Impacts of home energy management systems on electricity consumption

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HIGHLIGHTS

• Real-life consumption data was gathered in 10 households before and after the installation of the HEMS.
• Energy conservation increased and the daily consumption profile changed.
• HEMS brings savings up to 30% if householders value energy conservation over comfort.
• Even families, who value comfort above other values, gained savings.
• The level of energy conservation varies greatly in each household and between them.

ABSTRACT

Home energy management systems (HEMS) connect homes to a smart grid and may increase the overall use of renewable energy by directing energy demand to off-peak hours and increasing energy conservation. However, the promised changes in electricity consumption have yet to be proven in real-life experiments. We therefore analysed the changes in electricity consumption, daily consumption profiles, and number of low and high consumption hours after installing HEMS in 10 Finnish households. These changes were examined in the context of the values related to energy use in each household, which were derived from semi-structured interviews. In the real-life experiment, we showed that the HEMS reduced the total consumption of electricity in the winter months by up to 30%, shifted the consumption to off-peak hours and decreased the number of high consumption hours. These changes occurred even in the homes that valued comfort over savings or ecological sustainability. Nevertheless, the levels of energy conservation varied greatly between the households and between months in the same homes.

1. Introduction

Smart home energy technologies are attracting considerable attention due to the global energy transition [1,2]. The growing use of largely weather-dependent renewable energy sources (RES) and increasingly decentralised energy generation into the power grid, including households’ own energy production, have set new demands for home energy management. The revised European Performance of Buildings directive will require an automation or management system to optimise building energy use and provide demand flexibility [3]. Home energy management systems (HEMS) are a technology that can be used in homes to facilitate and automate energy management [4]. They can reduce overall energy demand and shift more consumption to off-peak hours while simultaneously enhancing household comfort and convenience [1,5]. HEMS make a home the end-use node of a smart energy system and allow flexible energy demand, thus advancing the use of RES and helping mitigate climate change [5-8]. With distributed and weather-dependent renewable energy resources, the time of day people use energy becomes increasingly important in the reduction of CO₂ emissions [9]. Despite the importance and potential of HEMS, the extent to which HEMS can increase the flexibility of domestic electricity consumption has not yet been established in real-life experiments. To date, changes in energy consumption due to HEMS have predominantly been demonstrated with simulations (e.g. [10-13]). Although simulations can present user-related variables, they do not always capture people’s usage in particularly realistic ways [1]. There is a need for actual energy savings and demand management outcomes among the adopters of HEMS to be assessed [1,14]. The aim of this study was to extend the current knowledge on HEMS energy savings and energy consumption profile changes using real-life data from 10 households before and after the adoption of HEMS.

There is further an identified need to combine energy consumption...
Our main research question was: What kinds of changes occur in the electricity consumption after the adoption of a HEMS in terms of consumption volumes and the times of use? We also had the opportunity to look at the values driving households energy consumption changes. Which values drive energy consumption reductions?

We answered these research questions by examining how households’ total electricity consumption was affected, how daily consumption profiles shifted and how the number of peak hours decreased in homes using installed HEMS. The novelty of our research stems from two features. The primary novelty is that we compare real-life, non-simulated consumption volumes (kWh) in the winter months of the year before the HEMS were installed with the same months in the following year. The second novelty is the visualisation of the changes in the consumption profiles after the adoption of the HEMS. In addition, we enquired regarding the values the households expressed in their choices regarding energy consumption and the use of the HEMS in particular. Overall attitudes towards energy and environmental friendliness and the behaviour of household members have previously found to affect the realised changes in energy consumption [20,22–24]. Interestingly and to the best of our knowledge for the first time in energy research we show how these changes may vary depending on the characteristics of households which were defined in this study by the settings the household members fed into the HEMS. We triangulated the consumption changes using qualitative, ethnographic data, with special attention to the values related to energy use in each household, which is a novel approach in the energy consumption literature. Our results contribute to the knowledge on the effectiveness of HEMS in energy conservation and peak load shifting and help to broaden the understanding of the values related to energy use and management, including HEMS use, in households. The results are relevant to home energy management technology design, citizen information, education campaigns on energy use and energy conservation and policy planning on home energy conservation and the appropriate technologies.

1.1. HEMS for energy conservation and demand flexibility

Energy conservation and demand flexibility are the main strategies in the energy transition towards the increased use of renewable energy resources (RES). Energy conservation refers to reducing end-user demand for energy by reducing the service demanded; for example, a reduction in the demand for electricity for space heating can be achieved by lowering the thermostat in a home [25]. Demand flexibility refers to all the measures used to adjust consumption based on the availability and price of electricity. Depending on the balance of the grid, the electricity price and the short-term forecast of supply and demand, it can mean reducing (peak shaving, conservation), increasing (valley filling, load growth) or rescheduling (load shifting) energy demand. Demand flexibility can be accomplished by changing energy use behaviours, with the aid of energy storage, authorising the electricity utility or distributor to manage the demand side, or the use of home automation systems. Users’ proactive calculations and analyses of energy use to reduce consumption during peak hours would be cheaper and simpler than installing home technologies, yet, this method it is not sufficiently reliable because people lack knowledge regarding the level of their energy consumption and hourly demand variations, and they are not willing to spend time thinking about and planning energy use [7]. However, HEMS do that automatically.

The HEMS on the market offer diverse capabilities for users, such as feedback about electricity demand, remote or scheduled control of appliances, and heating or appliance consumption adjustments based on consumer preferences or environmental conditions [26]. Householders usually program and control their energy use levels, but HEMS can also provide electricity utilities with an access to control heating and/or appliances in demand response events, or to receive demand response prompts from the utility [27–28]. Home energy micro-generation loads, electric vehicle charging, and many home appliances are increasingly being controlled by HEMS [29].

Early research on home energy technologies and their impact on energy consumption have focused largely on the impact of energy consumption feedback (e.g. [30–34]). The savings in energy consumption due to feedback seem to fall within a wide range of 5%-20% [35–38]. HEMS that offer functionality beyond scheduled thermostats and/or feedback on energy consumption have been the focus of more recent studies by for example [10,26]. The savings potential of HEMS has been estimated to range from negative (i.e. consumption has increased) to over 20% [28]. Simulations of different energy consumption scheduling through HEMS have brought about a 20%-41% reduction in electricity bills [10,12,39] and a 21%-25% reduction in peak-to-average ratios [39]. The New York State piloted HEMS installations in 50 households during 2016 and 2017, and reported yearly energy savings of up to 16% [40–41]. However, the study did not analyse changes in consumption profiles. The real-life trial of HEMS by [42] focused on the participatory design of HEMS user interface rather than measuring the change in the energy consumption level and daily profiles. Several studies have been based on simulations and models (e.g. the scale of rebound effect of HEMS) [43]. In effect, real-life experiences on the impacts of HEMS on energy consumption are rare [1,35], very expensive and time-consuming to organize [26,28].

The two types of HEMS used in this study here are used mainly to manage electric heating. In Finland, home heating and the provision of hot water comprise 83% of all home energy consumption, and about half of all detached houses use electric heating as the primary heating technology [44–45]. Heating during the consumption peaks in winter offers the potential for the demand side management in the residential sector [46]. The main objective of the two HEMS used in our study is to reduce and shift heating electricity consumption. Load shifting is based on price and comfort factors rather than emissions reductions.

Energy conservation and demand flexibility through HEMS require both quantitative and qualitative changes in energy consumption. Users need to seek and enter the optimal system settings, but they also have to reconsider their practices, habits and requirements in terms of comfort. HEMS in operation also causes quantitative and qualitative changes.

Energy consumption should decrease and the time of use of energy should shift. On the other hand, users may note other, qualitative consequences such as a more stable indoor temperature, more awareness of energy consumption and behavioural changes due to increased awareness. Values direct, but are also affected by, the use of HEMS. In this study, we sought to determine the connection and feedback between the
1.2. Values and energy use

Values are what people consider good and important in life [47–48]. People prioritise and use their values as the criteria to select their practices and actions and to evaluate people and situations. Values are inherently social and relatively enduring beliefs on ‘desirable modes of conduct’ or ‘end-states of existence in different situations, societies and cultural contexts’ [49–50]; yet, values and value priorities are subject to change due to insights gained through experience [47] or other factors such as time, social structures or even technology [51]. The importance of values in directing people’s behaviour has been acknowledged within several disciplines and research fields (e.g. [52]) including energy research (e.g. [23,53–54]) and human–computer interaction (e.g. [55–57]). While human values are considered relatively universal [48,58], there may be differences in how values are prioritised [59]. In this study, we focused on values related to energy behaviours and energy use in homes.

Several studies have analysed the human behavioural and demographic factors that influence energy consumption and the adoption of energy technologies (e.g. [60]), but only a few have evaluated values related to household energy consumption. Change levels. Additionally, there is still considerable ambiguity with regard to the association between values and energy use behaviours. Amasyali and El-Gohary [20] surveyed the energy-related values and satisfaction levels of residential and office building occupants in three US states and identified seven energy-related values: thermal comfort, visual comfort, internal air quality, health, personal productivity, environmental protection and energy cost savings. The survey respondents ranked health as having the most importance among their values although significant differences were found in the importance rankings of residential and office building occupants, with energy cost savings being significantly more important for residential building occupants and visual comfort and personal productivity more important for office building occupants. Fornara, Pattitoni, Mura and Strazzera [22] tested the value-belief-norm model with the intention to use RES at a household level. They concluded the model is suitable for estimating such intentions, and further found that moral norms and informational influences (i.e. trust in friends/relatives and neighbours) were the most powerful predictors of the intention to use renewable energy devices. However, the values behind HEMS use and subsequent energy consumption changes have not been studied.

Although values underpin behaviour, a value-action gap can be identified in environmental and energy conservation behaviours: people often do not act according to their higher values [24,61–62]. Household energy consumption is also not driven primarily by financial incentives or the pursuit of material interests [24].

We studied the values related to energy use by conducting semi-structured interviews and applying sensory ethnography lens. Since people do not always act according to the values they express verbally (see, for example, the value-action gap [63–64] and hedonic or pragmatic moral hypocrisy [65]), sensory ethnography lens with observations and the re-enactment of home practices in the context of energy use can reveal which values drive home energy use in practice. One study found that the key values related to energy use are economic savings, ecological sustainability, comfort, security and exploration [66]. These values influence how HEMS is used in the homes and thus the resulting impacts on energy consumption. For example, if householders value comfort, this will affect the level of energy used for space heating [67]. On the other hand, activating environmental values may lower the price sensitivity towards technologies promoting sustainability [68]. Furthermore, savings in energy consumption depend largely on how efficiently users apply the features of HEMS, the behaviour of residents (e.g. whether doors between rooms are kept open or closed), their required comfort level and the characteristics of the home.

2. Methods

We analyze the impacts of HEMS in household energy consumption using monthly and hourly electricity consumption data in kWh. The quantitative consumption data were also analysed in the context of household energy behaviours, specifically in relation to the households’ values with respect to energy use.

The analysis was derived from the hourly electricity consumption data of 10 households in Northern Finland, that adopted HEMS in autumn 2018. This real-life experiment with HEMS was formed as a part of a local energy efficiency project. The participating households could choose between two types of HEMS and received a 50% financial subsidy from the research project. All the households lived in single-family detached houses with electric heating and a total living space of 130–200 m². The price of the system, including installation, varied from 2000 to 3500 euros.

The main function of the HEMS is to automate and optimise home heating by adjusting the house temperatures based on preset settings, room temperatures and humidity, weather forecasts and electricity prices. A hot water boiler and air heat pump can be integrated into each system. A house with a heat-accumulating electric heating system or heating element (e.g. a water boiler, floor or roof) and time-based electricity contract can benefit from hourly-based electricity prices by retaining heat and releasing it to the heating system during the peak hours. The studied HEMS aim to provide households with reduced energy consumption by lowering the temperatures at the user-defined times and in user-defined spaces and to reduce energy costs by shifting the load to cheaper off-peak hours thus increasing energy conservation and the use of renewable energy. The two HEMS selected for use in this study are commercial ones that are available on the market. They were chosen based on the tender price for a standard house. Both systems consist of sensors that communicate with a central unit through a wireless home network. The central unit is installed within the main switchboard of the house. Sensors are installed in the rooms for room-based control and monitoring. Users control and monitor their energy use via a control application, that is connected to the cloud service of a system provider. The two systems differ in their main strategies for energy conservation. HEMS 1 emphasises the shifting of heating electricity consumption to off-peak hours. The system provider recommends that users enter into a spot-price-based contract with the electricity utility so that they can benefit from the changes in electricity prices. Although most of the savings from HEMS 1 are expected to come from automatic load shifting, users can make hourly heating profiles to reduce consumption at certain times of the day or week. In contrast, HEMS 2 focuses on room-specific temperature reductions (e.g. during day-time, when householders are absent or during night hours). HEMS 2 also promises to shift consumption depending on electricity prices and the type of the user electricity contract in place. In addition, it provides users with information about room-based energy consumption, to help them to target their energy-saving efforts. Both HEMS 1 and HEMS 2 are able to learn how a house reacts to changes in temperatures and settings and could thus be described as ‘smart’ HEMS (SHEMS). The systems combine information from the indoor and outdoor temperatures and humidity, weather forecasts, users’ settings and electricity prices to optimise electric heating. HEMS 2 can also be connected with a home’s air heat pump, solar panels and electric car charging point.

The HEMS were installed in the homes of 10 households in autumn 2018. The householders were interested in acquiring the systems and participated in an information event for the research project, which was advertised in a local newspaper and online. After the event, they discussed the options and entered into a contract with either of the two HEMS providers selected for the research project based on a bidding process.

We compared the electricity consumption of each household in the winter months before the installation of the HEMS with the consumption in the winter months following the installation. The proportion of
heating in the total electricity consumption was estimated based on the consumption of the household in the summer months, and the estimated proportion of heating was weather-corrected with using the heating degree day (HDD) factors provided by the Finnish Meteorological Institute [69]. The formula can be found in Appendix 1 and the changes in consumption for the households are presented in Table 1 and for the month of January in 2017, 2018 and 2019 in Fig. 3.

In addition to comparing the weather-corrected electricity consumption before and after the installation of the HEMS (Table 1, and Fig. 3), we analysed the changes in the total consumption profiles and the distribution of hourly demands for electricity in the households (in Appendix 2). The data used for the hourly consumption were not weather-corrected, because monthly HDDs are not pertinent in the analysis of daily consumption profiles and the distribution of low and high consumption hours.

The qualitative ethnographic data that we used to understand the values behind the consumption changes were acquired by applying a sensory ethnography methodology. Sensory ethnography is a method that aims to gain an understanding of people’s experiences, values, identities and ways of living by ‘exploring people’s multi-sensory relationships to the materialities and environments of their everyday lives, and to their feelings about them’ [70]. In the sensory ethnography interviews in this study a researcher first interviewed the family members about their values, expectations and perceptions of HEMS before the installation of the HEMS in their homes. The householders were then asked to enact their morning, afternoon and evening routines. Mornings and evenings are usually the peak hours of electricity use in homes, as that is when people carry out activities involving energy consumption. The re-enactments were recorded on video. A second interview was subsequently conducted. This interview focused on observing how the family had adapted to using the HEMS immediately following its installation. Later, after two to six months of HEMS use the householders were interviewed for a third time to gain insights into their experiences and the use of the HEMS in their homes.

3. Findings

The results of our study showed that the HEMS increased energy conservation, changed the households’ energy consumption profiles and shifted their times of consumption. Furthermore, the number of high consumption hours decreased and thus flattened the consumption peaks. Nevertheless, the extent of these changes depended on the users’ preferences and the values they expressed in the use of the HEMS. The users who preferred comfort more than ecological sustainability set the HEMS higher temperatures, and did not seek as many savings on a consumption level. However, their consumption also decreased, and the consumption profiles changed. The peaks flattened, and the hours with less consumption than average increased.

3.1. Changes in consumption volumes and profiles

In Table 1, we show the total monthly electricity consumption in kWh for the winter months of January, February and March 2018 and 2019. The total monthly consumption was weather-corrected using the formula in Appendix 1. The heating proportion of the total electricity consumption was estimated based on the monthly summer consumption of each household, and the estimated heating proportion was weather-corrected with the HDD factors provided by the Finnish Meteorological Institute [69]. Most households obtained considerable savings (up to 30%) in their electricity usage. But there were also interesting differences, in that some households increased their consumption for one or two months. This raised the question of what accounted for these differences, and whether they could be understood by differences in values and preferences.

In Table 2 we present the changes in the mean (μ), skewness and kurtosis values in the hourly consumption distributions of all the households in January, February and March 2018 and 2019. Daily weather corrections are not applicable on an hourly basis as they do not affect timely variations in hourly settings. January 2019 was significantly colder than January 2018, so these values were hard to compare from an energy-saving perspective as almost all households increased their hourly average consumption. As can be seen from February and March, the differences in the means of all households were negative with lower means in 2019 (negative difference). The skewness differences were positive for these months for most of the households, which shows that the distributions became more skewed to the right as the number of low consumption hours increased. In terms of distribution, there were mostly positive differences in the kurtosis values, with the right tail becoming relatively heavier. This is understandable as heavy consumption hours, for example, those relating to meal preparation and dish washing are difficult to change. Overall however, the peak consumption moved to lower consumption volume hours.

As demonstrated in Table 2, there were some exceptions to the trend of the changes. For example, in household 3 (HH3), the average consumption decreased, the number of high consumption hours decreased, and the tail became less heavy. The householders wanted to use the HEMS not only to flatten their peak hour consumption and improve their overall energy conservation, but also to use the hourly based electricity prices to direct consumption. They changed their electricity contract from a two-time electricity contract to a time-of-use tariff (spot price). Their high consumption hours then took place late at night and in the early hours of the morning when the consumption is desirable and cheaper. The household’s overall energy conservation following the

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**Table 1**

Changes in total electricity consumption (weather-corrected) for the 10 households in the winter months of 2018 and 2019.

<table>
<thead>
<tr>
<th>Household</th>
<th>January kWh</th>
<th>February kWh</th>
<th>March kWh</th>
<th>Energy saving %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houseold 1</td>
<td>2018</td>
<td>3008.6</td>
<td>2661.4</td>
<td>470.8</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>2955.1</td>
<td>2445.2</td>
<td>471.1</td>
</tr>
<tr>
<td></td>
<td>Energy saving</td>
<td>1.8</td>
<td>8.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Houseold 2</td>
<td>2018</td>
<td>3621.6</td>
<td>3577.7</td>
<td>318.6</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>3694.5</td>
<td>3290.1</td>
<td>383.8</td>
</tr>
<tr>
<td></td>
<td>Energy saving</td>
<td>-1.7</td>
<td>8.0</td>
<td>10.7</td>
</tr>
<tr>
<td>Houseold 3</td>
<td>2018</td>
<td>3092.4</td>
<td>2573.3</td>
<td>2108.2</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>2366.8</td>
<td>2179.3</td>
<td>1866.9</td>
</tr>
<tr>
<td></td>
<td>Energy saving</td>
<td>23.5</td>
<td>15.3</td>
<td>11.7</td>
</tr>
<tr>
<td>Houseold 4</td>
<td>2018</td>
<td>3060.3</td>
<td>2751.0</td>
<td>2465.0</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>2990.1</td>
<td>2566.7</td>
<td>2379.2</td>
</tr>
<tr>
<td></td>
<td>Energy saving</td>
<td>2.3</td>
<td>6.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Houseold 5</td>
<td>2018</td>
<td>2194</td>
<td>2042</td>
<td>2172</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>2365</td>
<td>1962</td>
<td>1889</td>
</tr>
<tr>
<td></td>
<td>Energy saving</td>
<td>-7.8</td>
<td>3.9</td>
<td>13.0</td>
</tr>
<tr>
<td>Houseold 6</td>
<td>2018</td>
<td>3339.6</td>
<td>2867.7</td>
<td>2622.0</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>2717.6</td>
<td>2498.9</td>
<td>1898.5</td>
</tr>
<tr>
<td></td>
<td>Energy saving</td>
<td>18.6</td>
<td>12.9</td>
<td>27.6</td>
</tr>
<tr>
<td>Houseold 7</td>
<td>2018</td>
<td>1886.3</td>
<td>1673.7</td>
<td>1629.9</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>2070.4</td>
<td>1875.8</td>
<td>1536.1</td>
</tr>
<tr>
<td></td>
<td>Energy saving</td>
<td>-9.8</td>
<td>-12.1</td>
<td>5.8</td>
</tr>
<tr>
<td>Houseold 8</td>
<td>2018</td>
<td>2827.7</td>
<td>2470.4</td>
<td>2297.3</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>2824.8</td>
<td>2142.9</td>
<td>1844.3</td>
</tr>
<tr>
<td></td>
<td>Energy saving</td>
<td>0.1</td>
<td>13.3</td>
<td>19.7</td>
</tr>
<tr>
<td>Houseold 9</td>
<td>2018</td>
<td>4411.8</td>
<td>3720.9</td>
<td>3243.9</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>3729.4</td>
<td>3245.0</td>
<td>2734.5</td>
</tr>
<tr>
<td>Change %</td>
<td>15.5</td>
<td>12.8</td>
<td>15.7</td>
<td></td>
</tr>
<tr>
<td>Houseold 10</td>
<td>2018</td>
<td>3749</td>
<td>3075</td>
<td>2649</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>2742</td>
<td>2292</td>
<td>1834</td>
</tr>
<tr>
<td>Change %</td>
<td>26.9</td>
<td>27.4</td>
<td>30.8</td>
<td></td>
</tr>
</tbody>
</table>
introduction of the HEMS was significant at 11.7% – 23.5%.

In HH6, the users indicated they took some time before adjusting the HEMS settings. They used the HEMS control application to monitor room-specific consumption and noticed that one room consumed a disproportionately large share of their total heating consumption. They improved the insulation of the room and started to keep the room door open to let in the heat from the air heat pump.

In HH8 the flexibility in consumption was marginal because there were small children in home. We found that, in addition to values, the households’ capacity to take full advantage of the HEMS influenced the performance of the HEMS.

In Appendix 2, we show the basic features of the 10 households (i.e. living space, heating system, number of residents, key values ascertained during interviews), daily consumption for the analysed winter months and distribution of the hourly volumes. In general, our results showed that the number of hours of electricity consumption skewed positively from high consumption hours to an increased number of low consumption hours. This can be clearly seen from the movement of the 2019 consumption distribution to the right in the graphs in Appendix 2 as it increasingly peaked around low consumption hours.

### 3.2. Values behind electricity-related decisions

In our previous study, the values most commonly identified during the user interviews were economic gains, ecological sustainability, comfort, security and stimulation [66]. People expect first and foremost to save money and energy with the use of HEMS. Savings in energy are expected to equal the savings in costs. We defined ecological sustainability as energy conservation and shifting times of use to hours when grid electricity generation emits less CO2. In terms of comfort and security, we mean that the room temperatures in home are stable and predictable and can be adjusted with one user interface and remotely. In a harsh climate such as that in Finland, the right house temperatures are not only for comfort but also for security. In this study comfort refers also to temperatures that are not too high, particularly in bedrooms. One interface for all heating settings removes the need for users to walk from one room to another to adjust the thermostats. We identified security as the possibility to control home temperatures, humidity and consumption remotely. Some of the users in this study valued the stimulation and excitement of a new home technology. Other values mentioned less often by the users were trust (reliability), privacy, ease of use and interoperability with other home technologies. The three most important energy use-related values for each household are presented in Appendix 2, together with other household information and the energy conservation resulting from the use of the HEMS.

As shown in Figs. 1 and 2, the consumption profiles and their changes differed depending on the households’ key values. Fig. 1 presents the consumption of a household (HH4), that primarily sought to maintain comfortable temperatures throughout the day and did not consider energy conservation or demand flexibility to be important for ecological reasons. The first graph in the figure presents the daily consumption in kWh for March 2018 and March 2019. The bold blue line is the average for March 2019, and the bold red line is the corresponding hourly average consumption in March 2019. In the second graph in the figure,
we show the distribution of the hourly consumption in kWh on the horizontal and the number of hours on the vertical axis.

As demonstrated in Fig. 1, the HEMS alone could bring dramatic changes in the consumption profile of the HH4 where the users valued avoiding discomfort above other values (e.g. ecological sustainability and the use of RES), and did not decrease the temperatures during the day. The users wanted to gain economic savings by shifting more consumption to the night hours and expected the hourly energy price of electricity (spot price) to result in the savings. However, after the installation of the HEMS night-time consumption was lower compared to the year before the use of the HEMS, and consumption was slightly increased during the (usually) more expensive day hours.

The corresponding results for the family in HH9 are presented in Fig. 2. HH9 emphasised ecological and sustainability-related values. The graph shows a clear shift in daytime hourly consumption and a notable increase in low consumption hours.

3.3. Decay effects

It is well known, that in nudging experiments, the effects decay to some extent after the nudging ends. For example, [71] found that as long as their two-years nudging experiment continued, which included the delivery of regular information letters, the savings continued to exist. However, as soon as a break occurred in the information nudging, the savings diminished. To our best knowledge, similar studies have not been conducted with using home energy automation systems. In our example, autumn 2018 is not a good choice for comparisons as the families may have been preparing for the experiment and applying various kinds of early adjustments. Our interviews with the families also confirmed this. However, the months of December in 2017, 2018 and 2019 could be compared as the automation systems were assembled in November 2018.

Our data in Fig. 3 from the months of December in these three consecutive years (2017, 2018, 2019) illustrate that in the first year with HEMS (2018), the energy consumption among seven of the households was lower than in the following year (2019), indicating a possible decay effect. The consumption in December 2018 was however still very similar to that at the beginning of the study and the lower consumption can potentially be explained by the enthusiasm with which the households used the new system as well as their increased awareness of their energy use due to the introduction of HEMS and discussions around energy conservation. Compared to December 2017, all households consumed less electricity in December 2019 based on the weather corrected data. However, from 2018 to 2019 the consumption decreased only in three households. While no firm conclusions on the decay effect can be made, our results point to the possibility that when HEMS are used, decay effects may emerge.

4. Concluding discussion

This study responded to the lack of prior research involving real-life experiments on the changes in domestic electricity consumption brought about by the use of HEMS. The study also addressed the unclear relationship between values and energy use behaviours; the connection between values and resulting quantitative energy consumption changes has not been studied in previous research. We analysed the changes in the level of energy consumption and the consumption profiles before and after the installation of HEMS in 10 homes. We showed that HEMS may bring savings of up to 30% if householders value energy conservation and are willing to sacrifice some comfort. Notwithstanding, even the families who valued comfort over other values gained savings. This is in line with the findings of a HEMS simulation study where the correlation between cost savings and degree of discomfort (DoD) is not linear (i.e. savings increased to some extent without any, or a minor increase in DoD) [12]. Nevertheless, our figures also showed that the level of energy conservation varied greatly between households, and even in different months in the same household. The level of energy conservation in households does not necessarily correspond with a decreased level of greenhouse gas emissions as the latter depends on factors such as the electricity production method and the degree of complementing heating methods (e.g. wood heating). This study has some limitations. First, the results were obtained from one country only. While the results may have been specific to Finland in many ways, we expect that similar results may be seen in other countries. Second, the small sample does not allow for the generalisation of the results or consider disproving the results via statistical testing. Third, the correlation between each household’s values (comfort, cost, sustainability, etc.) and consumption were only described in a qualitative way. In future studies, they should be clearly demonstrated using quantitative indicators. Fourth, although the consumption was weather-corrected according to HDDs, it was not corrected for occupancy, so the extent to which differences in consumptions between pre- and post-HEMS were due to changes in occupancy was not assessed. Fifth, the electricity used for heating was not metered; instead it was estimated from the total electricity and electricity consumption in summer. This introduces uncertainty due to the assumption that non-heating hourly use of electricity (lighting, appliances, domestic hot water heating if electric, etc.) stay the same in both summer and winter. Sixth, the final interview took
place after only two to six months of use of the HEMS. It therefore remains unclear whether the HEMS could have triggered persistent behavioural change over the upcoming one to two winter periods. Lastly, the households could have been biased as a result of their awareness of the purpose of, and their participation in this study. This could have made them particularly motivated and willing to save energy during the study period.

Regardless of the afore-mentioned limitations, our approach which combined detailed analyses of real-life consumption data with qualitative interview (our interviews with two households can be viewed at https://www.youtube.com/watch?v=i0aFLW-N0is&t=3s) and observational data, has the potential to illustrate the extent of energy conservation and load shifting resulting from the use of HEMS. Our results demonstrate HEMS impacts on energy consumption volume and the time of consumption, but the range of changes is wide and affected by human factors, such as people’s values. The present findings have important implications in the design of home energy technologies (e.g. optimisation, demand response and energy community peak load balancing models), but they could also be applied in energy system design, energy policy planning, communication and community planning.

The HEMS user population is heterogeneous, and their technical competence varies greatly. The users of a system set their own goals and tasks, with no performance supervision, standards or systematic optimisation, demand response and energy community peak load balancing models), but they could also be applied in energy system design, energy policy planning, communication and community planning.

The HEMS user population is heterogeneous, and their technical competence varies greatly. The users of a system set their own goals and tasks, with no performance supervision, standards or systematic feedback [72]. This places greater demands on the ‘smartness’ requirements of HEMS. Our results demonstrate the potential and critical points in the use of HEMS for optimised electricity usage. More research and larger data are needed for generalizable results.

CRediT authorship contribution statement

Sanna Tuomela: Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing, Investigation, Formal analysis, Visualization, Data curation. Mauricio de Castro Tome: Software, Formal analysis, Validation, Visualization, Data curation. Netta Iivari: Methodology, Supervision. Rauli Svento: Conceptualization, Methodology, Validation, Writing - review & editing, Formal analysis, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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Appendix 1. The formula used for weather-corrected electricity consumption.

1. The electricity consumption of heating = total electricity consumption in a winter month – average consumption of electricity in summer months (June, July and August in the two most recent years).
2. The electricity consumption of heating was normalized using the formula below for every winter month, and the reduced summer average was added to obtain the total, normalised consumption of the winter months.
3. The reduction percentage in electricity consumption was calculated using the normalised electricity consumption figures for the winter months before and after the installation of the HEMS.

The weather-corrected electricity consumption in Table 1 and Fig. 3 was calculated using heating degree days (HDDs) over the winter months (January - March) for the years 2018 and 2019. The HDDs were provided by the Finnish Meteorological Institute [69].

\[ Q_{\text{norm}} = \chi \times \frac{S_{\text{ref loc}} - \chi}{S_{\text{realised ref loc}}} \times (Q_{\text{realised}} - \chi) + \chi \]

- \( Q_{\text{norm}} \): Realised monthly electricity consumption in a household
- \( S_{\text{ref loc}} \): Normal monthly (1981–2010) heating degree days in the reference locality (Oulu)
- \( S_{\text{realised ref loc}} \): Realised monthly heating degree days in the reference locality (Oulu)
- \( Q_{\text{realised}} \): Mean of the monthly electricity consumption in the summer months (VI-VIII) in 2017 and 2018.
- \( \chi \): Municipality-specific factor (the municipality of Ii = 0.95)
- \( k_m \): Normal monthly (1981–2010) heating degree days in the reference locality (Oulu)

Appendix 2. Household features, daily and hourly consumption profiles before and after the HEMS installation

Household 1

<table>
<thead>
<tr>
<th>Description</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total living space m²</td>
<td>199</td>
</tr>
<tr>
<td>Number of residents</td>
<td>2 + 3</td>
</tr>
<tr>
<td>HEMS installed</td>
<td>8/18</td>
</tr>
<tr>
<td>Heating system</td>
<td>Partly reserving floor heating, wood stove, air heat pump</td>
</tr>
<tr>
<td>Key values</td>
<td>Economic gains, comfort, stimulation</td>
</tr>
</tbody>
</table>
Household 2

A family of 2 adults and 3 children. The temperature was lowered in the daytime, but because of the small child, it was not kept very low when the family was at home. They valued ecological sustainability, thus energy conservation and shifting the time of use, but did not want to compromise comfort of living.

<table>
<thead>
<tr>
<th>Total living space m²</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of residents</td>
<td>2 + 3</td>
</tr>
<tr>
<td>HEMS installed</td>
<td>08/18</td>
</tr>
<tr>
<td>Heating system</td>
<td>Direct electric, wood stove, air heat pump</td>
</tr>
<tr>
<td>Key values</td>
<td>Sustainability, security, comfort</td>
</tr>
</tbody>
</table>

Household 3

Empty-nester couple, both working during the day. The wood stove was used frequently for heating during winter. Temperatures were lowered on weekdays when both the householders were absent. The less-used rooms were kept cooler all the time. The users thought part of their energy conservation was due to their changed energy usage behaviour based on increased attention to energy use, yet, they did not want to compromise much on comfort.

<table>
<thead>
<tr>
<th>Total living space m²</th>
<th>136 + 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of residents</td>
<td>2</td>
</tr>
</tbody>
</table>

(continued on next page)
Household 4

Family of 2 adults and 4 school-aged children who did not want to compromise comfort. The temperature was high (23 °C in some rooms). They expected to gain economic savings with the HEMS via the automatic shifting of consumption to night-time, when the price of electricity is lower.

Household 5

HEMS installed 10/18
Heating system Direct electric, air heat pump
Key values Comfort, economic gains, stimulation
Retired couple, who stayed at home all the time. The temperatures were kept the same all the time downstairs, where the couple spent most of the daytime. The female adult was sensitive to cold, so the temperature was kept relatively high. The less-used rooms and upstairs areas were kept cooler. The temperature was increased before going to bed and in the morning.

<table>
<thead>
<tr>
<th>Total living space m²</th>
<th>130</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of residents</td>
<td>2</td>
</tr>
<tr>
<td>HEMS installed</td>
<td>10/18</td>
</tr>
<tr>
<td>Heating system</td>
<td>Direct electric, wood stove, air heat pump</td>
</tr>
<tr>
<td>Key values</td>
<td>Economic gains, comfort, security</td>
</tr>
</tbody>
</table>

Household 6

Empty-nesters, one of whom was retired and other worked as an entrepreneur close to home, so the house was occupied during the day. The temperatures were decreased in the less-used rooms and upstairs areas.

<table>
<thead>
<tr>
<th>Total living space m²</th>
<th>170</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of residents</td>
<td>2</td>
</tr>
<tr>
<td>HEMS installed</td>
<td>10/18</td>
</tr>
<tr>
<td>Heating system</td>
<td>Direct electric, wood stove, air heat pump</td>
</tr>
<tr>
<td>Key values</td>
<td>Economic gains, comfort, security</td>
</tr>
</tbody>
</table>
Household 7

Two working adults. The temperatures were decreased during the day when the householders were at work. With the HEMS, the couple noticed the garage heating consumed energy disproportionally, until they lowered the temperature for the garage. A poorly insulated garage can increase heating costs even with a slight increase in temperature.

- Total living space m²: 130 + 42
- Number of residents: 2
- HEMS installed: 10/18
- Heating system: Direct electric, wood stove
- Key values: Comfort, economic gains, security

Household 8

Family of 2 parents and 2 small children. The mother stayed at home with the children, and the father worked remotely at home. House was always occupied. Because of the baby, the temperatures were not lowered much in the rooms in which they spent most of their time. The temperatures were lowered in the day-time in the bedrooms.

- Total living space m²: 152
- Number of residents: 2 + 2

(continued on next page)
Household 9

Elderly couple, empty-nesters, who lived in a large two-floor house. Since they were both retired, the couple stayed at home during the day. The temperatures were lowered at night, and the wood stove was used regularly for heating to reduce the need for electric heating.

Total living space m² 200
Number of residents 2
HEMS installed 10/18
Heating system Direct electric, wood stove, air heat pump
Key values Economic gains, comfort, sustainability

Household 10
2 working adults, one of whom works in shifts. They kept the temperatures low and increased them only for some hours of 'active time' in the evenings and the mornings. The less-used rooms and bathroom were heated in the mornings. 

References


