Carbon Footprint of Mobile Devices: Open Questions in Carbon Footprinting of Emerging Mobile ICT Technologies

Tuomas Mattila, Jáchym Judl and Jyri Seppälä

Abstract Carbon footprinting is becoming a mainstream practice in product design and marketing. At the same time, consumer products are becoming so complex that their footprinting becomes increasingly difficult. The supply chain of a typical mobile ICT device (i.e., smartphone) contains hundreds of suppliers in several continents and the product itself is composed of several complex subassemblies. The use of the smartphones also has large systemic effects (e.g., cloud computing, server load, increased consumption, and green applications), which are commonly left outside the scope of product carbon footprints. In this chapter, we argue that the parts which are most easily left out of a study are in fact the most significant for the whole product life cycle. The chapter is arranged in subchapters for each topic: components and subassemblies without emission inventory data available, energy consumption of data transfer and storage in clouds, the effect of recycling and consumer behavior, induced consumption, and the potential of green applications.

Keywords Smartphone · Cloud computing · Hybrid LCA · Consumer behavior · Information theory · Networks

1 Introduction: The Rapid Emergence of Smartphones

All new innovations typically follow a bell-shaped diffusion curve with four distinct stages: introduction, growth, maturity, and decline (Bass 1969) (Fig. 1). After introduction to the market, the product is purchased as consumers find it useful. In the early stages, marketing and external information transfer drives the increase in

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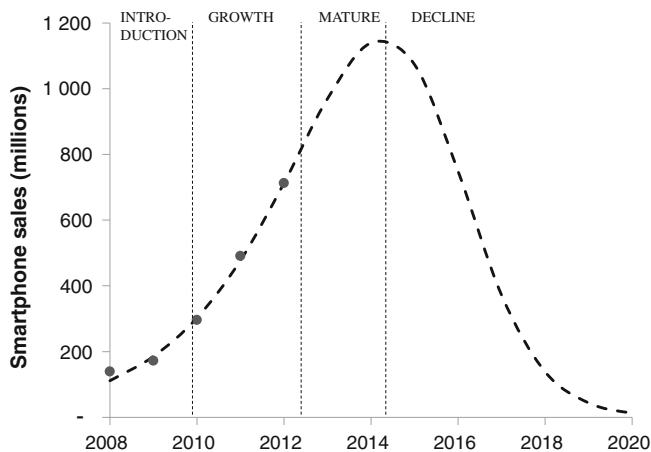e-mail: tuomas.mattila@ymparisto.fi

Fig. 1 World smartphone sales forecasted with a Bass diffusion model fitted to publicly available sales data (Gartner 2012; IDC 2012). The four stages represent the general stages of a product market diffusion

market. As more and more people use the product, the innovation spreads through word-of-mouth and social network effects (Peres et al. 2010). This results in a stage of exponential growth. At some point (usually around half of the market saturation), the product life cycle matures, growth ceases, and sales begin to decrease. During the decline stage, new consumers are found through cheaper versions of the product.

Most carbon footprinting studies have been done on products that are already in mature or declining markets. Examples are different shopping bags (Mattila et al. 2011), food items (Röös et al. 2010), waste disposal (Villanueva and Wenzel 2007), and paper production (Gaudreault et al. 2010). Carbon footprinting can then identify ways to improve efficiency and drive down both costs and climate impact. With mature products, companies have information collected about the production processes and consumer behavior, relatively stable supply chains, and reliable background inventories available. With emerging products, this is rarely the case.

Assessing the carbon footprint of emerging technologies presents a unique set of challenges. First, the inventory data available for emerging products are usually from products during their introduction stage, and the production processes are likely to change with the mass production of growth stage and the cost cutting concepts of decline. With new ICT products, many of the components are also so new that reliable emission inventories for the components and subassemblies (such as neodymium magnets or touchscreens) are rarely available from databases. The carbon footprint inventory of any rapidly developing product is therefore going to be incomplete and obsolete.

Second, the growth stage of an emerging product will also require the growth of the surrounding infrastructure. For the case of mobile ICT technologies, this will mean networks and cloud computing as well as the recycling of rare earth

minerals. Finally, a successful emerging consumer product will also affect consumer behavior. These consumer effects during the use phase of the product can be considerable and largely unknown during the initial stages of product emergence.

In this chapter, we will illustrate the problems of assessing emerging products with the example of smartphones. Smartphones are mobile communication devices that have an inbuilt operating system and are capable of running a diverse set of applications. Introduced to the world market after 2006, they are still in the initial stages of the product life cycle with rapidly growing sales (Fig. 1). The rapid increase in their use has also influenced data transfer and the infrastructure needed for cloud computing. Section 2 will consider the problems associated with finding reliable inventories for subassemblies and components of a completely new product. Section 3 discusses the external impacts to networks and servers. Section 4 discusses the challenges of recycling. Sections 5 and 6 discuss consumer behavior from two distinct viewpoints. Section 5 discusses the effects of increased consumption due to increased market information availability and Sect. 6 presents the potential of green applications for reducing climate impacts.

Typically, when a product has matured and several carbon footprints or life cycle assessments have been made, specific product category rules (PCRs) can be made on how to assess certain types of products. Because smartphones are still so new a product, these PCRs are not available. Consequently, the available carbon footprints of smartphones (HTC 2012; Nokia 2012; Apple 2012) have been made with general PCRs for electronics (see Table 1). Consequently, they include only the energy used by the product itself, but not the effect of data transfer and distributed computing services, which form a crucial part of the product usability. In a sense they are not in line with the publicly available specifications of carbon footprints (Sinden et al. 2008), which recommend containing all relevant services needed for the use of the product in the product carbon footprint. This is caused by the rapid development in technology; therefore, more research is needed to make the new PCRs for mobile communications devices which are directly linked to the Internet, such as smartphones.

The aim of this chapter is not to provide a cookbook for assessing ICT devices but to provide a roadmap for identifying problematic issues and to suggest possible ways around them. The suggestions are based on the authors' own experiences in constructing a life cycle assessment of smartphones in the Prosuite EU project (www.prosuite.org).

2 How to Get a Reliable Life Cycle Inventory for Components and Subassemblies?

The carbon footprints of smartphones published by different manufacturers in their environmental product declarations vary by a factor of five (Table 1). The largest difference is between Apple iPhone 5 and the Nokia Lumia 920. This difference is

Table 1 Reported carbon footprints (kg CO_2 eq./phone) of three smartphones, disaggregated to life cycle stages (Apple 2012; HTC 2012; Nokia 2012)

	Apple iPhone 5	Nokia Lumia 920	HTC Sense
Production	57	11	
Use	14	3	
Recycling	2	0,2	
Transport	3	2	
Total	75	16	33

mainly caused by the production of the device itself, and it can to some extent be explained by the different material composition. The iPhone 5 is made with an aluminum and steel body, whereas the Lumia is made from polycarbonate. However, because primary aluminum has a carbon footprint of approximately 12 kg CO_2 eq/kg (Ecoinvent 2010), the material selection of the 40 g body is of minor importance, compared to the overall difference between iPhone and Lumia production emissions (46 kg CO_2 eq.). Most likely, the difference is caused by different assumptions concerning the life cycle emission inventories of the electronic components and subassemblies. For example, the emission intensity of printed wiring boards is about 280 kg CO_2 eq./kg and for a microprocessor it is around 1,000 kg CO_2 eq/kg (Ecoinvent 2010). Therefore, minor differences in assumptions regarding these components may have a large difference in the overall results.

With a complicated product such as a smartphone, the collection of the primary inventory is a considerable task. The main option for an analyst without access to full production data from the subcontractors is to perform a manual disassembly of the product. The manual disassembly consists of disassembling, weighing, and identifying as many of the components as possible. Web searches of product codes found from individual components can then be used to identify the manufacturer and possibly the material composition of each component. These are then grouped and linked to available background information on component carbon footprints.

Without access to the primary data of the subcontractors, production processes, the analyst has to rely on background data for the components. The most commonly used database, Ecoinvent 2.2, contains 122 life cycle inventories for electronic components and modules (Ecoinvent 2010). Many of them are on a general level, such as "integrated circuit, IC, logic type" or "transistor, unspecified, at plant." The task of the analyst is then to find the most appropriate inventory item for estimating the upstream impacts of each component. Because of the limited amount of available life cycle inventories, this stage requires aggregating the individual subassemblies, which introduces further error to the assessment.

The manual disassembly and individual identification is time consuming and error prone. It is difficult to identify many of the subassemblies and a misclassification of a component might have considerable impacts on the whole analysis. For example, all of the neodymium in a smartphone is contained in the vibration unit, which on the outside will look like a small black cube connected to a rod. If it

gets grouped into general electronic components, a large share of the emissions associated with the mining of very rare elements is ignored.

Some of the efforts of manual disassembly can be avoided if a teardown report of the product can be obtained. These are commercially available for many new products from vendors such as IHS ISuppli. A teardown report will show a step-by-step disassembly of the product and identification of the subcomponents. Some teardown reports also present the costs of the identified components and a bill of materials. Intended for product developers and electronics repair companies, the teardown reports can be used as a basis of the primary inventory data for an emerging product. However, teardown reports are usually available only for products that are entering the growth stage.

From the viewpoint of product carbon footprinting, in both manual disassembly and teardown reports there are two critical issues to be discovered: the number of layers in the printed circuit board (PCB) and die area of the processor. The printed circuit board and the integrated circuits of the processor are the main contributors to electronics carbon footprint (Williams 2011) and they are dependent on the layers of the wiring board and the actual "die area" of the circuits. Processors contain silicon wafers, on which integrated circuits are etched. These etched areas are then called dies and are covered in protective casing and wiring to produce processors for electronics assembly. The manufacturing of the high-purity silicon is the most energy-intensive stage of the process and determines the environmental burden of the processor. Unfortunately during disassembly, the die area can be determined from within the processor only through x-ray microscopy. Therefore, for carbon footprinting purposes, either care must be taken to obtain a teardown report with the die area identified, this analysis has to be conducted separately, or a considerable amount of uncertainty has to be tolerated in the inventory.

With new and emerging products, many of the subassemblies do not yet have life cycle inventories. Examples of these would be the touchscreens and the new generation of processors found in smartphones. A proxy for the missing inventory item has then to be used. In the life cycle assessment (LCA) literature, hybrid-LCA based on economic input–output data is often recommended to fill the gaps in the process-based LCA (Suh et al. 2004; Lenzen and Crawford 2009). Previously, the economic input–output data have often been outdated and based on very aggregated results (i.e., electronics instead of communications equipment) (Lenzen 2001). With the introduction of new multiple region input–output models (MRIO), these problems have been largely avoided. The EORA database (www.worldmrio. com) contains, for example, carbon footprints for products manufactured in China with a resolution of 123 industries and from the year 2009.

However, for the purposes of high end new electronics, even the new disaggregated models may be too aggregated. Using the EORA data, the carbon footprint of \$1 worth of communications equipment from China is about 1.4 kg CO_2 eq. The bill of materials for a low end smartphone is approximately \$150, amounting to 211 kg of CO_2 eq. This figure is almost four times the amount reported for the iPhone 5 and almost twenty times that reported for the Lumia. The error is caused by the aggregation of low-volume/high-value and high-volume/
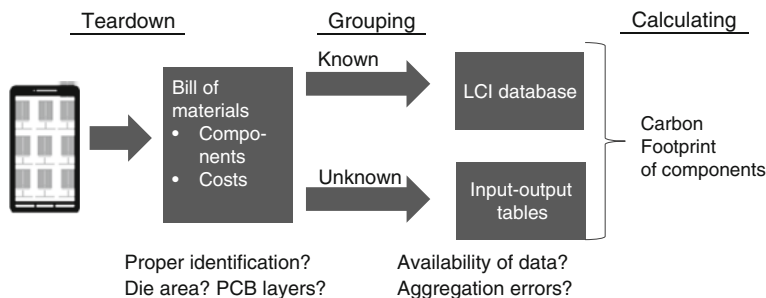
Fig. 2 An outline of the process for obtaining a carbon footprint for a new electronic device. The questions represent critical questions for minimizing the uncertainty of the study

low-value goods in the sector of communication equipment. The sector includes goods such as modems, cables, televisions, radios, and landline telephones, which have a large volume and a low value. The sector also includes smartphones; therefore, if the burdens are allocated to final products based on their economic value (as is commonly done in input–output analysis), the high-value products will get a disproportionate share of the total burden. Due to the aggregation errors in assessing high-value electronics, the focus should be on actually identified components and input–output analysis should be only used to estimate the magnitude of those components, which cannot be identified.

Figure 2 presents and overview of the recommended procedure for constructing and inventory for a new electronic device, when a company's inside information is not available. The main sources of uncertainty and critical questions are also presented. Because the main causes of uncertainty are due to human nature (identification and choices of aggregation), the process should be extremely well documented to maintain a level of transparency in the end results. Unfortunately, this is not commonly done, resulting in several factors of variation in smartphone carbon footprints, although the same methodology (ISO standardized LCA) has been used for all products (Table 1).

3 What are the External Influences to Networks and Servers?

In the published environmental product declarations of smartphones (Table 1), the use phase is dwarfed by the large emissions of manufacture. This could indicate that the role of the user is not important in the overall life cycle. However, the environmental product declarations include only the direct electricity consumed by the device during its use. In reality, a smartphone requires a considerable amount of infrastructure to provide its services. Networks and data centers are required to provide internet access and to allow phone calls. Data are more commonly stored

Fig. 3 The services and data storage properties of a smartphone are currently increasingly being covered outside the actual device in "cloud" storage and computing. See text for details on calculating the footprints for each part

7-99 kg CO_2 eq.

16-75 kg CO_2 eq.
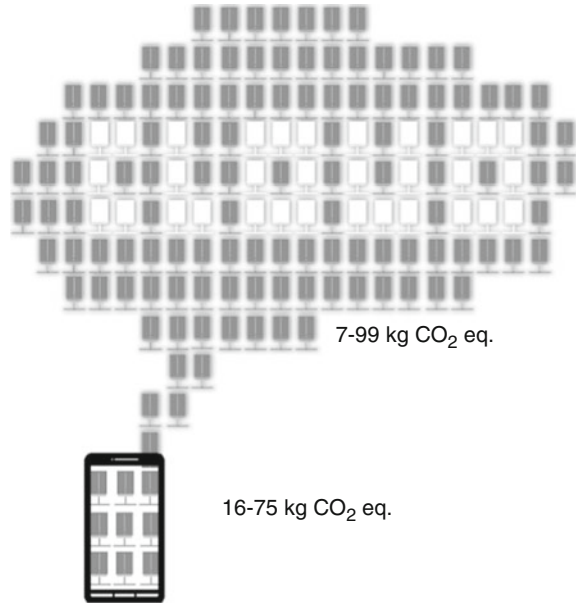
outside the phone and, also in an increasing manner, computation is done outside the device. For example, Google provides navigation services with Google Maps, which operate on distant servers. This "cloud computing" infrastructure cannot operate without energy and forms an integral part of the life cycle energy demands of mobile ICT technologies.

Figure 3 presents an illustration of a smartphone as a product, which is only partially represented by the physical phone. Most of the services required by the smartphone user are provided by the infrastructure outside the actual product. This requires a radical rethinking of the scope in environmental product declaration. If the product is useless without the infrastructure, then the infrastructure is an essential part of the product and should be included. Unfortunately, very few studies have been done on the carbon footprint of server computing and data transfer.

The order of magnitude of data transfer can be captured with a straightforward calculation based on published results. An average smartphone produced in 2012 342 MB of data traffic per month (Cisco 2013). Using published estimates for internet traffic electricity demand (7 kWh/GB) (Weber et al. 2010), this would amount to 86 kWh over the 3 years considered in the environmental product declarations (Table 1). Assuming similar carbon intensity for electricity than used in China (Ecoinvent 2010), the carbon footprint of this data traffic would be 99 kg CO_2 eq. This figure is larger than the rest of the carbon footprint (75 kg CO_2 eq.) reported for an iPhone in the environmental product declaration (Apple 2012) and an order of magnitude higher than the figures reported for the use stage (Table 1).

In addition, the data transfer of smartphones has increased 81 % per year (Cisco 2013). With development in technology, the data transfer has increased also

nonlinearly. Modern tablets produce twice as much data transfer as smartphones and 100 times the data transfer amounts of regular mobile phones (Cisco 2013). Also, an increasing amount of the data transfer is associated with cloud storage (uploading data for remote storage). With cloud storage, there is a substantial amount of "indirect" data transfer as data are also stored in backup copies, refreshed, and kept ready for immediate access.

Compared to local data storage, cloud storage will also increase energy consumption, even when data are not transferred. With local data storage on a computer hard drive, the hard drive is operating only when the computer is on and data are retrieved. In cloud storage, in order to maintain instantaneous access, the hard drives have to be on constantly. Also, the centralized hard drive racks require active cooling, which typically consumes more energy than the local hard drive, which can be passively cooled (Greenpeace 2013).

In spite of these hindrances in cloud storage and computing, there are some results that might suggest that cloud storage in a public cloud can be the most efficient way to provide services to a computer user. This is due to high utilization rate in servers and the rapid rate of updating servers to more efficient models (NRDC 2012). The range in data service provision per one office user per year ranged from 1 to 45 kg CO_2 eq. depending on the extent of outsourcing and modeling choices. The range in cloud computing was 1–15 kg CO_2 eq., making it plausible to claim that cloud computing may reduce overall emissions (NRDC 2012).

Although cloud computing may reduce the emissions of existing computing needs, it also has a great potential to increase computing needs, therefore offsetting the positive development. For example, the possibility of mobile access to video has increased data traffic considerably, with more than half of all internet video traffic now being associated with mobile devices (Cisco 2013). These aspects are problematic for carbon footprinting because they depend greatly on consumer behavior, which is the topic of the next two sections on recycling and on induced consumption.

4 What is the Effect of Consumer Behavior on Recycling?

Usually in product carbon footprinting of electronics, a full recycling rate is assumed (Apple 2012; Nokia 2012). In reality, however, only 5–12 % of the phones are reportedly recycled (Table 2). This has several implications for the product carbon footprint.

First of all, what has happened to the phones that were not recycled? Most of them have been initially stored as a spare, but eventually some of them might have ended up in waste incineration. In that case, the approximately 30 g of plastic in the phone is oxidized to carbon dioxide, resulting in an increase of 0.07 kg CO_2 eq. per phone. Compared to the overall carbon footprint of the product, the amount of (carbon dioxide) emissions from combustion of plastics is insignificant.

Table 2 Results from a global study on what people had done with their previous phone (Tanskanen 2012)

	Developed countries %	Developing countries %
Kept as a spare	40	32
Gave to friend/family	18	24
Traded for a new phone	9	16
Lost/stolen/broken	7	17
Recycled	12	5
Other	14	6

A more considerable effect is caused by the resources lost by non-recycling. The difference between primary and recycled aluminum for example is approximately 11 kg CO_2 eq./kg. The loss of aluminum from recycling would then increase the carbon footprint of an iPhone 5 by 0.23 kg CO_2 eq., which is again quite insignificant compared to the whole footprint. For steel and plastics, the difference between primary and recycled secondary materials is even less, so overall the lost resources are not a key issue for carbon footprint.

An exception might be the rare and precious metals, such as gold, silver, platinum, indium, and neodymium. Typical amounts found in a smartphone are presented in Table 3, together with an estimate of the potential emission savings from their recycling. Overall, the benefit from recycling could be approximately 1 kg CO_2 eq., which would be of same order of magnitude as the emissions caused by the recycling activity (Table 1). Most of the recycling benefits would come from the recovery of gold, silver, palladium, and copper. Of these, gold is the most significant, covering more than half of the overall benefit. No emission figures were available for neodymium, but neodymium is also not currently recovered in recycling (Reck and Graedel 2012). The potential emission saving is therefore not completely known, but would seem to be of such a scale that recycling should be better included in carbon footprint studies, preferably based on actual recycling behavior.

Table 3 Typical amounts of metals found in a smartphone (Villalba et al. 2012) and the potential benefit of their recycling (Ecoinvent 2010). All numbers are per one smartphone

	Amount in a typical smartphone (g)	Potential savings from recycling (g CO_2e)
Copper	13	62
Nickel	1.5	14
Tin	1	17
Silver	0.37	157
Gold	0.035	623
Palladium	0.015	139
Platinum	0.0005	7
Indium	0.006	1
Total	16	1,013

The benefits of recycling could be increased if whole components could be reused. Currently, the printed circuit boards, memory modules, and processors are the main cause of product carbon footprint. If the products would be designed for active disassembly and component reuse, some manufacturing of electronic components could possibly be avoided. This is a key idea in so-called cradle-to-cradle design (Braungart et al. 2007). Nokia has experimented on the idea since the year 2000, but the concepts have not gotten to mainstream production (Tanskanen 2002). If implemented, active disassembly would enable removing the valuable components and subassemblies from a recycled smartphone in two seconds. This would allow the reuse of components, which are not affected by the product age or do not develop at a very rapid pace.

Overall, the uncertainties associated with recycling play a minor role in the smartphone life cycle compared to the impacts of data transfer or the inventories for missing components. If recycling could be restructured into reuse of components, it might have a considerable effect on the overall lifecycle. Also, the overall benefits of recycling can only be quantified when data on the rare metal (especially neodymium) mining and recycling is available.

5 How to Account for the Increases in Other Personal Consumption?

Since their introduction and especially after they have reached the growth stage, smartphones have changed the society in a number of ways. In a recent survey, *Time* magazine asked people around the world how mobile technology has changed their lives. Among the responses, a few are of importance for product carbon footprint: mobile phones have made it easier for businesses to reach customers and they have made doing business more efficient (*Time* magazine, 27 Aug 2012).

Both of these effects are caused by the fact that smartphones are *information* devices, and information is a powerful tool in increasing consumption and improving markets. Most of the traditional economic models were constructed on the assumption of perfect markets and perfect information. More recently, the behavior of markets under imperfect information has become a research topic, resulting in research on information economics (Stiglitz 2002).

Under perfect information, markets operate on supply, demand, and pricing. Increased demand for a product drives up prices, which increases supply until all demand is met. Under imperfect information, the consumers are not aware of all of their options and obtaining knowledge through research costs time and money. Many operators take the benefit of this information asymmetry by having higher prices than could be maintained if customers would know the whole market. (An example would be a hotel breakfast, which has a much higher price than what is usually found in any of the restaurants within a few hundred meters of the hotel.) In this sense, by withholding information, companies are able to keep consumers

in a state where they do not know about competing alternatives (Stiglitz 2002). This is why most companies participate in marketing and some large companies try to control marketing. It is also why information technology has had such an influence on consumption and production behavior.

The effects of smartphones on the economy can be explained with a simple model with two variables: information and available income. From the viewpoint of consumption, information can be seen as a resource. With no information about available products and services, there is no consumption. Also, with no consumable income, there is no consumption. When income increases, consumption increases only if the information about available consumables increases. With increasing income level, the level of consumption finally becomes limited by the availability of information. In the case that a consumer does not know of any additional products that would increase his subjective welfare ("utility") more than additional savings, the consumer will save the money for later consumption.

Smartphones and ubiquitous access to the internet are removing the constraints of information by providing a large and low-cost connection between producers and consumers. Consumers can compare options in the global market, therefore ensuring near-perfect information (assuming that search engines and filters of misinformation keep up with the development).

Some life cycle assessment practitioners have included the rebound effects of consumption to the analysis by looking at the impact on available income from the purchase of a product (Finnveden et al. 2009). This consequential LCA is usually done on money- or time-saving products in order to see whether the net benefit is lost by increases in consumption. Taking the information component into account, the purchase of a smartphone can either increase or decrease personal consumption, depending on where on the curve of Fig. 4 a consumer is. Figure 5 illustrates this issue further. The purchase and use of a smartphone will always move a

Fig. 4 A simple conceptual model for relating consumable income, market information, and consumption level
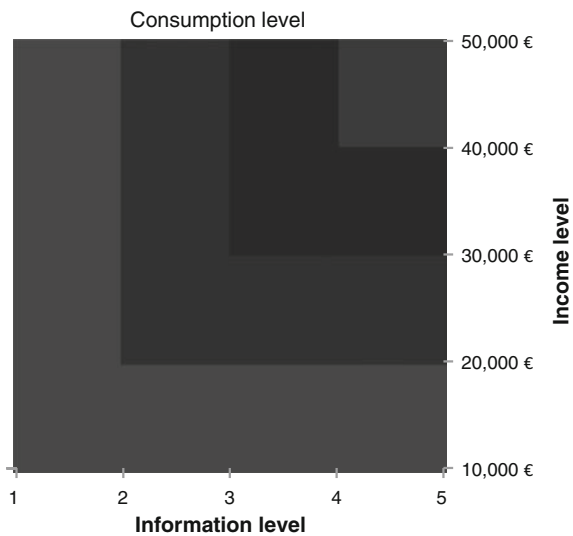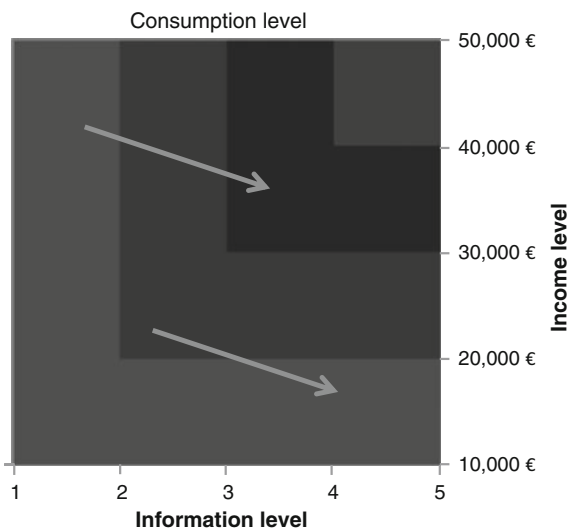
Fig. 5 An example of a smartphone either increasing or decreasing consumption, depending on the initial values of information and income levels for each consumer

consumer to a certain direction in the curve. With the purchase, money is consumed, so less money is available for consumption. At the same time, exposure to mobile media increases information about markets and consumption opportunities. If a consumer has a relatively high income but a low market information level, the purchase of a smartphone will increase overall consumption because more consumption opportunities are offered (Fig. 5, upper arrow). With lower income level and higher information level, the purchase of a smartphone may decrease consumption, as less is available for other purchases.

The effect of consumption can be considerable. The carbon footprint of an average European is 13 t CO_2 eq./capita (Steen-Olsen et al. 2012). A moderate 5 % increase would amount to 650 kg CO_2 eq., or almost an order of magnitude higher than the carbon footprint of an iPhone 5. Of course, it can be discussed whether the increased information can be allocated only to the smartphone or if the increased consumption can be tracked to improved information. However, generally it can be stated that mobile communication improves information flow and that increased information improves the functioning of the markets, which results in increased opportunities for production and consumption.

From the producer's viewpoint, smartphones and mobile internet offer other kinds of opportunities. The best documented case study is the introduction of mobile phones and internet to fishermen in Kerala, India (Jensen 2007). Prior to mobile phones, the local markets were highly inefficient. Fuel costs prevented the fishermen from circulating between docks and buyers had no information about the catch available at each dock. As a consequence, 5–8 % of the fish catch was dumped because it could not be sold; at the same time, buyers had to leave other docks without enough fish. With mobile phones, the dumping was eliminated, fishermen's profits increased by 8 %, and market prices declined by 4 %. Therefore, for producers, improved market information can result in growing economic activity. In the

best case, improved information increases production, which allows higher investments, which again increases production, resulting a spiral of economic growth due to better market information. Encouraged by the results in fishing industry, some ICT companies are now participating in case studies on introducing mobile internet services to fishermen to improve both market and production efficiency. Currently, the effect of mobile technology on economic development is a key research topic in economics (Donner 2008). Although currently there are no methods for quantifying the multiplier effects caused by increased information for producers, the issue should not be forgotten in carbon footprint studies. Again, a minor increase in regional consumption levels may have a carbon footprint that is an order of magnitude higher than that of the device itself.

6 Can Green Applications Offset the Other Emissions?

Mobile computing combined with GPS and social media presents very good options for improving environmentally conscious decision making. Because the main climate impacts of consumers are caused by activities other than smartphones (i.e., food, transport, housing) (Steen-Olsen et al. 2012), it is possible to offset the emissions caused by smartphone manufacture and use with so-called green applications.

The carbon footprint of an iPhone 5 is 75 kg CO_2 eq. (Table 1). This amounts to approximately 0.5 % of annual European consumers overall carbon footprint (Steen-Olsen et al. 2012). On the other hand, it corresponds to about 350 km of car driving. Many applications have been made that may reduce the distances driven with a personal car (Table 4). For example, Avego facilitates car sharing and may reduce driving by far more than the 350 km. Other applications focus on improving fuel efficiency, and on average driving habits resulting in a 2 % improvement in fuel economy would offset the emissions of manufacturing and using a smartphone.

Table 4 A sample of green applications from MyGreenApps (U. S. Environmental Protection Agency)

Application	Description	Reduction pathway
Avego, Carticipate,	Facilitates car sharing	Reduces personal transport needs
Get There by Bike	Recommends routes for urban cycling	Helps substituting cars with bikes on urban short trips
Green Gas Saver	Monitors driving performance and gives guidance	Improves car fuel efficiency through ecodriving habits
One Stop Green Mobile App	Building energy audit	Energy efficiency retrofits
Nexia Home Intelligence for iPhone	Remote controlling of home automation	Heating, cooling, ventilation, and lighting energy reduction
Locavore	Finds nearby farms, farmers markets, and seasonal food	Reduces the emissions from food consumption

Some applications aim to reduce emissions by improving home energy efficiency. This can be achieved either through environmental education for home owners concerning energy efficiency or through improved automation. Based on the energy carbon intensity in the United States (Ecoinvent 2010), a 100-kWh electricity savings would be necessary to offset the emissions of smartphone manufacture and use. This would represent approximately 0.7 % of the annual electricity consumption of an American citizen (World Bank 2013). With most of the electricity consumption related to air conditioning, improving the efficiency of house automation can have much higher emission savings than the emissions caused by smartphone manufacture.

Finally, some applications aim to educate consumers about green purchases. For example, Locavore gives information about local and seasonal food retailers based on current location. Combined with social media, this encourages people to shift their consumption habits.

Overall, many of the so-called green applications can have emission reductions that exceed the carbon footprint of the smartphone itself. However, a key issue in the potential of green applications is that not all smartphone users will use and benefit from them. For example, a large share of future smartphone users will be under 18 years old and therefore unlikely to make decisions concerning car fuel use or house ventilation. Therefore, on a larger level, it is unlikely that individual green apps would offset the whole carbon footprint of smartphones and their external impacts.

7 Summary

Overall, the carbon footprint assessment of smartphones was found to be much broader than what could be expected from the environmental product declarations. Many of the components are so new that no reliable background information about their emissions is available. In addition, the identification of hundreds of components and subassemblies is costly and difficult. Beyond the product itself, the use of smartphones requires a considerable amount of infrastructure in data transfer and storage. Based on most calculations, the external impacts are likely to be larger than the emissions of manufacturing and using the device. With the rapid development in the smartphone market, devices are becoming obsolete quite rapidly. Contrary to common assumptions, only a minor fraction of the devices is actually recycled. This results in a loss of resources, which if recovered could offset emissions in primary material production. However, the offsets are likely to be of minor importance. Smartphones and other information devices have great potential to influence consumer behavior. On one hand, the increased information will make more efficient markets and increasing both production and consumption. On the other hand, green applications can provide environmental education rapidly to a large group of consumers, potentially even offsetting the overall impacts of smartphone manufacture.

Based on this review, our recommendation is to include a quantification of the effects of data transfer through networks and data centers to all carbon footprinting studies related to smartphones or other mobile communications equipment. The data transfer seems to have a major impact on the results, so it cannot be ignored. On the other hand, the use of the smartphone may result in considerable emission savings through green applications. However, because these aspects depend largely on consumer behavior, they aspects should be treated with a high uncertainty in the analysis.

The carbon footprinting of mobile communications equipment is still developing. Even at this stage, it is very useful to identify the hotspots in the product life cycle, but the quantitative results may not be accurate until the product category rules have been defined and updated. Until that stage, it may be useful to separate the traditionally reported device manufacturing emissions from the more recent additions of data transfer and consumer behavior. The latter should not be excluded, however, because their impact dominates the overall life cycle.

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