TECHNOLOGY ASSESSMENT OF WIRELESS CHARGING USING LIFE CYCLE TOOLS

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Abstract: Smartphone market has experienced an exponential growth in the last decade. Numerous studies have modelled and characterised the energy consumption of smartphones using many approaches such as inner component consumption, network connection consumption or recharging process consumption. On the latter, extensive study has been carried out around conventional technologies of charging, but in the late years wireless inductive charging method has been increasingly popular, while little attention has been paid to it. This study aims to provide an overall insight into this technology by analysing its energy use and environmental impacts. For that, a life cycle approach is assumed, focusing in two areas: the chargers themselves as electronical devices and the impact that wireless charging compatibility has in smartphone design. As an outcome, the results characterize the environmental performance of this technology, opens up space for further investigation and suggests possible routes to improvement.

1. INTRODUCTION

Wireless charging technology has been around for a while in daily electronic appliances such as electric toothbrushes and other. In the latest years, the smartphone industry has started adding this feature in their devices, to the point that two official standards (Qi [1] and PMA [2]) exist nowadays in the market.

However, it was not until year 2017, when Apple announced that the new iPhone 8 and iPhone X models would support wireless charging technologies that the wireless charging market rocketed, the overall market reporting to grow up to 40 % in recent years [3] mainly fuelled by electronic appliances (primarily smartphones). However, literature has paid little to no attention to the energetic or environmental implications of such change.

This study aims to assess wireless charging technology for smartphones by performing a comparative life cycle analysis of a wireless charger as opposed to a conventional wired charger and a smartphone model with inbuilt wireless charger compatibility compared to a regular smartphone. This project involves empirical measurement and characterisation of wireless charging technology´s energy use.

2. GOAL AND SCOPE

This study´s pursued goals are the following:

- Studying comparatively the environmental impacts of wireless charging and conventional wired charging.
- Contributing to the characterization of wireless charging technology both in terms of energy use and environmental impacts.

For the complete life cycle analysis of both charging devices and smartphone models, the following boundaries are established:

Chargers. For the chargers the whole life cycle is considered: raw material extraction and device manufacturing, transport phases, use phase and end-of-life. Within the usage part, empirical energy-use tests of both wireless charger types are used as inputs for the modelling estimations. They will be explained in their own section in detail. For the production part, real devices were disassembled and used as a reference for the model.

Smartphone design. In the case of smartphone design, the focus is set on the changes needed in a smartphone model to make it compatible with this charging technology. Therefore, the LCA only includes the production and end-of-life phases, neglecting transport (because it is not affected by the phone design) and the usage (because it is already accounted for in the charger part). The models in this case are based on the Fairphone 2 LCA [4].

3. METHODOLOGY

In order to assess the environmental impact of wireless charging technology, two parallel procedures will be followed: empirical measurements of real energy consumption of such devices and a LCA study of the charging devices and the smartphone models.

For the energy use analysis, on-site tests have been carried out using several smartphones of different companies. Using the actual values of different charging parameters, the energy efficiency values for the wired and wireless chargers are obtained. Once those efficiencies have been derived, they are used to estimate the energy consumption, which is included in the broader LCA.

For the environmental assessment part, standard LCA procedure has been used. For this study, the ReCiPe impact methodology has been used, since it provides appropriate midpoint impacts.

The chosen functional units are, for the charger part, one charger to be used for one year and, for the smartphone part, one smartphone device (with and without inbuilt wireless charging capability) also to be used during one year. Additionally, the lifetime of both devices is assumed to be of one year.

3.1. Energy use

The main energy consumption of a smartphone can be understood as the amount of energy extracted from the grid while charging, since that is the energy that the phone will then use to run all its functions.

Previous literature on smartphone charging and energy use (see Heikkinen et al. [5] and Manchester et al. [6]) identify three *power levels* during the functioning of a charging device: charging mode, idle mode and no load mode. Although only the first one is energy that is actually transmitted to the phone and then used by it, the other two modes also appear during usage and represent actual energy consumption. Therefore, they are included in our measurements and models.

In order to measure those, the setup defined in the scheme shown in Figure 1 was used. Different smartphone models were charged using different charging models (both wireless and wired) and the parameters of the incoming electricity were monitored using a measurement device located between the charger and the grid. More specifically, three smartphone models were used, combined with three wireless chargers and three conventional wired ones. All devices represent various smartphone generations and battery sizes, which has an important effect on the results.

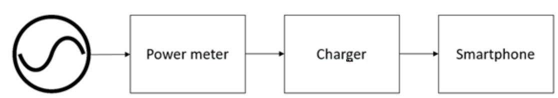

Figure 1 - Measurement layout scheme

The parameters measured by the power meter, in intervals of 5 seconds, are the following: grid voltage, grid current and active power. From those, the total amount of consumed energy was then calculated by multiplying the power measured for each interval with the time step. From there, the energy drawn from the grid is computed. The estimation of the efficiency is done by using the technical specs of the battery: multiplying the nominal tension and capacity we can get an idea of the amount of energy that the battery can store. Equation 1 and Equation 2 show this:

Equation 1 - Energy calculation

$$E_{total}(Wh) = \sum P_{\ interval}(W) \cdot \ t_{interval}(h)$$

Equation 2 - Efficiency calculation

$$\eta = \frac{V_{nom}\ (V) \cdot Cap\ (Ah)}{E_{total}\ (Wh)}$$

3.2. Life cycle analysis

Within this LCA two parts can be distinguished: the assessment for the charging device itself and on the one for the smartphone design and wireless compatibility. In both cases the study is comparative, that is, the aim is to study to what extent wireless charging technologies imply more environmental impacts compared to those conventional ones, rather than the absolute values.

For the LCA the GaBi software [7] has been used. The vast majority of the materials and processes are extracted directly form GaBi database and, occasionally, from Ecoinvent database (also available within GaBi). The modelling approach has been to identify and follow the bill of materials (obtained via disassembly of the components) of every device modelled and to use the aforementioned databases to account for the related impacts.

3.2.1. Manufacturing

In order to model the manufacturing phase of the chargers, real devices were disassembled, the composing materials identified and the different pieces weighted. The wired charger model is composed by an AC adapter and a USB cable, which are connected to the smartphone when charging (the phone not being included in the model). On the other hand, the wireless charger includes a wireless charging pad (with several pieces and elements in it, the transmitter being the central part) and also an AC adapter and a cable.

For both charger models, different devices were used as reference: a Samsung Induction Wireless Charger was disassembled in order to model the wireless charging pad. For the AC adapter, a unit by Samsung (which provides fast charge) was disassembled. Finally, the USB cable was not fully disassembled, but just weighted.

All the mechanical parts have been modelled by assigning the most suitable model from the GaBi database and rescaling it by mass. Passive electronic components have followed two different approaches: the ones that were big enough to be individually removed from the PCB and weighted were modelled using GaBi electronics library. On the other hand, the smaller ones were treated as unspecified electronics from the Ecoinvent database, their masses being estimated from their size. Finally, the integrated circuits were modelled using the package type and number of pins to choose a suitable model in the GaBi electronics database and then using die size to rescale them.

As for the smartphone design, no specific device has been used as reference for the model. Rather, starting from an already existing model for a non-wireless charged smartphone design (see Proske et al. [4]) various components have been adapted to turn it into a hypothetical wireless compatible smartphone device. The extra elements added for this wireless compatibility are: the receiver coil, the wireless charging chip and the back cover.

The receiver coil is the piece to which the transmitter induces the charging current. The receiver coil is composed by three elements: the coil, the flexible printed circuit (FPC) and the plastic cover. The coil and the plastic cover have been modelled as simple materials (copper and plastic respectively) and scaled by mass, using actual wireless compatible smartphone pieces as references. The FPC is a flexible cable connecting the coil to the motherboard. It is modelled as a one layer PCB.

The wireless charging chip refers to the set of electronic elements required to convert the AC current flowing through the coil into the DC current needed by the battery, as well as for the regulation of the signal. The charging chip fulfils that need. According to datasheets of actual wireless charging receiver chips by the main manufacturer of integrated circuit components for smartphones (Texas Instruments [8] and [9]) the following elements can be found within the chip: capacitors, resistors, thermistors, diodes, transistors and integrated circuits (tension regulators, rectifiers…).

Although different phones will most likely use different IC models and passive element set, this model is thought to be fairly representative since it involves all the elements needed for energy conversion and uses several references.

The back cover, the last extra element added to the phone design, accounts for the fact that, for a phone to be wireless charging compatible, it needs to have a non-metallic back cover (in order to avoid interferences in the energy transfer happening through it). Most commonly used in the industry are either plastic or Gorilla Glass [10]. For this study, we consider two base case scenarios: A reference phone with a plastic back cover (and therefore being no need to replace it) and a reference phone with an aluminium cover. As for the non-metallic cover in the wireless charging compatible model, the focus will be on the plastic cover option.

The aluminium cover was modelled using Aluminium 6003 alloy (AZO Materials [11]), one of the most common alloys in smartphone applications (Isalinis [12]) and then scaled by mass, which was measured from actual smartphone back covers and then adapted to the model´s dimensions.

3.2.2. Transport

Taking as a reference the approach from Proske et al. [4], the transport phase can be divided in three differentiated parts: to final assembly, to distribution hub and to customer.

Since both chargers modelled are based on Samsung devices, the publicly available information about Samsung´s manufacturing sites (Samsung Electronics [13]) has been used. China is chosen as the most representative production location. Also it is known that Samsung works with several testing and packaging sites (Samsung Electronics [14]) in China and South Korea, so it will be assumed that production is done in one place, and then assembly and packaging are done in another one. Therefore, in our model production is assumed to take place in Xi'an (China) and assembly and packaging in Onyang (Korea).

For the distribution hub, we focus on the European market. The main logistic hub for international companies in their entrance to Europe is the Netherlands [15]. Those include, of course, Samsung. Finally, the transport to customers it is not included in this study since not enough data was found in order to make solid estimations. The transport within a same country is considered to be done by truck. The international transport is modelled to be by plane.

3.2.3. End of life

The EOL is a phase considered in both parts of the LCA (chargers and phone design). The modelling approaches for both have been a little different.

For the phone design, the end of life scenario has been modelled after the one presented in Proske et al. [4]. This approach basically considers just two parts of the recycling: the battery removal and the metal recovery. In our case, the battery removal is not considered since the new components necessary for the wireless charging compatibility do not affect this process and therefore is not interesting for comparative purposes. The metal recovery, however, is indeed affected by those and is taken into account.

For the chargers, the modelling approach has been based on the bill of materials. No transport process is considered during the EOL phase. The metal recovery processes have been modelled the same way as in for the phone design and the rest of the processes have been extracted from GaBi database. Any recovery process not found in the database has been neglected.

4. RESULTS

In this section the results of both parts of the study will be presented. Regarding the energy use, first the energy efficiency levels during charging process will be explained. Also, the idle and no load mode consumptions will also be shown.

As for the life cycle analysis, we focus on the following environmental impacts:

- Climate change (excluding biogenic carbon), measured in *kg* CO_2*-eq.*
- Human toxicity, measured in *kg-1,4-DB-eq.*
- Freshwater ecotoxicity, measured in *kg 1,4-DB eq.*
- Fossil depletion, measured in *kg oil eq.*
- Water depletion, measured in m^3.

These categories are covered by the ReCiPe 2008 LCIA methodology. This methodology gives three cultural perspectives according to which estimate the conversion factors to calculate the endpoint impact categories. Those perspectives are based on choices such as time horizon, expected technological advance and so on, as described in Goedkoop et al. [16] . In this study the egalitarian point of view was chosen since it represent the most conservative point of view, based on the precautionary principle.

Not all those impacts will be equally relevant throughout the life cycle and the different processes and phases, but in general they provide a complete insight to the environmental effects of the devices.

This paper will focus mainly on the results related to manufacturing and energy use, since those are the most complete parts of the model as well as the most affected by the technology change. Although, as mentioned, transport and EOL are part of the overall impacts consideration, no more detailed analysis will be provided regarding those.

4.1. Overall overview

First of all, we will take a look at the overall impacts of the two technologies and then we will look into more detail to the different life cycle phases identifying possible hotspots. Table 1 shows the overall impact values.

Table 1 - Absolute impact values for smartphone life cycle

Impact category	Reference	Wireless
Climate change	32,4 kg CO2 eq.	32,4 kg CO2 eq.
Human toxicity	65,9 kg 1,4-DB eq.	73,6 kg 1,4-DB eq.
Freshwater ecotoxicity	0,103 kg 1,4-DB eq.	0,122 kg 1,4-DB eq.
Fossil depletion	2,8 kg oil eq.	2,81 kg oil eq.
Water depletion	21,7 m3	17 m3

In some cases, like fossil depletion or water depletion, the actual overall impact is lower in the case of the wirelessly rechargeable phone model than in the reference model.

Although this may seem as a contradiction, the key point here is the back cover. As metallic back covers are not compatible with wireless charging one of the changes in design considered was the change in the back cover material. It turns out that this change in the back cover has impacts that outrange the ones of the wireless compatibility itself. Figure 2 shows the impact of water depletion (the most representative) only for the back cover part in each model. It can be seen how the plastic cover has much less impact than the reference cover, made out of aluminium.

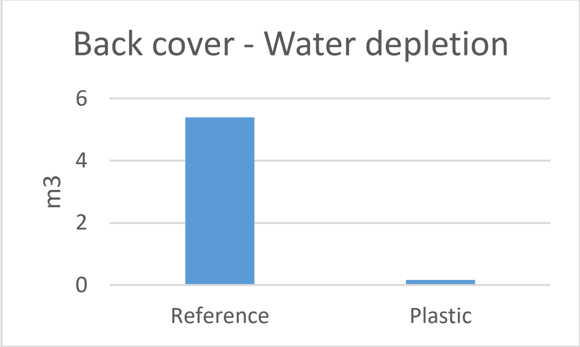

Figure 2 - Overall impact comparison (water depletion) for back cover

Therefore, to see more clearly the effects on the life cycle impacts related to the addition of the new elements of wireless charging compatibility, we established a plastic cover on the reference model, so that there are no such interferences.

Table 2 - Absolute impact values for smartphone life cycle (same back cover material)

Impact category	Reference	Wireless
Climate change	32,3 kg CO2 eq.	32,4 kg CO2 eq.
Human toxicity	65,8 kg 1,4-DB eq.	75,7 kg 1,4-DB eq.
Freshwater ecotoxicity	0,103 kg 1,4-DB eq.	0,131 kg 1,4-DB eq.
Fossil depletion	2,78 kg oil eq.	2,79 kg oil eq.
Water depletion	16,5 m3	17,1 m3

As for the chargers themselves, the increase of environmental impact is much more noticeable. In all categories the impact is around or even above two times higher (see Table 3).

Table 3 - Absolute impact values for chargers life cycle

Impact category	Wired charger	Wireless charger

Climate change	6,24 kg CO2 eq.	11,8 kg CO2 eq.
Human toxicity	9,59 kg 1,4-DB eq.	21,8 kg 1,4-DB eq.
Freshwater ecotoxicity	0,015 kg 1,4-DB eq.	0,0399 kg 1,4-DB eq.
Fossil depletion	1,72 kg oil eq.	3,48 kg oil eq.
Water depletion	25,4 m3	40,7 m3

4.2. Energy use

Throughout all the tests performed a difference of around 24 % was observed in the charging efficiency of both technologies.

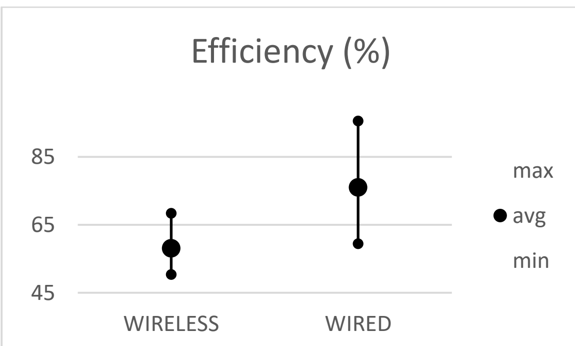

Figure 3 - Charger efficiency span

The conventional wired chargers show a mean efficiency of around 76 % during charge, while the wireless ones show a more modest value of 58 %. However, different chargers and smartphone models were used and these differences affect efficiency too, as shown in Figure 3. As seen, in some cases wireless charging can actually achieve higher efficiency values than wired charging. This is because power management within the phone itself has a great deal of relevance for charging efficiency.

Tests were also run for the idle and no load modes. Figure 4 shows, for example, the idle powers measured for phone 3 in tests performed with different chargers. In red, the wireless chargers are shown, in blue the conventional ones. As it can be seen, although each charger has a different idle consumption (suggesting again the important role that power management plays), in any case wireless chargers show a higher value, even if the difference is minimal. Using an average value through all the chargers, we can summarise it as shown Table 4.

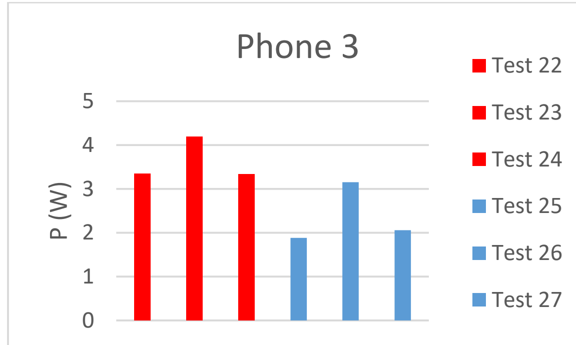

Figure 4 - Idle power comparative, phone 3

Table 4 - Idle power summary

Charging technology	Average idle power (W)
Wired	1,09
Wireless	2,78

The measured no load average values are presented in Table 5. It shall be noted, however, that the wireless chargers showed much higher variability between different models (in a range of around 0,2-0,4 W no load power) while all the wired chargers were much more uniform.

Table 5 - No load power summary

Charging technology	Average no load power (W)
Wired	0,078
Wireless	0,294

In order to estimate the amount of energy consumed by a wireless charger in daily operation, a recharging schedule needs to be fixed. That is, an estimation on how frequently a phone is charged and for how long. A study on user recharging habits by Ferreira et al. [17] reports an average charging duration of almost 4h, ranging from 2h to over 14h in some cases. In terms of no load behaviour, the study shows a predominant trend of around 5h of no load situation per day. Some other sources aiming to measure smartphone energy consumption also characterised user recharging behaviour. While Heikkinen et al. [5] estimated less than an hour of charging and around one more hour of idle (being the rest of the day in a no load state); Bento [18] reports around 5 h of charging and idle processes followed by 5 minutes of no load. As it can be seen, different sources get to notably different conclusions.

With the aim of being as representative as possible, the following scheme is assumed in this study:

- One overnight charge per day, from 0 % to 100 %.
- The overnight charge is assumed to last 8 hours, from which the charging time is deduced from the performed tests and the rest is assumed to be idle mode.
- The charger remains plugged the whole day, so the remaining 16 h are for no load mode. This may not be all that common when it comes to conventional wired chargers, but it is definitely the way in which wireless chargers are thought to be used.

Due to the variability in the efficiency values of the two charging methods we will be considering different scenarios. Those scenarios are based in the range of charging efficiency values presented in Figure 3. Based on those and on the use profile, we can create three consumption profiles, presented in Table 6.

Table 6 - Final estimated scenarios

	Wired daily (Wh)	Wire-less daily (Wh)	Wired yearly (Wh)	Wireless yearly (Wh)
Average	19,96	29,59	7286,14	10800,3
Minimum	17,49	27,2	6385,04	9928,78
Maximum	23,35	32,02	8522,84	11688,46

4.3. Life cycle analysis

4.3.1. Manufacturing

In terms of smartphone design, the wireless charging compatibility represents a variable fraction of the overall impacts, ranging from less than 1 % in some impact categories to up to 15 % in others.

Table 7 - Relative and absolute impact values of manufacturing (phone design)

Impact category	Relative contribution of wireless compatibility	Absolute impact values
Climate change	1 %	2,48E-1 kg CO2 eq.
Human toxicity	11 %	8,25 kg 1,4-DB eq.
Freshwater ecotoxicity	15 %	1,51E-2 kg 1,4-DB eq.
Fossil depletion	3 %	8,05E-2 kg oil eq.
Water depletion	3 %	6,02E-1 m3

Going more into detail in the wireless compatibility, highest impacts are related to the wireless charging chip, representing, in all impact categories, the greatest share of the related value and surpassing in most cases 90 %.

Alternatively, the RX shows a much more volatile inner distribution of the impact share, with very varied compositions depending on the analysed impact. However, in most cases it represents less than 0,5 % of the total smartphone impacts.

This being all regarding phone design, the manufacturing impacts for the charging devices shall be commented in the same fashion: in Table 8 a comparative of both manufacturing impacts can be seen, both ranging a relative difference of around 70 % in the greatest case (climate change) and 60 % in the lowest (human toxicity).

Table 8 - Chargers manufacturing impact values

Impact category	Wired	Wireless
Climate change	0,899 kg CO2 eq.	2,86 kg CO2 eq.
Human toxicity	4,99 kg 1,4-DB eq.	12,4 kg 1,4-DB eq.
Freshwater ecotoxicity	0,00528 kg 1,4-DB eq.	0,0166 kg 1,4-DB eq.
Fossil depletion	0,31 kg oil eq.	1 kg oil eq.
Water depletion	1,62 m3	5,28 m3

In all the impact categories studied, the charging pad has a greater contribution than the cable and the adapter together (see Figure 5). The charging pad contains the transmitter system. This system is basically composed by a transmitter coil and the power management circuitry (ICs and some passive elements). Similarly, in the adapter part of the charger the assembled PCB within is the element with the highest impact.

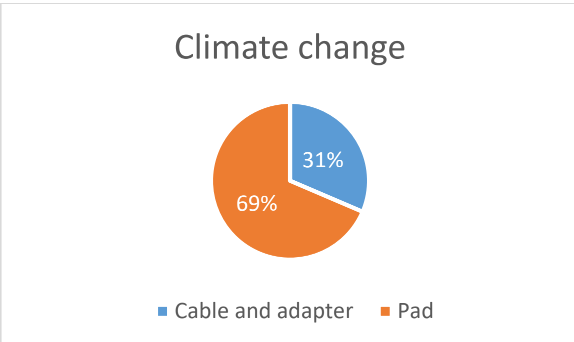

Figure 5 - Climate change impact contribution in wireless charging manufacturing

4.3.2. Use phase

In Table 9 the values for impact categories are presented for all usage scenarios. Noticeably, there is a big difference between both technologies, being the minimum consumption scenario for wireless charging still more impactful than the worst case scenario for wired charging.

Table 9 - Use phase impact values in the three defined scenarios

Impact category	**Wired**	**Wireless**
Climate change (kg CO2 eq.)	Max: 5 Avg: 4,27 Min:3,75	Max: 6,86 Avg: 6,34 Min: 5,82
Human toxicity (kg 1,4-DB eq.)	Max: 3,37 Avg: 2,88 Min: 2,53	Max: 4,63 Avg: 4,28 Min: 3,93
Freshwater ecotoxicity (kg 1,4-DB eq.)	Max: 0,00119 Avg: 0,00102 Min: 0,000894	Max: 0,00164 Avg: 0,00151 Min: 0,00139
Fossil depletion (kg oil eq.)	Max: 1,21 Avg: 1,04 Min: 0,908	Max: 1,66 Avg: 1,54 Min: 1,41
Water depletion (m3)	Max: 27,6 Avg: 23,6 Min: 20,7	Max: 37,8 Avg: 35 Min: 32,1

5. CONCLUSIONS

Environmental impacts of wired charging are under almost all conditions lower than impacts of wireless charging. Product durability of smartphones without a charging port might be better, but life cycle impacts for same assumed product lifetimes are higher for the wireless version.

5.1. Phone design

The main driver for the wireless compatibility impact are the electronics, composed by passive electronic elements and integrated circuits. This is consistent with other LCA results like Proske et al. [4] in which the electronic elements are reported to be much more impactful than other elements like framing materials. The end of life phase, at least in the way it has been modelled in this study, has almost no effect compared to this of the production phase.

When the reference smartphone had an aluminium cover and this was replaced for a glass or plastic cover, the overall impact of the inbuilt wireless charging smartphone could actually be smaller than the reference case for some impact categories. Nevertheless, electronic components and ICs are a hotspot of the environmental impacts of smartphones, and wireless charging compatibility requires more and better circuitry, therefore resulting in more severity on such hotspots. The results for the same back cover case confirm this.

5.2. Chargers

For the chargers, there is a clear difference in impacts between the wired and wireless charger production, which can be significant in some impact categories. The charging pad takes up almost 70 % of the impact contribution, making the overall values significantly higher. The main driver within the pad is the assembled

PCB, followed by the adapter´s PCB. Again, as seen in the case of the smartphone, the electronic components, the ICs and the printed wiring board are the outstanding elements in terms of environmental impacts. Therefore, any improvement involving a reduction of die size or reduction of the amount of required components would have a significantly positive effect on the production impacts.

As for the energy use, there are some noteworthy observations. Firstly, by an average difference of 26 % in charging efficiency, the accumulative energy use difference between wireless chargers and conventional ones is high. However, this study has shown a considerable variability in the energy use data, suggesting the complex nature of the process. In fact, one of the main findings is that the power management strategy of the smartphone itself affects importantly the charging energy consumption, being therefore one of the main areas for improvement. Also it is noticeable the difference in no load consumption for both charger types, especially considering that wireless chargers by their predictable usage behaviour will remain most of their time plugged but with no phone connected. Although in absolute terms the differences are small (0,5 kWh per person per year) the cumulative effect in the large scale it is still to be considered.

In overall impact terms, the use phase varies from low to medium share in the impacts. Anyway, in this model the use phase was assumed to last one year of daily use. Depending of the actual lifespan of the charger the share may increase substantially. Under those conditions, main drivers are production and transport. Being transport not really dependent on the technology of the charger (wired or wireless), it is clear that an improvement in the life cycle shall target the production and the usage. Also, wireless charger can double the impacts of the conventional ones, meaning that there is a great room for improvement.

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