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# Environmental Impacts and Benefits of Smart Home Automation: Life Cycle Assessment of Home Energy Management System

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*Abstract*: This paper discusses the life-cycle environmental impact of Home Energy Management System (HEMS), in terms of their potential benefits and detrimental impacts. It is the expectation that adapting smart home automation (SHA) would lead to reduced electricity usage in the household and overall environmental advantages. The purpose of this research was to quantify the negative environmental impacts of SHA and balance them with their benefits. The evaluation of SHA has been done by conducting a generic Life cycle assessment study using SimaPro programme and the EcoInvent database. The LCA study concluded that the largest environmental impact of HEMS is the use-phase electricity consumption of home automation devices. The paper concludes that the energy payback time of home automation in term of the electricity consumption of the devices is negative by 1.6 years. The largest part of this is due to the energy consumption of smart plugs. Therefore, the paper concludes that in terms of home automation, we need to find the balance between what we actually need to control and the resulting energy consumption of the control system.

*Keywords*: Energy Management System, Environmental Engineering, Life Cycles, Smart Power Applications, Environmental Impact of Automation.

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## 1. INTRODUCTION

Smart home automation (SHA) refers to the control of home appliances and it is an integral part of smart grids. It is the expectation that adapting SHA would lead to reduced energy usage in the household and overall environmental advantages. However, the components of the SHA system also contribute to life-cycle impacts. The purpose of this research was to quantify the impacts and balance with benefits. The evaluation has been done by conducting a generic Life Cycle Assessment (LCA) methodology.

## 2. PREVIOUS RESEARCH

Environmental impact assessment of technology has been recurrent and fully used for the EuP Directive. Quantifying the environmental impact of the smart grid is an on-going discussion (Hledik, 2009) as well as the role of smart metering in carbon management (Darby, 2013). Prior research has developed a simulation tool for modelling the electricity consumption within detached houses in Finland (Louis, 2012; Louis et al., 2013). It creates synthetic hourly electricity consumption comprising 21 appliances and based on the usage profile specific to a country. The research showed that the use of home automation system could have a positive impact on the local peak load demand and reduction of energy consumption. Later research focused on the environmental impact of home automation by using hourly emissions from the electricity generated in Finland (Louis et al., 2014). The research showed that the home automation could have a positive environmental impact by decreasing the peak load and shifting part of the energy consumption from daytime to nighttime. It has been found that on a 1-year modelling, a 4-persons house emits 543 $kgCO_2/y$ and the home automation reduced the emissions to 473 $kgCO_2/y$, therefore a 70 $kgCO_2/y$ taken away from the basic profile. In order to fully implement a Home Energy Management System (HEMS), multiple sensors are necessary for recording climatic data, or the energy consumption within the house precisely enough to know where are the energy leaks and accurately assess the potential for energy reduction and decrease in emission levels.

## 3. METHODOLOGY

LCA is a method used to analyse the environmental impacts of a product throughout its lifetime. A life cycle starts from obtaining materials from the nature, continues with processing and transporting the material, manufacturing, delivering, using,

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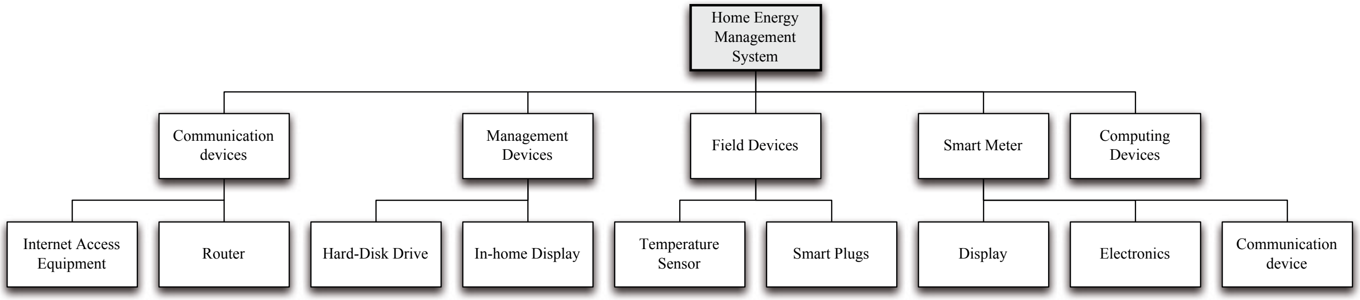


Fig. 1. System boundaries of the house studied

reusing, repairing and recycling the product, and ends when the product is discarded. LCA is one of the techniques developed to better understand and address the environmental impacts followed from these steps. The purpose of this generic LCA was to assess the environmental load of an energy management system in a dwelling. For this matter, we have considered different elements to be present in the house. For modelling purposes, it is possible to take away elements of the system and therefore make it more flexible to model. The system has been built according to the ISO 16484-2 (CEN, 2004) and a previous study on the evaluation of the environmental impact of three types of home energy management systems (van Dam et al., 2013). It has been decided that the system will be split up into five main segments as represented in Fig. 1.

The first segment, the smart meter, is common to all type of houses. In case of carrying out the LCA assessment for using such technology, it could be assumed that the smart meter should not be included in the scope of this study because most of the buildings are equipped with it. Therefore, when comparing the added value of home energy management system, the smart meter element could be left out from the scope. Nevertheless, for the purpose of this study, it has been included.

The smart meter element has been selected from Elster Company (Elster REX2, (IFIXIT, 2014)). It includes multiple elements such as the casing, the display, the electronics and the communication devices. The smart meter is collecting information within the house. It can be done at the appliance level in case smart plugs are installed. Each appliance need a smart plug to record and transmit the information to the smart meter. Having smart plugs is optional and, therefore, the electricity consumption is recorded at the end-point. Smart plugs are part of another segment that compose the energy management system that is the field device segment. The field devices group all the electronic equipment and/or communication equipment that allow the recording and control of appliances. Field devices are connected to the smart meter and to the management devices. Field devices also include technology such as an external temperature sensor. The management devices, the third segment in the energy management system, include the in-home display, the hard drive for storing the information, and the computing power for processing the data. Two main streams for retrieving energy consumption in houses are used: web based, or with in-home display. In-home display is optional in a way that another existing display can be used for retrieving the information regarding the energy consumption. When a web-based system is used, it can be assumed that it is using an existing computer that the users are already using for another purpose. Once information are gathered, they should be processed for integrating the home automation to the network. For this matter, a computing device should be available all the time. It is possible to use an existing computer but it should be noted that it will be active 24/24. Finally, a communication device is required for transmitting the data internally (to the plugs or appliances), and externally (to other users or to a centralised aggregator). It is assumed that it requires an internet connection although other types of communication system for smart metering device exist such as the GSM/LTE networks.

The inventory is using the EcoInvent 3.01 database and therefore, the related assumption to its database are included. Assumptions are made and are highlighted in each section.

### *3.1 Smart meter*

The smart meter is considered to be a permanent part in this system. We considered an existing smart meter. We were limited with the amount of information available, especially in terms of elements present and their quantities. In brief, we assumed that a smart meter is made of plastic for the casing, screws, a printed circuit, a communication device, and a small display. The section below details the quantities and specification for each element within the smart meter.

#### *1) Display*

As no knowledge about the precise specifications of each element that are embedded in the system, some assumptions have been made. The display material is an existing material in the EcoInvent database. Nevertheless, only the 17 inches version is available. Therefore, to approximately match the size of the display on the smart meter, the quantity of display has been divided by 17 in order to have an equivalent display of 1 inch. No processes have been included. Nevertheless, a general process for transporting the smart meter from the retailer place to the house could be included but is considered out of the scope.

#### *2) Electronics*

As mentioned earlier, the smart meter is a piece of electronic equipment that records a digital signal to send forward to a central unit (external or internal). The considered smart meter include the printed circuit accompanied by some copper and aluminium plates. There are also a couple of small electric wires. The quantity of copper is calculated using the following equation:

$$M_{copper} = V_{copper} \times \delta_{copper} \quad (1)$$

Where $M_{copper}$ is the mass of copper used [g], $V_{copper}$ is the estimated volume of copper [cm$^3$], and $\delta_{copper}$ is the density of copper 8.95 g/cm$^3$.

The amount of cable has to be given in terms of weight. It is assumed that an electric wire weight 2.5 g, thus both wires weight 5 g. A default value of 75 cm$^2$ is assumed to be the surface area of the printed circuit installed in the smart meter.

### 3.2 Communication devices

The communication device can be made separately from the smart meter. In this case, it is considered that the communication within the building and towards the outside require extra equipment. Therefore, it has been chosen that an internet access equipment and a router compose the communication device. Both devices are already existing in the EcoInvent database. Although it might be removed later on to be added in the MatLab simulation, the operation process grant a fulltime internet access resulting in a 4.2 W at 1 Mb/s internet rate exchange.

### 3.3 Field devices

Field devices are a set of two types of technology: the temperature and humidity sensor and the smart plug. It is considered that there are as many smart plugs as appliances in the house in case direct recording of the appliances is carried out in the house. It can also be used in the case appliances are controlled remotely. Usually, such technology uses WIFI (IEEE 802.11 protocol) for transmitting information to the central base and to receive information from the control panel (the interface by which the user is setting the specificities).

#### 1) *Temperature Sensor*

Any temperature sensor could have been selected. The environmental wall sensor has been randomly chosen among a set of technology. The Omega sensor (Omega, 2014) is able to record temperature and the relative humidity of the air. The specification given by the manufacturer are the dimensions, the quantities of elements present in the sensor and the total weight. The main elements from the sensor is its composition of plastic, assumed to be polyvinylchloride element with a total weight of 100g. Metal is used to fix the sensor and consists of aluminium 2 plates and 6 screws. The volume of a screw is assumed to be 0.1 cm$^3$ and the volume of a plate is assumed to be 3 cm$^3$. Using similar method as described in (1), using the density of aluminium of around 2.7 g/cm$^3$, it gives us a total amount of aluminium of 17.82g. Finally, it is assumed that the sensors are included in the printed circuit integrated in the casing of the sensor. Note that no processes have been integrated into the system.

#### 2) *Smart Plugs*

Smart plugs can read the electricity consumption of an appliance. Multiple manufacturers are offering technical solutions (Vuppala and S, 2013) but the principle is similar to all: a plug-in-a-plug system is inserted into the socket and read the current passing through. The information is then forwarded directly to a processor where the information can be analysed and further retrieved to the end-user through its in-home display. The processor can be internally or externally done. In this study, we considered that information are processed internally. Similarly to the temperature sensor, the smart plug is assumed to have specific weight. Three major components are assumed to be present in a smart plug: the pins, the casing, and the electronics inside the smart plugs (including the communication device). The pins are usually made of brass. The mass of brass included in the smart plug is calculated using the same approach than in (1). The volume of a pin is calculated using standard value (SFS, 2004) of a 5 A plug. Using a standard value for the density of brass of 8.5 g/cm$^3$, it gives us a total mass for 1 pin of 2.55g. The plastic casing surrounding the smart plug is considered to have a standard weight of 100g and made of PVC. The remaining parts of the plug are assumed to be made of a diode that changes colour depending on the state or message the plug want to transmit to the user, a radio chip that communicates the information to the central station, and the printed circuit for read and/or receiving information related to the electricity consumption.

### 3.4 Management Devices

As mentioned earlier, "management devices" is the set of devices that allow for retrieving, receiving, computing and storing energy information from the entire building. All units considered in this section are already existing devices in the EcoInvent database. They are not considered as having a mass and are therefore neglected when assessing the impact of disposal of the entire LCA of the house.

The management devices group is primarily made of an in-home display. Similarly to the smart meter display, the size of the display from the database is considered too large (17"). Therefore, a standard size of 4" has been arbitrarily selected for retrieving the information about the energy consumption and acting as the interface for inputting user preferences in the automation system. The management system is further composed of an external hard drive for storing historical information regarding the energy consumption. Finally, a processing device completes the set of management devices for processing the data (performed for the home automation part, and eventually to the statistical calculation of the energy consumption).

No processes are associated to the installation of the equipment in the house (transport from the store to the house, energy for installing each equipment, etc…). Also, no energy for running the devices has been introduced in the processes as it is considered to be integrated as part of the simulation. Every

**Table 1. Home Energy Management System material composition**

| Materials/Assemblies | Qts | Unit |
|---|---|---|
| ***Display*** | | |
| Display, cathode ray tube, 17 inches {GLO}\| market for \| Alloc Def, S | 0.059 | p |
| ***Electronics*** | | |
| Copper, cathode {GLO}\| market for \| Alloc Def, S | 14.3 | g |
| Cable, unspecified {GLO}\| market for \| Alloc Def, S | 5 | g |
| Printed wiring board, for through-hole mounting, Pb containing surface {GLO}\| market for \| Alloc Def, S | 75 | $cm^2$ |
| ***Communication devices*** | | |
| Internet access equipment {GLO}\| market for \| Alloc Def, S | 1 | p |
| Router, internet {GLO}\| market for \| Alloc Def, S | 1 | p |
| Operation, internet access equipment {GLO}\| market for \| Alloc Def, S | 24 | hr |
| ***Temperature Sensor*** | | |
| Screw | | |
| Aluminium alloy, AlMg3 {GLO}\| market for \| Alloc Def, S | 1.62 | g |
| Polyvinylchloride, bulk polymerised {GLO}\| market for \| Alloc Def, S | 16.2 | g |
| Printed wiring board, for through-hole mounting, Pb containing surface {GLO}\| market for \| Alloc Def, S | 30 | $cm^2$ |
| ***Smart Plug*** | | |
| Brass {GLO}\| market for \| Alloc Def, S | 2.55 | g |
| Polyvinylchloride, bulk polymerised {GLO}\| market for \| Alloc Def, S | 0.1 | kg |
| Printed wiring board, for through-hole mounting, Pb containing surface {GLO}\| market for \| Alloc Def, S | 30 | $cm^2$ |
| Inductor, miniature radio frequency chip {GLO}\| market for \| Alloc Def, S | 1 | g |
| Light emitting diode {GLO}\| market for \| Alloc Def, S | 1 | g |
| ***Management Devices*** | | |
| Display, liquid crystal, 17 inches {GLO}\| market for \| Alloc Def, S | 0.2353 | p |
| Hard disk drive, for laptop computer {GLO}\| market for \| Alloc Def, S | 1 | p |
| Computer, desktop, without screen {GLO}\| market for \| Alloc Def, S | 1 | p |
| Electricity, low voltage {FI}\| market for \| Alloc Def, S | | kWh |

details of the HEMS components are summarised in Table 1.

## 4. END-OF-LIFE MANAGEMENT SCENARIOS

In 2003, the European Community implemented the Waste Electrical and Electronic Equipment (WEEE) Directive (2002/96/EC), in order to control the end-of-life (EOL) management of electronic devices. The Directive defines general requirements to comply with mandatory collection and recycling objectives. Currently, the mandatory percentages stand at 75% recovery rates for IT and telecommunications equipment and a 65% re-use and recycling rate. Further to the WEEE Directive, electronic devices cannot be disposed through regular municipal waste management channels and cannot be directly landfilled. Consumers shall return their non-functional devices to designated collection points or retailers, from where the WEEE is transported to regional treatment plants. From the treatment plants, functional devices may be oriented for re-use, while the rest is sorted according to WEEE categories. As the devices such as those used in HEMS are not high value in terms of their material content, the most likely scenario is that they are sent for incineration. There is a small likelihood that larger devices (e.g. large surface area displays) are disassembled and valuable parts such as printed circuit board and hazardous parts such as the LCD screens are separated and sent for material recovery or treatment. In case of disassembly, non-recoverable parts might be sent for landfill disposal. However, since the HEMS Devices are rather plastic-rich, they are more likely to be incinerated, as landfilling of plastics is also phased out, further to the Landfill Directive (Directive 1999/31/EC) and its Waste Acceptance Criteria. Therefore, we assume that the smart meters, smart plugs and temperature sensors and other communication and management devices are 100% incinerated. Due to the limitation of the LCA programme, the most likely scenario of EOL management cannot be simulated. Therefore, the following EOL scenarios are used to best match the real-life conditions of electronics EOL management in Finland.

### *4.1 Smart meter disposal*

As explained in section 3.1, the smart meter is made off a display, electronics that support the processing of the information, and a communication device that allow the reception of information from outside and from the management devices, and send information to a third-party and to the management devices that will further process the information to make them readable to the end-users. Therefore, it means that each of the three sub-assemblies will be treated separately in the disposal scenario and will have their own.

Each of the four main components that makes the smart meter is disassembled. Therefore, there should be one disposal scenario for each of the disassembled elements. All of the sub-assemblies have been assumed to be considered as municipal waste that will be incinerated.

Transportation has been included in the disassembly phase, and no transportation has occurred between the disassembly phase and the disposal phase, meaning that the disposal has happened at the same place than the disassembly. Note also that the communication device does not have any impact because SimPro assumes that it has a 0 mass (taken from the database). Therefore, it is not included in the disposal scenario.

### *4.2 Smart plug disposal*

Smart plugs are made of three sub-assemblies: pins, plastic, electronics. Each of them are made of different substances as reviewed in section 3.3. Similarly to what is explained previously, each of the sub-assembly will be treated differently depending on their respective disposal scenario.

Smart plug disposal scenario works in the same way than for the smart meter scenario. As a starting principle, all waste generated from the smart plugs go directly to the incineration scenario established by the EcoInvent database.

### *4.3 Temperature sensor disposal*

Temperature sensor can be easily disassembled. As reviewed in section 3.3, the temperature sensor is made of: metal, a plastic casing, and electronics. The same rule as explained above apply to the temperature sensor and the respective disposal scenario of each sub-assemblies.

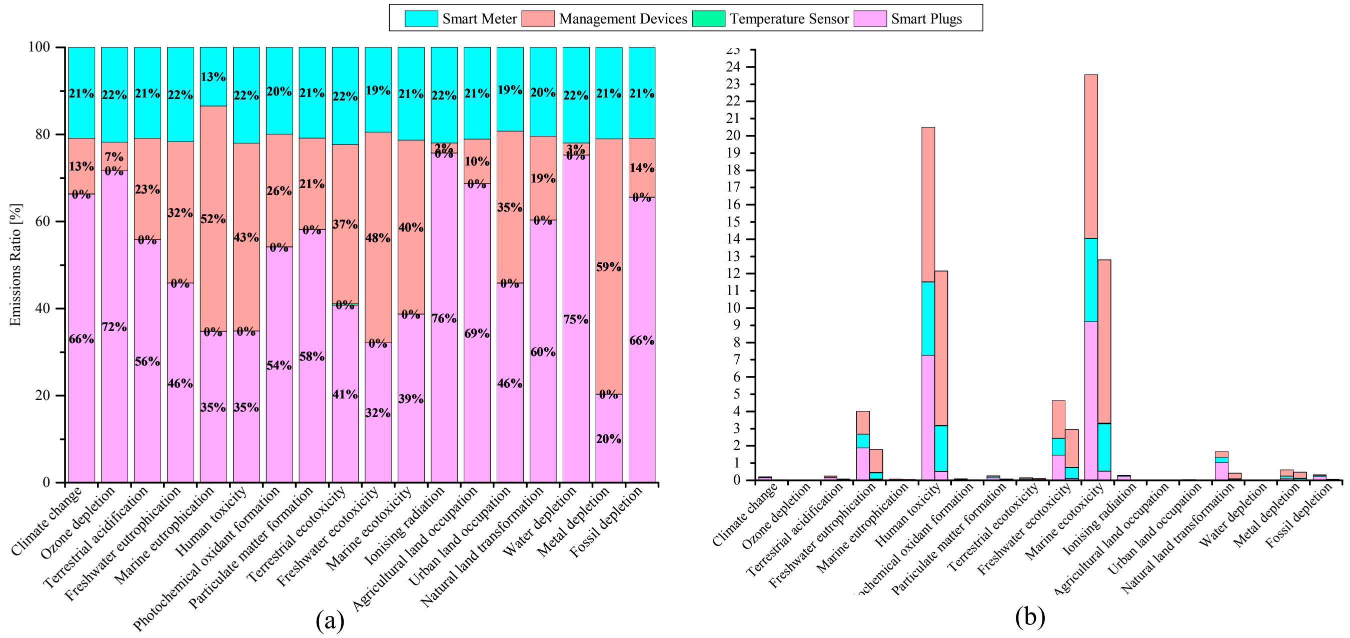
Finally, the temperature sensor can also be disposed in a similar way. Each of the three sub-assemblies has got their personal disposal scenario. Similarly to the two above, category, transportation is defined in the disassembly phase.

## 5. SYSTEM PHYSICAL BOUNDARIES

A number of assumptions have been set in order to model the use-phase of the system. The house considered in the simulation integrates 25 appliances in which 21 are distinct in a 4-persons house. There are 21 smart plugs installed in the house and are constantly in use in order to measure the electricity consumption from each plug. It is assumed that the system has an average life expectancy of 5 years. Therefore, the use-phase considers 5 years of electricity consumption throughout the life cycle. According to manufacturers' data, a smart plug consumes 4 W constantly, which results in a yearly consumption of 35.06 kWh/y of electricity or 3681.72 kWh for all smart plugs throughout the life cycle. According to the manufacturers, a smart meter consume around 20 W in order to run, transmit data, and display the energy consumption on the LCD screen, which represents an electrical consumption of 175.32 kWh/y of electricity or 876.6 kWh for the smart meter throughout the life cycle.

## 6. LCA RESULTS

The environmental impacts of the HEMS can be split down in multiple sub-impacts. First of all, 99.4 % of the emissions occur during the assembly and the use-phase, where the use-phase represents 84 %. Secondly, 18 environmental indicators are given in which we can find the climate change



(a) (b)

Fig. 2. Environmental Impact of the HEMS. (a) Relative emissions showing the impact of each components relatively to each other, (b) absolute emissions illustrating the relevant impact when considering the use-phase (left bar), and without the use phase (right bar).

indicator expressed in $kgCO_{2eq}$, the impact on land-use, metal depletion and so on. The factor having the highest impact is the marine toxicity where the main components contributing to it are the smart plugs and the management devices. Human toxicity is the second largest and the main contributor to it is the management devices as well. Considering the climate impact factor, smart plugs have the biggest impacts due to the quantity of devices in place in the model but also because of the continuous use of electricity throughout the simulation period. The climate change impact is equal to 354 $kgCO_{2eq}$ when electricity is not considered and, therefore, groups all the other processes' impacts. When considering the electricity consumption over a 5-years period, the climate change impact rises up to 2076 $kgCO_{2eq}$. Thus, the $CO_2$ emission due to the electricity consumptions from the HEMS is equal to 1722 $kgCO_{2eq}$. The temperature sensor clearly plays a minor role in terms of environmental impacts as it has the smallest quantities for raw materials. The smart meter has a fairly stable share on the environmental impact of around 20% for each impact factors evaluated. The management device is the one that has the most fluctuation, as it is the main contributor of resource depletion (59% of the entire system), but plays a minor role in other impact factor such as water depletion.

## 7. DISCUSSION AND CONCLUSIONS

The starting argument of this work was that smart home automation contributes to reducing the energy consumption of households and also flattens peak consumption profiles. Based on earlier work (Louis 2014), it was assumed that home automation can contribute to 12 % reduction of energy consumption in an average Finnish household. The household has been modelled including 21 electronic equipment. Assuming that these equipment are controlled by smart home automation devices, we need to contrast the savings with the energy consumption and overall environmental impacts of these devices. As the LCA study presented in this paper indicates, the largest environmental impacts of home automation consists of use-phase energy consumption of the HEMS. Assuming a 5-years operation time, smart plugs consume 3681.72 kWh, whilst smart meters consume 876.6 kWh in total. This indicates that the environmental "investment" in terms of home automation does not pay itself back. Nevertheless, the smart meter itself can be paid back within 3.5 months meaning that the remaining months of the year are beneficial in terms of energy consumption. In terms of $CO_2$ payback, the smart meter would pay itself back after the 11th month. Whilst European legislation concentrates on also on the EOL phase of electronics, the environmental impact of EOL management is very low compared to other life-cycle impacts. One of the weak points of the presented LCA assessment is that it considers a fixed emission factor. In our case, the database considered an emission factor of 265 $gCO_2$/kWh consumed for Finland. In contrast, IEA evaluated the emission factor to be around 199 $gCO_2$/kWh as an average value on the period of 2008-2010 (IEA, 2013). Therefore we made our assumptions of environmental payback time based on IEA data and available $CO_2$ emissions information that lower the amount of $CO_2$ saving potential. Still, the full system does not pay itself back in terms of reduced $CO_2$ emissions. As the largest part of HEMS electricity consumption is due to smart plugs, we can conclude that we need to find the balance between what we actually need to control and the resulting energy consumption of the control system. Ultimately, the authors argue that the issue of electricity demand of smart control devices should be more present in the discussion about smart home automation.

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