallic elements for electronic products such as fuel cells, LEDs, and solar cells. The production process of metals such as copper, lead, and zinc typically results in byproducts such as gold, silver, bismuth, and indium. A conventional IOA is based on the assumption that one activity relates to one product, and thus excludes the environmental impacts resulting from the joint production of byproducts. In order to capture the environmental impacts resulting from the mutual interdependence among the metal production processes, including the generation of byproducts, Nakamura et al. [88] disaggregated the metal production IO model into detailed steps and employed a process-based analysis.

The third type of hybrid approach is integrated hybrid analysis, which fuses the computational structure of an LCA with an input–output analysis within a consistent mathematical framework throughout the life cycle of a product. Such an approach was implemented by Deng et al. [89] to study the energy requirements for laptop computers. The integrated hybrid analysis approach incorporates process level information into the energy input–output model for the life cycle of a laptop computer. The total energy associated with producing a laptop computer is expressed as:

$$E = E^{\text{Process}} + E^{\text{Additive}} + E^{\text{RV}} \tag{2}$$

where E^{Process} represents the energy associated with steps such as computer assembly and semiconductor fabrication. The E^{Additive} term accounts for the energy requirement associated with components or materials used in laptop production and for which data are available. Finally, E^{RV} denotes the factors representing processes for which neither materials nor economic energy requirement data are available.

Bush et al. [6] employed an integrated hybrid LCA method to measure the full lifecycle emissions of solar PV and micro-wind technologies in order to avoid truncation errors. Bush et al. [6] linked the requirement matrix A_{gp} which describes the inputs of goods to processes in physical units to the compound technology matrix $I - A_{ss}$ which is derived from financial transactions between economic sectors via the upstream C_u and downstream C_d matrices. The downstream matrix represents the flow of goods, in physical units, produced by specific processes. The upstream matrix on the other hand includes commodity flows in monetary terms from the IO product sectors thereby complementing the requirements that had been cut off in the process data. Thus the total requirement matrix H is a hybrid matrix including both process and IO parts (Eq. (3)).

$$H = \begin{bmatrix} -A_{gp} & -C_d \\ -C_u & I - A_{ss} \end{bmatrix} \begin{matrix} \rightarrow & \text{process part} \\ \rightarrow & \text{I/O part} \end{matrix} \tag{3}$$

The total GHG emissions are calculated by pre-multiplying the requirement matrix with direct emissions data and post-multiplying by the demand vector for the system under consideration.

Although existing standards, such as ISO 14040 and PAS 2050, provide guidance for measuring the CF at the product-level, they do not provide rules for monitoring and managing GHG emissions during the use phase. This is critical to electronic products used in data centers, manufacturing equipment, and avionics, as the use phase of these products serves as a significant (greater than 50%) contributor to the total CF of a product. In order to address this concern, Scipioni et al. [90] developed a model that combines the ISO 14040 and 14064 standards. However, this model, as with other life cycle approaches, is limited by the element of subjectivity in defining the operational boundaries. Combining this model with a hybrid approach will ensure clear system boundary definition and the monitoring of emissions over time, which will, in turn, enable organizations to make decisions to reduce a product's CF during the product's use phase.

5.3. Integrating CF into a product's supply chain

An electronic product manufacturer is expected to take both direct and indirect emissions into account when estimating and reporting the CF of a product to their customers. Huang et al. [91] studied the GHG emissions in electronics manufacturing and the computer services industry and found that Scope 3 accounts for more than 75% of the total emissions. Scope 3 mainly includes the indirect emissions in the product supply chain and the use phase. However, one challenge that electronic product manufacturers face is the scarcity of data on supply chain emissions (Scope 3).

The recommended action for electronic product manufacturers to address this challenge is to integrate CF practices into supply chain management. By doing so, manufacturers can identify the

GHG emission hotspots in a product's supply chain and undertake actions to reduce them. Lee [92] demonstrated a three-step method for integrating CF into supply chain management for automobiles. The first step is to identify the key supplier's CF. This can be accomplished by setting up guidelines and providing measurement manuals to suppliers in order to enable suppliers to calculate their Scope 1 and Scope 2 emissions. The second step is to develop a carbon process map that identifies individual components and parts at each stage of the supply chain. The purpose of this map is to enable suppliers to identify the GHG emission hotspots of their components or parts that go into the actual product's development, report the results, and work together with electronic product manufacturers to reduce GHG emissions. The final step is to calculate the CF contribution of the product's supply chain using the data gathered in steps 1 and 2.

Data from suppliers can be gathered through site visits and interviews with the supplier's facility management. The gathered data can be further enhanced by reviewing secondary source material such as, supplier environmental performance reports and internal documents. In addition, carbon emission data can also be gathered through a calculation- or measurement-based methodology. A calculation-based methodology involves "determining emissions from source streams based on activity data obtained by means of measurement systems and additional parameters from laboratory analyses or standard factors." A direct measurement-based method, on the other hand, involves "determining emissions from an emission source by means of continuous measurement of the concentration of the relevant GHG" [93]. While the calculation-based methodology suffers from inherent uncertainties in quantifying the emission factors, the measurement-based methodology provides greater accuracy in quantifying GHG emissions. However, it is not possible to employ a direct measurement-based methodology in all scenarios.

6. Case study: DC–DC converter

In this section, we employ our multipronged approach discussed above to estimate and compare the CF of class I and III DC–DC buck converters (15 V to 5 V, 3 A). According to the IPC [97], class I includes electronic products that are suitable for applications where the major requirement is the function of the completed assembly (e.g., DC–DC converters used in commercial laptops or desktop computers). On the other hand, class III (high reliability) includes electronic products where continued high performance or performance-on-demand is critical, equipment downtime cannot be tolerated, the end-use environment may be uncommonly harsh, and the equipment must function when required, such as power converters used in military communication systems.

6.1. Methods overview

As mentioned in Section 5.1, in order to enable comparisons between the CF studies of commercial- and military-grade DC–DC converters, the risks of omitting important life cycle stages have to be minimized. At this juncture, no product-group-oriented standard is available for DC–DC converters. Hence, we have developed a set of rules to ensure consistency in the CF studies for commercial- and military-grade DC–DC converters. First, a systematic disassembly of the DC–DC converters was performed to generate a bill of materials. Disassembly was carried out until no further mechanical separation was possible. Both commercial- and military-grade DC–DC converters are assumed to have the same set of components and PCB size.

All disaggregated components were weighed using a microbalance, and the material content was identified and measured using X-ray fluorescence (XRF) equipment. The EcoInvent database (v2.0) contains information on equivalent carbon emission during component production, material extraction, and production phases. Since data on emissions from electronic component and material production phases were available from the EcoInvent database, this study did not require the integration of CF into the supply chain. However, if the electronic product under study is a system-of-systems (e.g., an electronic control module for automotive applications), GHG emission information on sub-systems (e.g., a power converter) might not be covered by the EcoInvent database. In such cases, the integration of CF in the supply chain is required to get supply-chain-related emissions for sub-systems.

Next, the emissions related to manufacturing and assembly of the DC–DC converter must be captured. For this purpose, the following manufacturing and assembly process flow was identified for the commercial-grade DC–DC converter in this study.

1. Printed circuit board (PCB) pre-bake
2. Wave solder assembly
3. Visual inspection after assembly
4. Wash
5. Automated Optical Inspection (AOI)
6. 2-D X-ray inspection
7. Assembly of connectors
8. Visual inspection
9. Environmental Stress Screening (ESS) test

In addition to the above steps, the following steps are added for the manufacturing and assembly of military-grade DC–DC converter:

10. Pre-coat baking
11. Masking
12. Conformal coating
13. Curing of conformal coating.

6.2. Economic-balance hybrid LCA

In order to minimize the truncation error resulting from excluded processes in the bottom–up process LCA model and the approximation error resulting from the top–down IO LCA model, we employed a hybrid LCA that was suggested by Deng et al. [89]. In this hybrid LCA method, two EIO correction factors E^{Additive} and E^{RV} were included (discussed in Section 5.2, see Eq. (2)). The additive factor, E^{Additive}, accounts for emissions resulting from relevant industries from the EIO-LCA model for which specific economic data on requirements per product is available. The remaining value factor, E^{RV}, on the other hand estimates the emission contributions from processes for which neither materials nor economic data are publicly available. The details regarding how the E^{Process}, E^{Additive}, and E^{RV} terms are estimated are not within the scope of this paper; hence, interested readers are referred to Deng et al. [89] for details.

6.3. Carbon footprint estimation results

Details of CO_2 emissions result from the fusion of process sum analysis with EIO model is presented in this section. Emissions from known processes in manufacturing of components and materials, and assembly of the power converter are estimated using process sum analysis. Emissions from processes for which direct process-related emissions related data was not available, were estimated that using EIO method.

6.3.1. Process data analysis

The DC–DC converter considered in this study consisted of 6 thin-film capacitors, 2 small electrolytic capacitors, 1 tantalum capacitor, 1 large MOSFET transistor, 2 small FET transistors, 1 core inductor, 9 metal film resistors, 1 8-pin DIP Pulse Width Modulator, 1 Schottky diode, 1 small signal diode, 2 BNC connectors, and a 3 in. × 4 in. double-sided PCB (casing not included). Based on XRF measurements and information in the EcoInvent database [94] on electronic components, materials in the converter were identified, which summed up to 80 g. Using the emission data from the ICE [95] and EcoInvent [94] databases, the materials' production-related emissions were estimated. Table 1 lists the top 15 materials in the DC–DC converter with highest emissions. Based on the material composition of the converter and the energy consumption during component production, the total life cycle CO_2 emissions from the bulk materials were estimated to be around 566.26 g CO_2.

Table 2 summarizes the associated assembly process emission data estimated based on a PCB size of 3 in. × 4 in. with 27 PCBs per panel. Based on Table 2 and process sum analysis, the total life cycle CO_2 emissions associated with the manufacturing and assembly of a commercial- and military-grade DC–DC converter are 169.77 and 347.54 g CO_2, respectively. The use of chemicals in bulk materials production and DC–DC converter manufacturing and assembly is not taken into consideration in the process-sum analysis. However, the emissions related to electronic chemicals usage are accounted for through E^{Additive} correction factor (Section 6.3.2).

6.3.2. Additive IO correction

The additive IO correction is applied when specific data on economic content for a process is available. Such data was found for one process: electronic chemicals and materials. The additive IO factor is estimated by multiplying the cost per product with supply chain intensities. Van Arnum [96] had noted that, the global market economic value for chemicals and materials used in electronic manufacturing was USD$16.86 billion in 1999. Since the market share of power converters is not available, we assume that the total DC–DC 15 V to 5 V converter production was meant to serve laptop and desktop computers. From Deng et al. [89] we found that around 140 million laptops were shipped in 2002. Hence, we assumed that around 300 million (140 million for laptops, 140 million for desktops, and 20 million for miscellaneous purposes) DC–DC converter units were shipped in 2002, and these 300 million units used 5% of the specialized chemicals and materials used in electronics manufacturing. The results of data calculation indicate that $2.75 worth of electronic chemicals is contained in a model power converter. For EIO sector selection, the "Photographic Film and Chemicals" sector was chosen as the IO sector most nearly approximating electronic chemicals (as discussed in Williams [98] and Deng et al. [89]), as no analoge exists. Multiplying $2.75 with the sectoral carbon intensities obtained from the 2002 EIOLCA model results in an estimated contribution of 1.55 kg CO_2 from electronic chemicals and materials.

Table 1
Embodied CO_2 in materials.

Materials	Amount per converter (g)	CO_2 intensity (kg CO_2/kg)	CO_2 per converter (g CO_2)
Glass (fiber reinforced)	23.15	8.1	187.50
Gold	0.0406	3000	121.82
Nylon 6-6	15.75	6.5	102.36
Copper	21.97	3.5	76.892
Polycarbonate	3.458	6	20.748
Brass	4.021	4.39	17.652
Tin	0.5668	13.7	7.7658
Zirconium	0.0769	97.2	7.4756
Encapsulation	1.0479	5.5	5.7633
Hardener	0.7755	5.5	4.2653
Aluminum	0.4289	8.24	3.5344
Epoxy resin	0.3925	9	3.5326
Glass (borosilicate)	1.700	0.85	1.4446
Iron	0.5494	1.91	1.0493
Nickel	0.0563	12.4	0.69762

6.3.3. Remaining value IO correction

The remaining value factor estimates the contribution from those processes not included in either process-sum analysis or the additive IO term by accounting for how much of the total economic value of the product has been covered by these analyses and using IO analysis to determine the impact of the value left over [89]. As of 2014, the purchase price of a DC–DC 15 W (5 V, 3 A and 2.15 in. × 2.05 in.) is $43.5. Adjusting this to the dollar value in 2002 results in a cost of $34.58. In 2002, the producer price share was 78%; thus the producer price for a DC–DC converter was around $27 in 2002. The results from Table 3 indicate that around $18 has been accounted for in the process-sum analysis and additive IO corrections. This leaves a remaining value of $9 per converter in 2002 USD. Emissions associated with the remaining value are calculated by allocating the remaining value to IO sectors that are not yet covered, according to supply chain purchases of the "Other Electronic Component Manufacturing" sector. The top 33 sectors accounted for ~99% of the remaining value share. However, 7 sectors out of these 33 were removed in order to avoid double counting. These include (1) PCB manufacturing; (2) copper rolling, extruding, and alloying; (3) electronic capacitor, resistor, coil, transfer and inductor manufacturing; (4) electronic connector manufacturing; (5) all other chemical product and preparation manufacturing; (6) bare PCB manufacturing; and (7) oil and gas extraction. The rest of the 26 sectors accounted for 91% of the remaining value. The results show that 5.395 kg CO_2 is associated with $8.19 of the remaining value. More than half of the remaining value is attributed to sectors of wholesale trade; management of companies and enterprises; semiconductor and related devices manufacturing; computer terminals and other peripheral equipment manufacturing; and scientific research and development services.

6.3.4. Life cycle carbon intensity of DC–DC converter

The total estimated embodied CO_2 emissions in the raw material extraction, manufacturing, and assembly of commercial- and

Table 2
Embodied CO_2 in manufacturing and assembly processes.

Process	Avg. power consumption (kW h)	PCBs per hour	CO_2 equivalent (kg CO_2)	CO_2 per converter (g CO_2)
Baking	8	45	6	133.33
Wave assembly	20	2520	14	5.5556
Batch washing	7.5	1242	5	4.0258
AOI system	1.5	120	1	8.3333
X-ray inspection	2.8	270	2	7.4074
ESS test chamber	8	540	6	11.111
Curing of coating	8	135	6	44.444

Table 3
Remaining Value (RV) IO correction calculation and embodied CO_2 per DC–DC converter.

	Value per converter (US $)	Fraction accounted (%)	Value accounted for in analysis (US $)
Process-sum			
1. Circuit boards	$6.30	41	$2.58
2. Bulk materials	$9.52	17	$1.62
3. Manufacturing	$27.0	41	$11.05
Additive IO			
1. Electronic chemicals	$2.75		$2.75
Total value accounted in process-sum and addition IO			$18
Purchaser price in 2002 USD			$34.58
Producer price in 2002 USD			$27
Remaining Value (RV)			$9
Total RV CO_2 per DC–DC converter (kg CO_2)			5.395

military-grade DC–DC converters are 7.681 and 7.859 kg CO_2, respectively. Note that in this analysis use phase emissions were not taken into account. Lifespan (i.e., the length of time used as a primary device) is a key variable needed for estimating use phase emissions. While the lifespan for a commercial-grade DC–DC converter can be estimated by verifying the usage pattern of laptop or desktop computers, the same cannot be found for a military-grade converter. In military applications, the usage pattern can vary drastically depending on the demand. Hence, we refrain from making conclusions on the use phase emission of the two types of converters considered. However, it is safe to assume that the number of commercial converter units manufactured per year (in hundreds of millions) is greater than the number of military-grade converters (less than a million units). Thus, even though military-grade converter units have a little higher CO_2 emissions per unit, on a global scale the commercial-grade converter dominates CO_2 emissions.

7. Conclusions

In anticipation of tougher legislation subsequent to the Kyoto protocol and regulatory carbon requirements, electronic product manufacturers have started adopting traditional LCA-based carbon footprinting practices to assess their products' contributions to global warming. However, adopting the current CF practices for electronic products will ultimately lead to the underestimation of a product's CF.

Inconsistencies arising due to differences in the system boundary selection methods and life cycle inventory databases employed by the software tools used to compute a product's CF make it difficult to compare the CF of a product or component of the same category from different manufacturers. Furthermore, existing standards still employ a PA or IOA-based LCA approach for CF analysis. PA or IOA-based LCA approaches impose practical difficulties in drawing a clear system boundary for CF analysis. Unless a clear system boundary is established during the CF estimation process, it is not possible to obtain a reliable estimate of a product's GHG emissions. In addition, existing standards have difficulty handling out-of-house contributors to a product's CF, and the supply chain for the electronics industry is extremely complex, involving multiple tiers of suppliers. Neglecting GHG emissions from a products' supply chain will lead to the underestimation of the CF of electronic products.

In this paper, we have recommended a multipronged approach to address the challenges with current CF practices. This comprehensive multipronged approach, involving the use of product group-oriented standards, hybrid LCA techniques, and the integration of CF into the supply chain, will lead to a more reliable method for estimating a product's CF and identifying GHG emission drivers in a product development cycle. Product group-oriented standardization will eliminate the risks of omitting life cycle stages while calculating a product's CF, which will ensure that the environmental impacts of a product of the same category from different manufacturers can be compared. By using product group-oriented standards, we can also eliminate inconsistencies in the current CF methods that result from the selection of a cradle-to-grave or cradle-to-gate scenario.

The use of hybrid LCA techniques allows for the integration of sector- and process-level data by exploiting the advantages of both the EIO and PA LCA methods. Hybrid LCA techniques will eliminate the inconsistencies in CF estimation that result from the subjective choice of boundary selection in a product life cycle.

Manufacturers can identify GHG emissions drivers in their products upstream by integrating CF practices into their supply chain. This will encourage the participation of suppliers in a product's CF estimation process, which will help in capturing the GHG emissions resulting from the actions of the supplier and the supplier's product.

Electronics companies need to monitor all of their activities that can contribute to their products' CFs. Members of the supply chain should cooperate with electronic product manufacturers by identifying their CFs and maintaining consistency in how calculations are carried out. Academia has identified ways that companies can monitor both the direct and indirect contributors to their CFs. CF methods should include not only emissions from within a company, but also emissions from the supply chain, usage, and disposal of products. While standards help companies identify their direct costs, there is room for improvement in the inclusion of indirect CF contributors.

Acknowledgements

The authors would like to thank Prof. Kam-Chuen Yung and Dinesh Mahadeo for discussions related to CF practices in the electronics industry, and Kelly Smith and Mark Zimmerman for providing English edits. The authors also thank the more than 100 companies that support research activities at the Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, annually.

References

[1] Peters G, Hertwich E. Trading Kyoto. Nat Rep Climate Change 2008;2:40–1.
[2] Peters G, Marland G, Le Quere C, Boden T, Canadell J, Rauach M. Rapid growth in CO_2 emissions after the 2008–2009 global financial crisis. Nat Climate Change 2012;2:2–4.
[3] Bose B. Global warming: energy, environmental pollution, and the impact of power electronics. IEEE Ind Electron Mag 2010;4:6–17.
[4] Environmental Protection Agency. Mandatory reporting of greenhouse gases. Fed Reg 2010;75(242).

[5] Carbon Disclosure Project. Lower emissions, higher ROI: the rewards of low carbon investment. Carbon action program 2013 report; published 2014.

[6] Bush R, Jacques D, Scott K, Barrett J. The carbon payback of micro-generation: an integrated hybrid input–output approach. Appl Energy 2014;119:85–98.

[7] Legislation 197. Directive 2012/19/EU of the European parliament and of the council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE). Off J Eur Union 2012;55:38–71.

[8] Legislation 174. Directive 2011/65/EU of the European parliament and of the council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment. Off J Eur Union 2011:88–110.

[9] British Standard Institute (BSI). Publicly Available Specification (PAS) 2050: specifications for the assessment of the life cycle greenhouse gas emissions of goods and services. BSI Report PAS 2050; 2008.

[10] Matsumoto M, Fujimoto J, Tekawa M. A macroeconomic analysis of the relationship between IT industries and environmental policies. In: Proceedings of the IEEE international symposium on electronics and the environment; 2004. p. 17–22.

[11] Black R. Countries rally against EU carbon tax on airlines. BBC News Europe; February 2012. <http://www.bbc.co.uk/news/world-europe-17114312> [accessed 09.03.2014].

[12] Crowe P. Worldwide EV sales to reach 3.8 million annually by 2020. HybridCars; January 2013. <http://www.hybridcars.com/worldwide-ev-sales-to-reach-3-8-million-annually-by-2020/> [accessed 09.03.2014].

[13] Bishop J, Martin N, Boies A. Cost-effectiveness of alternative powertrains for reduced energy use and CO_2 emissions in passenger vehicles. Appl Energy 2014;124:44–61.

[14] Sorrentino M, Rizzo G, Sorrentino L. A study aimed at assessing the potential impact of vehicle electrification on grid infrastructure and road-traffic green house emissions. Appl Energy 2014;120:31–40.

[15] Happell M. Carbon pricing implications for the mining sector. PricewaterhouseCoopers; 2011. <http://www.pwc.com.au/industry/energy-utilities-mining/assets/Carbon-Pricing-Mining-Sector-Implications-Aug11.pdf> [accessed 09.03.2014].

[16] Doucette R, McCulloch M. Modeling the prospects of plug-in hybrid vehicles to reduce CO_2 emissions. Appl Energy 2011;88:2315–23.

[17] Lin C, Liou F, Hang C. Grey forecasting model for CO_2 emissions: a Taiwan study. Appl Energy 2011;88:3816–20.

[18] Peters G. Carbon footprints and embodied carbon at multiple scales. Curr Opin Environ Sust 2010;2:245–50.

[19] UNFCCC. The Kyoto protocol to the United Nations convention on climate change. New York: United Nations; 1997. <http://unfccc.int/kyoto_protocol/items/2830.php> [accessed 09.03.2014].

[20] Minx J, Widemann T, Wood R, Peters G, Lenzen M, Owen A, et al. Input–output analysis and carbon footprinting: an overview of applications. Econ Syst Res 2009;21(3):187–216.

[21] Carbon Trust. Carbon footprints in the supply chain: the next step for business; 2006. <http://www.carbontrust.com/media/84932/ctc616-carbon-footprints-in-the-supply-chain.pdf> [accessed 09.03.2014].

[22] Hertwich E, Roux C. Greenhouse gas emissions from the consumption of electric and electronic equipment by Norwegian households. Environ Sci Technol 2011;45(19):8190–6.

[23] Torello A. EU keeps airlines in carbon market. Wall Street J. December 2011. <http://online.wsj.com/news/articles/SB10001424052970204464404577112004147787954> [accessed 09.03.2014].

[24] Knight V. EU takes pollution fight to aircraft; to limit greenhouse gases, emissions caps are floated; threat of tax Irks airlines. Wall Street J. 2005. <http://online.wsj.com/news/articles/SB110790204439949256> [accessed 09.03.2014].

[25] Chancellor of the Exchequer. Investing in Britain's potential: building our long term future. A pre-budget report presented to British Parliament; 2006. <http://www.official-documents.gov.uk/document/cm69/6984/6984.pdf> [accessed 09.03.2014].

[26] Malina R, McConnachie D, Winchester N, Wollersheim C, Paltsev S, Waitz I. The impact of the European Union emissions trading scheme on US aviation. J Air Transport Manage 2012;19:36–41.

[27] Carbon Disclosure Project. Collaborative action on climate risk. Supply chain 2013–14 Report; published 2014. <https://www.cdp.net/cdpresults/cdp-supply-chain-report-2014.pdf> [accessed 09.03.2014].

[28] Australian Government. Securing a clean energy future. The Australian Government's Climate Change Plan; 2011. <http://www.acci.asn.au/Files/Government-Carbon-Tax-Plan> [accessed 02.14.2014].

[29] Stamford C. Gartner estimates ICT industry accounts for 2% of global CO_2 emissions; 2007. <http://www.gartner.com/newsroom/id/503867> [accessed 09.03.2014].

[30] Malmodin J, Moberg A, Lunden D, Finnveden G, Lovehagen N. Greenhouse gas emissions and operational electricity use in the ICT and entertainment and media sectors. J Ind Ecol 2010;14(5):770–90.

[31] Joyce T, Okrasinski T, Schaeffer W. Estimating the carbon footprint of telecommunications products: a heuristic approach. J Mech Des 2010;132(9):094502(4).

[32] Enkvist P-A, Vanthournout H. How companies think about climate change. Mckinsey Quarterly; December 2007. <http://www.nyu.edu/intercep/lapietra/ClimateChangeAttitudes.pdf> [accessed 09.03.2014].

[33] Congress of the United States. Policy options for reducing CO_2 emissions. A Congressional Budget Office (CBO) Study; February 2008. <http://www.cbo.gov/sites/default/files/cbofiles/ftpdocs/89xx/doc8934/02-12-carbon.pdf> [accessed 09.03.2014].

[34] Congress of the United States. A bill to require the administrator of the Environmental Protection Agency to conduct a study on black carbon emissions. A Congressional Budget Office (CBO) Study; September 2008. <http://www.cbo.gov/publication/20719> [accessed 09.03.2014].

[35] 110th Congress of the USA. Consolidated appropriations act; 2008. <http://www.gpo.gov/fdsys/pkg/BILLS-110hr2764enr/pdf/BILLS-110hr2764enr.pdf> [accessed 09.03.2014].

[36] Congress of the United States. Effects of a carbon tax on the economy and the environment. A Congressional Budget Office (CBO) Study; May 2013. <http://www.cbo.gov/publication/44223> [accessed 09.03.2014].

[37] The Economic Times. Climate laws advancing in many countries: a survey; January 14, 2013. <http://articles.economictimes.indiatimes.com/2013-01-14/news/36331905_1_climate-change-carbon-emissions-carbon-tax> [accessed 09.03.2014].

[38] Harrabin R. Car drivers will save cash thanks to CO_2 rules. BBC News Science and Environment; March 2013. <http://www.bbc.co.uk/news/science-environment-21803635> [accessed 09.03.2014].

[39] European Commission. Amending regulation (EC) No. 443/2009 to define the modalities for reaching the 2020 target to reduce CO_2 emissions from new passenger cars. Proposal for regulation of the European parliament and of the council; July 2012.

[40] Wilcox M, Fleming P. Investors file a record 95 climate change resolutions: a 40% increase over 2009 proxy season. Investors Network on Climate Risk, Ceres; March 2010. <http://www.csrwire.com/press_releases/29019-Investors-File-a-Record-95-Climate-Change-Resolutions-a-40-Increase-Over-2009-Proxy-Season> [accessed 03.14.2013].

[41] Consumer Electronics Association (CEA). Environmental sustainability and innovation in the consumer electronics industry. Consumer electronics industry environmental sustainability report; 2008. <http://ce.org/CorporateSite/media/Government-Media/Green/Environmental-Sustainability-and-Innovation-in-the-Consumer-Electronics-Industry.pdf> [accessed 09.03.2014].

[42] Keogh O. Wood-cased computer that shows its mettle. Innovation – Irish Times; 2012. p. 6. <http://www.irishtimes.com/newspaper/innovation/2012/0224/1224312020430.html> [accessed 09.03.2014].

[43] Ospina J, Maher P, Schischke K, Schlosser A. Environmental product assessments for small computer and laptop companies – MicroPro's experience with eco-design of product service systems. In: Proceedings of the electronics goes green 2012+ conference; 2012.

[44] Fargo B, MacAvoy D. A practical approach to greening the electronics supply chain. Report commissioned by Electronic Industry Citizenship Coalition; 2010. <http://www.bsr.org/reports/BSR_EICC_A_Practical_Approach_to_Greening_the_Electronics_Supply_Chain.pdf> [accessed 09.03.2014].

[45] Apple and the Environment. <https://www.apple.com/environment/> [accessed 09.03.2014].

[46] Khasreen M, Banfill P, Menzies G. Life cycle assessment and the environmental impact of buildings: a review. Sustainability 2009;1:674–701.

[47] Minx J, Wiedmann T, Barrett J. Methods review to support the PAS process for the calculation of the greenhouse gas emissions embodied in goods and services. Final report to the Department for Environmental, Food and Rural Affairs, Ref. No. EV2074; 2008.

[48] Widemann T. Editorial: carbon footprint and input–output analysis – an introduction. Econ Syst Res 2009;21(3):175–86.

[49] Lenzen M. Errors in conventional and input–output-based life cycle inventories. J Ind Ecol 2001;4(4):127–48.

[50] Hendrickson C, Horvath A, Joshi S, Lave L. Economic input–output models for environmental life cycle assessment. Environ Sci Technol 1998;32(7):184A–91A.

[51] Joshi S. Product environmental life cycle assessment using input–output techniques. J Ind Ecol 2000;3(2 and 3):95–119.

[52] Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, et al. Life cycle assessment – Part 1: Framework, goal, and scope definition, inventory analysis and applications. Environ Int 2004;30:701–20.

[53] Pennington D, Potting J, Finneveden G, Lindeijer E, Jolliet O, Rydberg T, et al. Life cycle assessment – Part 2: Current impact assessment practice. Environ Int 2004;30:721–39.

[54] Finnveden G, Hauschild M, Ekvall T, GUinee J, Heijungs R, Hellweg S, et al. Recent developments in life cycle assessment. J Environ Manage 2009;91:1–21.

[55] ISO 14040. Environmental management-life cycle assessment: principles and framework; 2006.

[56] ISO 14044. Environmental management-life cycle assessment: requirements and guidelines; 2006.

[57] ISO 14067. Greenhouse gases – carbon footprint of products – requirements and guidelines for quantification and communication; 2013.

[58] GHG protocol initiative for a product and supply chain accounting and reporting standard, World Resources Institute and World Business Council for Sustainable Development; 2011.

[59] ISO 14064-1. Green-house gases – Part 1: Specification with guidance at the organizational level for quantification and reporting of greenhouse gas emissions and removal, Switzerland, Geneva; 2006.

[60] GHG protocol initiative for a corporate value chain accounting and reporting standard, World Resources Institute and World Business Council for Sustainable Development; 2011. <http://www.ghgprotocol.org/files/ghgp/public/ghg-protocol-revised.pdf> [accessed 09.03.2014].

[61] The Carbon Trust. Carbon footprinting: the next step to reducing your emissions. Management Guide, London, UK; 2012. <http://www.carbontrust.com/media/44869/j7912_ctv043_carbon_footprinting_aw_interactive.pdf> [accessed 09.03.2014].

[62] Fujitsu. Life cycle assessment and product carbon footprint: primergy TX/RX 300 S5 server. White Paper; 2010. <http://fujitsu.fleishmaneurope.de/wp-content/uploads/2010/12/LCA_PCF-Whitepaper-PRIMERGY-TX-RX-300-S5.pdf> [accessed 09.03.2014].

[63] Bottner H, Schischke K, Nissen N. Carbon footprinting of information technology products based on ISO standards. In: Proceedings of the IEEE conference on consumer electronics; 2011.

[64] Higgs T, Cullen M, Yao M, Stewart S. Developing an overall CO_2 footprint for semiconductor products. In: Proceedings of the IEEE international symposium on sustainable systems and technology; 2009. p. 1–6.

[65] Andrae A, Andersen O. Life cycle assessment of integrated circuit packaging technologies. Int J Life Cycle Assess 2011;16:258–67.

[66] Boyd S. Bio-based versus conventional plastics for electronics housings: LCA literature review. The Sustainability Consortium; 2011. <http://www.sustainabilityconsortium.org/wp-content/themes/sustainability/assets/pdf/whitepapers/2011_Boyd_TSC_Bio-Plastics.pdf> [accessed 09.03.2014].

[67] Thomas M. Conserving resources: producing circuit boards with plasma. Fraunhofer-Gesellschaft; 2010. <http://www.fraunhofer.de/en/press/research-news/2010/10/circuit-boards-with-plasma.html> [available 09.03.2014].

[68] Woidasky J. Beyond tomorrow project: molecular sorting for resource efficiency. Fraunhofer-Gesellschaft; 2011. <http://www.fraunhofer.de/en/research-topics/production-and-environment/productionsaving-energy-and-raw-materials/molecular-sorting.html> [accessed 09.03.2014].

[69] GE team investigates carbon footprint of healthcare plant. General Electric. <http://www.gecitizenship.com/ge-team-investigates-carbon-footprint-of-healthcare-plant/> [accessed 09.03.2014].

[70] End of life is a serious matter for air conditioning. Mitsubishi Electric. <http://www.mitsubishi-aircon.co.uk/default.asp?url=http%3A//www.mitsubishi-aircon.co.uk/mitsubishi_electric.asp%3Fid%3D199302> [accessed 09.03.2014].

[71] Carbon footprinting of information technology products based on ISO standards. Fujitsu Limited. <http://sp.ts.fujitsu.com/dmsp/Publications/public/ps-Carbon-Footprinting-of-IT-Products.pdf> [accessed 09.03.2014].

[72] Jah A. Sony Ericsson unveils 'green' handsets that cut carbon footprint by 15%. The Guardian; June 2009. <http://www.guardian.co.uk/environment/2009/jun/04/mobile-phones-sony-ericsson> [accessed 09.03.2014].

[73] GE Energy Savings and Usage Calculator. <http://www.gelighting.com/LightingWeb/na/consumer/inspire-and-learn/energy-savings-calculator/> [accessed 09.03.2014].

[74] GE LED Energy Savings Calculator. General Electric Lighting. <http://www.gelighting.com/LightingWeb/na/consumer/inspire-and-learn/energy-savings-calculator/led-calculator.jsp> [accessed 09.03.2014].

[75] Jenkins D, Newborough M. An approach for estimating the carbon emissions associated with office lighting with a daylight contribution. Appl Energy 2007;84:608–22.

[76] New generation water heating – huge cost and carbon emissions reduction. Eco heat systems. <http://www.ecoheatsystems.co.uk/news.html> [accessed 09.03.2014].

[77] Fujitsu's Eco-Friendly Servers Reduce Cleanup Corp's Carbon Footprint. Fujitsu Limited. <http://www.fujitsu.com/global/news/pr/archives/month/2010/20100616-01.html> [accessed 09.03.2014].

[78] Andrae A, Andersen O. Life cycle assessments of consumer electronics – are they consistent? Int J Life Cycle Assess 2010;15:827–36.

[79] Suh S, Lenzen M, Treloar G, Hondo H, Horvath A, Huppes G, et al. System boundary selection in life cycle inventories using hybrid approaches. Environ Sci Technol 2004;38(3):657–64.

[80] US EPA. Emerging trends in managing supply chain GHG emissions. December 2010. <http://www.epa.gov/climateleadership/documents/managing_supplychain_ghg.pdf> [accessed 09.03.2014].

[81] Matthews H, Hendrickson C, Weber C. The importance of carbon footprint estimation boundaries. Environ Sci Technol 2008;42:5839–42.

[82] SETAC Europe LCA Steering Committee. Standardization efforts to measure greenhouse gases and carbon footprinting for products. Int J Life Cycle Assess 2008;13:87–8.

[83] Scharnhorst W. Life cycle assessment in the telecommunications industry. Int J Life Cycle Assess 2008;13:75–86.

[84] NSF CarbonFree Product Certification. <http://www.nsf.org/services/by-industry/sustainability-environment/claims-validation/carbonfree/> [accessed 09.03.2014].

[85] US EPA Energy Star Certification. <https://www.energystar.gov/about/> [accessed 09.03.2014].

[86] LEI Electronics Inc. Eco alkalines batteries run on NSF CarbonFree certification. <http://www.nsf.org/newsroom_pdf/SU_LEI_Electronics_Case_Study_LT_EN_LSU27410812.pdf> [accessed 09.03.2014].

[87] Krishnan N, Boyd S, Somani A, Raoux S, Clark D, Dornfeld D. A hybrid life cycle inventory of nano-scale semiconductor manufacturing. Environ Sci Technol 2008;42:3069–75.

[88] Nakamura S, Mukrakami S, Nakajima K, Nagasaka T. Hybrid input–output approach to metal production and its application to the introduction of lead-free solders. Environ Sci Technol 2008;42:3843–8.

[89] Deng L, Babbitt C, Williams E. Economic-balance hybrid LCA extended with uncertainty analysis: case study of a laptop computer. J Cleaner Prod 2011;19:1198–206.

[90] Scipioni A, Manzardo A, Mazzi A, Mastrobuono M. Monitoring the carbon footprint of products: a methodological proposal. J Cleaner Prod 2012;36:94–101.

[91] Huang Y, Weber C, Matthews H. Carbon footprinting upstream supply chain for electronics manufacturing and computer services. In: IEEE symposium on sustainable systems and technology; 2009. p. 1–6.

[92] Lee K-H. Integrating carbon footprint into supply chain management: the case of Hyundai motor company in the automobile industry. J Cleaner Prod 2011;19:1216–23.

[93] European Commission. Establishing guidelines for the monitoring and reporting of greenhouse gas emissions pursuant to directive 2003/87/EC of the European parliament and of the council; 2008.

[94] Hischier R, Classen M, Lehmann M, Scharnhorst W. Life cycle inventories of electric and electronic equipment: production, use, and disposal. EcoInvent Report No. 18; 2007.

[95] Hammond G, Jones C. Inventory of carbon energy (ICE); 2008. <http://www.uea.ac.uk/~e680/energy/NBS-M016/ICE%20Version%201.6a.pdf> [accessed 09.03.2014].

[96] Van Arnum P. Electronic materials. Chemical Market Reporter; 2000.

[97] IPC-A-610 Acceptability of Electronic Assemblies. <http://www.might.com.tw/comm/upfile/d_080506_09649.pdf> [accessed 09.03.2014].

[98] Williams E. Energy intensity of computer manufacturing: hybrid assessment combining process and economic input–output methods. Environ Sci Technol 2004;38:6166–74.