Environmental Impact Assessment Review 67 (2017) 109–116

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

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

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

Jean-Nicolas Louis*, Eva Pongrácz

*University of Oulu, Faculty of Technology, Energy and Environmental Engineering, P.O.Box 4300, FI-90014 Oulu, Finland*

A R T I C L E I N F O

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

A B S T R A C T

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.

## 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 decentralized 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 decentralized electricity production, storage and consumption (Di Fazio et al., 2013; Keane et al., 2013; Marra et al., 2014; Eid et al., 2016; Özkan, 2016). Other studies focus on management of consumption by controlling appliances (Chavali et al., 2014; Özkan, 2015; 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

* Corresponding author.
*E-mail addresses:* jean-nicolas.louis@oulu.fi (J.-N. Louis), eva.pongracz@oulu.fi (E. Pongrácz).

http://dx.doi.org/10.1016/j.eiar.2017.08.009
Received 21 February 2017; Received in revised form 25 August 2017; Accepted 27 August 2017
Available online 19 September 2017

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 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 (European 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, 2016). 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, 2014).

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 (CEN, 2006). However, in order to evaluate the life cycle environmental impact of a system, indicators must be carefully chosen (Khan et al., 2004; May and Brennan, 2006; Vera and Langlois, 2007; Afgan and Carvalho, 2008; Stamford, 2012; GRI, 2015). 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. (2014) 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., 2016). 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.

#### 2.1.1. 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 Fig. 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 Fig. 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

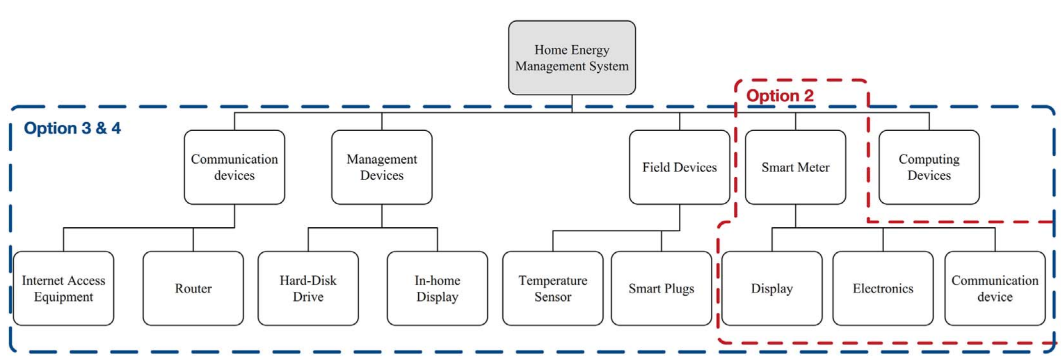


**Fig. 1.** System boundaries of the smart house studied in the present life cycle impact assessment (LCIA), based on Louis et al. (2015) (print B & W).