 doi:10.1016/j.eiar.2017.08.009

Life cycle impact assessment of home energy management systems (HEMS) using dynamic emissions factors for electricity in Finland

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Abstract

Decarbonising the European economy is a long-term goal in which the residential sector will play a significant role. Smart buildings for energy management are one means of decarbonisation, by reducing energy consumption and related emissions. This study investigated the environmental impacts of smart house automation using life cycle impact assessment. The ReCiPe method was selected for use, in combination with dynamic emissions factors for electricity in Finland. The results indicated that a high level of technology deployment may be counter-effective, due to high electricity consumption by the sensor network, automation system and computing devices. The results also indicated that number of inhabitants per household directly affected the environmental impacts of home automation. A single-person household saw its environmental impacts increase by 15%, while those of a five-person household increased by 3% in the worst-case scenario. The manufacturing phase contributed the major share of environmental impacts, exceeding the use phase in multiple categories. These findings indicate that finding the sweet spot in which technology can promote decarbonisation will be crucial to achieving the goal of a low-carbon economy.

Keywords:
Smart house, Life-cycle impact assessment, Modelling, Dynamic indicators, Technology deployment, ReCiPe model.

1. Introduction

In efforts to reduce the dependence of the European economy on fossil energy, the European Union (EU) has established an energy roadmap to decarbonise the energy system by 2050 (European Commission, 2011). Decarbonisation involves decreasing the carbon intensity of energy by using alternative energy sources. The current target for 2050 is for a cut of 95% in greenhouse gas emissions in the power sector and 90% in the buildings sector, compared with the 1990 levels. In response, multiple studies are being carried out to shape the future electricity mix by the horizon of 2050 (Blumberga et al., 2016; Lunz et al., 2016; Sithole et al., 2016). Decarbonisation of the electricity system must be carried out for power generation, but also on the consumption side (Alderson et al., 2012). Therefore every sector must contribute, with energy source being a crucial point. In 2015, energy from the residential sector represented 26.51% of overall energy consumption in the EU (European Commission, 2011; Odyssee-Mure, 2015). Electricity and thermal heating are the two main sources of energy consumption and should thus be the main focus of decarbonisation work. One of the ways to handle energy consumption is through demand-side management (DSM) programmes (Blumberga et al., 2016; Esther and Kumar, 2016; Lunz et al., 2016; Sithole et al., 2016). Smart grids and distributed generation are viable technological solutions for integrating intermittent energy production sources with electric vehicles and other production (Sonnenschein et al., 2015). However, multiple DSM programmes are needed to cover the management of decentralised energy production systems, energy storage systems, smart metering and other smart devices.

Smart buildings for energy management represent the future of the residential sector. Their purpose is to manage the energy flux (incoming, internal and outgoing) in homes in energy production systems (Alderson et al., 2012; Esther and Kumar, 2016). Models have been developed to handle decentralised electricity production, storage and consumption (Özkan, 2016; Keane et al., 2013; Eid et al., 2016; Fazio et al., 2013; Marra et al., 2014). Other studies focus on management of consumption by controlling appliances (Özkan, 2015; Chavali et al., 2014; Anees and Chen, 2016) and developing tools for predicting their usage (Arghira et al., 2012). Consumption management for thermal appliances involves using dynamic pricing (Barzin et al., 2015) and enhancing load shifting. Ultimately, it is believed that smart buildings will be a vital tool for reducing and shifting energy consumption, thus reducing energy generation and use and related emissions.

Smart buildings for energy optimisation can be created through the development and implementation of home energy management systems (HEMS). HEMS mainly involve implementation of automation through demand response in the residential sector (Beaudin and Zareipour, 2015; Vega et al., 2015). They represent an advanced use of smart metering infrastructure, with smart meters acting as a gateway to the house. The

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areas of application for HEMS are extensive and cover both thermal and electrical energy consumption management, e.g. they may include a scheduler for postponing the use of appliances or water-based heating systems. The use of HEMS is still in an early phase and much development is to be expected. When HEMS are used in residential homes, their main targets are e.g. to handle the use of electric vehicle power storage, reduce the electricity bill, shift peak load and manage the lighting system (Kobus et al., 2015). The number of inhabitants in a household influences the life cycle impacts, with larger household size providing more flexibility to manage peaks Kuzlu et al. (2015). Outstanding challenges are to maximise the benefits of HEMS by integrating the variability of the energy mix in the electricity system and to evaluate the environmental impact of HEMS including all use phases.

Smart metering installations are increasingly being deployed across Europe, with particularly high uptake in Sweden and Finland (Commission, 2014). In smart metering, electricity consumption information is retrieved on a regular basis and communicated to a third party (usually the distribution system operator). Smart metering can also retrieve information for end-users, be fitted with a remote connection switch, support advanced tariffing structures and prevent fraud (Joint Research Centre, 2017). The system has been shown to be quite effective, although with somewhat diverging results, in reducing electricity consumption by individual users (Darby, 2006). However, studies often highlight the need for continuous improvement of feedback strategies to keep end-users engaged, as otherwise the reductions can fade away (Wilson et al., 2015). Ultimately, smart metering could lead to a reduction in carbon dioxide (CO_2) emissions from homes by supporting DSM programmes and also by enabling optimal use of renewables in the electricity mix at national scale (Darby, 2013).

One way to influence the environmental emissions from electricity consumption is by improving the energy efficiency of appliances (Wada et al., 2012). Another way is to use a DSM programme together with a HEMS.

The objective of this study was to assess the environmental impacts of HEMS, through life cycle assessment (LCA) of a simulated smart energy home. LCA studies review the environmental impact of a system from raw material acquisition, through processing, assembly and use to final disposal (ISO, 2004). However, in order to evaluate the life cycle environmental impact of a system, indicators must be carefully chosen (Vera and Langlois, 2007; Stamford, 2012; Afgan and Carvalho, 2008; GRI, 2015; Khan et al., 2004; May and Brennan, 2006). Despite the rapid development and commercialisation of smart technologies for controlling homes, the question of whether these technologies can actually reduce the environmental footprint of homes has not yet been resolved. The literature on life cycle studies of intelligent systems for energy management is rather limited. A study by Gangolells et al. (2015) showed that half the environmental impacts of these intelligent systems for energy management may arise in the use phase and slightly less than half during the assembly phase. However, van Dam et al. (2013) concluded that energy consumption from communication devices and the number of devices for automation purposes must decrease before HEMS become economically and environmentally profitable. To better understand the overall effect of building automation, a recent study examined the potential of HEMS for heating technologies to reduce environmental emissions (Beucker et al., 2015). They listed 18 indicators taken from the ReCiPe 2008 method for life cycle impact assessment. An interesting finding of their study was the apparent need for a decreasing role of automation technologies to reduce greenhouse gas emissions.

In order to determine whether more control and sensing devices in future households will promote decarbonisation, in the present study we considered three different levels of HEMS deployment with response models for multiple end-users. We also sought to determine the break-even point between the benefits of monitoring and automation and the environmental impacts of technology implementation.

2. Methodology

2.1. Goal and scope

Because HEMS behave dynamically, any impact assessment of the use phase has to include a dynamic evaluation of the system. The outcomes of LCA depend on the boundaries set for the study and on the methodology used for evaluating the overall environmental impact. There are a number of methods available for characterising and assessing the environmental impact of technology use and interpreting the results.

2.2. System boundaries

The smart house considered in this study integrated multiple components such as management devices to control the flow of data and electricity, smart plugs that measure the electricity use in each appliance, a smart meter that measures the flow of electricity, communication devices for transmitting data and a computing device. The different devices involved are described in detail in Louis et al. (2015) and summarised in Figure 1. The manufacturing phase of each element was considered in the present study, as was the disposal phase.

Different smart house architecture options were considered and allocated a number (1-4) and are detailed later in Table 3. The elements involved in each option are shown in Figure 1. The EcoInvent 3.01 database (Wernet et al., 2016), where the impacts of the manufacturing phase are embedded in the data, was used as the source of model input. The disposal phase scenario was set according to the EU Waste Electrical and Electronic Equipment (WEEE) Directive (2002/96/EC). HEMS devices tend to be plastic-rich and are likely to be incinerated, because landfilling of plastics is being phased out under the EU Landfill Directive (Directive 1999/31/EC) and its waste acceptance criteria. Therefore, in this study we assumed that all smart meters, smart plugs, temperature sensors and other communication and management devices are incinerated (Louis et al., 2015).

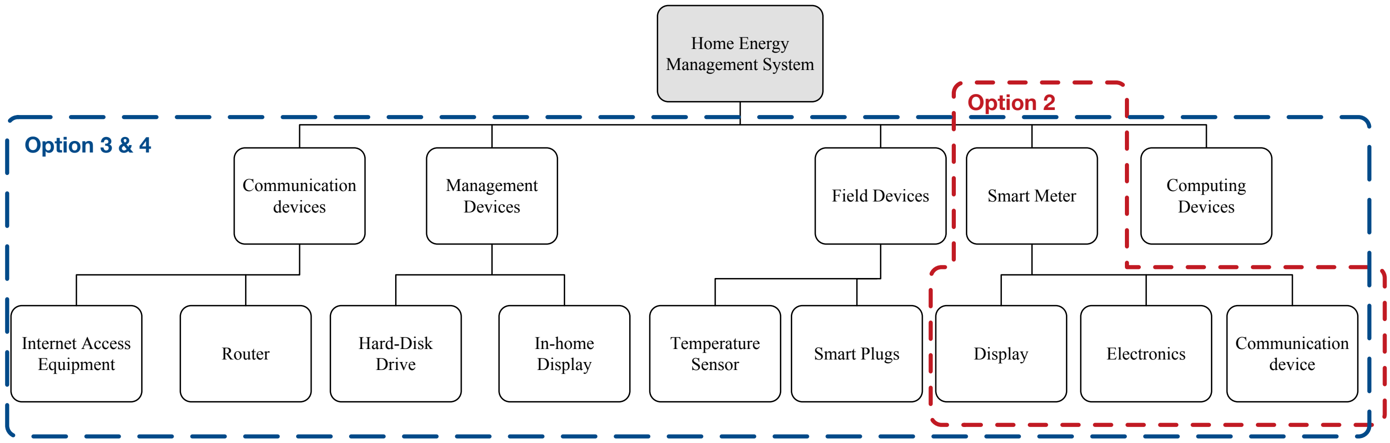

Figure 1: System boundaries of the smart house studied in the present life cycle impact assessment (LCIA), based on Louis et al. (2015). (print B&W)

2.3. *Impact assessment method*

Conducting a life cycle impact assessment (LCIA) of HEMS requires the use of indicators that best illustrate the overall environmental impact. Here, the ReCiPe 2008 characterisation method v1.11 and v1.12 (Goedkoop et al., 2013) were used, together with the SimaPro software. The ReCiPe characterisation method was applied to assess the environmental impact of different processes using the 18 indicators listed in Table 1. The ReCiPe method allows each impact to be evaluated in three perspectives: individualist (I), hierarchist (H) and egalitarian (E), following theory developed by Thompson et al. (1990) Each perspective represents the impact of the indicator in different periods, but also through a not exclusively policy or technology perspective. For the purposes of this study, the midpoints (H) method was chosen as best representing the overall environmental impact. The overall LCA was split into three distinctive processes: the manufacturing phase, the use phase and the disposal phase. Each perspective represents the impact of the indicator in different periods, but also through a not exclusively policy or technology perspective. For the purposes of this study, the midpoints (H) method was chosen as best representing the overall environmental impact. The overall LCA was split into three distinctive processes: the manufacturing phase, the use phase and the disposal phase.

Table 1: Abbreviations and related units of the ReCiPe environmental impact characterisation method.

Indicator	Abb.	Unit [/kWh$_{pro}$]
Climate change	CC	kgCO$_{2eq}$
Ozone depletion	OD	kgCFC-11$_{eq}$
Terrestrial acidification	TA	kgSO$_{2eq}$
Freshwater eutrophication	FE	kgP$_{eq}$
Marine eutrophication	ME	kgN$_{eq}$
Human toxicity	HT	kg1,4-DB$_{eq}$
Photochemical oxidant formation	POF	kgNMVOC
Particulate matter formation	PMF	kgPM10$_{eq}$
Terrestrial ecotoxicity	TEco	kg1,4-DB$_{eq}$
Freshwater ecotoxicity	FEco	kg1,4-DB$_{eq}$
Marine ecotoxicity	MEco	kg1,4-DB$_{eq}$
Ionising radiation	IR	kBqU235$_{eq}$
Agricultural land occupation	ALO	m^{2}a
Urban land occupation	ULO	m^{2}a
Natural land transformation	NLT	m^2
Water depletion	WD	m^3
Metal depletion	MD	kgkgFe$_{eq}$
Fossil depletion	FD	kgOil$_{eq}$

2.4. *Inventory analysis*

The SimaPro software was used to model the manufacturing phase and the disposal phase of the different elements of the HEMS. The electricity consumption of the HEMS was included in the use phase, which was implemented dynamically on a MatLab platform that includes the EcoInvent database characterised by the ReCiPe model and factors for the Finnish electricity system. Emissions in the use phase were implemented using a dynamic factor, as opposed to a fixed CO_2 emissions factor, because the intrinsically rapid change of state in the electricity grid cannot be well represented by a fixed indicator. Moreover, the assumptions made when creating the EcoInvent v3.01 database consider an electricity mix that may not be representative of the actual electricity mix of Finland. In particular, the share of electricity produced by wind power in the Finnish mix is greatly underestimated, as is the share of electricity from nuclear power. This discrepancy is because the data in EcoInvent refer to the year 2011, since then the electricity mix of Finland has changed significantly. In the EcoInvent import/export data for 2011 a large share of Finnish electricity comes from Russia, but in 2012-2015 a major share actually came from Sweden (Table 2). This is a significant difference, as Russian electricity has a high environmental impact, thus increasing the apparent overall environmental impact of Finnish electricity, whereas Swedish electricity has a greatly lower environmental impact, thus decreasing the overall environmental impact of electricity consumption in Finland.

Another consideration is that home automation aims not only at decreasing the overall electricity consumption, but also at

Table 2: Percentage of electricity imports and exports by Finland and its trading countries, 2004-2015 (Itäpää and Huttunen, 2017)

	2004*	2005*	2006*	2007*	2008*	2009*	2010*	2011**	2012	2013	2014	2015
							Export [%]					
Sweden	100	100	100	100	100	100	100	92.32	1.44	11.44	0	0.03
Norway	0	0	0	0	0	0	0	0.70	5.45	6.09	3.62	1.22
Russia	0	0	0	0	0	0	0	0	0	0.14	0.01	0.47
Estonia	0	0	0	0	0	0	0	6.99	93.11	82.34	96.37	98.28
							Import [%]					
Sweden	1.86	35.98	16.21	22.62	19.81	12.71	13.70	31.30	74.96	70.60	84.05	80.82
Norway	0	0	0	0	0	0	0	0.24	0.40	0.26	0.25	0.69
Russia	98.14	64.02	83.79	77.38	80.19	87.29	86.30	66.89	22.72	26.55	15.55	18.35
Estonia	0	0	0	0	0	0	0	1.57	1.92	2.59	0.15	0.13

*Data available only for Sweden and Russia, ** Data available for all countries from October

shifting load, which helps to cut peak demand and possibly to reduce the environmental impact of consumers. These discrepancies call for a dynamic assessment of the environmental impact of Finnish electricity consumption.

2.5. *Use phase*

A MatLab model was developed to simulate multiple smart house configurations at different stages of technological deployment (Louis et al., 2016). The model integrates three types of end-user responses that represent higher and lower thresholds: 'Green' houses have a 70% positive response to acceptance of behaviour change, 'Orange' houses 50% and Brown houses 30%. Only 'Green' houses were considered in the present study, in order to assess the maximum possible gain from smart technologies. The response levels were further modified by altering the feedback strategies. Three feedback strategies were tested: personal historical consumption, peer comparison of electricity consumption and targeted electricity consumption. Thus the overall response could be increased or decreased depending on how the feedbacks and actions already undertaken are perceived. The levels of technology deployment (architecture options) in the smart house model were as follows: option 1 is a regular house without any smart devices, option 2 involves implementation of a smart meter, option 3 involves full deployment control but requires the approval of the end-user before undertaking a shift, and option 4 is fully automated electricity consumption Table 3: The automatic control option uses multiple pricing schemes to shift load or reduce electricity consumption whenever possible. Therefore, the environmental impact is not an input for the controller, but a result of the automation itself. Our simulation considered the fact that HEMS may decrease the overall electricity consumption when option 2 is deployed and appropriate feedback is communicated to end-users. In options 3 and 4, overall electricity consumption increased by up to 15% but the HEMS affected the overall load profile by shifting electricity use from evening to night time, which is one of the anticipated benefits of a smart house (Kuzlu et al., 2012). The simulations were run for a one-year period for the year 2012. As the electricity consumption by the HEMS does not change over time, its overall electricity consumption was also extrapolated for a five-year period.

The number of devices is directly dependent on the option studied and the number of inhabitants. A one-person house requires 21 smart plugs, a two-person house 23, a three-person house 26, a four-person house 28 and a five-person house 33. Moreover, each option includes a number of devices that represent the HEMS (see Figure 1). The electricity demand for the HEMS was based on systems. The active power of smart plugs, which arises when transmitting the information to the smart meter (otherwise the devices are in idle or off mode) was set at 4 W and the smart plugs were assumed to communicate with the smart meter every 10 seconds. The smart meter itself was assumed to have a power rating of 20W in active phase (during transmission of data) and otherwise to be in idle mode, and to communicate the electricity consumption of the house every 25 minutes.

2.6. *Environmental impacts during the use phase*

The environmental model was based on an hourly CO_2 emissions model (Louis et al., 2014). In this model, all indicators from the ReCiPe methodology were considered. LCA is commonly performed using static models, where the indicators use fixed emissions factors, but in this study the indicators were re-calculated hourly to illustrate the variation in emissions from electricity production. Finland produces electricity from a diversified technology mix that includes nuclear power stations, combined heat and power (CHP) from district heating power stations, CHP from industrial power stations, hydro power, wind power and some thermal power plants. The thermal power plants and CHP units use a variety of fuels, such as coal, oil, gas, peat, wood and other types of biofuels. As Finlands power production capacity is not sufficient to cover the peak demand, electricity is imported from neighbouring countries: Sweden, Russia and, to a minor degree, Norway and Estonia. Emissions from these trading partners were set using fixed emissions factors, while the electricity mix for Finland was modelled on an hourly basis. Emissions from Finland integrate the change in fuel quantity used for producing electricity on a monthly basis.

 doi:10.1016/j.eiar.2017.08.009

Table 3: The four technology levels (architecture options) implemented in the MatLab model

Option	Description
1	No automation system in place (reference case)
2	Smart metering system in place and providing information on overall electricity consumption
3	HEMS technology enhanced, without automatic control
4	HEMS technology enhanced, with automatic control

The fuel mix is further disaggregated to give an hourly emissions factor that is recalculated iteratively. Data on the electricity mix of the trading countries were taken from EcoInvent 3.01. In order to incorporate the exchange of electricity between Estonia and Finland, the electricity mix for Estonia set by Itten et al. (2014) was used.

The use phase thus integrated the dynamic variation in multiple indicators by having an emissions factor specific to the hour of consumption. These indicators were used with the different smart houses simulated.

3. Results and discussion

The influence of number of inhabitants on the environmental impact of the HEMS was analysed. Furthermore, the overall environmental impact was compared with the relative impact due to the level of technology deployed. The results from the LCIA were obtained using the mid-point 'H' perspective method to avoid weighing problems. Results were further evaluated using the 'E' and 'I' perspective method and are available in supplemental information (SI). Furthermore, sensibility analysis of the emissions factors for seasonal and daily variation were carried out and made available in the SI.

3.1. Impact of technology level

Analysis of the environmental impact of different life cycle phases demonstrated that the manufacturing phase made the greatest contribution to the overall life cycle of the HEMS. The HEMS itself affected overall electricity consumption and the load profile for the households, resulting in an decrease or increase in their overall environmental impact. In order to quantify these impacts, they were compared with those of the reference house (option 1), which did not have any feedback strategies or smart devices installed.

The results of the LCIA considering only option 1 are summarised in Table SI 1 in the Supplementary Information for five household sizes (1-5 inhabitants). The emissions presented in Table SI 1 account only for the electricity consumption of the houses, as they had no automation system. The climate change indicator varied from 412 $kgCO_{2eq}$/y for a one-person house to 1479 $kgCO_{2eq}$/y for a five-person house. The two-person house had the lowest emissions per capita. These climate change emissions are higher than statistical CO_2 emissions for residential dwellings, as the ReCiPe method accounts for emissions as CO_2-equivalents, which includes various sources of CO2 and methane. Ionising radiation in option 1 (Table SI 1) results mainly from the share of nuclear power in the overall Finnish electricity mix. The environmental impacts for the other architecture options (2, 3 and 4) for the HEMS are compared with the base emissions in Figure 2.

The deployment of smart metering (option 2) had a positive impact on the overall LCIA of households with two or more inhabitants. When installed in a one-person household, smart metering increased the environmental impact of 15 of the 18 indicators in the ReCiPe method. It had a minor positive impact on marine eutrophication, which it reduced by 0.173% (standard deviation (SD) = 0.012), urban land occupation, which it reduced by 0.015% (SD = 0.012) and water depletion, which it reduced by 0.114% (SD = 0.011). This is because shifting the load used different sources of fuel for producing electricity. The impacts for two- to five-person houses ranged from 0.331% (SD = 0.021) to 2.69% (SD = 0.0108), with the four-person house having the greatest impact.

The deployment of a full HEMS (options 3 and 4) had a negative impact on the environment, regardless of the number of inhabitants per household. Nevertheless, there was a general trend for the negative impact to decrease with increasing number of inhabitants in the household. For a one-person household, the environmental impact peaked at 16% (SD = 0.02) for ozone depletion and an average increase of 15% (SD = 0.02) was seen in every category. The smallest increase in environmental impact was observed for the four-person house, for which the average increase was 3.44% (SD = 0.019) in option 3 and 3.36% (SD = 0.012) in option 4. The shift between from infrastructure needing end-user agreements (option 3) to fully automated infrastructure (option 4) did not decrease the environmental impact significantly. This is explained by the number of devices installed for monitoring the houses and the electricity consumption of these devices. Thus in order to be environmentally benign in the use phase, HEMS must decrease the power demand from the devices connected to it. However, this will increase the share of the environmental load borne by the manufacturing phase.

3.2. Contribution of each life cycle phase

In order to quantify the environmental impacts of HEMS, only the electricity consumption of the HEMS and the manufacturing and disposal phases were considered. To identify the phase with the highest impact per category, the results were aggregated using relative values. Figure 3 shows the relative environmental impacts for the four levels of technology. deployed in a five-person house. As options 3 and 4 involved the same

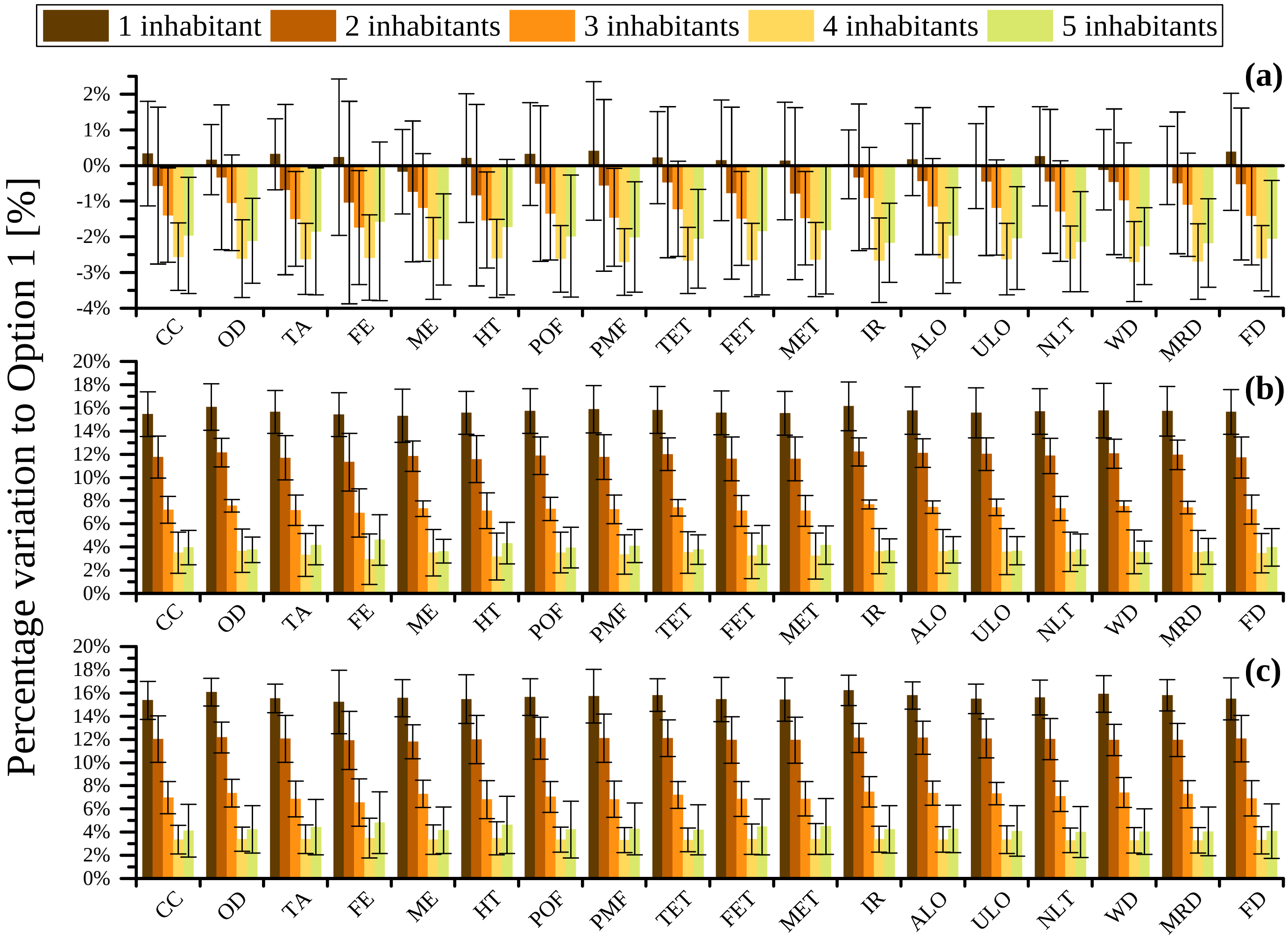

Figure 2: Environmental impact of HEMS considering the number of inhabitants per household and three levels of technology deployed: (a) option 2: smart metering; (b) option 3: full sensing system for control option; and (c) option 4: automation of appliances with their related uncertainties. (print B&W)

set and number of devices, they were grouped into one option in this case.

When only smart metering was deployed (option 2), the use phase contributed a somewhat lower share (~44%) of overall environmental impacts than the manufacturing phase (~55%). For climate change impacts, however, the use phase was more significant, contributing 59% or 74.4 $kgCO_{2eq}$, while the manufacturing phase contributed 39% or 49.9 $kgCO_{2eq}$ and the disposal phase 2% or 2 $kgCO_{2eq}$ of total emissions. The highest amount of ionising radiation and agricultural land occupation also arose during the use phase, which contributed 96% or 157.9 $kgBq_{eq}$ and 97% or 84 m^2y , respectively. However, 89% (0.18 kgP_{eq}) of the freshwater eutrophication impact, 93% (323 $kg1{,}4\text{-}DB_{eq}$) of the human toxicity impact, 89% (6.56 $kg1{,}4\text{-}DB_{eq}$) of the freshwater ecotoxicity impact, 89% (6.3 $kg1{,}4\text{-}DB_{eq}$) of the marine ecotoxicity impact and 97% (71.8 $kgFe_{eq}$) of the metal depletion impact occurred during the manufacturing phase. Thus the manufacturing phase had a similar impact to the use phase of smart metering (option 2) and therefore great care should be taken when realising the trade-off between the components of a smart metering system and the electricity it consumes. However, these figures do not consider the impact that a smart meter with appropriate feedback may have on the overall electricity consumption and load profile of the house.

The disposal phase had a major impact when options 3 and 4 were used. The main reason was the large numbers of sensing devices needed for measuring the electricity flow to every appliance. The disposal phase had its greatest impact in the marine ecotoxicity and water depletion category, contributing an average of 47% or 33.7 $kg1{,}4\text{-}DB_{eq}$.As the number of household appliances increased with the number of inhabitants per household, the share of the use phase increased proportionally. Concerning climate change impact, a one-person house had emissions from the use phase of 52% or 391 $kgCO_{2eq}$ over a five-year period, while a five-person house had emissions from the use phase of 62% or 573 $kgCO_{2eq}$. With options 3 and 4, the use phase mainly caused impacts in the climate change, ozone depletion, ionising radiation, agricultural land occupation, urban land occupation, water depletion and fossil depletion categories of the 18 proposed in the ReCiPe method, while the

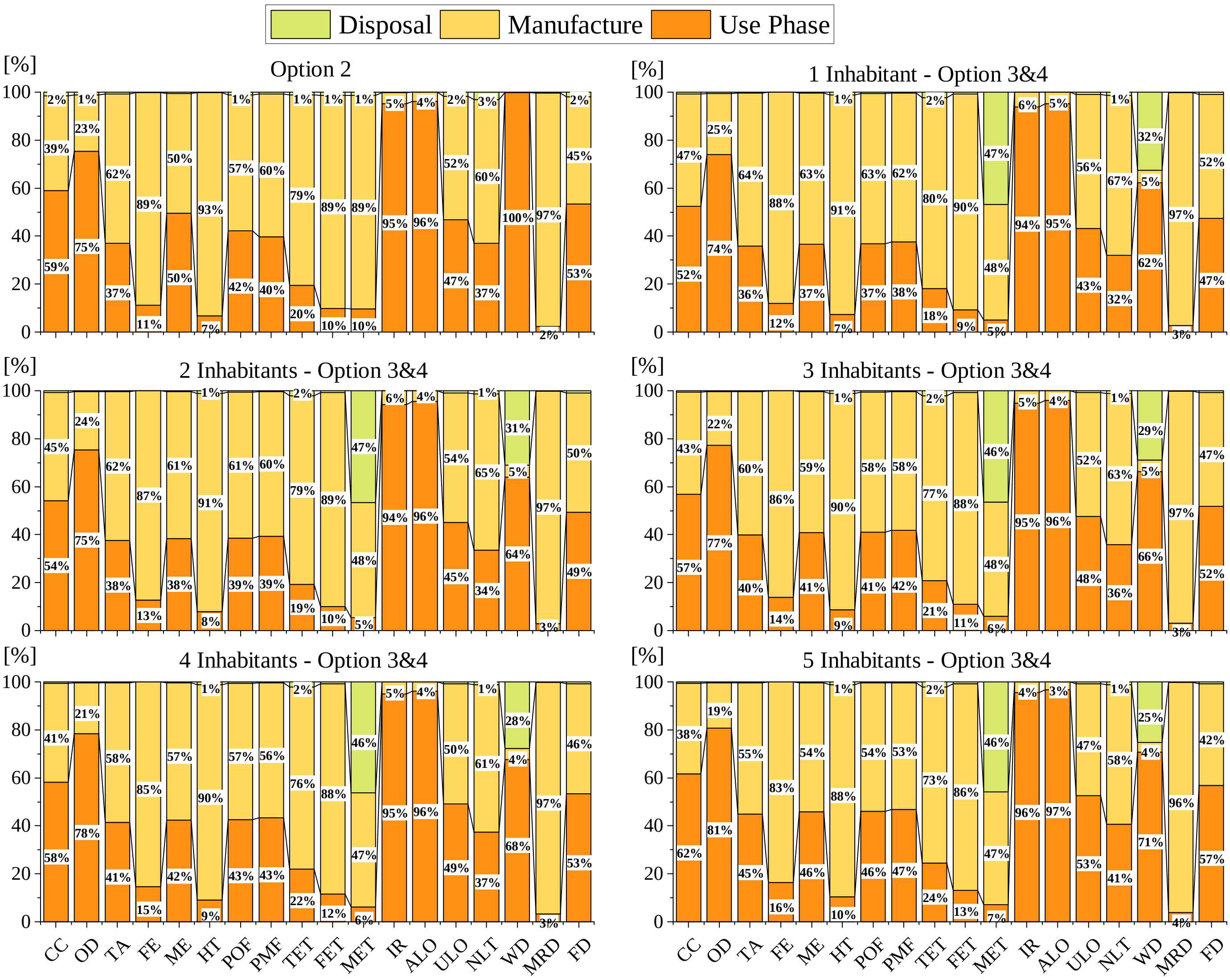

Figure 3: Five-year life cycle impact assessment (LCIA) of home energy management systems (HEMS) for different numbers of inhabitants per household (1-5) and levels of technology (options 1-4). (print B&W)

manufacturing phase had impacts predominantly in 10 categories. This shows that the manufacturing phase is also critical when assessing the environmental impact of smart buildings.

Overall, the dynamic indicators used here for electricity provided a better understanding of the share and effect of emissions associated with time variations in the emissions factors. The resulting emission factors are available in SI for all 18 indicators. All emissions categories except ionising radiation were negatively correlated with the external temperature and positively correlated with the spot price variation (Figure SI 3). This is due to the fact that most of the emissions are linked to CHP or separate production power plants, while the ionising radiation emissions factor is strongly correlated with electricity production from nuclear power plants.

The emissions during the use phase are country-specific and vary depending on the overall electricity mix of a particular country and the fuel usage on an hourly basis, and thus the input data should be set specifically for that country. Therefore, the results of an LCIA cannot be generalised to other countries. To test the replicability of the results presented here, future studies should look at a representative panel of European countries using a multiple energy technology mix that reflects the diversity in electricity production and development trends to the horizon of 2050.

As the energy efficiency of energy-using devices increases, this will decrease the share of environmental impacts from the use phase and increase that of the manufacturing phase. These changes must be considered in relation to the overall impact that the HEMS has on electricity consumption in different households.

3.3. HEMS as a tool to reduce environmental impacts

The smart grid and its components are expected to reduce the yearly CO2 emissions from the electricity sector by 10.7%

(Darby et al., 2013). This study highlighted the importance of the manufacturing and use phase of HEMS within the building sector. In the residential sector, large households with smart metering (option 2) contribute to decrease the environmental impact from electricity consumption. On the contrary, small households e.g. homes occupied by a single user will play a minor role and may even contribute to an increase of environmental impacts. The use of HEMS (option 3 and 4) increased the overall environmental emissions but also flattened the household load curve (Louis et al., 2016). This calls for a self-coordinated system of HEMS or by using demand aggregators as suggested by McKenna and Darby (2017). Moreover, the inclusion of hourly emission factors will set a new paradigm for HEMS to be able to shift load not only to more economically time but also to more environmentally friendly time. Attempts were done by considering the energy mix by technology, however, they tend to use the same primary energy mix for each technology (Kopsakangas-Savolainen et al., 2017). In this work, the primary energy mix for each technology varies in time to reflect the changes of fuel within and among power plants. This brings a higher accuracy to real-time CO_2 emissions as well as represents better the fluctuation in the energy market. However, this requires an in-depth knowledge of the energy system and the primary energy sources used in power production plants, which is possible in Finland as all producers must report their monthly primary energy consumption.

One of the limitations of this study is its generic aspect, in which the LCA outcome uncover a set of general scenarios. Nevertheless, applying LCA methodology to a dynamic system allows considering not only combustion technologies but also renewable energy technologies. It was considered that all the appliances of a household are recorded and controllable to some degree. This is only a hypothetical scenario in order to investigate the potential of recording every appliance in a dwelling. From this perspective, a fully monitored and controllable smart house of tomorrow may not translate into a more energy efficient house, unless the electricity consumption of the sensing network decreases and the energy saved with recording an end-point is not offset by the energy consumed recording it.

In this study, the smart meter consumed about 67 kWh/y and the full HEMS deployment from 350 to 520 kWh/y. This is consistent with the findings of van Dam et al. (2013) in which the HEMS was limited to a certain appliances. In terms of environmental impact, the smart meter is accountable for about 14.8 $kgCO_{2eq}$/y while a fully deployed HEMS would generate from 78 to 114 $kgCO_{2eq}$/y. Although these numbers seems low and would justify an increased use of HEMS in heating (Beucker et al., 2015), but this may not be the case for the electricity system. Control of larger appliances for load shifting may indeed be required, however the extent of HEMS should be limited, and the electricity consumption of HEMS need to be optimised (Darby, 2017). If HEMS is to be used for the purpose of reducing environmental impact, it should focus on shifting and controlling large loads, and should only be considered for households with more than 2 inhabitants.

4. Conclusions

This study investigated the overall environmental impacts of HEMS in an LCA that compared scenarios with different numbers of inhabitants per household (1-5) and levels of smart technology deployed (smart metering, a full sensing system for control and full automation of appliances). A smart house model was developed to simulate electricity consumption in the households and the impact of the HEMS on their load profile. The results were used as input to an LCIA model that employed the mid-point ReCiPe v1.11 and v1.12 method to quantify the environmental impacts, combined with dynamic evaluation of the environmental state of the electricity system in Finland. Only the manufacturing, use and disposal phases were studied.

The dynamic indicators used provided a better understanding of the share and effect of emissions associated with time variations in the emission factors. The results revealed that the use phase of a HEMS does not necessarily represent the largest share of environmental impacts from smart metering, but rather that the manufacturing phase may contribute a larger share. This is mostly due to the large number of sensing devices and the computing device required in HEMS. Furthermore, the power consumption from the smart metering device is rather low and thus has a minor role in the use phase. Moreover, when coupled with appropriate feedback and end-user willingness to change behaviour, the overall electricity consumption can decrease by up to 2.5%. The environmental impact would then decrease accordingly and the contribution from the use phase would be negative, while the manufacturing phase would become the main source of environmental impacts. Thus great efforts are needed to reduce the environmental impacts of manufacturing, an aspect which should be integrated into mandatory energy efficiency evaluations.

Implementation of the HEMS (options 3 and 4) did not reduce the overall environmental impact of households. On the contrary, it increased the overall environmental impact for every indicator considered, mainly due to the sensing network with which every appliance was equipped. Moreover, the use phase contributed only 62% to the ‘climate change’ indicator, while the remaining 38% occurred mostly in the manufacturing phase. Therefore, the energy consumption of sensing devices must drastically decrease for HEMS to become environmentally beneficial and economically viable in future deployment.

The greater the number of inhabitants in a house with a HEMS (options 3 and 4) or smart metering system (option 2), the greater the reduction in environmental impacts. Nevertheless, smart metering increased the environmental impacts of a one-person household, while for households with 2-5 inhabitants the environmental impacts decreased. This is important considering the increasing amount of one-person households in Finland.

The simulation tool used in this study included three levels of technology deployment. It is likely that more levels of technology will be available in the future, with more flexibility in the devices needed to run a HEMS. Therefore, the results for the highest threshold may be most relevant in future. Implementing a wider range of automation architecture is likely to result in a broader palette of environmental impacts of smart buildings. Defining the sweet spot in which technology can promote the decarbonisation process will be crucial to reach the goal of a low-carbon economy.

LCA proved to be a useful tool for assessing the environmental performance of HEMS. It revealed negative impacts, but also potential positive effects, of energy management systems for households. It also showed that HEMS should accommodate dynamic external factors such as electricity prices and should be able to react to changing environmental indicators. A novel contribution of this study was to demonstrate the importance of using dynamic indicators that influence daily environmental emission profiles to evaluate the performance of HEMS in the use phase. This is important in order to reach the ultimate goal set for HEMS, i.e. to reduce the environmental impacts associated with energy consumption. However, as the changes in profile impacted each environmental impact indicator differently, further work is needed to determine whether multi-objective optimisation of HEMS for all or certain indicators is required. Moreover, we recommend that more effort be devoted to reducing the environmental impact of HEMS products already in the manufacturing phase, which would further enhance the capacity of HEMS products as an optimisation tool. Ultimately, the expectation is that HEMS will evolve into household environmental impact reducing systems.

5. Acknowledgements

This research was made possible by the funding provided by the Academy of Finland for the SEN2050 project (Decision 287748), and the Fortum foundation (Grant 201500108).

6. References

Afgan, N.H., Carvalho, M.G., 2008. Sustainability assessment of a hybrid energy system. Energy Policy 36, 2903–2910. doi:doi:10.1016/j.enpol.2008.03.040.

Alderson, H., Cranston, G.R., Hammond, G.P., 2012. Carbon and environmental footprinting of low carbon UK electricity futures to 2050. Energy 48, 96–107. doi:doi:10.1016/j.energy.2012.04.011.

Anees, A., Chen, Y.P.P., 2016. True real time pricing and combined power scheduling of electric appliances in residential energy management system. Applied Energy 165, 592–600. doi:doi:10.1016/j.apenergy.2015.12.103.

Arghira, N., Hawarah, L., Ploix, S., Jacomino, M., 2012. Prediction of appliances energy use in smart homes. Energy 48, 128–134. doi:doi:10.1016/j.energy.2012.04.010.

Barzin, R., Chen, J.J., Young, B.R., Farid, M.M., 2015. Peak load shifting with energy storage and price-based control system. Energy 92, 505–514. doi:doi:10.1016/j.energy.2015.05.144.

Beaudin, M., Zareipour, H., 2015. Home energy management systems: A review of modelling and complexity. Renewable and Sustainable Energy Reviews 45, 318–335. doi:doi:10.1016/j.rser.2015.01.046.

Beucker, S., Bergesen, J.D., Gibon, T., 2015. Building energy management systems: Global potentials and environmental implications of deployment. Journal of Industrial Ecology 20, 223–233. doi:doi:10.1111/jiec.12378.

Blumberga, A., Lauka, D., Barisa, A., Blumberga, D., 2016. Modelling the baltic power system till 2050. Energy Conversion and Management 107, 67–75. doi:doi:10.1016/j.enconman.2015.09.005.

Chavali, P., Yang, P., Nehorai, A., 2014. A distributed algorithm of appliance scheduling for home energy management system. IEEE Transactions on Smart Grid 5, 282–290. doi:doi:10.1109/tsg.2013.2291003.

Commission, E., 2014. Country fiches for electricity smart metering – Benchmarking smart metering deployment in the EU-27 with a focus on electricity. European Commision , 1–10URL: http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1403084595595{&}uri=COM:2014:356:FIN{%}5Cnhttp://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0356{&}from=EN, doi:doi:10.1017/CBO9781107415324.004, arXiv:arXiv:1011.1669v3.

van Dam, S., Bakker, C., Buiter, J., 2013. Do home energy management systems make sense? assessing their overall lifecycle impact. Energy Policy 63, 398–407. doi:doi:10.1016/j.enpol.2013.09.041.

Darby, S., 2006. The Effectiveness of Feedback on Energy Consumption. Environmental Change Institute University of Oxford 22, 1–21. URL: http://www.eci.ox.ac.uk/research/energy/downloads/smart-metering-report.pdf.

Darby, S., Strömbäck, J., Wilks, M., 2013. Potential carbon impacts of smart grid development in six european countries. Energy Efficiency 6, 725–739. doi:doi:10.1007/s12053-013-9208-8.

Darby, S.J., 2013. The role of smart meters in carbon management. Carbon Management 4, 111–113. doi:doi:10.4155/cmt.13.8.

Darby, S.J., 2017. Smart technology in the home: time for more clarity. Building Research & Information , 1–8doi:doi:10.1080/09613218.2017.1301707.

Eid, C., Codani, P., Perez, Y., Reneses, J., Hakvoort, R., 2016. Managing electric flexibility from distributed energy resources: A review of incentives for market design. Renewable and Sustainable Energy Reviews 64, 237–247. doi:doi:10.1016/j.rser.2016.06.008.

Esther, B.P., Kumar, K.S., 2016. A survey on residential demand side management architecture, approaches, optimization models and methods. Renewable and Sustainable Energy Reviews 59, 342–351. doi:doi:10.1016/j.rser.2015.12.282.

European Commission, 2011. Energy Roadmap 2050. Technical Report SEC(2011) 1565 final. European Commission. Brussels.

Fazio, A.R.D., Fusco, G., Russo, M., 2013. Decentralized control of distributed generation for voltage profile optimization in smart feeders. IEEE Transactions on Smart Grid 4, 1586–1596. doi:doi:10.1109/tsg.2013.2253810.

Gangolells, M., Casals, M., Forcada, N., Macarulla, M., Giretti, A., 2015. Environmental impacts related to the commissioning and usage phase of an intelligent energy management system. Applied Energy 138, 216–223. doi:doi:10.1016/j.apenergy.2014.10.070.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., van Zelm, R., 2013. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Technical Report. PRé Sustainability.

GRI, 2015. Sustainability Reporting Guidelines & Electric Utilities Sector Supplement. Technical Report. Global Reporting Initiative. Amsterdam.

ISO, 2004. ISO 14040:2006, environmental management - life cycle assessment - principles and framework (ISO 14040:2006). URL: https://www.iso.org/standard/37456.html.

Itäpää, A., Huttunen, J., 2017. Cross-border transmission. Accessed 08.2017. URL: http://www.fingrid.fi/en/electricity-market/cross-border-transmission/Pages/default.aspx.

Itten, R., Frischknecht, R., Stucki, M., 2014. Life Cycle Inventories of Electricity Mixes and Grid. Technical Report. treeze. Uster. URL: http://esu-services.ch/fileadmin/download/publicLCI/itten-2012-electricity-mix.pdf.

Joint Research Centre, 2017. Smart metering deployment in the european union. Accessed 8.2017. URL: http://ses.jrc.ec.europa.eu/smart-metering-deployment-european-union.

Keane, A., Ochoa, L.F., Borges, C.L.T., Ault, G.W., Alarcon-Rodriguez, A.D., Currie, R.A.F., Pilo, F., Dent, C., Harrison, G.P., 2013. State-of-the-art techniques and challenges ahead for distributed generation planning and optimization. IEEE Transactions on Power Systems 28, 1493–1502. doi:doi:10.1109/tpwrs.2012.2214406.

Khan, F., Sadiq, R., Veitch, B., 2004. Life cycle iNdeX (LInX): a new indexing procedure for process and product design and decision-making. Journal of Cleaner Production 12, 59–76. doi:doi:10.1016/s0959-6526(02)00194-4.

Kobus, C.B., Klaassen, E.A., Mugge, R., Schoormans, J.P., 2015. A real-life assessment on the effect of smart appliances for shifting households' electricity demand. Applied Energy 147, 335–343. doi:doi:10.1016/j.apenergy.2015.01.073.

Kopsakangas-Savolainen, M., Mattinen, M.K., Manninen, K., Nissinen, A., 2017. Hourly-based greenhouse gas emissions of electricity – cases demonstrating possibilities for households and companies to decrease their emissions. Journal of Cleaner Production 153, 384–396. doi:doi:10.1016/j.jclepro.2015.11.027.

Kuzlu, M., Pipattanasomporn, M., Rahman, S., 2012. Hardware demonstration of a home energy management system for demand response applications. IEEE Transactions on Smart Grid 3, 1704–1711. doi:doi:10.1109/tsg.2012.2216295.

Kuzlu, M., Pipattanasomporn, M., Rahman, S., 2015. Impacts of house sizes, appliance ratings and usage patterns on demand response applications: A case-based study. Intelligent Industrial Systems 1, 345–357. doi:doi:10.1007/s40903-015-0028-3.

Louis, J.N., Caló, A., Leiviskä, K., Pongrácz, E., 2014. A methodology for accounting the co2 emissions of electricity generation in finland - the contribution of home automation to decarbonisation in the residential sector. International Journal on Advances in Intelligent Systems 8, 560–571. URL: http://www.thinkmind.org/index.php?view=article&articleid=intsys_v7_n34_2014_17.

Louis, J.N., Caló, A., Leiviskä, K., Pongrácz, E., 2015. Environmental impacts and benefits of smart home automation: Life cycle assessment of home energy management system. IFAC-PapersOnLine 48, 880–885. doi:doi:10.1016/j.ifacol.2015.05.158.

Louis, J.N., Caló, A., Leiviskä, K., Pongrácz, E., 2016. Modelling home electricity management for sustainability: The impact of response levels, technological deployment & occupancy. Energy and Buildings 119, 218–232. doi:doi:10.1016/j.enbuild.2016.03.012.

Lunz, B., Stöcker, P., Eckstein, S., Nebel, A., Samadi, S., Erlach, B., Fischedick, M., Elsner, P., Sauer, D.U., 2016. Scenario-based comparative assessment of potential future electricity systems – a new methodological approach using germany in 2050 as an example. Applied Energy 171, 555–580. doi:doi:10.1016/j.apenergy.2016.03.087.

Marra, F., Yang, G., Traeholt, C., Ostergaard, J., Larsen, E., 2014. A decentralized storage strategy for residential feeders with photovoltaics. IEEE Transactions on Smart Grid 5, 974–981. doi:doi:10.1109/tsg.2013.2281175.

May, J., Brennan, D., 2006. Sustainability assessment of australian electricity generation. Process Safety and Environmental Protection 84, 131–142. doi:doi:10.1205/psep.04265.

McKenna, E., Darby, S., 2017. How much could domestic demand response technologies reduce co2 emissions?, in: Conference proceedings ECEEE on Consumption, efficiency and limits, pp. 337–347. URL: http://proceedings.eceee.org/visabstrakt.php?event=7&doc=2-107-17.

Odyssee-Mure, 2015. Energy Consumption Statistics. Odyssee. URL: http://www.odyssee-mure.eu.

Özkan, H.A., 2015. A new real time home power management system. Energy and Buildings 97, 56–64. doi:doi:10.1016/j.enbuild.2015.03.038.

Özkan, H.A., 2016. Appliance based control for home power management systems. Energy 114, 693–707. doi:doi:10.1016/j.energy.2016.08.016.

Sithole, H., Cockerill, T., Hughes, K., Ingham, D., Ma, L., Porter, R., Pourkashanian, M., 2016. Developing an optimal electricity generation mix for the UK 2050 future. Energy 100, 363–373. doi:doi:10.1016/j.energy.2016.01.077.

Sonnenschein, M., Lünsdorf, O., Bremer, J., Tröschel, M., 2015. Decentralized control of units in smart grids for the support of renewable energy supply. Environmental Impact Assessment Review 52, 40–52. doi:doi:10.1016/j.eiar.2014.08.004.

Stamford, L.J., 2012. Life cycle sustainability assessment of electricity generation: a methodology and an application in the UK context. Ph.D. thesis. The University of Manchester. Manchester. URL: https://www.escholar.manchester.ac.uk/uk-ac-man-scw:166964.

Thompson, M., Ellis, R.J., Wildavsky, A., Wildavsky, M., 1990. Cultural Theory. Westview Press. URL: https://westviewpress.com/books/cultural-theory/.

Vega, A., Santamaria, F., Rivas, E., 2015. Modeling for home electric energy management: A review. Renewable and Sustainable Energy Reviews 52, 948–959. doi:doi:10.1016/j.rser.2015.07.023.

Vera, I., Langlois, L., 2007. Energy indicators for sustainable development. Energy 32, 875–882. doi:doi:10.1016/j.energy.2006.08.006.

Wada, K., Akimoto, K., Sano, F., Oda, J., Homma, T., 2012. Energy efficiency opportunities in the residential sector and their feasibility. Energy 48, 5–10. doi:doi:10.1016/j.energy.2012.01.046.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part i): overview and methodology. The International Journal of Life Cycle Assessment 21, 1218–1230. doi:doi:10.1007/s11367-016-1087-8.

Wilson, G.T., Bhamra, T., Lilley, D., 2015. The considerations and limitations of feedback as a strategy for behaviour change. International Journal of Sustainable Engineering 8, 186–195. doi:doi:10.1080/19397038.2015.1006299.

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