Preferred attributes of home energy management products for smart grids - Results of a design study and related user survey

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Preferred attributes of home energy management products for smart grids – results of a design study and related user survey

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Abstract: This paper presents an insight into end-users' perception of smart grid products for households. The analysed products included three types of home energy management products (HEMPs) namely: smart thermostats, smart plugs and smart wall sockets. The analysis involved existing commercial HEMPs, as well as newly designed HEMPs from a students' project executed at University of Twente (Netherlands) in 2013 and 2014. Various industrial design methods were applied, and an online survey was utilised for data collection. The smart thermostat was considered the product with the greatest potential to stimulate energy-efficient behaviour. Features most preferred by end-users are: 1) visual display of energy information; 2) monitoring of energy use of appliances; 3) remote control, and expected ease of use. Appearance also appeared to have influenced the preferences of end-users regarding specific HEMPs. This study highlights the main features that household end-users desire in products that could stimulate energy-efficient behaviour.

Keywords: smart grid products; home energy management products; HEMPs; energy-efficient behaviour; industrial design methods; IDMs.

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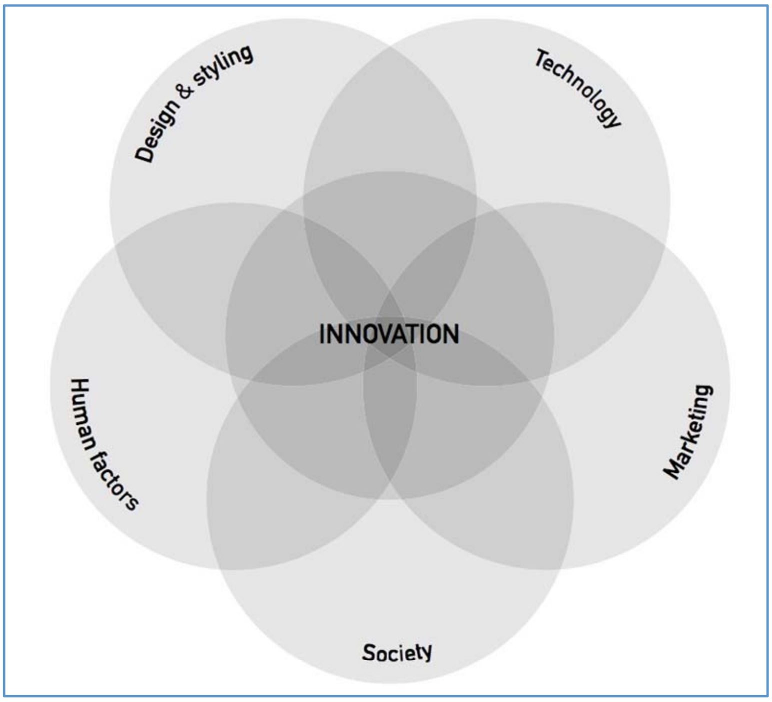
1 Introduction

The transition of the energy system to a decentralised and intelligent system, known as a 'smart grid', will require a more active participation of end-users in household energy management (Geelen et al., 2013). It is expected that the transition to smart grids will occur in the coming years (IEA, 2011), resulting in the need to develop new innovative smart energy products and services at the household and residential areas. These smart products and services stimulate a more active role for end-users in the management of their electricity system, by enabling them to have greater management ability over their energy consumption (Geelen et al., 2013).

Figure 1 Innovation flower of industrial product design (see online version for colours)



Source: Reinders et al. (2012)

The development of new products is usually achieved through technological innovation. Industrial product designers play a strategic role in technological innovation and product development processes (Eggink and Reinders, 2013). Industrial design methods (IDMs) are also useful in product development processes. IDMs help to convert the needs of the end-users and market into detailed information for manufacturable products and services. In the context of industrial design engineering (IDE), innovation is made up of technology, design and styling, human factors, marketing and society (Reinders et al., 2012). Here, technology refers to product technologies and manufacturing processes. Design and styling relates to the appearance of products and their market image. Human factors refer to the user context or the functional design of products. Marketing is related mainly to market value costs and sales, and society refers to policies, regulations and societal acceptance. These five components of the so-called innovation flower (Figure 1) are considered essential components for product development and the final success of a product (Reinders et al., 2012). Reinders and colleagues assume that interdisciplinary design methods can create better solutions compared to methods that focus only on optimising energy solutions.

Various smart grid products and services currently exist, namely: micro-generators, storage systems, smart appliances, time variable prices and contracts, and energy monitoring and control systems.

Energy monitoring and control systems are also referred to as home energy management systems (HEMS) (Van Dam et al., 2010, 2012; Geelen et al., 2013). Van Dam et al. (2010) described HEMS as ‘intermediary devices that can visualise, monitor and/or manage domestic gas and/or electricity consumption’; whose main purpose is to give users direct and accessible insight into their energy consumption [Van Dam et al., (2010), pp.458–469]. HEMS, therefore, play an important role in end-user interaction with other smart grid products and services such as micro-generators, storage systems, smart appliances, and time variable prices and contracts or dynamic pricing (Van Dam et al., 2012; Geelen et al., 2013).

HEMS can be divided into three groups of products namely:

1 user interfaces

2 software platforms

3 smart hardware (Karlin et al., 2015).

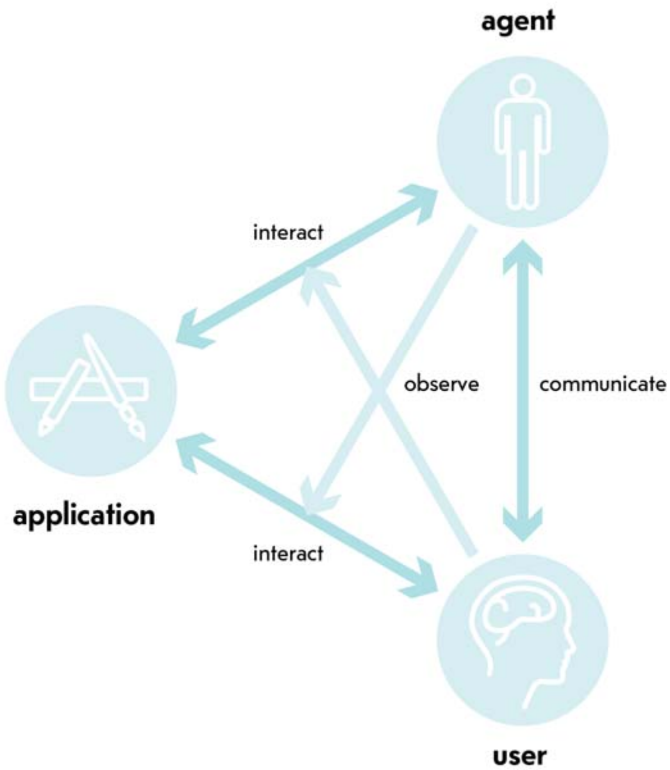
User interfaces provide data about end-user electricity consumption in various forms, namely in the form of numbers, or graphs or other visualisations. Software platforms include smart home platforms, data analytics platforms, and web services platforms. They collectively facilitate the communication of information between users, utilities, and hardware in the home and provide end-users additional functionality for managing connected devices.

Smart hardware comprises of products such as smart appliances, thermostats, lighting, and plugs that physically enable household energy demand to be controlled such that the energy demand patterns of particular appliances are modified to meet household energy needs (Karlin et al., 2015). Our study, therefore, focuses on smart hardware, and we will refer to them as ‘home energy management products’ (HEMPs), instead of more commonly used terms such as ‘smart grid products’ or HEMS’ that may include a broad range of separate elements that mainly function automatically in the background, with limited or no interaction with end-users.

In this study, we define HEMP as a product that is part of a HEMS, and which has an active interaction with the end-users. Many HEMPs are already commercially available (Netherlands Consumers’ Association, 2016). These range from single control devices, such as smart thermostats, lighting control with motion sensors, dimmers, remotes or scheduling; inventive thermostats; smart plugs; smart power strips that allow the end-users to actively control energy use, to centralised home automation systems. About 52 different smart energy products are currently available in the Netherlands (Netherlands Environmental Center, 2016). These include various smart thermostats such as Toon, Nest, Honeywell and Netatmo and electricity monitors such as Plugwise, BeeClear, Neurio and/or combined HEMPS such as Anna, Plugwise, i-care, Smappee and Oxio's HEMS.

Though the effective application of HEMPs may support and stimulate energy-efficient behaviour and reduce energy consumption in households, HEMPs have often been criticised for their perceived complexity. This complexity results mainly from various hidden functionality and range of functions that tend to autonomously take decisions without considering the user context and needs (Van Dam et al., 2012).

Figure 2 The collaborative paradigm (see online version for colours)



Source: Rich et al. (2001)

To ensure that end-users actively engage with products such as HEMPs, it is important for end-users to have control over the product instead of the product controlling the user (Van Dam et al., 2012). The perceived complexity of HEMPs could be reduced by designing more goal-based collaborative interfaces (Rich et al., 2001; Van Dam et al., 2012). These kinds of interfaces supports the user to learn more about the product and also have some level of control, instead of becoming totally dependent on an external wizard or agent (Rich et al., 2001; Van Dam et al., 2012). Figure 2 shows that goals can be communicated between the user and the product such that the product can help the user to meet a goal. The product agent as shown in Figure 2 could then play a more tutoring or supportive role instead of taking actions autonomously.

In general, it is assumed that HEMPs can contribute to 4% energy savings on the long run per household. However, the expected energy-efficiency potential of HEMPs is estimated to be in the range of 2% to 20% (LaMarche et al., 2011; Karlin et al., 2015). This is however an expectation by the developers of HEMPs. In practice, there is little evidence of the energy-efficiency stimulating influences of the use of HEMPs on the long run. Studies and reports on the subject of HEMPs have shown that they have not always stimulated energy-efficient behaviour as projected by the manufacturers (Van Dam et al., 2012; Netherlands Consumers' Association, 2016). Even worse, rebound effects and an increase of energy consumption have been reported.

End-user adoption and effective use of HEMPs are being limited because of complexities in deployment, set-up and use, and the often too technical information presented (LaMarche et al., 2012). Previous studies have shown that current approaches in developing smart energy products and services has often resulted in technically complex products that are not always easily understood by end-users, and therefore do not effectively fulfil the needs and wishes of end-users (Geelen, 2014; Obinna et al., 2016). This could be partly attributed to the current method employed in developing smart energy products and services, which is mainly focused on technology development, and the limited attention paid to end-user behaviour and interaction with smart grid technologies (Verbong et al., 2012). A study on stakeholders' involvement in residential smart grids development concluded that there should be more attention for end-user involvement, especially with regards to product and service development (Obinna et al., 2016). Smart energy products such as HEMPs can help to establish this end-user involvement, and that is the reason for which the research presented in this paper was carried out.

Studies by Reinders et al. (2012), Park et al. (2014) and Geelen et al. (2013) have concluded that end-user adaptation and acceptation of smart energy products and services will determine their effective functioning. In this regard, it is important to take the end-users' needs, wishes and abilities into consideration during the development and implementation of smart energy products and services such as HEMPs. Also, in order to properly develop and effectively spread new smart energy products for households, it is necessary to achieve a better understanding of the exact functionalities that would make end-users accept or reject these HEMPs. In addition, the relevance of good designs for effective man-machine interaction has been advocated by previous studies (such as Peslak, 2005; Karray et al., 2008; Steen, 2012). The field of study of human-machine interaction has however hardly paid attention to the design of HEMPs. Besides this, knowledge about specific attributes or functionalities of the products that end-users interact with could further be explored. Also, as far as we could determine, only limited experience exist with research on newly designed HEMPs. For instance, in a project evaluation carried out in the experimental smart grid pilot project Powermatching City in Groningen, a new design was established for the HEMP that was tested during the project (Powermatching City, 2014; Geelen, 2014). This HEMP was not, however, commercially available and will not be commercially available in the future. The same can be said about user interfaces in the your energy moment smart grid pilot project (phase 1) Zwolle, executed by energy company Enexis (Kobus et al., 2012). In this project the user interface design was changed multiple times. On the basis of the evaluations, the design was modified.

Our expectation is that the application of IDE methods in the development of new conceptual HEMPs, and evaluation of these newly designed HEMPs, alongside already existing commercial HEMPs, may help to determine to what extent new design features may influence end-users' perception of HEMPs. Therefore, a twofold objective is formulated for this study as follows:

1. To explore the role of IDMs for the development of smart energy products for households.
2. To evaluate end-users' perceptions of and preferences for existing and new conceptual smart energy products, and the functionalities of these products that may best stimulate energy-efficient behaviour.

2 Research method

2.1 Application of IDMs

In order to realise the *first research aim*, the following approach and research methods were chosen.

2.1.1 Development of new HEMPs

The conceptual HEMPs used as the basis for this questionnaire study (second research aim) were designed during two students' design projects (2013 and 2014), at the Faculty of Industrial Design Engineering, University of Twente (The Netherlands) in the framework of the Master course 'Sources of Innovation'. This course positions product development in the context of the innovation flower and provides theory about innovation processes and useful tools for the design of innovative technology-based products related to emerging technologies, such as smart grids (Reinders et al., 2012; Obinna et al., 2014). For detailed information about the design process of the conceptual smart grid products, see Reinders and van Houten (2006), Eggink et al. (2009), Reinders et al. (2011, 2009), Eggink and Reinders (2013) and Obinna et al. (2014).

Students involved in this project were asked to design innovative HEMPs that can be applied in or around smart grid households. The products are also expected to be aesthetically appealing to household end-users and at the same time, stimulate energy-efficient behaviour in a durable, intuitively understandable and comfortable way.

The students focussed their research in the Dutch context regarding the smart grid stakeholders and end-users interviewed, and market needs and trends related to smart energy products.

To achieve the proposed design task, various IDMs were applied. The purpose of applying these IDMs is to get insight in which methods are most suitable for designers in general, as we do not have specific numbers.

These methods (Reinders et al., 2012) are briefly described in Table 1.

Table 1 IDMs used in the students' design project

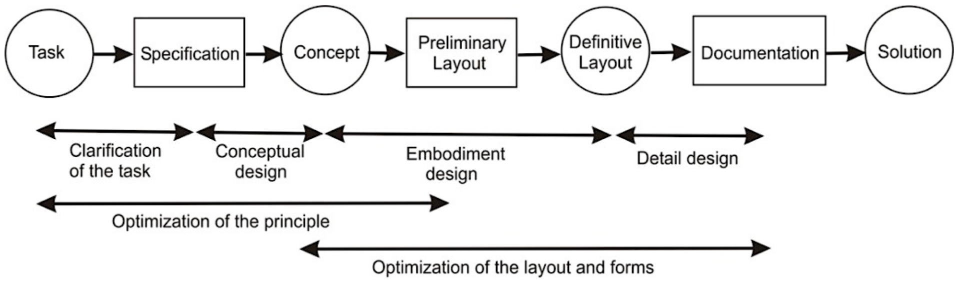
	Industrial design method	*Function*
1	Platform-driven product development (PDPD)	Defines a set of related products (product families) that can be developed and produced in a time- and cost-efficient manner (Halman et al., 2003)
2	Innovative design and styling (IDS)	Refers to the appearance of products and their image in the market (Eggink and Reinders, 2013)
3	Delft innovation model (DIM)	Aims to optimally combine the intrinsic value of technology with opportunities in the market (Buijs, 2003)
4	Theory of inventive problem solving [TRIZ (Russian acronym)]	A comprehensive method based on long-term patent research leading to certain basic rules governing problem solving in product development (Altshuller, 1996)
5	Multilevel design model (MDM)	Describes the mutual relationship between new products and societal change processes (Joore, 2010)
6	Constructive technology assessment (CTA)	Focuses on the improvement of the role of actors in innovation journeys and consumer acceptance of new products (Deuten et al., 1997)
7	Innovation journey (IJ)	Refers to patterns followed in product development (Rip, 2010)
8	Technology roadmapping (TRM)	Establishes correlation between identified market needs and trends with existing and emerging technologies for a specific industry sector (Souchkov, 2005)
9	Lead user study (LU)	Provides useful information to product designers by evaluating those who are the first to face needs that will eventually affect a larger market (Von Hippel, 2005)
10	Risk diagnosing methodology (RDM)	Aims to identify and evaluate technological, organisational, and business risk in product innovation (Keizer et al., 2002)

The product development had to be supported by using the PDPD method and at least three other given IDMs, consulted in a sequential order. The students were supported in this task with various weekly lectures on both methodological and technological aspects. These lectures were supported by a guest lecture on smart grids, which was the main subject of this design task. A smart grid expert from Stiftelsen Det Norske Veritas and Germanischer Lloyd (DNV GL), a global firm operating in the field of smart grids implementation in the Netherlands and elsewhere, delivered this lecture. Next the design task was executed for the case of the Netherlands. Also the information that supported them in their various tasks was obtained from mainly Dutch smart grid and energy stakeholders. Regarding the knowledge of existing smart energy products, supporting information was based on the current Dutch energy market.

The students worked in teams of two for a period of 20 weeks (September to November 2013 and September to November 2014). Theory was provided by the publication the power of design: product innovation in sustainable energy technologies (Reinders et al., 2012).

The design project had a total workload of five European Credits. The design approach was based on a standard design process developed by Pahl and Beitz (1984). This approach (Figure 3), which is widely used in design engineering, entails the following phases: clarification of the task, conceptual design, embodiment design and detail design. Optimisation of the working principles of the product is carried out in the first three phases, while optimisation of the final layout and form is done in the last three phases.

Figure 3 Flow chart representing the basic IDM



Source: Pahl and Beitz (1984)

2.1.2 Selection of existing and newly designed HEMPs

The design projects in 2013 and 2014 yielded 41 various promising future product concepts that could be applied in future smart grid households. Figure 3 shows some of the developed product concepts. These included mainly HEMPs such as smart plugs, smart thermostats, in-home energy displays smart wall sockets, a smart energy meter, a smart energy planner, an innovative lighting device, smart refrigerator, an electric vehicle charging station, a solar energy harvester, an innovative playground, smart energy storage devices, an innovative shower concept and various applications integrated with these products that communicate with the smart meter. Examples of the new conceptual smart grid products are shown in Appendix C (http://doi.org/10.4233/uuid:d2d37a85-5c7c-4e9d-bb37-1283af0d3909, pp.199–210).

In general, almost all the developed product concepts were aimed at providing a better insight into energy demand and supply in households, in order to influence the behaviour of end-users to increase energy efficiency in households and reduce peak electricity demand.

For our evaluation, three categories of existing (commercially available) product and newly design conceptual products were selected as samples for this study namely:

a smart thermostats/in-home displays

b smart plugs

c smart wall sockets.

These products were selected because they were the predominant categories developed in the design project, and also appear to be the major products existing in the current market of smart energy products. Focussing on product categories, instead of single products, helps to focus on the most important aspects of the product, instead of the specific characteristics that are of secondary importance (Bork et al., 2015). The specific products that have been selected were considered the most innovative, and most suitable for application in smart grid households. The product concepts selected for evaluation have been presented in the master reports of: Ten Brink et al. (2014), Young et al. (2014) and Bergsma and Binnema (2013).

Some of the product concepts are shown in Appendix C. Each of the selected HEMPs gives insight into the entire energy use in households or energy use of specific household appliances. However, differences exist in their level of complexity and how they are used (for example, manual versus automatic usage), and the type of energy information they provide. For instance, while a smart thermostat gives insight in the total thermal energy consumption of households, the smart plug and smart wall socket provide information about the electricity use of specific household appliances connected to them.

We chose three brands of already existing and commercially available HEMPs namely: Toon smart thermostat from energy company Eneco, Fibaro wall socket and Wemo insight smart wall socket. The most popular commercially available HEMPs in the Netherlands were selected. For instance, the Toon thermostat was selected instead of the Nest thermostat because based on a Google search, it appeared to be most frequently used among end-users in the Netherlands (Netherlands Consumers' Association, 2016).

The conceptual products (Appendix C) were either new ideas or ideas adopted from already existing commercially available HEMPs.

Although the three types of HEMPs evaluated in this study perform different functions, the main reason why these products were compared with each other is because they are control devices that enable households to manage their energy consumption, and collectively belong to the same category of HEMPs referred to as 'smart hardware' (Karlin et al., 2015). Also, we wanted to use the newly designed HEMPs to trigger additional information from respondents.

2.2 End-user perceptions of and preferences for HEMPs

In order to realise the second aim of this study, the following approach and research methods were used:

1 setting up of online questionnaire survey

2 selection of respondents, sending out questionnaire

3 data collection and analysis.

2.2.1 Setting up online questionnaire

In this study a web-based questionnaire was used as the primary method of data collection. A questionnaire survey that took approximately 15 to 20 minutes was used in order to have more quantitative and representative data.

For the questionnaire, the selected products were presented including a brief description of the product, highlighting the major functions these product concepts are expected to perform in Dutch households (see Appendix A) (http://doi.org/10.4233/uuid:d2d37a85-5c7c-4e9d-bb37-1283af0d3909, pp.183–191).

Table 2 shows the already existing HEMPs, including a brief description of their features and attributes. Table 3 shows the conceptual HEMPs developed by the students (part of the first aim).

Table 2 Existing commercial HEMPs (see online version for colours)

Products		*Features/attributes*
Product A. Smart thermostat 	1	Gives insight in thermal energy use, generation, and energy costs of household appliances
	2	Connected appliances could be switched on and off from a distance with a smart phone
	3	Displays the energy use in households and the average use in the neighbourhood
Product B. Smart plug 	1	Gives insight in energy use and costs of household appliances
	2	Possesses illuminating LED-rings that changes colour based on the energy consumption. The light flashes when the maximum load (2.5 kW) is exceeded
	3	Connected appliances could be switched on and off from a distance with a smart phone
Product C. Smart wall socket 	1	Remote control on a smart phone
	2	Possibility to set timetables for setting the smart plug on and off
	3	Measures the power consumption of connected devices

The questionnaires consisted of 22 questions, both open and closed-ended questions and were related to the following topics:

1 characteristics of respondents (i.e., gender, age, household composition, educational level and type of houses respondents live in)

2 ownership of smart energy products, and types of smart energy products owned

3 preferences for existing and conceptual smart energy products and reasons for the preferences

4 features found most attractive in the chosen products and concepts and other features desired

5 product concept considered to best stimulate energy-efficient behaviour

6 likelihood of acquiring their chosen products or concepts, and remarks, ideas and suggestions related to smart energy products.

These questions were selected because they cover the most important issues related to the evaluation of end-user perception of the attributes of HEMPs that could make them more engaged with their energy at home.

Table 3 Conceptual HEMPs (see online version for colours)

Concepts		*Features/attributes*
Product A. Smart thermostat 	1	Displays feedback on energy use (water gas use; history of energy use and cost savings in Wh, €/hr; energy usage of other households via a manually controlled projector
	2	Wireless communication module that provides communication between the device and appliances or control devices
	3	Battery/transformer module for power supply
	4	Controlled through applications on mobile devices
Product B. Smart plug 	1	Communicate with a user interface e.g., smart phone application with a wireless module to display energy information
	2	Provides information about energy availability, prices using colour indicators (Green: energy abundance/cheap price, Blue: equal demand and supply/standard price, Red: scarcity/high price)
	3	An energy unit monitors energy consumption of devices
	4	Manually switched on and off by the user
Product C. Smart wall socket 	1	Provides information about current energy situation and prices through LED indicators (green light= lower energy prices, red light=higher energy prices)
	2	Contains replaceable batteries that store energy during off peak hours
	3	Possibility to stack devices on top of each other to increase storage capacity
	4	Mobile energy and remote use: device can be carried around

2.2.2 Selection of respondents, sending out questionnaire

The target group for the questionnaire was a broad range of end-users, comprising of those early adopters that already have an interest in sustainable energy and those who do not. This approach was used in order to have a high response rate, and also to elicit the views of people who already know about HEMPs and those that do not know.

The questionnaires were distributed through various outlets in the Netherlands namely:

a People that are contained in the database of the Renewable Resources Research Group of the NHL University of Applied Sciences Leeuwarden, The Netherlands. The group focuses on the development and translation of knowledge in the field of renewable energy and technology into economic activities.

b Stakeholders in the mailing list of the sustainable innovations program of the Provincial Government of Friesland. The program focuses on various innovation projects in the area of energy and the environment. The distributed it through their mailing list.

c Stakeholders in the mailing list of the municipal government of Leeuwarden. Also, the Facebook page of households involved in the 'Smart living in Leeuwarden project' was used as a channel to distribute the questionnaires. This project supports households to implement energy efficient measures in their homes and install renewable energy technologies such as solar panels.

d The energy and environmental coordinators of the municipality of Leeuwarden helped to distribute the questionnaires to people in their network.

e The entire NHL mailing list managed by the marketing department.

f Contacts at the University of Twente, where one of the co-authors work.

In general, the questionnaire survey was distributed via email to more than 1,000 end-users.

In order to ensure that a substantial number of people filled out the questionnaires, a 50-euro tourist receipt was offered to the respondents.

2.2.3 Data collection and analysis

The online questionnaire was circulated between June and September 2016 via Qualtrics research suite survey software resulting in 87 respondents.

Qualtrics software program performed the analysis of the questionnaire results. However, in order to ensure that the analysis performed by the Qualtrics software was accurate, the data gathered from the questionnaire survey were also transcribed in an excel worksheet, where new tables and graphs were generated. The various answers and comments given by the respondents were also transcribed in the excel worksheet.

3 Results

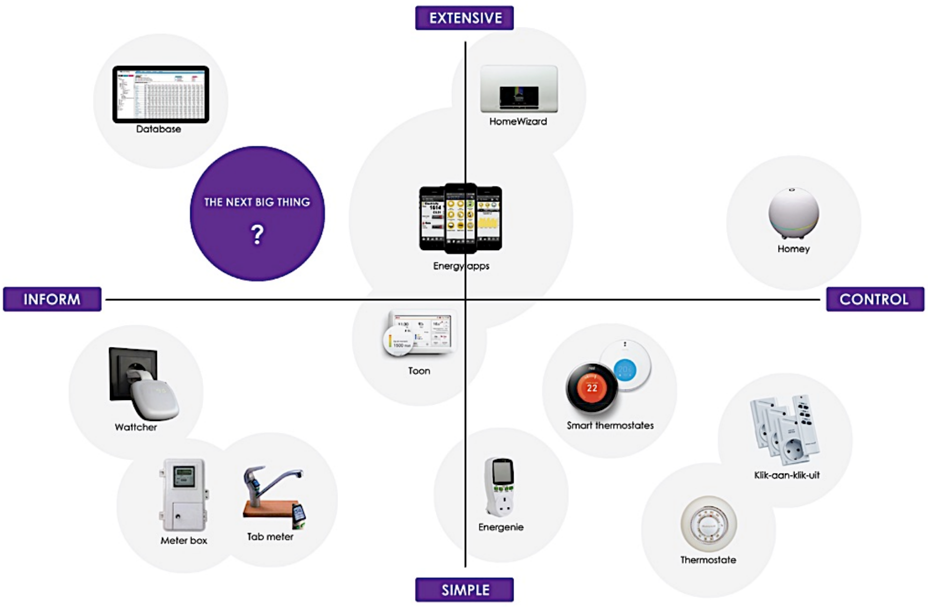
3.1 Application of IDMs

At the beginning of both projects, 10 IDMs were provided for the design of innovative product concepts that could be applied in smart grid households. This study revealed that in 2013, besides the use of PDPD (compulsory method), the methods TRIZ (n = 12), DIM (n = 11), IDS (n = 9), and TRM (n = 8) were mainly applied in the development of the product concepts. In 2014, in addition to the use of PDPD, the methods DIM (n = 15), TRM (n = 14), TRIZ (n = 11), and CTA (n = 8) were mainly applied in the development of the product concepts. The results therefore show that four IDMs (PDPD, DIM, TRIZ, and TRM) were mainly used in designing the product concepts. These four IDMs, and their functions based on some product concept examples are presented below.

3.1.1 Delft innovation method

The students in the start-up of the design process mainly used the strategy formulation and the design brief phases of DIM to define search areas related to smart grid technology and to discover opportunities in the market of smart energy products. An external and internal analysis is performed during the strategy formulation stage. External analysis includes an analysis of competitive products, needs, and external trends and developments in emerging technologies. The internal analysis shows the value of a brand and its strengths and weaknesses. For instance, in the development of a smart plug [Appendix C (Figure E.18, p.208)], one of the design teams carried out an external analysis of existing HEMS. These HEMS were ranked on two aspects, namely whether they are simple or extensive and whether they inform the user or are control devices. These aspects are shown on respectively the y- and x-axis. The systems were then placed in the overview.

Figure 4 External analysis of HEMS (see online version for colours)



Source: Rutgers and van den Belt (2014)

Figure 4 shows that a standard thermostat is mainly used to control appliances such as heating devices. It is a very simple product, which does not involve a lot of data or functions. As it only provides minimal information to the user, it is placed in the lower right corner. A database, on the other hand, has as a main function to inform the user, and does not autonomously control devices. To inform the user, it contains a lot of extensive information. Although a database is not really a product, it is considered in this scheme, since it also indicates that a real product is missing in the upper left corner and even in the entire upper left quadrant.

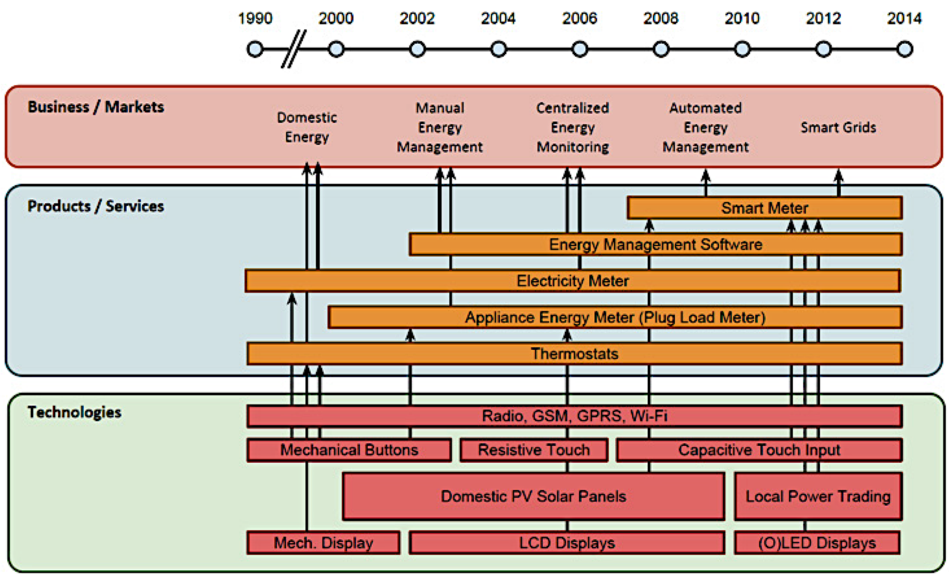
From this external analysis, the conclusion can be drawn that a product that mainly informs the user about energy consumption, but still allows some level of control on different devices is needed. In order to perform this function well, extensive information is needed, but it also has to be simple enough for the average user. This way, extensive and maybe complicated information can be transferred to the user in a user-friendly way, supporting the user to be more aware of his energy consumption.

The use of DIM therefore provided the platform to generate search areas for new innovative products that could be used in smart grid households.

3.1.2 Technology roadmapping

In the design project, TRM was mainly applied in the embodiment design phase to assess how various smart grid technologies will develop in the near future. It helped to create product features that are based on predicted technological maturity and market demand in relation to smart grids. For example, a student group that developed the smart thermostat [Appendix C (Figure E16, pp.206–207)] used TRM to explore the innovation trajectory of domestic energy products and recent smart grid technologies, shown in Figure 5.

Figure 5 Subcategories within the enabling technology categories (see online version for colours)



Notes: LCD: liquid crystal display, OLED: organic light emitting diode, Mech. Display: mechanical display; PV: photovoltaic.

Source: Lamarche et al. (2011)

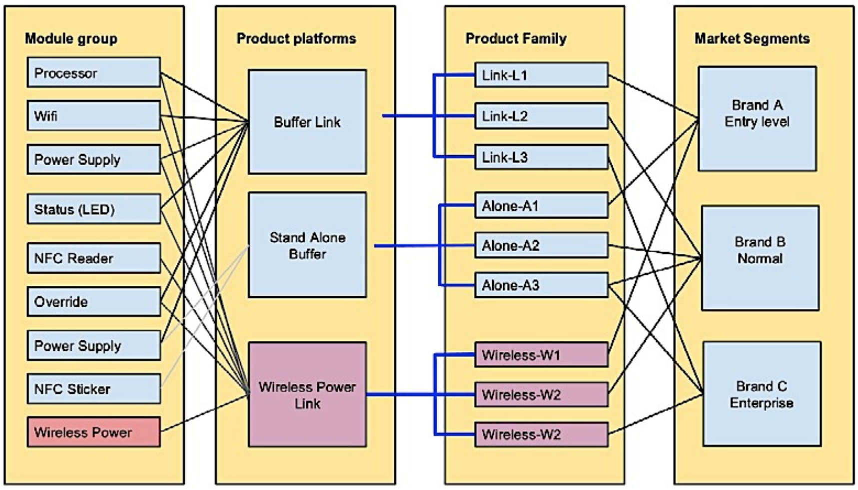
The diagram covers about 20 years of development, as the electricity meter and thermostats (both consisting of mature technologies today) can be considered the first stages leading into the smart meter used today by households. The conclusion can be drawn that no emergent technologies have led up to the development of the smart meter, except for 'local power trading', which has been rising slowly recently. This technology was considered as a direction of opportunity, and incorporated in the new product design. The other technologies appeared less important for this purpose, but were accounted for to add to a sufficient adequacy of the new product idea.

By analysing technologies that have led up to recent products such as the ‘smart meter,’ innovation was achieved by extrapolating mentioned technologies to form potential product compositions.

3.1.3 Platform-driven product development

PDPD is a tool used to develop modular products. It can increase variety, accelerate development and reduce complexity in product development. This helps to speed up development of new products, since it takes less time to build up a new product out of existing blocks, than to design it from scratch. For this project, PDPD was the compulsory method used by all student groups. It supported the development of product families and increased the modularity of the products.

Figure 6 Product platforms for the smart wall socket (see online version for colours)



Source: Appendix C (Figure 8, p.202)

For instance, in developing a smart plug that enables automatic and smart charging behaviour for mobile devices [Appendix C (Figure E8, p.202)], PDPD helped to combine several product platforms (Figure 6). The components include:

- power adapter components (coils, regulators, resistors, capacitors and diodes)
- system on a chip micro-controllers (central processing unit, random access memory and read-only memory in one package)
- near field communications (NFC) controllers
- USB controllers
- Wi-Fi controllers and antennae
- NFC transceiver chips
- wireless power (possibly in the future).

These components form the backbone to the internal modularity of the smart plug [Appendix C (Figure E8, p.202)]. Using PDPD, the general idea of the smart plug was broken up into different components, modules and platforms. These platforms were combined using interfaces to form architectures for different variations of potential smart plugs.

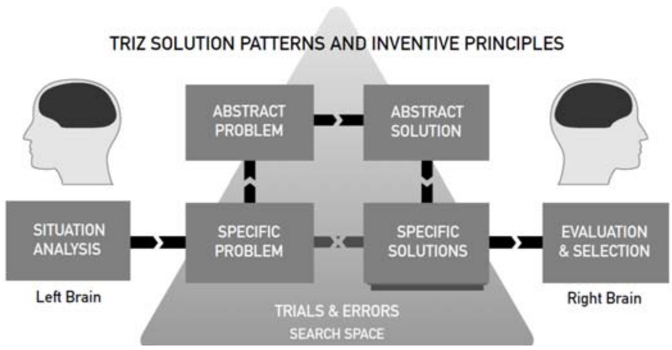
By standardising the enabling technologies – such as sensors and display modules – multiple product families can be created at a low cost. Also, this allows for low cost maintenance, as standard modules are often mass-produced, thus allowing for replacement of these modules in case of failure.

In all design tasks undertaken in this project, PDPD was used to divide the functional concepts of the products into different modules that could be applied on other product platforms. It was mostly applied during the concept development stage, to design modular products, consisting of several standardised components. This way the product can be produced more cost-efficiently, the time to market can be reduced and it will be easier and more cost-efficient to create different product families for different market segments.

3.1.4 TRIZ

Theory of inventive problem solving (TRIZ) includes several methods that support various stages of the idea generation process. Contradictions arise when solutions for one problem lead to problems in other solutions. TRIZ states that to obtain inventive solutions, contradictions must be eliminated without compromising other advantages of a product or technology, and without causing negative side effects. This is achieved by the use of 40 inventive principles that are the result of analysing a huge database of pre-solved problems and structuring its solutions. The theory consists of a systematic step-by-step approach (Figure 7).

Figure 7 Problem solving with TRIZ



Source: Alsthuller (1996)

The problem solving between contradictions does not appear with the specific problem, but is done by abstracting the problem to a higher level. When the problem is at a higher abstract level, TRIZ offers tools to find abstract solutions, which then can be converted to specific solutions.

The majority of TRIZ principles were used in the later part of the ideation stage into the early concept development stage, after most of the product requirements have been established.

For example, in designing a smart plug [Appendix C (Figure E1, p199)], a group found out that their product concept required a large amount of electricity to function, whilst the goal of the product is reducing energy use in households. TRIZ supported the redesign of the product to one that uses electricity periodically (when needed), instead of continuously. Another example is the development of a product that provides end-users with insight and interface feedback to run appliances [Appendix C (Figure E10, p.203)], TRIZ made it possible to realise that providing too much information would lead to confusion for end-users. Specifically, it could result to more time and effort in understanding the given information, which could result in missing of relevant information. The solution lied in developing the interface in such a way that it provides feedback that is easily understandable by the user. This gave rise to the idea of incorporating a graph and pictograms/icons, and different levels of complexity, which supports the switch from a simple ‘normal setting’ to a more complex ‘advanced setting’.

3.2 End-user perceptions of and preferences for HEMPs

3.2.1 Respondents’ characteristics

In total, 87 respondents filled out the questionnaire survey. Considering the time and effort required in completing this questionnaire, and given that not many people are familiar with these kinds of products, we consider this a high response rate.

45% of these respondents did not own any HEMP. Therefore, their response was not influenced by prior experiences with HEMPS, but on their perception of the products and concepts evaluated.

The result shows that 72% of the respondents were male, while 28% were female. The majority of the respondents (54%) were 46 years and older, 24% were between the ages of 20 and 35, while 22% were between 36 and 45 years of age.

Most of the respondents (34%) lived in households made up of 4 persons, 30% lived in households composed of two persons, while 18% had three persons living in their household. Most respondents (45%) lived in detached houses. This is almost three times as much compared to the average percentage in the Netherlands living in a detached house, which is 16.4% (OECD, 2014). 33% of the respondents lived in semi-detached houses.

Regarding their educational status, the result shows that 62% of the respondents possess a master’s degree or a higher qualification, while 33% have a bachelor’s degree. Together this means that 95% of the respondents had a higher education level, which is more than double the percentage of the average Dutch population, of which only 45% has a higher education (OECD, 2014). All in all this indicates that a relatively high amount of respondents are – compared to the average Dutch household – somewhat older, highly educated, male respondents living with their family in a detached house, which should be taken into account when reflecting on the results of the study.

3.2.2 Possession of HEMPs

While 35 respondents stated that they had one or more types of HEMPs installed in their homes, 39 had no HEMP in their homes. The remaining 13 respondents had no idea if they owned a HEMP.

The HEMPs that where owned included mainly smart meters (n = 8), smart thermostats such as Toon and Anna brands (n = 7), energy monitoring systems such as 'icare' from Energq, Plugwise and Smappee (n = 7), energy-efficient lighting systems (n = 5) and smart appliances such as washing machines and dryers (n = 3). Five respondents had solar panels and heat pumps installed in their homes.

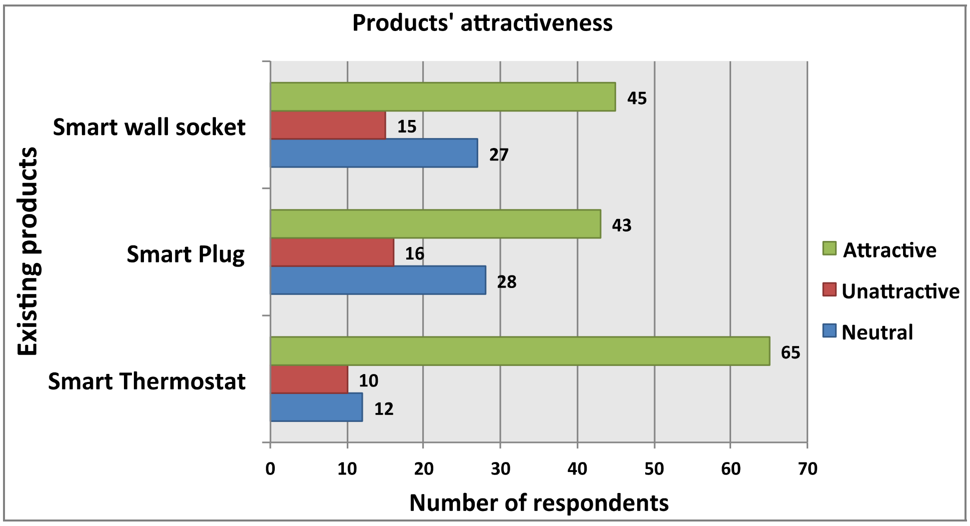
Of the 39 respondents that did not own a HEMP, 14 stated that they are not familiar with these kind of products, 14 stated that they do not yet see the urgency of acquiring these products, six had no interest in these kind of products, three respondents said they saw little financial gains associated with acquiring these products and two found them too expensive.

3.2.3 Evaluation of HEMPs

3.2.3.1 Attractiveness of the (existing and conceptual) HEMPs

Figure 8 shows how the respondents evaluated the attractiveness of the existing HEMPs. Attractiveness in this study refers to aesthetic appeal of the HEMPs.

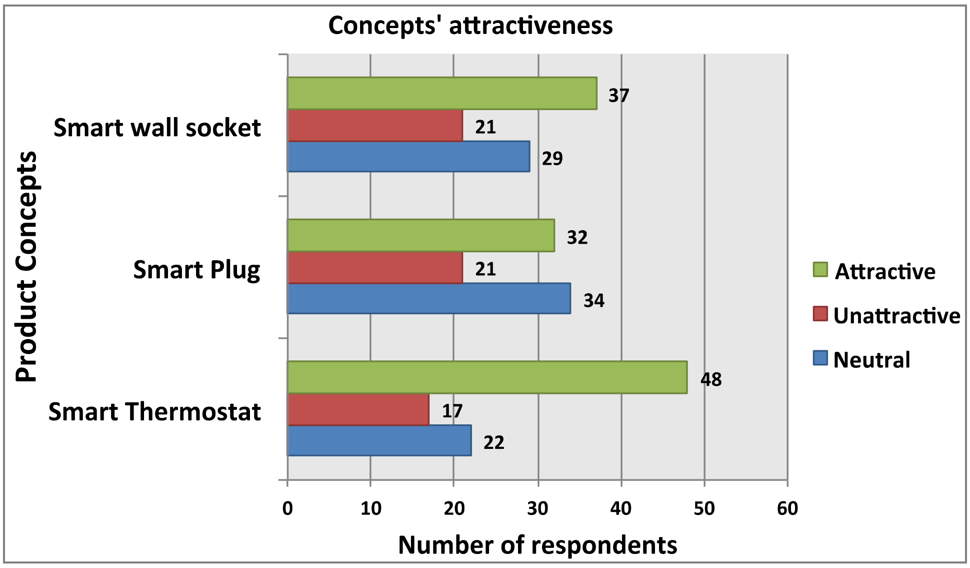
Figure 8 Attractiveness of the evaluated existing commercial available HMEPS (see online version for colours)



When being asked how attractive the presented existing three HEMPs where, the smart thermostat was generally rated the most attractive by the respondents compared to the smart plug and the smart wall socket.

Figure 9 shows how the respondents evaluated the attractiveness of the product concepts. With regards to the respondents' opinion about the three conceptual HEMPs, the smart thermostat was generally considered the most attractive HEMPs.

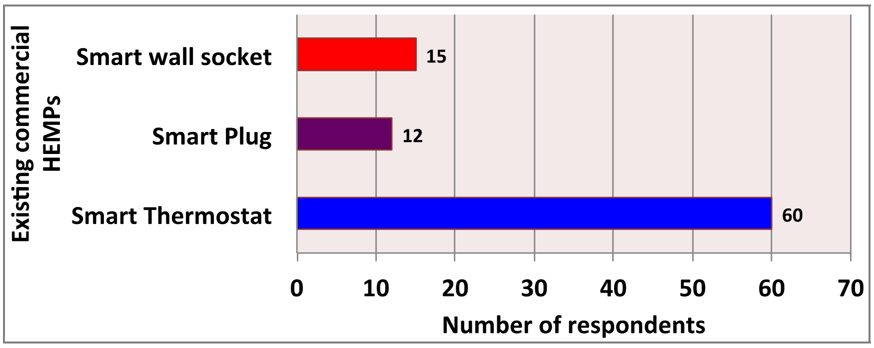
Figure 9 Attractiveness of the evaluated conceptual products (see online version for colours)



3.2.3.2 *Selection of favourite (existing and conceptual) HEMPs*

When being asked which existing HEMP they would select, if they had to choose between them, 60 respondents considered the smart thermostat to be their favourite product, whereas 15 respondents preferred the smart wall socket, and the remaining 12 respondents selected the smart plug as their favourite product (Figure 10).

Figure 10 Preferences for the evaluated existing commercial available HEMPS (see online version for colours)



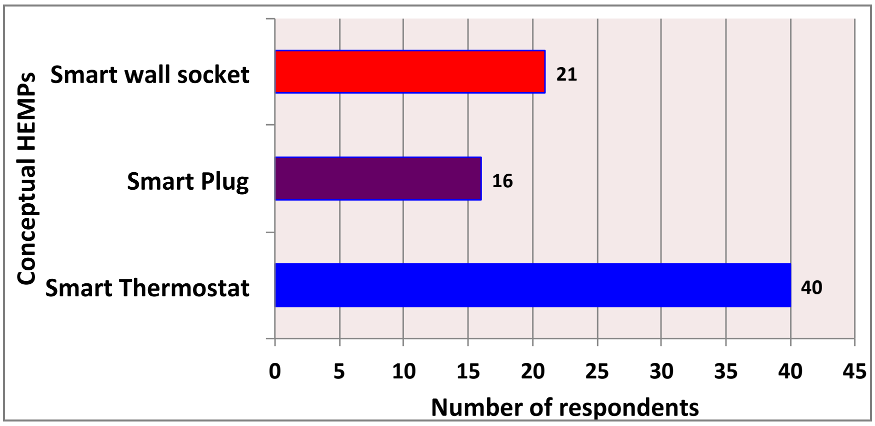
From the 39 respondents that did not possess a HEMP, 33 chose the smart thermostat as their favourite HEMP, three respondents respectively chose the smart plug and smart wall socket.

Out of the 13 respondents that had no idea if they possessed a HEMP, ten stated that the smart thermostat was their favourite product. The remaining three had preference for the smart wall socket.

From the 35 respondents that owned HEMPs, 17 respondents had preference for the smart thermostat, nine respondents preferred the smart plugs and another nine respondents preferred the smart wall socket.

With regards to the three conceptual HEMPs, 40 respondents stated that the smart thermostat was their favourite concept, 21 respondents preferred the smart wall socket, while 16 respondents considered the smart plug to be their favourite concept (Figure 11). ten respondents had neutral opinions about the evaluated product concepts.

Figure 11 Preferences for the evaluated conceptual HEMPS (see online version for colours)



Similar to the existing products, almost all respondents that did not possess a smart energy product chose the conceptual smart thermostat as their favourite product.

From the 35 respondents that owned smart energy products, 11 had preference for the smart thermostat, ten respondents preferred the smart plugs, while seven respondents preferred the smart wall socket. The remaining seven respondents had no preference for the conceptual products.

3.2.3.3 Buying preference

When being asked if they would actually buy their chosen existing commercial HEMP, 64 respondents stated that they would like to acquire it, while 23 said they had no interest in acquiring their chosen products.

With regards to the chosen conceptual HEMPs, 50 respondents stated that there is a possibility of acquiring their chosen product. Seventeen respondents had no interest in acquiring their chosen products, while 20 were neutral.

3.2.3.4 Relevant features for selecting a product

Figure 12 shows the features of the smart thermostat most preferred by the respondents. When being asked what made them choose a certain existing product as their favourite, 28 respondents liked the smart thermostat features that support the monitoring of energy use of individual household appliances. Fourteen preferred features that enabled them to compare their energy usage with other households. Twenty-four considered expected ease of use as an important feature, while 27 were attracted to the remote control features. Thirty-six respondents found the visual display of energy information the most important feature that influenced them in choosing the smart thermostat, four based their choices on manual control features, while six were attracted by the physical appearance of the smart thermostat.

Figure 12 Existing thermostat preferred features (see online version for colours)

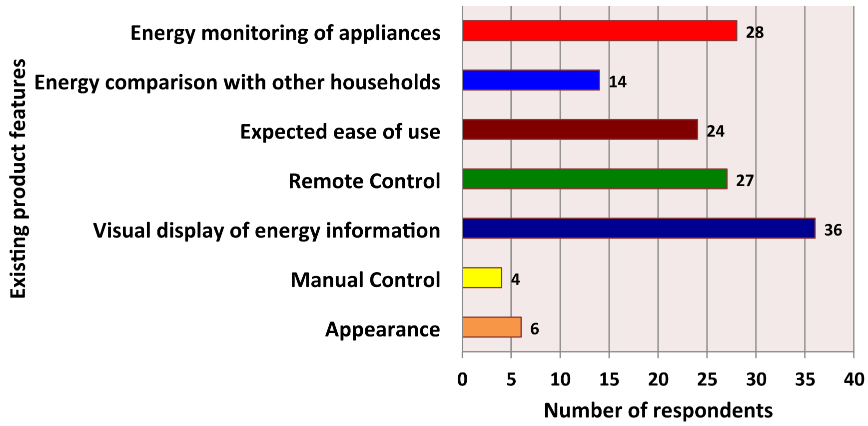


Figure 13 Conceptual thermostat preferred features (see online version for colours)

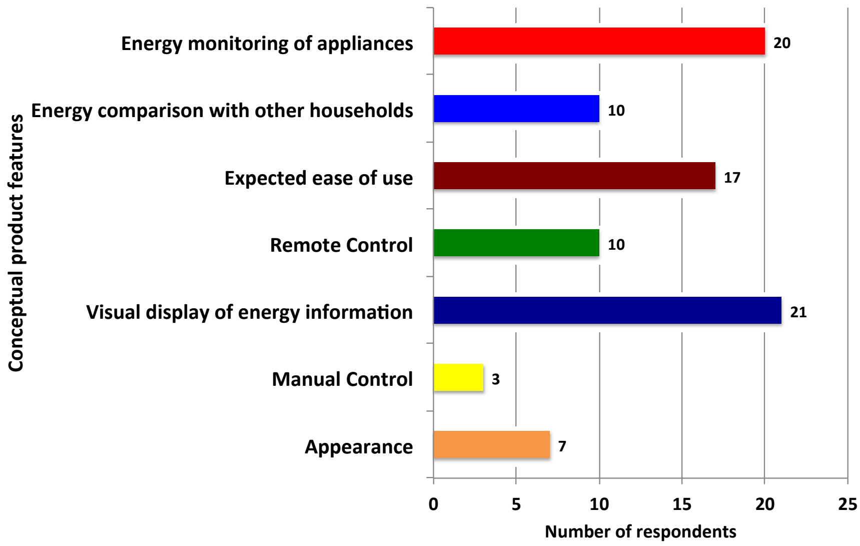


Figure 13 shows the features of the conceptual smart thermostat most preferred by the respondents. With regards to the newly designed concepts, 20 respondents preferred the features that support the monitoring of various household appliances. Ten considered ability to compare their energy use with other households as the most important features that made them choose the conceptual smart thermostat. Seventeen respondents were attracted to the conceptual smart thermostat due to expected ease of use, while ten respondents liked the remote control features the most. Twenty-one respondents stated that visual display of energy information was the most appealing feature that influenced their interest in the conceptual smart thermostat.

Figure 14 Features most preferred in the existing smart energy products (see online version for colours)

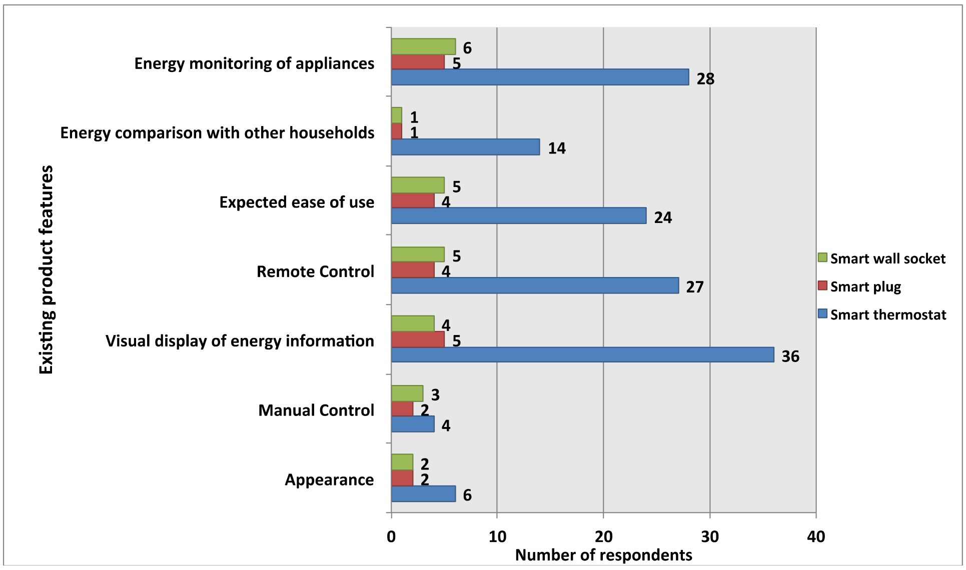
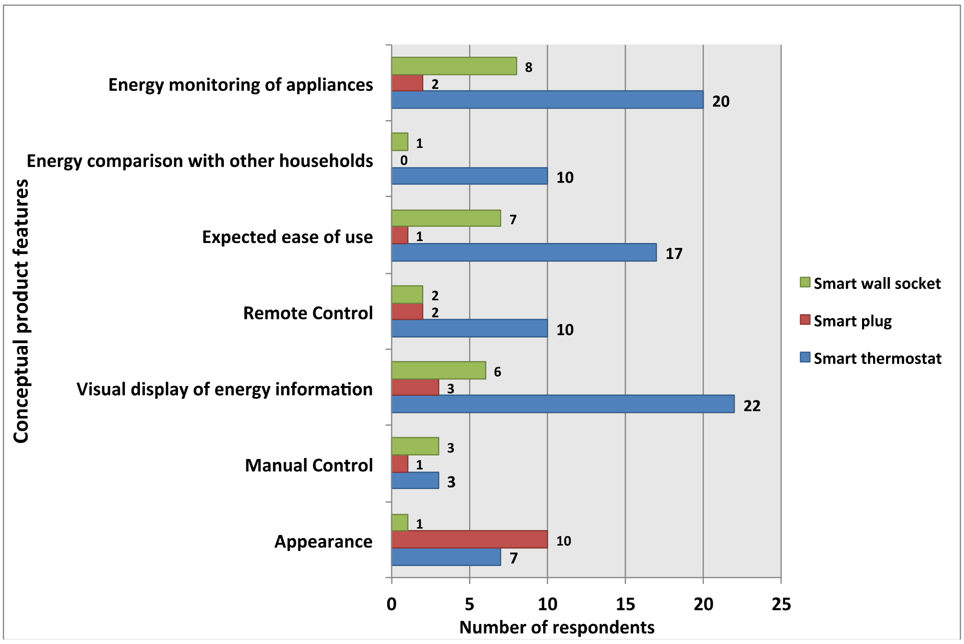


Figure 15 Features most preferred in the conceptual smart energy products (see online version for colours)



Three respondents based their choices on the ability to manually control the smart thermostat while seven were attracted by the physical appearance of the smart thermostat.

Visual display of energy information and remote control features were also considered important features that influenced end-users' choice of the conceptual HEMPs. However, for the respondents that chose the conceptual smart plug, appearance was considered a very important feature that influenced their choice (n = 10).

Figure 14 shows the features most preferred in the existing smart energy products. In general, for the three evaluated existing commercial HEMPs, visual display of energy information was considered as the most important feature desired in these products. Fourty-five respondents chose this feature as the influencing factor in their choice of the smart energy products. Monitoring of the energy use of individual household appliances appeared to be another feature desired in smart energy products, with 39 respondents liking this feature. Thirty-six respondents were attracted to the remote control features of existing smart energy products, while 33 considered ease of use as an important criteria. Sixteen respondents preferred features that enabled them to compare their energy usage with other households. Physical appearance features attracted ten respondents, while nine based their choices on the ability of their chosen concepts to be manually controlled.

Figure 15 shows the features most preferred in the conceptual HEMPs. In general, for the three conceptual HEMPs, 31 respondents considered visual display of energy information as the most appealing feature that influenced their choice. Thirtry respondents chose the new concepts because they possess features that support the monitoring of various household appliances. Twenty-five respondents were attracted by the expected ease of use of the newly designed smart energy product. Fourteen respondents based their choices on remote control features, while 11 respondents found the features that supported energy comparison with other households to be very interesting. Eighteen respondents considered physical appearance as an essential feature that influenced their choice of the concepts, while seven respondents were attracted to the manual control features.

The entire numeric results of the questionnaire survey analysed are presented in Appendix B (http://doi.org/10.4233/uuid:d2d37a85-5c7c-4e9d-bb37-1283af0d3909, pp.192–198).

3.2.3.5 Perception of energy saving potential

When being asked, which product had the highest potential to stimulate energy efficiency in households, 75% of the respondents selected the smart thermostat. Respondents stated that this was mainly because the smart thermostat performs the following functions:

1 Provides total and continuous insight in the entire household energy use.

2 Creates better insight and awareness in energy use in general and in particular gas usage, which accounts for the highest energy usage in households.

3 Monitors all connected individual household appliances.

One respondent stated that,

> "The smart thermostat is the most complete smart home energy manager. Unlike the smart plug and the smart wall socket, the smart thermostat is not fixed on any particular household appliance. It also shows a good overview on

> the wall and compares with the neighbour. This creates a kind of peer-pressure or competition with the rest of the neighbourhood."

Another respondent added that, "Although the smart plug and the smart wall socket support optimal energy use in households, they are incomplete solutions focused too much on a detail level". One respondent said: "We have a smart thermostat, since 2 years and this has saved us a lot of energy. Our energy bill has reduced enormously".

Only 15% and 11% of the respondents considered the smart plug and the smart wall socket respectively as the product that best supports efficient energy behaviour in households. For the respondents that had preference for the smart plug, the visual display of energy information and monitoring of energy use of individual household appliances were considered as the most important feature that influenced their choices. Remote control and expected ease of use were jointly considered as the second most important feature.

3.2.3.6 Other desired features

The respondents were asked to mention other features not given in the questionnaire, that they thought might be required in future HEMPs that stimulate energy-efficient behaviour in households. Fourty-four respondents provided answers to this question. Automatic/remote control of appliances was mentioned 15 times as an essential feature of any smart energy product. According to one of the respondents, "I prefer automatic energy saving. I would like the smart thermostat to automatically set my connected appliances on and off, especially when these are not in use (example the computer or television as a sort of standby-killer)". Other respondents (n = 29) mentioned the manual control of appliances, the monitoring of the power generated from photovoltaic (PV) systems, simplicity or ease of use as the features that should be incorporated in smart energy products.

Similar to the existing products, one of the questions in the survey was related to other features the respondents considered important in future HEMPs that stimulate energy-efficient behaviour in households. Twenty-six respondents provided answers to this question.

Most of the respondents (n = 8) stated that they would like features that enable them to compare their energy use independently with their neighbours. A respondent stated that, "I want to have the possibility to compare my own self-generated with other end-users. I also do not need any form of mediation from third parties such as energy companies that could make use of all information the way they want".

Another group of respondents (n = 7) said they would like to incorporate features that combine household energy use, generation from solar PV's and electric cars. One of the respondents stated, "the most important is to have a central system where various products could be connected irrespective of brand or protocol. Products should not only work with their software or infrastructure, this is unattractive". One respondent was of the view that incorporating features that provide an advice for extra savings in the smart thermostat could stimulate a better energy efficient behaviour. In the words of one of the respondents, "It will be nice if the smart thermostat could furnish us with hints on how to save energy based on the registered personal profile". Another respondent considered it important that the smart thermostat gives an overview of energy use of all household appliances, self-generated renewable energy and use.

Two respondents suggested that the HEMPs should just be simple and make clear the added value for the end-user.

4 Discussions and conclusions

To support a more active involvement of end-users in household energy management, especially in a smart grid context, the development and introduction of new innovative smart energy products and services such as home energy products HEMPs will be required. The objective of this study was twofold:

1. To explore the role of IDMs for the development of smart energy products for households.
2. To evaluate end-users' perceptions of and preferences for existing and new conceptual smart energy products, and the functionalities of these products that may best stimulate energy-efficient behaviour.

With regards to the first objective, our study shows that four IDMs namely: PDPD, Delft innovation method (DIM), TRIZ and technology roadmap (TRM) appear to be the most suited for developing future HEMPs for households by design students. This is because they were predominantly used in developing the conceptual HEMPs, and the students also asserted that a combination of these IDMs effectively supported them in the entire design process from a given task to the solution.

Specifically, the use of DIM at the start of the design process helped the students in exploring what the best fields of interest might be in terms of smart grids related products and services. The predominant use of DIM shows that the development of future HEMPs for households will depend not only on the internal strengths of the companies now spearheading smart grids development, but also on the external wishes of end-users. DIM supported the clarification of the role and interests of various actors in the design process, and was found to be useful for determining a focus point out of the large smart grid topic.

Using TRM, the students were able to choose the most promising smart grid technology directions generated with DIM. TRM supported the identification of gaps in products for which there will be a need when the smart grid transition gains momentum on a household level. Different technologies, products, services, as well as markets and businesses were mapped with TRM. TRM showed that a market pull rather than a technology push approach would be required to develop future HEMPs for households. Currently, a technology push approach is being experienced with regards to the development of smart energy products and services for households (Verbong et al., 2012; Obinna et al., 2016). This has in most case limited end-user engagement and interaction with these products and services. TRM allowed the extrapolation of future developments, from changes in technologies up to future market developments.

The use of TRIZ highlighted the importance of anticipating problems and conflicts that could arise in the design process of HEMPs. TRIZ supported the elimination of problems and contradictions that could negatively impact on the functionality of the product concepts. TRIZ mostly provided a set of solutions for problems which might not be overcome with normal design methods. The application of TRIZ helped the students to make crucial and innovative design decisions that formed the basis for the rest of the product development process.

The PDPD method had to be used by the students, and showed to be useful for this project to create a product that consists of components that can be shared across a family of products, and then be developed and produced in a time- and cost-efficient manner. PDPD was used mostly in this project to make product design or parts of it easier implementable for future designs. It supported a transition from a modular towards more integral product architecture. These product platforms can be combined to different product families, which serve the different market segments.

The method served as a successful strategy to create variety with an eye on efficient use of resources. On the one hand, PDPD results in standardisation of components in order to efficiently use available resources, at the other hand it results in identification of new target markets and product concepts in order to create variety and finally maximise profits.

Concerning the second objective of this study, our evaluation shows that for both the existing and conceptual HEMPs, the smart thermostat was considered to be the most attractive and favourite product. It was also considered to be the product with the highest potential to stimulate energy-efficient behaviour in households, mainly because it provides the most comprehensive insight in households' energy consumption and generation. In addition, the smart thermostat was considered a more complete solution compared to the smart plug and the smart wall socket that only measures the electricity use of specific household appliances connected to them. The smart wall socket appeared to be the second best-liked product, while the smart plug was considered the least attractive and least favourite product.

Though studies such as Kobus (2016), Wood and Newborough (2007) have suggested developing simple interfaces with limited information, people still like to have comprehensive insights in their electricity production and consumption.

This study shows that the features desired by end-users appeared in general to be the same for both the existing and new conceptual HEMPs. Visual display of energy information was considered the most appealing feature that influenced end-users' interest in both the existing and conceptual smart thermostat.

Other desired features for all categories of evaluate products include monitoring of various household appliances, expected ease of use, remote control features and ability to compare their energy use with other households.

Our study establishes that new design features have an influence on user perception of HEMPs. Respondents indicated that appearance features appeared to be one of the least desired features for HEMPs. However, appearance did actually seem to influence people's opinion about a product. This can be seen in the evaluation of the conceptual smart plug, where the number of respondents that chose the conceptual smart plugs was much higher compared to the existing smart plug. When being asked why people selected these products, they indicated that this was mainly a result of the design features such as appearance, which appeared to be better in the conceptual product. This may indicate that although people may not indicate that the physical appearance is relevant when selecting a new HEMP, the design of a product does actually influence their opinion towards the product. This reaffirms the importance of good designs and aesthetics for effective man-machine interaction and in the communication of the function of a technology as advocated by previous studies such as Peslak (2005), Karray et al. (2008), Hargreaves et al. (2010), Steen (2012) and Karlin et al. (2015).

The importance of visual information and monitoring feedback in stimulating energy-efficient behaviour has also been highlighted in this study. Although our evaluation focused on the category of HEMPs referred to as smart hardware, the results reveal the need to integrate intuitive user interfaces in this category of products. This will make the functioning of smart hardware such as smart plugs and smart wall sockets to be more visible to users, thereby increasing end-user control and engagement with these products. As concluded by Kobus (2016), it is essential to develop intuitive user interfaces that could support users in using complex energy management systems. Kobus stressed the importance of clear, appealing and direct feedback that users can easily comprehend. Feedback is considered beneficial to change households' energy consumption, because it provides users with information about the results of their actions (Abrahamse et al., 2005; Kobus, 2016). Feedback has also been shown as an effective method of making energy information visible to consumers and results in whole-home energy savings ranging from 4–12% (Ehrhardt-Martinez et al., 2010; Spagnolli et al., 2011). Therefore, the design of energy feedback devices impact consumer engagement (LaMarche et al., 2012).

Finally, a desire for integrated solutions was also highlighted in this study. Features desired by end-users in future smart grid products for households were mainly related to more incorporation of automatic and remote control features in smart energy products, and further simplifying future products. Also, our study shows that end-users would prefer HEMPs that combine information about various household energy generation and use to HEMPs that measure and report the energy use of separate household appliances. This shows that the integrated development of the whole can lead to more results than the sum of all parts.

The first conclusion of this study is that the sequential application of these IDMs supported a detailed exploration and incorporation of technological possibilities, the opportunities that exist in the energy market and end-user preferences in the design of the innovative product concepts presented in this study. The IDMs proved to be useful for the exploration towards inventive features, and provided a structured approach that aided the implementation of the most relevant aspects for an integrated development of the product concepts.

The second conclusion is that HEMPs that make energy use most visible to end-users, that could be remotely controlled and which requires minimal effort to operate, may best stimulate energy-efficient behaviour in households. We therefore suggest that product and service suppliers pay more attention to the incorporation of features that support more visual interaction, that can automatically and remotely control energy use and requires the least operational effort, in the development of future HEMPs for households.

This study, to our knowledge, is the first public opinion survey carried out in the Netherlands focusing on current smart energy products. Previous studies such as (Van Dam et al., 2010; Apostolou and Reinders, 2016) have either focused on photovoltaic (PV)-powered products such as lights and chargers or a specific device such as energy monitors.

Our findings supplement the emerging but limited body of smart grid literature by highlighting the contribution of design in the development of new smart energy products for households, and the main features that household end-users desire in products that could stimulate energy-efficient behaviour, and with particular emphasis on the transition to smart grids. It contributes to the literature by providing a better understanding of the perceptions of electricity end-users about home energy products (HEMPs). Since there is still significant progress to be made in the development and implementation of HEMPs, insights from this study could support the design and development of future HEMPs. It has also established that intermediary products such as user interfaces are important in ensuring a more active involvement of end-users in household energy management.

This study however has several limitations. First is the use of only questionnaire survey to evaluate both existing and conceptual HEMPs. Second is the limited respondents and conflict due to 50 euros that was offered as incentive to fill out the questionnaire.

Third, our survey focused mainly on one stakeholder group (end-users) and did not involve other stakeholder groups such as the government, utilities, NGOs, experts and academics. Fourth is that almost half of the survey respondents were already smart with their energy use, and lived in their own homes. They are therefore not representative of the average Dutch population. Another limitation is that our study focuses on the perceived features of the products but not on the actual use experience regarding the interaction between users and their HEMPs. An additional user study would for instance show how easy the visual information can be managed and whether this complies with the advance assumptions of the users.

Additionally, the needs and expectations of the market regarding the conceptual products developed in this study are only estimated. It is therefore recommended to execute a usability study in order to evaluate the functioning of the newly developed HEMPs.

These limitations outlined above make our findings indicative rather than conclusive.

Since we focussed more on obtaining a general and representative insight from a broad range of stakeholders at this stage, we intend to complement the findings from the questionnaire with interviews in a follow-up study.

Despite the limitations inherent in this study, it provides a direction for future discussion about the attributes of HEMPs that could have the most potential to effectively engage and stimulate energy-efficient behaviour in end-users.

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Appendix A

Questionnaire survey for evaluation of HEMPs

http://doi.org/10.4233/uuid:d2d37a85-5c7c-4e9d-bb37-1283af0d3909, pp.183–191.

Appendix B

Numeric results of questionnaire survey of analysed HEMPs

http://doi.org/10.4233/uuid:d2d37a85-5c7c-4e9d-bb37-1283af0d3909, pp.192–198.

Appendix C

Examples of some of the innovative product concepts developed in the students' design projects

http://doi.org/10.4233/uuid:d2d37a85-5c7c-4e9d-bb37-1283af0d3909, pp. 199–210.