A switch by design

User-centred design of smart energy technologies to change habits of using energy at home

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CHARLOTTE KOBUS

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PROEFSCHRIFT

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'Dag olifant,' zegt de porseleinkast,
'kom voorlopig maar niet meer terug.'
De olifant staat bij de deur,
maar heeft geen deurknop nodig.
Hij snuift de najaarsgeuren op –
regen ruikt hij, storm –
klappert met zijn oren, holt recht naar voren –

die porseleinkast is mijn ziel, dat wist ik al,
maar die olifant
die al weer verder dendert,
alles op zijn weg verplettert
en ook nog voortdurend om zich heen trompettert:
'Ik heb gelijk!'
wat is die olifant van mij?

Toon Tellegen,
uit: Een langzame val
Querido 1991

CONTENTS

SUMMARY

Yes, well designed smart energy technologies can change habits of using energy at home!

We are all familiar with rush-hour avoidance programs as a solution for our too synchronous transport movements. An off-peak discount subscription for the Dutch railways has already been introduced in 1979 to make more efficient use of trains. Recently, several major cities in the Netherlands have launched programs (e.g. wildvandespits.nl) where car drivers can save around 150 Euros per month if he or she uses the car outside rush-hours.

Shortly said, the subject of this research is similar to a rush-hour program for electricity use at home. Our electricity infrastructure is designed to facilitate the electricity peak demand of today. Now, the demand for electricity is increasing as polluting energy carriers are replaced by electricity. An example is the introduction of the electric car. At the same time, households start to produce their own renewable electricity. When many households in the same city block produce solar electricity, supply peaks on a sunny summer day can be as high as the demand peak on a winter weekday evening. When peak demand is restrained and self-consumption of solar electricity to deal with peaks in supply is stimulated, large investments in the existing energy infrastructure can be avoided and sustainable energy is used more efficiently. Smart grids are seen as a solution to make optimal use of renewable energy and of the existing electricity infrastructure by matching demand to supply conditions more efficiently.

Often, smart grids aim to influence electricity demand to more efficient and sustainable patterns of demand by using smart energy technologies and new tariff structures. However, uncertainties exist regarding households' willingness and possibilities to accept smart grids to change demand. As electricity is still relatively cheap, big financial gains - like the gains possible with rush-hour avoidance programs - are difficult to achieve. Moreover, using energy at home is a result of highly habitual behaviour and habits are known to be difficult to change.

Technologies must be developed that fit user needs and are able to change behaviour at the same time. The research presented in this thesis demonstrated how a user-centred design approach is applied to develop user-friendly technologies and showed the positive effect on a residential demand shift in the long run.

The content of this thesis | We elaborate on the relevance of a change in the way energy is used at home and why it is found difficult to change these patterns of energy demand in Chapter 1. To explore the value of design for changing patterns of demand, Chapter 2 examined the variations in energy savings between two different Energy Management System (EMS) designs in a large field study. An EMS gives computerised feedback on patterns of energy demand. We found that easy to use and accessible EMS designs are important to increase the chance that people will remain using the EMSs over time to achieve lasting energy demand reductions.

To explore the factors that affect households' tendency to shift their electricity demand, Chapter 3 describes a qualitative field study amongst households shifting the use of electrical appliances in time. Participants were asked to match their electricity demand with their own local electricity production. Participants were assisted by an EMS, which provided feed forward on the solar production besides giving feedback on patterns of demand. Participants also received a smart washing machine. Participants could schedule the operation of the smart washing machine on the EMS, so the smart machine would receive a signal to start when the solar panels produce most electricity. We gained rich insights in the way users interact with a smart washing machine and an EMS in a real-life setting and in the possibilities and impossibilities of shifting electricity demand to match supply. We gained promising results with respect to the potential of using technology in assisting households to shift demand. Chapter 4 builds on the insights of Chapter 2 and 3 and is dedicated to the design of the large scale longitudinal field study on shifting demand. In three residential areas in Zwolle and Breda, households produced their own solar energy and received a dynamic electricity tariff and smart energy technologies. We describe in Chapter 4 how we have made these technologies user-friendly by applying a user-centred design approach. In Chapter 5 we focus on a demand shift of the washing machine and the value of the semi-autonomous function of the smart washing machine in helping households to shift electricity demand. We concluded that, compared to a reference group, participants washed relatively more frequently during hours of sunshine and relatively less frequently during peak hours, confirming the preliminary results of Chapter 3. Moreover, households who regularly used automation of the smart washing machine, also shifted the timing of using the washing machine away from the evening to the night.

Chapter 6 investigates a shift of other appliances than the washing machine over time. Participants indicated that the use of the dishwasher and the tumble dryer is also shifted to moments electricity is abundantly available. The fun of matching demand reduced, but the behaviour of shifting electricity demand to match supply conditions remained. We also investigated the use of the dedicated display in the living room that was provided in this study. Again, we revealed a positive relationship between use frequency of the EMS and the shift in demand of electricity. We argue in this chapter that giving feed forward on electricity supply besides giving feedback on patterns of demand is beneficial for higher levels of use frequency in the long run.

Chapter 7 summarises the main findings and implications from this research. We discuss the suggestions for further research and discuss the relevance of this research for different future scenarios. Our results on shifting the use of appliances such as the washing machine are encouraging for achieving an affordable ánd sustainable electricity supply system.

Conclusion | This doctoral thesis demonstrates that households are able and willing to permanently change their habits of using energy, if they are supported by well-designed, user-friendly technology. Previous studies have assessed the impact of smart energy technology and new tariff structures to make optimal use of sustainable energy supply and the existing energy infrastructure. However, these studies did not investigate the desired behaviour change on such a large scale and/or over such a

long time. Moreover, there has been little focus on developing user-friendly smart energy technology. The findings from both quantitative and qualitative research demonstrate that only when people are able and willing to use smart energy technology over time, the technology can bring about a lasting change. Therefore, this thesis includes practical design guidelines for developing smart energy technology that must have a lasting effect on the way energy is used at home.

01

ENERGY AT HOME

Changing habits of using energy by design

Anyone who has tried to change his or her own habits has most probably experienced that changing habits is difficult. Changing the habits of somebody else is even more difficult. Often, people think it is a matter of attitude. When one's attitude towards new behaviour changes, new behaviour will follow. If only it would be that simple… Positive attitudes often evaporate once there is some kind of effort needed, or when the context that triggers the existing habit remains stable. I can provide you with many personal examples of me trying to change the habits of my parents, sisters, room mates, promotors etc., most often without success. But, this thesis is about changing habits of people I do not know on a personal basis. This thesis is about changing habits of using energy at home to become more environmentally friendly.

The focus of most preceding studies on making household energy demand more sustainable has been on lowering demand in general (e.g., see Abrahamse et al. 2005 for a review). However, only saving energy is insufficient for a sustainable energy system (Agentschap NL 2012). Production has to become more sustainable as well. The introduction of clean energy producing technologies from renewable resources, in short renewables, is taking up. The amount of installed solar power doubled in the Netherlands in 2013 (ECN et al. 2014). Furthermore, fossil and unclean energy carriers like gas and oil are being replaced by electricity (e.g. by introducing electric vehicles). This is causing a significant rise in electricity use. More electricity usage is especially problematic on peak moments. Peak demand occurs on moments with high simultaneity of demand. Peak demand cannot exceed the maximum transportation or distribution grid capacity, because overload creates overheating, which leads to serious damage. Grid components are now protected against damage, but overload still leads to blackouts. Hence, the electricity grid is designed to facilitate peak demand on winter weekday evenings, while in off peak moments during the rest of the year, this capital and material intensive capacity remains unused. When peak demand increases, for example, by charging electric vehicles simultaneously after coming home from work, vast grid investments are needed (Veldman et al. 2013). If the increase in peak demand can be restricted, the existing grid capacity is used more efficiently.

Peak demand is also problematic for production capacity, because production has to match demand at all times. Storing electricity is still too expensive. Society is used to production units that produce the right amount of electricity whenever it is needed. Most users are unaware that the prices of electricity fluctuate during the day: that it is far more expensive to match demand during peak moments and that energy supply can be cheaper and more sustainable if demand responds to supply conditions. The introduction of renewables makes balancing demand and supply more complex, because the electricity production by renewables is often dependent of the weather and therefore less controllable. Production is also decentralised by the introduction of renewables, while the system is designed for centralised production. Therefore, it is important that, next to energy demand reductions and increasing sustainable supply, electricity demand shifts to moments when electricity is available.

The main research question of this thesis is: *How can households be encouraged to change habits of using energy at home to more environmentally friendly habits?* And more specifically: *How can households be encouraged to shift electricity demand away from peak moments, to moments of (local) sustainable electricity production?*

1.1. WHY RESIDENTIAL ENERGY DEMAND HAS TO CHANGE

Electricity and gas were pushed to the market respectively around 1920 and around 1960 for the economy of scale. Modern society is built on these sources of energy and became dependent of the energy supply system. The energy system is designed - physically, but also regulatory - for unimpeded access to energy. However, unimpeded access does not seem realistic in the long run: when renewables are a significant share of the production capacity and when electricity is the main energy carrier.

This future scenario is rapidly coming closer now the disadvantages of *old* sources for energy production become more apparent: climate change by emissions, cities with unhealthy levels of particulate matter by burning fossil fuels locally, dependency of unstable regions, oil disasters as a result of more complex drillings, human rights violations, etc. Deny one, but it is impossible to deny all. At the same time, clean energy technologies develop rapidly and become more efficient and affordable.

When I started my graduation project on this topic in 2010, scarcity of energy supply felt far away. Today, the province Groningen in the Netherlands has problems with earth quakes from gas extractions. And for an outlook into the future on the possible problems of supply and peak demand of electricity, we can take the example of our neighbouring country Belgium. In the winter of 2014-2015, Belgium was struggling with their electricity supply due to the unavailability of two nuclear power plants. Major cut offs of whole towns were announced when the situation became too critical. For example, to save electricity, especially on peak moments, citizens were asked to cook meals in one pan for example (see Figure 1.1). This campaign was called good preparation by the Belgian government (they did not need to cut off whole towns, hurray!), but though the campaign is impressive, can it be called good preparation? Do we need a crisis before we can actually change?

FIG.1.1 LEAFLET OF A BELGIAN CAMPAIGN ON ELECTRICITY DEMAND REDUCTION, ESPECIALLY BETWEEN 17-20 H.

Because of the acknowledgement of the disadvantages of fossil fuels, and the possibilities brought by renewables, the energy system is changing to a more sustainable energy system. The so called energy transition, the transition from fossil fuels to sustainable resources for our energy supply, is put in motion to save our environment and to maintain our level of welfare. In this process, it is necessary to further invest in clean consuming and producing energy technologies, in saving energy and in matching demand with sustainable supply.

Energy saving in households has been in the spotlight of scholars and governments since the late seventies. Today, even energy suppliers, who make money selling energy, are helping their customers to save energy by providing more feedback on energy use. In the case of shifting electricity demand, industries or enterprises can cooperate in programs for some years (e.g., enernoc.com/for-utilities/demand-response). Until recently, the energy industry and scholars did not focus on households for a demand shift, because the demand per household is relatively small and the assumed effort to change the demand patterns of households too high. However, circumstances are changing because households are starting to produce their own energy now solar panels become cheaper, more easily available and people are convincing each other of the benefits. Furthermore, households are replacing appliances that consume gas or gasoline by appliances that run on electricity (mainly appliances for cooking, driving and heating). These developments imply that the way demand and supply of electricity is matched needs to change. Today, supply is designed to meet demand. More electricity is generated and transported when more electricity is needed. When this system design of matching demand and supply is maintained, sustainable energy is not used optimally and large grid investments are needed (Veldman et al. 2013).

The alternative is often referred to as smart grids. Smart grids must lead to more efficient use of renewables and existing power plants and to more efficient use of the electricity grids (tki-switch2smartgrids.nl). According to the Dutch grid operator association, *a smart grid is a grid with advanced technologies that is able to inform about electricity flows and grid conditions. It facilitates controllability of electricity flows to assist the energy transition* (Netbeheer Nederland 2009). The working principles range from adjustable electricity supply, electricity storage in batteries or electric vehicles and making electricity demand more responsive to supply conditions. In case of the last option, as well as in our case, smart grids are often also meant to be a pervasive technology, influencing the daily life of users (Verbong et al. 2013).

1.2. EXPLAINING RESIDENTIAL ENERGY DEMAND

Before we elaborate further on smart grids that influence the daily life of users to change patterns of demand, we discuss how the energy demand of today got its shape and discuss the relevant trends. Current levels of energy demand and the timing of demand are locked in by the way society has evolved. To increase the successfulness of smart grids that have to change energy demand, it is important to understand how demand is locked in (Walker 2014). Demand for energy grew by the increased availability of energy (infrastructure), the promotion of energy use at first and later the promotion of reduction by the government (institutional), the development of applications (technology), the price increases of energy over the years (economics), the role of women in households, changing norms around cleanliness and increased expectations around comfort and convenience (social) (De Rijk 1998, Van Overbeeke 2001, Verbong et al. 2002, Chappells & Shove 2004, Walker 2014). We focus on how energy demand evolved in Dutch households.

1.2.1. GAS DEMAND

Van Overbeeke (2001) has investigated how residential gas demand developed in The Netherlands. The relatively high gas demand in the Netherlands (gas accounts for 78% of the GJs consumed in households [CBS, 2015]) is facilitated by the advanced gas infrastructure, which is deployed in the sixties after finding huge natural gas reserves near Slochteren in the province of Groningen. Because of the expectation that eventually nuclear energy would make gas commercially uninteresting, the government had an interest in selling this stock as soon as possible (Verbong et al. 2002). Households were persuaded to get connected to the gas grid by attractive gas tariffs and a new application besides cooking and water heating: space heating. Space heating with clean gas offered much more ease of use than burning dirty and expensive coal (Van Overbeeke 2001). Households who refused gas were given the label *old fashioned* or even *fogey*. The number of connected households and the gas demand per connected household increased rapidly. The result was that in 1980 97% of the Dutch households were connected to the gas grid and the demand per household ran from 460 m3 per year in

1965 to 2700 m3 in 1975. Besides space heating by gas, the increase of hot water demand (e.g. for showering and bathing and the accompanied changing norms of cleanliness and comfort [Shove 2010]) caused the increase in gas demand.

The oil crisis of the seventies led to changes in gas demand of households. People started to realize that fossil fuels are finite and burning fossil fuels got linked to negative environmental effects. Gas prices increased (see Figure 1.2), which made it also financially more interesting to save gas. The Dutch government changed its strategy from selling as much as possible to encouraging gas demand savings (see Figure 1.3). Savings were achieved through home insulation, application of better boilers and behavioural changes of residents. Thanks to these savings, the average residential gas demand for heating decreased from 2800 m3 in 1980 to 1800 m3 in 1990 to 1500 m3 in 1998.

The gas demand in the Dutch households reduced even more the past years (23,2% from 2000-2012). In 2012, the average gas demand per household was 1341 m^3 (ECN et al. 2014). This is mainly caused by better home insulation and more efficient heating equipment. The expectation is that gas demand will reduce even more in the near future by the introduction of several innovations. Better insulation and more efficient heating equipment of the existing housing stock regarding energy efficiency are incentivised by the mandatory energy label when a house is sold or rented (the label indicates the energy efficiency of a home) and by subsidies or loans with low interest rates (e.g., ikinvesteerslim.nl/Energiebespaarlening). In the social housing

Distributiebedrijven:
Prijs van gas staat niet vast

DEN HAAG (ANP) – Het staat nog niet vast, hoeveel de gasprijs voor de huishoudingen op 1 januari aanstaande omhoog zal gaan. De sterke stijging van de stookolieprijzen, waaraan de gasprijs is gekoppeld, maakt het waarschijnlijk, dat de aardgasprijs voor de kleine verbruikers met ongeveer vier cent per kubieke meter zal moeten worden verhoogd.

FIG.1.2 NEWSPAPER ARTICLE ON THE RISING GAS PRICES FROM 'LEIDSCH DAGBLAD', 19 SEPTEMBER 1979, PAGE 27

FIG.1.3 STILLS FROM AN ENERGY SAVING CAMPAIGN FROM THE SEVENTIES HTTP://WWW.RIJKSOVERHEID.NL/ONDERWERPEN/OVERHEIDSCOMMUNICATIE/GESCHIEDENIS-POSTBUS-51

sector, houses built in the sixties and seventies are getting 'wrapped'. This means that a prefabricated insulation shell is placed around the buildings in five days while the residents can stay at home.

Reduction in gas demand is mainly, but not only caused by energy savings. In 2011, the major energy carrier for cooking became electricity instead of gas (ECN et al. 2014). Newly built houses are increasingly *all-electric*, because the use of electricity itself does not omit carbon-dioxide locally and the future of gas supply is insecure. Also, insulation requirements for new houses are becoming more stringent, which means that new houses will hardly need any energy for spatial heating. The costs of a gas infrastructure within these newly built areas are too high to be interesting for the limited demand. Furthermore, alternatives for gas to heat houses are (re)gaining interest. For example, the small scale combined heat and power plants or other forms of efficient use of waste heat and low temperature heat pumps are rapidly improving. Hence, it is expected that newly built homes will not get connected to the gas grid at all and that the existing housing stock will use the existing gas infrastructure less intensively.

1.2.2. ELECTRICITY DEMAND

In the early 19th century, lighting was gas fuelled. Gas received competition of electricity in the market for lighting in 1881 when Edison demonstrated a generator that provided the electricity needed for the hundreds of light bulbs that lighted his pavilion (Van Overbeeke 2001). Both scientists and the general public were eager to see the magic lamp with their own eyes. Almost no one at that time had any knowledge of electricity whatsoever and it was seen as something mysterious. The relative advantages were that this new lamp could not get extinguished by the wind, and did not need ignition with a match. Electricity was not directly publicly available. At first, it was limitedly available for the homes of people who lived close to a place where electricity was produced and where it was easy to extend the electric wires to their home. Around 1900, there was increasing demand for electricity. This resulted in an increase in the number of power stations (Van Overbeeke 2001). In the cities (municipal) electricity production companies were founded. Many households in the middle and upper class obtained a connection with the electricity grid and adapted their homes with electrical lighting and sockets. The electricity company from Amsterdam offered free home installations in combination with a coin meter to attract the less fortunate households and increase the number of connected households (De Rijk 1998). The less fortunate households used electricity only for lighting at first, which created a large peak demand in the evenings and limited overall demand per connected household. To increase efficiency, the electricity company started to look for ways to stimulate demand, especially at off-peak hours (De Rijk 1998, Van Overbeeke 2001). Residential electrical appliances, such as hot plates, space heating and irons were therefore rented and sold by the electricity company in their own showrooms and shops. The company adjusted electricity rates and organized campaigns which resulted in a booming number of grid connections and the accompanying booming electricity demand in Amsterdam around 1920. The rest of the Netherlands followed around 1930. By the introduction of electrical appliances in the home, the view on housekeeping radically changed in that time era. Electricity would make housekeeping more efficient so women would find housekeeping more attractive and had time to do other things (De Rijk 1998, Van Overbeeke 2001).

To make electricity affordably available all over the country, an interconnected grid was built to facilitate centralisation of production (Verbong et al. 2002). The scale increase of production and transmission systems matched the development of demand of electricity. Electricity demand peaked in 1979 (around 3200kWh per household), but as with gas, the oil crisis changed the perspective on electricity demand and production. Resources for electricity production needed to become more diverse and even renewable to reduce dependency and the environmental impact. Moreover, efficiency in production received more attention (e.g. using the heat from electricity production as well). Last, the government targeted electricity saving behaviours by national campaigns. At first, the electricity demand per household dropped, but after 1988 demand increased again until 2008 (approximately 3600 kWh). The electricity demand of around 3400 kWh per household in 2012 is still below the level in the period 2005 to 2008, but did grow compared to 2011 (see Figure 1.4). Electric appliances in the home became more efficient (also by the introduction of energy labels for appliances), but the amount and the intensity of usage of appliances grew vast. From 2000-2010 the number of appliances in the home grew by 23% to an average of 93 appliances per household (Huisman at al. 2012).

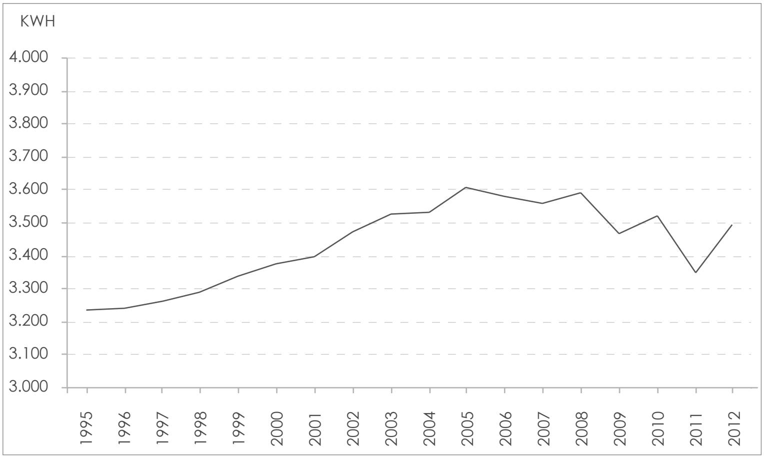


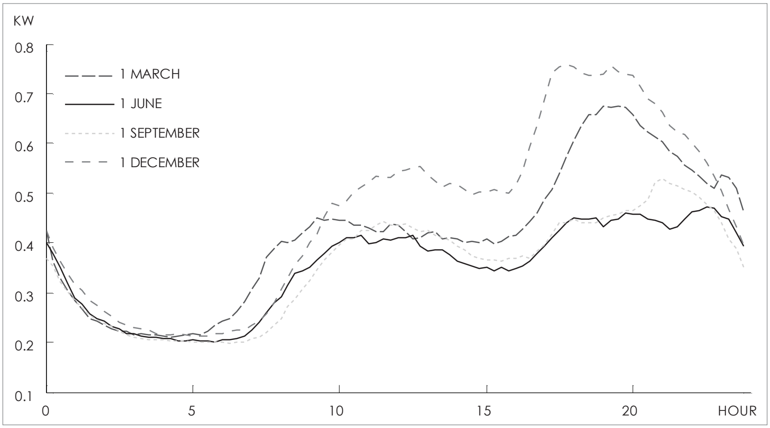
FIG.1.4 AVERAGE YEARLY ELECTRICITY CONSUMPTION PER DUTCH HOUSEHOLD IN KWH (ECN ET AL. 2014)

The European government is taking action to lower residential electricity demand further and decided to phase out incandescence lighting in 2012 and to introduce digital energy meters that can transmit energy demand data. These metres (Figure 1.5) are called smart meters and enable more feedback on energy demand to encourage energy savings. By the time of 2020, 80% of the households should have a smart meter (directive 2012/27/EU on energy efficiency 2012). Furthermore, the Dutch government is investing in projects to develop smart grids for more efficient use of (renewable) electricity production capacity and of electricity grids (tki-switch2smartgrids.nl), often by aiming to influence the timing of electricity demand (Verbong et al. 2013).

Patterns of electricity demand are quite predictable. For example, electricity demand is higher in winter than in summer time (see Figure 1.6). Moreover, little electricity is used at home during the day when people are off to work, demand is higher in the evening, when a warm meal is prepared and the TV is switched on (see Figure 1.7). Weekends and holidays have a different demand curve than working

FIG.1.5 EXAMPLE OF A SMART METER CONNECTED TO A COMPUTERISED FEEDBACK DEVICE

FIG.1.6 AVERAGE DEMAND PROFILE OF (400 RESIDENCES) WITH AN ANNUAL DEMAND OF 3400 KWH. (VELDMAN ET AL. 2013)



week days, because many people spend more time at home in weekends and holidays. Hence, peak demand is especially a problem on winter weekday evenings. The large scale introduction of renewables and new electrical applications lead to greater fluctuations in supply or demand for electricity. More specifically, the growing market share of solar panels (photovoltaic, PV) and electric vehicles (EVs) and heat pumps (HPs) that replace the polluting oil and gas fired vehicles and heating equipment are expected to have the biggest impact and require smart solutions (Veldman et al. 2013).

Solar panels change electricity demand in a way, because households that produce own electricity by PV panels, need less electricity from the grid. Moreover, these households become small suppliers of electricity, because surpluses of electricity are delivered back to the grid. Solar

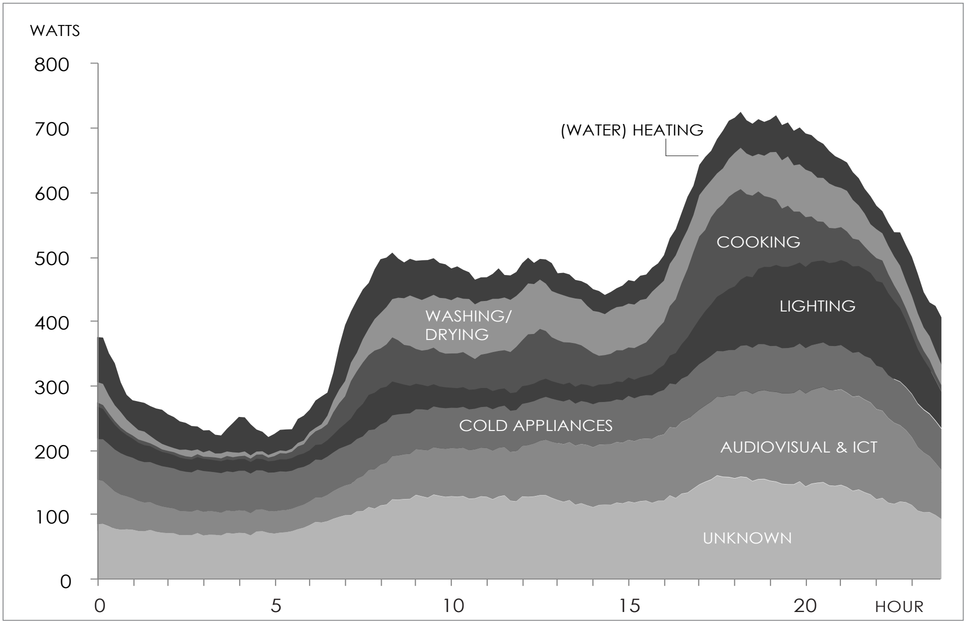


FIG.1.7 DEMAND PROFILE PER APPLIANCE GROUP OF UK HOUSEHOLDS (PALMER AND COOPER 2013)

electricity production has reached almost a giga Watt (a coal power plant on Maasvlakte-1 produces 520 MW). The number of households that own a PV installation rose to 246.031 in 2014 (Rotterdams Milieucentrum 2015). Important reasons for this development is that the price of PV is decreasing (see Figure 1.8). Furthermore, energy collectives are often offering PV installations by buying installations together in their neighbourhood. Neighbours are convincing each other

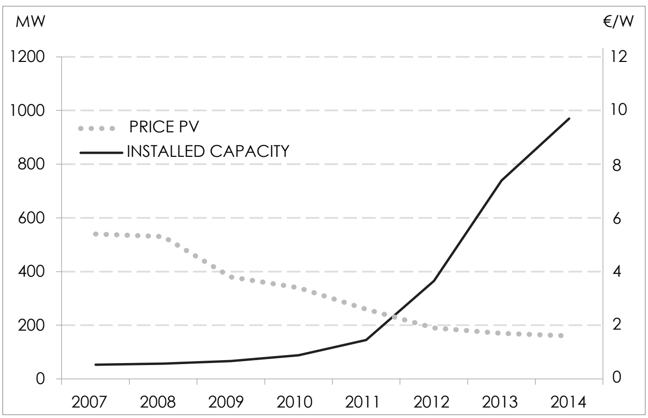
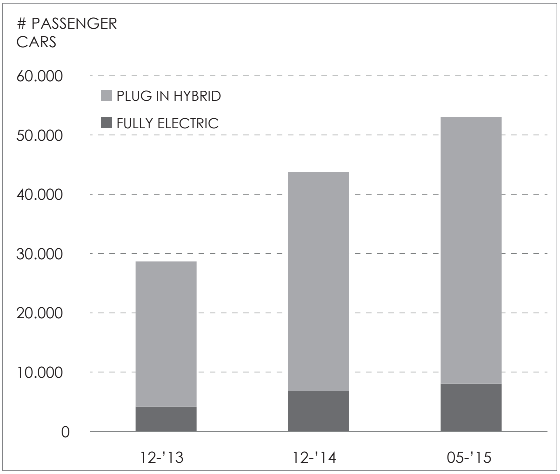


FIG.1.8 INSTALLED SOLAR PRODUCTION CAPACITY IN THE NETHERLANDS (IEA PVPS 2014, SOLAR MONITOR 2015) AND THE AVERAGE PRICE PER WATT (INCLUDING INSTALLATION) (PERNICK ET AL. 2013)

FIG.1.9 GROWTH IN NUMBER OF ELECTRIC PASSENGER CARS SINCE 2013 (RVO, 2015)



of the advantages (e.g. deh-energie.nl/zonnepanelen) of PV. When many households in the same city block have a PV installation, peaks (in the opposite direction) on a good summer day can be as high as the demand peak in winter. It is not only interesting to lower peak demand, but it will also be interesting to stimulate self-demand of PV production to deal with peaks in supply and reduce electricity transportation losses.

The amount of electric cars is rapidly growing in the Netherlands (see Figure 1.9). By stimulation of the government, further development of (charging) batteries, price developments of electric vehicles, range expansion, the increased availability of charging points and the high oil prices (and probably the introduction of the Tesla, which provides the owner status), the interest for the electric car increased. The expected break through of the electric car has a huge impact on the total demand of electricity. The demand of one household will increase with an EV from 3400 kWh to 7200 kWh a year (Energieraad 2009). People come home from work more or less at the same time and will plug in their EV simultaneously. When this happens, grid investments are needed, because the existing grid is not designed to facilitate this peak demand (Veldman et al. 2013). On the other side, each EV, with its battery, is a potential electricity buffer for surpluses of local, sustainable electricity production and an interesting opportunity in covering peak demand. On average, a car remains unused for 23 hours of the day, because the average driving distance per car is only 37 kilometres in the Netherlands

(CBS 2012). If all electric cars are connected to the grid when not in use, this equals a big source of reserve capacity.

The increase of installed heat pumps is particularly evident in new homes. A heat pump is an appliance that can heat a building by extorting heat from the environment. In 2013, more than 65,000 homes are heated with a heat pump (see Figure 1.10). Despite this overall number is relatively small, the number installed heat pumps in the Netherlands is increasing fast. Heat pumps have a serious effect on the total demand of a household as well. In the new area Meulenspie in Breda, which was part of the research in this thesis, we have seen that the heat pump demand is almost half of the total electricity demand in the household (see Figure 1.11).

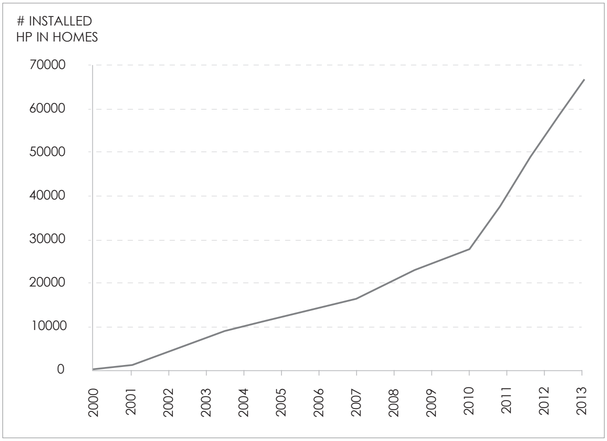


FIG.1.10 NUMBER OF INSTALLED HEAT PUMPS IN HOMES (CBS, 2014)

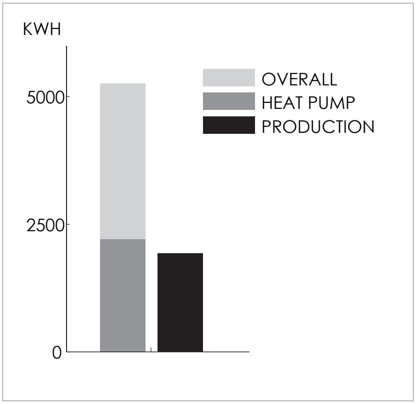


FIG.1.11 AVERAGE ELECTRICITY USE AND PRODUCTION IN MEULENSPIE, BREDA (05/13 - 05/14) (KLAASSEN ET AL. 2015)

To summarise, electricity (peak) demand and decentralised fluctuating production capacity will increase in residential areas. One way to solve the issues raised by these developments, is the way it has been done until now: to enlarge electricity networks and reserve production capacity. Large European transmission grid expansions are planned to ensure that sustainable electricity is transported from areas where it is produced to areas where there is demand. Furthermore, storing electricity on moments of surpluses to save it for moments of deficits gains interest. However, next to these often capital and material intensive options of meeting the growth of electricity (peak) demand, patterns of demand can be reshaped (Walker 2014).

1.3. SMART GRIDS TO CHANGE ENERGY DEMAND

Smart grids can be aimed at reshaping patterns of demand (Verbong et al. 2013). If so, smart grids aim to stimulate self-consumption of on-site PV electricity (Widén 2014) and/or to reduce peak demand (e.g. Faruqui et al. 2010a). The most common strategies to change patterns of energy demand in general are financial incentives and rewards, campaigns and smart energy technologies.

1.3.1. FINANCIAL INCENTIVES AND REWARDS

Last year, only 12% of the households switched energy suppliers, although households can easily save money by switching suppliers (ECN et al. 2014). Though this percentage is slowly taking up (it used to be 6%), the number of households who switch suppliers remains relatively low. Still, a dominant assumption in the energy sector is that the most important reason for change in the way households use energy, because of the low involvement, is a significant economic advantage (e.g. Watson et al. 2002). Therefore, the economic advantage is often used as an argument for energy savings (see the next paragraph on campaigns).

By saving energy, households will automatically save money. Furthermore, an additional financial reward seems to have a positive effect on energy demand reduction (Abrahamse et al. 2005). But, when the reward is taken away, households fall back to their old routines. In the case of incentivising a demand shift, a day and night pricing scheme exists in the Netherlands. It was introduced around 1930 in Amsterdam and at first meant for shifting the use of the electric boiler to the night when demand for electricity is low. People who join the program today pay a couple of cents (≈ €0.02) less per kWh at night when demand for electricity is low, than during the day. Though this price differential is small now, many households are still accustomed to using their white goods only at night or in weekends. These households have learned that energy is cheaper for them at night and in weekends and do not wonder how much cheaper.

Translating price fluctuations for electricity into more advanced pricing schemes, is being investigated as a measure to reduce peak demand. It is concluded in a review study that more advanced pricing schemes induce changes in energy demand patterns. Usage is shifted in the studies (mostly American studies) from peak moments to off-peak moments between 5% and 30% (Faruqui et al. 2010a).

Last, self-consumption of electricity produced by solar panels is gaining interest as a way to reduce the impact of solar energy on the grid (Widén 2014). In the Netherlands, the electricity that households feed-in to the grid has the same price as the electricity that is bought from the supplier. There is no economic advantage in using one's own electricity. When the government decides to take this feed-in support away, it becomes economically interesting to use electricity when it is locally produced.

1.3.2. CAMPAIGNS

The hypothesis behind communication for more sustainable behaviour in general is that people have an information deficit (Van Dam et al. 2010). The deficit can entail the consequences of behaviour (why) and/or what behaviour must change and how (Abrahamse et al. 2005). Lindén, et al. (2006) argue that even if a campaign is very intensive, it takes time to notice the effect and it is often difficult to measure the direct effects. Nevertheless, for changing residential energy demand, campaigns have been a popular method since the first oil crisis. The method is relatively cheap and reaches a large audience.

Most campaigns until now are targeting energy savings. The recent mass media campaign in Belgium (www.ofon.be) also targeted peak demand. The most dominant arguments in existing campaigns is that people can save money and save the environment. The campaign in Belgium also targeted security of supply*. Research has demonstrated that providing information about the costs of energy use does not necessarily affect

* In other countries than the Netherlands this can be a valid argument. The Netherlands has a very reliable electricity supply today with an average downtime of only 22 minutes yearly

energy use behaviour, because the financial benefits are small (e.g. Lindén et al. 2006). Bolderdijk (2010) argues that environmental benefits are a more effective argument. However, it is also concluded that the value of the inclusion of fear appeals of future environmental problems is limited unless they are combined with behavioural alternatives that provide a solution to the threat (De Vries et al. 2002). Furthermore, people must be able to apply the advice on behavioural alternatives to their situation (Abrahamse et al. 2005).

1.3.3. SMART ENERGY TECHNOLOGIES

Energy use can be reduced or shifted in time in response to a price signal or other stimuli as a result of an household action (automated, manual, or both) (Darby & McKenna 2012). We will briefly describe two often used smart energy technologies for reducing or shifting energy demand that received most attention in recent years: Energy Management Systems (EMSs) and smart appliances.

EMSs | It is argued that an Energy Management System (EMS or Home Energy Management System, HEMS) is a useful device for changing patterns of energy demand (e.g. Erhardt-Martinez et al. 2010). Households are still unlikely to know how much energy they use when by the lack of feedback. Most households only receive feedback through an annual energy bill. More frequent and transparent feedback should induce several kinds of energy-saving behaviours by making energy use less 'invisible' (Strengers 2011). An EMS makes energy use less invisible by giving computerized, real-time (visual) feedback on gas and/or electricity demand (Van Dam et al. 2010). Research has demonstrated, that when feedback is given real-time, it is most effective (for reviews see Abrahamse et al. [2005], Darby [2006], Fischer [2008] and Ehrhardt-Martinez et al. [2010]).

Many different EMSs have been developed in the past years. Often, EMSs do not only give real-time feedback, but also include feed forward on the availability of sustainable electricity or electricity prices, historical and normative comparisons of demand patterns, goal setting and other persuasive techniques to improve the effectiveness of the EMS. Households can use feedback (and feed forward) from the EMS to manually reduce or shift demand. Besides leaving it up to the user to act upon the feedback, some EMSs can also automatically switch appliances on or off for energy saving purposes*.

* For example, smart plugs that are used as stand-by killers

Smart appliances | A smart appliance helps a user to select the most desirable time for consuming electricity, for example, by taking into account weather forecasts and electricity prices. There are different concepts of smart appliances, which are defined by three different levels of autonomy (see Figure 1.12 for a schematic overview of the options). A time-critical appliance (e.g. appliances for cooking) can be interrupted during use, but this form of smart appliances is unlikely to receive user acceptance. If the use of the appliance is not perceived time-critical, a *semi-autonomous* way of shifting demand exists besides using feedback and feed forward from the EMS to manually shift demand. In this case, the user gives the appliance a time frame in which the complete use cycle must take place (Gottwalt et al. 2011, Timpe 2009). The semi-autonomous smart appliance then decides when it is most optimal to run the cycle. For example, a washing machine that takes into account the solar production, but will be ready within the time frame given by the user. Last, when the appliance is used continuously, such as the refrigerator and heat pump, responding to weather forecasts and electricity prices needs to be done by an *autonomous technology*. For example, a smart refrigerator can automatically cool more intensely when local electricity is abundant. If appliances are not used continuously, but the use is not time-critical either, concepts exist that automatically interrupt the use cycle, often without the user noticing it. Shifting electricity demand by fully autonomous technologies does not need any interference of the

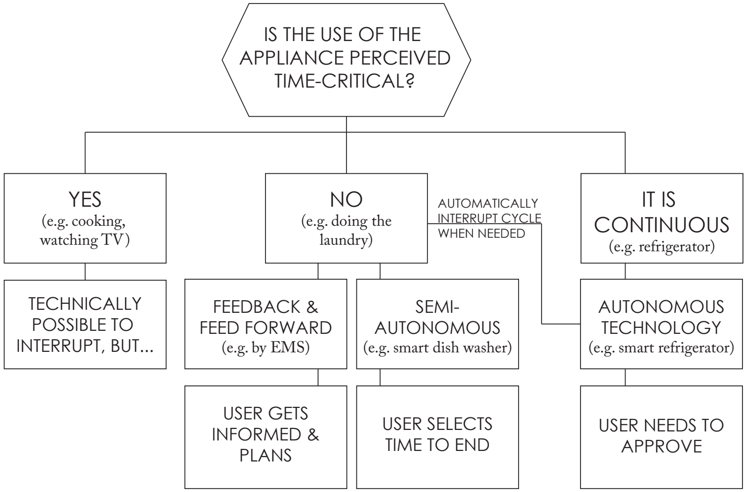


FIG.1.12 OVERVIEW OF ELECTRICITY CONSUMPTION, TECHNOLOGY AND USER INTERACTION

user, other than an approval to apply. Most existing studies on shifting residential demand in combination with smart appliances (see Faruqui et al. [2010a] for an overview) make use of this autonomous technology in smart air-conditioners or electric heating systems. These studies are moderately relevant for the Dutch context, because the Netherlands is characterised by a cold climate and spatial heating is often done by gas.

1.4. A SWITCH BY DESIGN

Researchers have mathematically assessed the potential size and value of smart grids in residential areas. Compared to business as usual, vast benefits for different actors are postulated (e.g. Erdinc 2014, Veldman et al. 2013, Rastegar et al. 2012, Finn et al. 2013, Faruqui et al. 2010a). According to Verbong et al. (2013), the extent to which users are willing and able to accept and use smart grids determines the success of smart grids. However, research on user acceptance of smart grids is still limited (Geelen et al. 2013). This thesis aims to address this knowledge gap by investigating user acceptance of smart grids and how user needs can be incorporated in designing smart grids. The design research field that is especially interesting for bridging this specific knowledge gap is design for sustainable behaviour (e.g. Wever et al. 2008, Daae 2014).

Design for sustainable behaviour is a strongly emerging design research field. Norman (1988) was one of the first researchers that investigated how designers influence users' behaviour in general. Today, more and more designers and design researchers are focusing on design for desired behaviour (e.g. Lockton et al. 2010, Tromp 2013) such as sustainable behaviour. Researchers in this field use existing models and theories from social sciences on changing behaviour. The two main schools in the field of design for sustainable behaviour are (social) psychology (e.g. Bhamra et al., 2008) and practice theory from sociology (e.g. Kuijer 2014). The main difference between the two is that (social) psychology centres the individual, possibly interacting with its environment at the centre of attention and practice theory centres the practice (Daae 2014).

A practice is a form of routinised behaviour that consists of several elements, interconnected to one other (Reckwitz 2002). According to Shove (2006), these elements are inter-related and co-evolve constantly. The elements of which a practice (e.g. bathing) consists are summarised by Kuijer 2014 as: *images* (comfort and cleanliness), *stuff* (e.g. bathtub, soap, water) and *skills* (e.g. know-how). The design approach related to practice theory is called a practice-oriented design approach (Pettersen 2013, Kuijer 2014). Though practices cannot be broken down into its single elements and outcomes on a practice level are unpredictable, every element is important in changing a practice (Pettersen 2013). In designing the *stuff*, designers might contribute in a positive way. A practice-oriented design approach focuses on understanding and influencing the co-evolution of separate practices over space and time (Kuijer 2014).

The present research does not target one specific practice though. Using energy in general is not a practice in itself, but is a result of different practices. Our aim is to investigate how households can be encouraged to lower demand or to shift electricity demand away from peak moments, to moments of (local) sustainable electricity production in general. How households achieve this demand reduction or a demand shift, is left up to them. Nevertheless, we intent to facilitate households by introducing innovative smart energy technologies. We are especially interested in the way households interact with smart energy technologies and how the technologies change patterns of energy demand. With this research aim, our stance in the field of design for sustainable behaviour belongs to the (social) psychological school. Models from (social) psychology in the field of design for sustainable behaviour are often combined with an User-Centred Design approach (Lilley 2007, Tang 2010, Wever et al. 2008, Daae 2014, Strömberg 2015). User-Centred Design (UCD) means that technologies are designed by engaging with the potential users during the development phase to understand their needs, tasks and environments and by applying an iterative approach of evaluation and adapting by the multidisciplinary design team (ISO-9241-210). UCD contains a large number of methods to investigate how users interact with technologies and how to use these insights in the (further) development of these technologies. The application of a UCD approach to gather upfront user insights and (early) user testing to evaluate the effectiveness, is considered of great importance in the attempt to facilitate sustainable behaviour (Daae 2014).

Considered from a (social) psychological perspective, changing the way households use energy requires that a person is motivated to change his/her behaviour (e.g. Fiske and Taylor 1991). The motivation to behave in an environmentally responsible manner is related to people's environmental values (Kaiser et al. 2005). However, only a minority of people embrace ecological values to such extent that they are willing to change their behaviour (CBS 2011). Perceived financial benefits can also motivate people to change their electricity demand (Watson et al. 2002). But, substantial financial gains are difficult to attain for electricity demand because electricity is relatively cheap. The financial gain of changing one's electricity demand will often not compensate for the inconvenience of having to change. Moreover, it is often difficult to grasp the financial benefits of reducing electricity demand, because households are unlikely to know the price or volume of their electricity demand (Burgess and Nye 2008).

Residential patterns of energy demand are a result of habits. For example, people switch on the light without thinking and have developed routines for using their washing machine. Shortly said, habitual behaviour is a form of automaticity that develops as people repeat actions in stable circumstances (Verplanken and Aarts 1999). When people repeatedly perform the same actions, their actions are automatically cued by stable features of the environment. Past research has shown that changing habits is difficult, especially when people are not motivated (Bagozzi 1982, Verplanken and Wood 2006). As discussed, most households will feel they have little to gain from changing their energy consuming habits and thus their motivation to do so is relatively low. In order to successfully change people's habits, Verplanken and Wood (2006) argued that undesired habits should be disrupted by changing the stable context cues that trigger habits. Habit formation involves the creation of associations in memory between actions and stable features of the context in which they are performed. Successful interventions should focus on disrupting contextual cues that trigger and maintain the old habit. Moreover, the new context should promote the repetition of new actions so that new associations are formed, resulting in the creation of a more desirable habit and its maintenance over time. One way to achieve such a desired change in contextual features is through new technologies (Verplanken and Wood 2006). We introduce design as an important variable in the success of these technologies, because our hypothesis is that these technologies can only be successful if users are able and willing to use the technologies.

In the field of design for sustainable behaviour, little attention has been paid to the maintenance of the desired behaviour over time.

The maintenance over time is an extremely important topic for this thesis, because previous research showed that often, the effect of the interventions to save energy do not last (e.g. Abrahamse et al. 2005). Although households' reduced energy demand directly after the intervention, people returned to their former habits and no long-term behaviour changes were achieved. It is important that ways for lasting change in energy demand are found and incorporated in the designs (Van Dam et al. 2010).

1.5. RESEARCH OBJECTIVE AND APPROACH

As introduced, the main research objective of this thesis is to investigate how households can be encouraged to change habits of using energy at home to more environmentally friendly habits. In particular, we answer the question how households can be encouraged to shift electricity demand away from peak moments, to moments of (local) sustainable electricity production. Because habits are assumed to be automatically cued by a stable context (Verplanken and Aarts 1999), the studies in this thesis bring about important changes to the stable context by the presence smart energy technologies (and new tariff structures in Chapter 4-6). We focus on the way households interact with smart energy technologies and how the design of these technologies influences more desirable habits regarding energy use at home.

Design researchers have an active goal of making something happen, instead of describing, explaining or predicting phenomena (Strömberg, 2015). Our research approach focused on continuous practical experimentation that naturally matches with a design research process, and fits with the pragmatist tradition of doing research (Rylander 2012). Pragmatists are generally more concerned with applications and solutions to problems and are not committed to any one system of inquiry (Creswell 2014). Pragmatists generally apply a mixed methods approach in which both quantitative and qualitative research methods are used to provide the best understanding (Creswell 2014). In our research, a mixed methods approach is chosen because of its strength in minimizing the limitations of both quantitative and qualitative approaches. This way, we were able to develop a more complete understanding of how households interact with smart energy technology and how the design of technologies influences more desirable habits regarding energy use at home.

We started this research with a quantitative explanatory study on the value of design in the related and already more heavily investigated topic of energy demand reduction. Because the topic of shifting electricity demand at home was relatively new, we used exploratory sequential mixed methods. This means that we have started with qualitative research on exploring important variables and to gain insights for developing smart energy technologies. In the quantitative follow-up where we investigated the effect of the developed smart energy technologies on behaviour and how these technologies were perceived and used in a larger, more representative group. These quantitative studies had a longitudinal set-up to be able to investigate habit formation in particular.

The cooperation with Enexis B.V., a Dutch distribution system operator, provided the unique opportunity to investigate our hypotheses through high quality field studies. Field studies provide the opportunity to investigate objective behaviour and interaction with smart energy technologies at their own homes. Many prior studies on user acceptance of smart grids did not have this opportunity and are based on intentions of acceptance and behaviour change (Timpe 2009, Gyamfi & Krumdieck 2011, Mert et al. 2008, Stamminger et al. 2008, Broman et al. 2014). The advantage of studying objective behaviour instead of intentions and attitudes is that intentions deviate strongly from real behaviour (Kollmuss and Agyeman 2002). Figure 1.13 gives a visual overview of our research approach.

1.6. OUTLINE OF THIS THESIS

In the next chapter of this thesis, **Chapter 2**, the set up and results of a field study amongst a large sample of households is described where EMSs were installed to reduce energy demand. Although giving more direct feedback in general seems promising for encouraging energy saving behaviours, meta studies show that energy savings that result from giving feedback vary widely (McKerracher and Torriti 2012). This research contributes to the literature by examining the variations in energy savings between two different designs of EMSs. The hypothesis tested in this study is that easy to use and accessible systems are important to increase the chance that people will remain using the EMSs over time to achieve lasting energy demand reductions.

Chapter 3 describes a qualitative field study amongst households shifting the use of electrical appliances in time, in order to match their own local electricity production. We gained rich insights in the way

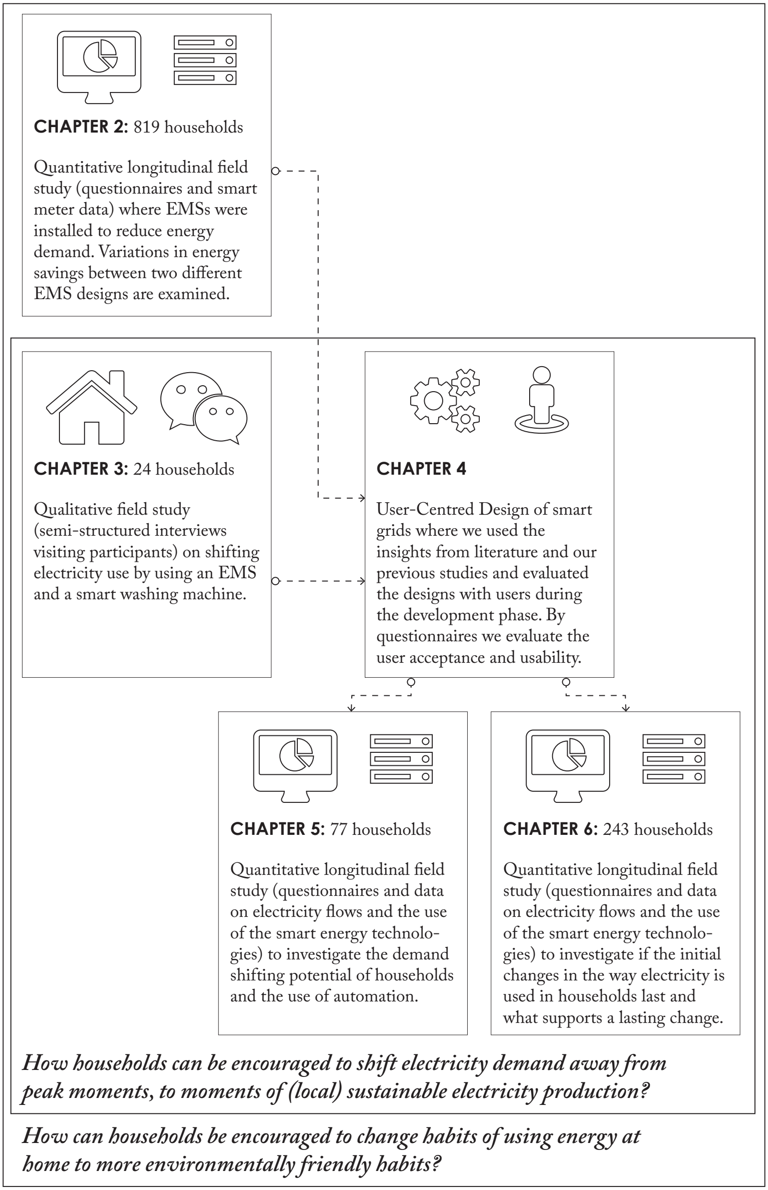


FIG.1.13 OVERVIEW OF OUR RESEARCH APPROACH

users interact with a smart washing machine and an EMS in a real-life setting and got first insights on the possibilities and impossibilities of shifting electricity demand to match supply. We chose for a qualitative approach, because this research was amongst the first field studies on shifting electricity demand at home, using smart energy technologies.

Chapter 4 is dedicated to the design of the large scale field study on shifting demand in Zwolle and Breda, because designing a study of this magnitude and length with actual users, needs a thorough and UCD approach. The UCD approach is unique in the field of smart grids. Often, designers are not or limitedly involved in these kind of studies resulting in technologies of engineering excellence, but at the same time, the technologies are too difficult for households to use. The way a UCD approach is applied in developing the technology and the set up of the field study is described. Insights from previous research, also the two prior chapters are used to develop a design brief. We describe the way we tested the designs during the development phase. Furthermore, we investigated the user acceptance and how the usability of the final EMS designs were perceived to evaluate our results of this approach.

The value of shifting demand depends on the load shifting ability and willingness of households. Therefore, it is important to investigate the assumptions (e.g. Veldman et al. 2013) made on the demand shifting potential of households. In **Chapter 5,** we analyse the shift in demand that was achieved by a large group of Dutch households in a real life setting. For one year, we collected data on the electricity use of the washing machine and on the use of the smart planning function. We evaluate both self-demand of on-site PV electricity production and peak demand reductions. This chapter focusses especially on the value of the semi-autonomous function of the smart washing machine.

Chapter 6 focusses on habit formation in a broader sense than Chapter 5 by investigating the demand shift of other appliances and the use of the EMS. During the operation of our field study, more studies with a similar set up emerged (e.g. Kießling 2013, D'hulst et al. 2015). What remains unique about our set up, besides the UCD approach, is the length of the study period. This set-up enabled us to investigate if the initial changes in the way electricity is used in households lasted. Other studies were performed on a smaller scale (e.g. Geelen et al. 2013) and previous larger field studies often lasted relatively short (e.g. Kießling 2013).

Chapter 7 summarizes the main findings and implications from this research for different audiences. We discuss the suggestions for further research and discuss the relevance of this research for different future scenarios.

02

LOWERING ENERGY DEMAND

Investigating the long-term influence of the design of Energy Management Systems

Saving energy use at home is a first step in reducing the impact on our environment. Therefore, many researchers have studied ways to reduce residential energy demand. It is concluded that providing households with real-time feedback on their energy use can result in energy savings. However, not all forms of real-time feedback have resulted in lasting energy savings. The main conclusion of this chapter is that real-time feedback given by an EMS can only be effective over time if households remain using the EMS frequently. This means that the design of the EMS is of utmost importance: the EMS should be easy to use and accessible.

This chapter is an adapted version of Charlotte B.A. Kobus, Ruth Mugge and Jan P.L. Schoormans. (2015) Long-term influence of the design of energy management systems on lowering household energy consumption. International Journal of Sustainable Engineering 8 (3). p. 173-185

A good way to reduce the impact of using energy on our environment is to lower energy demand. Households are an important target group for reducing energy demand because they account for one fourth of the total Dutch energy consumption (ECN et al. 2014). Today, most households only receive indirect and aggregated information on the financial consequences of their energy consumption through an annual energy bill. According to Burgess and Nye (2008), more frequent and transparent feedback should make the relationship between daily practices and energy use more clear. In this way, it is expected that households can start to negotiate about and gain new understandings of their so-called 'invisible' energy use (Strengers 2011) and by that initiate several kinds of energy-saving behaviours.

Giving more feedback to households about their energy consumption is one of the most heavily investigated interventions for lowering energy demand (for reviews, see Abrahamse et al. 2005; Darby 2006; Fischer 2008; Ehrhardt-Martinez et al. 2010). The question if feedback works is answered positively by these researchers. Also based on this idea, the European Commission formulated directive 2012/27/EU on energy efficiency (2012), which states that at least 80% of the households should be equipped with smart meters by 2020. A smart meter is defined in this directive as an electronic meter that measures energy consumption and can transmit these data using a form of electronic communication to give feedback about actual residential energy consumption and costs with the intention to encourage households to lower their consumption.

Households can acquire feedback on their energy consumption in various ways. Indirect feedback has been processed and is presented through a medium, like the energy bill. There is some time between action and feedback, sometimes even a year. On the other side of the spectrum, there is direct feedback: users get immediate computerised feedback (Darby 2006). Direct feedback can be given by energy management systems (EMSs). This research focuses on EMSs because direct feedback presented by an EMS has shown most successful for encouraging energy-saving behaviours. An EMS (or home energy management system) is defined as a device that gives computerised, real-time (visual) feedback on gas and/or electricity consumption (Van Dam et al. 2010).

Although EMSs in general seem promising for encouraging energy-saving behaviours, meta studies show that energy savings caused by

EMSs vary widely. Even results between meta studies results vary widely. For example, Ehrhardt-Martinez et al. (2010) state that energy savings by EMSs vary between 0.5% and 18%. McKerracher and Torriti (2012) argued that a more realistic large-scale conservation effect from feedback is estimated in the range of only 3–5%. Even though field studies have found these differences in energy-saving results, studies have just begun to look into the factors causing these large variations in energy savings. Most important for this research are the variations caused by the fact that EMSs vary widely in their design and features. Designers can influence users of EMSs to behave more environmentally friendly through successful designs (Lockton et al. 2008; Wever et al. 2008; Bhamra et al. 2011). It is thus important to shift the research question from 'Does feedback work?' to 'How can we design systems that make feedback work?'

Research has started to explore the role that the design of EMSs and the given feedback have on its effectiveness for energy reduction. First, user preferences for and comprehensibility of feedback have been investigated qualitatively in interviews using paper prototypes (Karjalainen 2011) and among a large group of people with prototypes and web surveys (Bonino et al. 2011). Second, how feedback systems actually work in the home (in the long run) has been investigated qualitatively among small samples (Strengers 2011; Van Dam et al. 2010; Hargreaves et al. 2010, 2013). Finally, good feedback is conceptualized by psychological and design theory (Wood and Newborough 2007; Fischer 2008; Anderson and White 2009). Only some of these concepts are supported by empirical evidence.

What is still missing in this field is a quantitative exploration of the long-term effect of design variations in EMSs on the desired behaviour. This research contributes to the literature by examining the variations in energy savings between two different EMS designs and compared the results to a control group that received a smart meter without an EMS in a longitudinal field study among a large sample.

2.1. SUCCESSFUL FEEDBACK: A LITERATURE REVIEW

Numerous researchers have shown that feedback affects energy savings (for reviews, see Abrahamse et al. 2005; Darby 2006; Fischer 2008; Ehrhardt-Martinez et al. 2010). Moreover, steps have been taken to uncover user preferences, comprehensibility, user interactions with

EMSs, and conceptualized good feedback by psychological and design theory. This section will summarize the main design recommendations for feedback that have resulted from these studies.

First, the more frequent feedback on energy consumption is given, the more effective it is: frequent feedback enables the user to link behaviour to consequences (Abrahamse et al. 2005; Darby 2006; Fischer 2008; Ehrhardt-Martinez et al. 2010). An EMS can give feedback by different media, such as a dedicated (portable) device, an app, a computer program or a website, or a combination of media. An EMS is a device that is able to give frequent feedback. However, Alahmad et al. (2012) found that even small delays of a couple of minutes in giving feedback by EMSs could frustrate the user. In this respect, it is important that the feedback on residential energy consumption is not only frequent, but even real time.

Second, feedback needs to become part of daily life. Results of more recent, qualitative studies showed that the initial energy savings of households could not be sustained and the use of the EMS slowly drifts into the background (Van Dam et al. 2010; Hargreaves et al. 2013). It is proposed that only if households remain using the EMS frequently, this will result in lasting energy savings. Therefore, researchers advised to encourage daily use of an EMS by design. Design can enable habits if EMSs obtain attention by being attractive and interesting in the first place and hold this attention over time by becoming part of the daily routine (Anderson and White 2009; Hargreaves et al. 2010). In addition, it is important that the EMS is accessible and attractive to use to all people in the household because all residents contribute to the overall household energy consumption. Promoting that other residents use the EMS besides just one (often male) household member (Van Dam et al. 2012; Hargreaves et al. 2010) can intensify the dialogue between different household members about energy consumption.

Almost all EMSs give feedback on current usage. This is often done with scientific terms, such as Watts, m^3 of gas and costs, and sometimes supported by a visual. Efforts are needed to facilitate comprehensibility of feedback. Designers of EMSs must recognize the fact that many people have difficulties in dealing with numbers and are unfamiliar with scientific terms, such as kWh. It is also not advised to express energy consumption in CO_2 emissions because this is too difficult to comprehend for most people. Expressing energy consumption in costs is preferred (Karjalainen 2011). Bonino et al. (2011) found in their survey that colour-based feedback is easily understood and well appreciated.

In order to interpret the consumption data, it can be valuable to provide comparisons. Historic comparisons can make clear what patterns of energy use look like (Anderson and White 2009; Fischer 2008). Most EMSs provide historical feedback next to real-time feedback, so users can compare their current patterns of demand with patterns of the past. Often, historical data are presented in bar charts. Normative comparisons, comparisons with the average of other households, are used sometimes, but have not revealed their effectiveness (Fischer 2008). People who use more energy than the average might lower demand, but the energy saving effects are cancelled out by the people who used less than average, because people will tend to level out to the middle (Schultz et al. 2007). To make normative comparisons relevant, research has shown that it is important that people feel the comparison is right (comparisons with households like them) (Karjalainen 2011). Comparing households with the top 10% also has shown to be more successful· (e.g. Asensio and Delmas 2015). McCalley and Midden (2002) found that feedback was most effective when it was combined with goal setting (self-set and assigned goals, both were found effective) and accompanying the feedback by smiling or frowning faces.

Feedback from the EMS can be dedicated to the use of the entire household, of specific appliance (groups) or both. In preference studies, when people are asked which features they would prefer in EMSs, people demonstrate a preference towards appliance-specific breakdowns (Bonino et al. 2011). Fischer (2008) also suggested that an appliance-specific breakdown is most effective, while it directly links the provided feedback about energy usage to certain activities like washing. From a design perspective, it is warned that it might become too complex and expensive to give a full appliance-specific breakdown and that it might only confuse and distract users. The worst-case scenario is that such breakdowns may even result in decreased effectiveness (Wood and Newborough 2007).

The designs of the EMSs used in this study both provide users with real-time and historical feedback, and overviews of their energy usage in graphs with colours with the aim to lower residential energy demand. The EMSs differ from each other in the following aspects: the first EMS has an appliance-specific breakdown and a user interface that is web-based. The second EMS has a dedicated display that is attached to the wall in the living room. This EMS does not offer an appliance-specific breakdown, but does incorporate more visuals and goal setting. The control group used in this study received a smart meter without an EMS.

2.2. METHOD

2.2.1. STUDY DESIGN AND EMS CHARACTERISTICS

The EMSs were selected based on a pre-test in which 622 respondents evaluated three out of nine concepts. These concepts were described with usage scenarios (Synovate 2010). All respondents answered a questionnaire including the following topics: review of concepts on five-point scales ('How attractive is this product?' 1 = 'very unattractive', 5 = 'very attractive'; 'How credible is this product?' 1 = 'very incredible', 5 = 'very credible'; 'How relevant is this product for you?' 1 = 'very irrelevant', 5 = 'very relevant') and the direct comparison of concepts ('Which product is most attractive to you?' and 'Which product is least attractive?').

The technology concepts Smart Plugs and Smart Thermostat were selected, because they were market ready and had the most similarities with the 'winning concepts' from the review study. Market ready, and thus reliable technology, was needed because of the longitudinal set up and the large samples in the main study. The EMS Smart Plugs consist of a set of nine plugs and a web portal. The appliances connected to these plugs can be read out and controlled in the web portal. The EMS has a link with the smart meter to give insight in real-time and historical energy consumption of the entire home. Furthermore, it gives an appliance-specific break down of the energy consumption. The Smart Thermostat is a display, replacing the thermostat in the living room and includes feedback on patterns of electricity and gas demand. As the Smart Thermostat is also connected to the smart meter, one can control the heating system and get insight into energy consumption through this display. Goal setting is applied in the Smart Thermostat. The Smart Thermostat provides feedback in colours if one is below or over target usage.

This field study was performed among two test groups that were provided with one of these two EMSs as well as a smart meter and

	SMART METER (CONTROL)	SMART PLUGS	SMART THERMOSTAT
Hard and software	Smart meter is located next to the front door in a closet	Web application with 9 smart plugs connected to a smart meter	Display on the wall, connected to the thermostat and a smart meter
Real-time feedback	x	Electricity in Watts, Euro or CO_2 (refresh rate on demand) and gas meter reading (refresh rate every hour)	Electricity in Watts or Euro (refresh rate 10s) and gas in m^3 or Euro (refresh rate 1h) on home screen
Historical comparisons	x	Electricity in kWh and gas in m^3. Both are presented in Euro and CO_2 emissions and visually in a bar chart.	Electricity in kWh or Euro. Both are presented in numbers and visually in a bar chart.
Normative comparisons	x	x	x
Feeling of achievement	x	x	Showing energy usage in comparison to the goal in a cumulative bar meter. The bar is green and turns red when the target usage is exceeded.
Appliance specific breakdown	x	Real time and historical. Grouping of appliances for example by room is possible	x
Control other appliances	x	Users can make a time-table when to shut connected devices on and off.	x

TABLE 2.1 CHARACTERISTICS OF THE EMS DESIGN PER GROUP (INCLUDING CONTROL GROUP)

one control group that only received a smart meter (see table 2.1 for an overview of the characteristics of the different EMSs and Appendix 1 for visualised characteristics). The EMSs were installed by the suppliers of these EMSs.

2.2.2. PARTICIPANTS

Because of the length of the study, a total of 819 participants were recruited. We expected a mortality rate of 40–60%, because this is not uncommon in longitudinal studies (Bijleveld et al. 1998) and we wanted to have 100 respondents in all three groups at the end of the study. Hence, we intended to obtain around 250 respondents per group. The study took place in the Netherlands with residential customers of a Dutch distribution system operator. Households were assigned randomly to one of the three experimental groups and were invited to participate by a direct mailing. There has been contact with a total of 1426 households.

2.2.3. PROCEDURE

This research relied on meter readings and questionnaires to not only answer the question if feedback works, but also how it works. The electricity and gas meters were read daily in an uninterrupted period of 25 weeks including wintertime of all 819 participants. Gas consumption was measured separately because Dutch households often use gas for space heating and cooking. As a result of technical issues, some data were missing (18% of the gas meter readings and 5% of the electricity meter readings). Furthermore, we checked the data for extreme values. These were values for which the saved or increased energy usage was +/-3 *Sd* compared with this household's meter reading of the year preceding the study, resulting in the deletion of 4% of the data (>64% increased electricity usage and >63% electricity savings, from >65% increased gas usage and >29% gas savings). These readings were excluded from the analysis. This was done because the self-reported readings of the year preceding the study are not always reliable. It may be that these readings are incorrect (e.g. one meter reading indicated that the yearly electricity consumption was only 1 kWh) or that other important changes have occurred that radically shift a household's energy usage.

Next to the meter readings, questionnaires that were sent to the participating households aimed to provide insight into demographics, motivations to save energy, use frequency of the EMS and participants' evaluation of the EMS. The first questionnaire (T1) took approximately 10 min to complete and was filled in by 388 participants (47% response rate). They had been using the EMS for 4–16 months (variation due to installation time).

In the questionnaire, the various motivations to save energy were measured by several five-point scales anchored by 'very unimportant' (1) to 'very important' (5). To develop different motivation scales, we performed a factor analysis (with Varimax rotation, see Table 2.2) on the eight motivation items (eigenvalue >1). Three factors were found: (a) environmental and future-oriented (α = .87), (b) enjoyment (α = .79) and (c) financial (α = .81). For each factor, the items were averaged to form three motivation scales.

The questionnaire also included various scales to measure participants' evaluation of the EMS (see Table 2.3). These scales involved overall product satisfaction including satisfaction measures on specific characteristics, ease of use and self-reported use frequency. The last question was repeated for the respondent's partner/inmates and children to investigate who uses the EMS on what frequency.

TABLE 2.2 FACTOR ANALYSIS ON MOTIVATION ITEMS (ONLY ITEMS THAT SCORED >.4 ARE REPORTED)

	ENVIRONMENTAL AND FUTURE-ORIENTED	ENJOYMENT	FINANCIAL
Running out of resources	.91		
Secure the future for next generations	.85		
Less environmental pollution	.83		
I think it is a challenge		.86	
It gives me a good feeling		.78	
I think it is my responsibility		.75	
Saving money			.92
Getting a grip on the energy bill			.88

TABLE 2.3 MEASURES FROM QUESTIONNAIRE

	QUESTIONS	ANSWERS
Scale product satisfaction (α =.89) based on Mägi (2003)	'How satisfied are you with Smart Plugs/Smart Thermostat in general?'	1='very dissatisfied' 5='very satisfied'
	'The Smart Plugs/Smart Thermostat meets my expectations'	1='strongly disagree' 5='strongly agree'
Specific evaluation measures	'appearance' 'access to information' 'gas usage information' 'electricity usage information'	1='very dissatisfied' 5='very satisfied'
Scale ease of use (α=.95) adapted from Nysveen, Pedersen, and Thorbjørnsen (2005)	'The use of Smart Plugs/Smart Thermostat was easy to learn for me' 'Using the Smart Plugs/Smart Thermostat is easy for me'	1='strongly disagree' 5='strongly agree'
Self-reported use frequency	'How often do you consult the Smart Plugs/Smart Thermostat?' (question repeated for respondent's partner and children)	1='Never'; 2='Rarely'; 3='Once a month'; 4='Once every two weeks'; 5='Weekly; 6='Once a day'; 7='Several times a day'

The same questionnaire was distributed again 7 months later (T2) to measure the persistence of usage of the EMS. The second questionnaire was filled in by 319 participants (82% response rate of the T1 respondents). Table 2.4 provides an overview of the number of meter readings and respondents in each group.

2.3. RESULTS

2.3.1. DEMOGRAPHICS AND MOTIVATION

The demographic differences between groups were assessed. One-way ANOVAs (with Bonferroni post-hoc tests) and Kruskal–Wallis tests were performed with the demographic variables as dependent variables and the groups (control, Smart Plugs and Smart Thermostat) as independent variables. The only significant differences that were found was that the Smart Plugs had somewhat bigger houses in general than the control group ($p < .05$) and was educated higher than the test group with a Smart Thermostat ($p < .05$). See Table 2.5 for an overview of the demographics.

Three one-way ANOVAs were performed with the different motivation scales as dependent variables and the groups (control, Smart Plugs and Smart Thermostat) as independent variables. The groups did not differ

TABLE 2.4 NUMBER OF METER READINGS AND RESPONDENTS

	# METER READING BEFORE STUDY AND REPEATED METER READINGS DURING STUDY			QUESTIONNAIRES	
		ELECTRICITY	GAS	T_1	T_2
Smart Meter (control)	Valid	255	216	136	114
	Missing	5	48		
	Outliers	13	9		
	Total	273			
Smart Plugs	Valid	252	224	117	89
	Missing	14	47		
	Outliers	16	11		
	Total	282			
Smart Thermostat	Valid	236	199	135	116
	Missing	21	53		
	Outliers	7	12		
	Total	264			

	SMART METER (CONTROL)	SMART PLUGS	SMART THERMOSTAT
Mean age	55	54	54
% Male	74	82	74
Median income	<< between 1 and 2 times average >>		
Median education level	higher general secondary education	higher vocational education	intermediate vocational education
Property type	22.8 % detached; 37.5 % semidetached; 26.5% terraced house; 2.9% apartment	38.5% detached; 33.3% semidetached; 21.4 % terraced house; 0 % apartment	28.1 % detached; 37.8 % semidetached; 26.7% terraced house; 2.2% apartment
Mean number of residents	2.6	2.8	2.8
Mean gas usage in m^3	2026	2086	1961
Mean electricity usage in kWh	4512	4772	4443

TABLE 2.5 OVERVIEW OF DEMOGRAPHICS

significantly on motivation levels to conduct energy-saving behaviours (all $p > .05$). As expected based on prior research (Watson et al. 2002), the financial motivation appeared to be perceived as the most important motivation to save energy ($M = 4.26$), followed by the environmental and future-oriented motivation ($M = 4.08$), and finally, the enjoyment motivation ($M = 3.81$).

2.3.2. EFFECT OF EMS ON ENERGY CONSUMPTION

During the study, we obtained electricity and gas meter readings for an uninterrupted period of 25 weeks. First, the sum of these 25 weeks was extrapolated to yearly consumption (by energy consumption profiles from EDSN [2013]). To focus on demand reduction or increase and not on the total amount of energy used in the study, scores were normalized based on each household's meter readings of the year preceding the study (After/Before * 100).

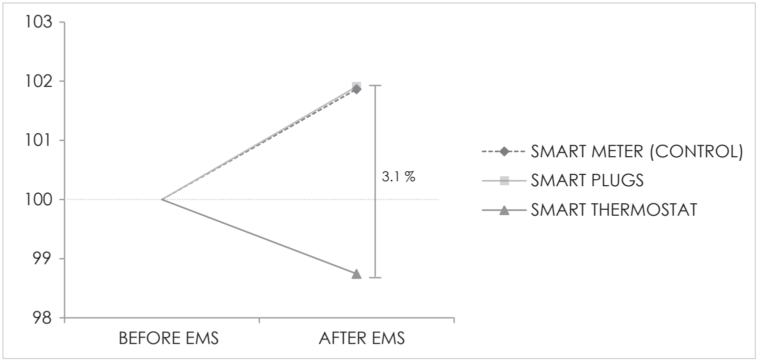
Because research has found that giving feedback reduces energy demand (e.g. Abrahamse et al. 2005), we have used one-way ANOVAs with planned contrasts for the analysis. The normalized electricity meter readings were used as dependent variables and the three groups (control, Smart Plugs and Smart Thermostat) as independent variables. The results revealed an overall effect of group on electricity savings (F (2, 740) = 3.00, p = .05). Furthermore, we conducted two planned comparisons: one to test whether the control group was different from the two groups that received an EMS (Smart Plugs and Smart Thermostat), and the other to check whether the Smart Plugs differed from the Smart Thermostat in electricity savings. Planned contrasts revealed that giving feedback through an EMS in general did not have a significant effect on electricity savings because the normalized electricity usage of the two test groups with an EMS together did not differ from that of the control group (t (740) = 2.69, p = *ns*). However, the Smart Thermostat did significantly reduce electricity usage by 3.1% compared with the Smart Plugs (t (740) = 22.36, p < .05). These results are illustrated in Figure 2.1.

Correspondingly, a one-way ANOVA with normalized gas meter readings as dependent variables showed that there is also an overall effect of group on gas usage (F (2, 636) = 8.09, p < .001). In addition, planned contrasts revealed that in general giving feedback through an EMS reduced gas usage significantly because the normalized gas usage of the two test groups together was 2.4% lower compared with the control group (t (636) = 22.29, p < .05). However, planned contrasts also revealed that this effect should actually be ascribed to the Smart Thermostat because using this EMS resulted in 4.2% reduction of gas usage compared with the Smart Plugs (t (636) = 23.38, p < .01). These results are illustrated in Figure 2.2. This figure shows an overall rise in gas consumption because these meter readings are not controlled for weather conditions.

2.3.3. EFFECT OF USE FREQUENCY

These results demonstrate that different EMSs have different effects on residential energy consumption. The question remains: what causes this

FIG.2.1 MEAN NORMALIZED ELECTRICITY USAGE



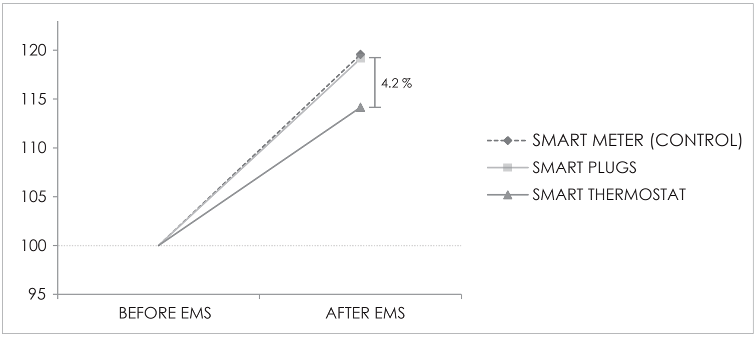


FIG.2.2 MEAN NORMALIZED GAS USAGE

difference? As introduced, Van Dam et al. (2010) conceptualized that use frequency of EMSs can influence energy savings. If people use an EMS more frequently, it is more likely to result in energy savings. Therefore, we have investigated use frequency as the underlying mechanism that can explain the different effects of the two EMSs on the obtained energy savings in this study.

These one-way ANOVAs were performed with one of the three self-reported use frequency scales as the dependent variable and the three test groups as the independent variables. The results revealed that the test groups differed in use frequency for the main respondent, and if applicable his/her partner/roommate, as well as his/her children ($F_{respondent}(2, 377) = 262.85$, $p < .001$; $F_{partner}(2, 345) = 209.83$, $p < .001$; $F_{children}(2, 207) = 47.63$, $p < .001$). The control group looked rarely at the Smart meter ($M_{respondent} = 2.83$; $M_{partner} = 1.67$; $M_{children} = 1.18$). The Smart Plugs were used slightly more than once a month by the respondents themselves ($M = 3.35$), but hardly by partners/inmates ($M = 1.74$) and children ($M = 1.36$). However, the Smart Thermostat was used daily by the respondents themselves ($M = 6.05$), but also weekly by partners/inmates ($M = 4.97$) and monthly by the children ($M = 3.32$). These findings provide tentative support for our proposition that use frequency may explain the obtained energy savings.

To further investigate the role of use frequency as the underlying mechanism for the effect of test group (Smart Plugs vs. Smart Thermostat) on electricity and gas savings, a mediation analysis was performed using the bootstrapping methodology proposed by Zhao et al. (2010) and Preacher and Hayes (2004). Only the use frequency of the respondent was taken into account because the reported use frequency of the respondent itself is most reliable. In this analysis, a dummy variable of the test group variable (Smart Plugs = 0 and Smart Thermostat = 1) was included as the predictor variable; respondent's use frequency of the EMS was designated as the mediator; energy savings (either normalized electricity or gas usage) as the dependent variable; and the three motivation scales ([a] Environmental and future-oriented, [b] Enjoyment and [c] Financial motivation) were included as covariates. To demonstrate support for use frequency as a mediator of the relationship between test group and energy savings, the 95% confidence interval associated with the point estimate of the indirect effect of test group on energy savings must not include zero (Preacher and Hayes 2004). This point estimate represents the product of the regression coefficients (a.k.a. the indirect effect) calculated when test group predicts use frequency and when use frequency predicts energy savings.

The analysis for electricity savings replicated the ANOVA results concerning the direct effects of test group on use frequency ($b = 2.75$, t = 15.95, $p < .001$) and electricity savings ($b = 23.57$, t = 21.83, $p < .07$, marginally significant due to the smaller sample). Again, it demonstrated that households with the Smart Thermostat used the EMS more often and consumed less electricity than households with the Smart Plugs. Furthermore, only the covariate financial motivation had a marginally significant effect on electricity use, suggesting that households saved more energy when they were financially motivated to do so ($b_{financial} = 23.76$, $t = 21.83$, $p < .07$). Most importantly, the results revealed that use frequency mediated the effect of test group on electricity savings as the 95% confidence interval, 28.40 to 2.07, for the point estimate of 23.60, did not include zero. No effect of use frequency on electricity savings was found ($b = 1.31$, $t = 21.62$, $p = ns$), but as indicated by Zhao et al. (2010), this is not a requirement to establish mediation.

For gas savings, the results also replicated the ANOVA results concerning the direct effects of test group on use frequency ($b = 2.78$, $t = 14.56$, $p < .001$) and gas savings ($b = 25.08$, $t = 22.39$, $p < .05$) demonstrating that households with the Smart Thermostat used the EMS more often and consumed less gas than households with the Smart Plugs. Furthermore, the mediator use frequency ($b = 21.71$, $t = 21.98$, $p < .05$) and the covariate financial motivation ($b = 24.38$, $t = 21.99$, $p < .05$) had significant effects on gas savings. Most importantly, use frequency mediates the effect of group on gas savings as the 95% confidence interval, 29.17 to 2.74, for the point estimate of 24.76, did not include zero.

These results imply that the type of EMS (Smart Plugs vs. Smart Thermostat) affects the energy use of households, and use frequency serves as a mediator for the effect of test group. See Figure 2.3 for the model that summarizes these results.

2.3.4. USE FREQUENCY OVER TIME

After seven months, a second questionnaire (T_2) was completed, to investigate whether the participants continued to use the feedback devices as frequently or whether they had slowly drifted into the background. Repeated-measures ANOVAs were performed with time as the within-subject factor and the two test groups (Smart Plugs and Smart Thermostat) as a between-subjects factor. There was a significant main effect of time on reported use frequency of respondents and their partners/inmates ($F_{respondent}(1, 195) = 8.67, p < .01$; $F_{partner}(1, 173) = 5.57, p < .05$). No significant main effect of time was found for children ($F_{children}(1, 85) = 1.62, p = ns$). Furthermore, the interaction effects between time and group on the reported use frequency of respondents and of their partners/inmates were not significant ($F_{respondent}(2, 195) = 1.40, p = ns$, $F_{partner}(2, 173) < 1$). This indicates that the use frequencies of both EMSs were reduced to a similar extent over time. Specifically, for the Smart Plugs, the use frequency of respondents was reduced to once a month ($M_{T1} = 3.35$ vs. $M_{T2} = 3.02$), whereas their partners/inmates hardly made use of it ($M_{T1} = 1.74$ vs. $M_{T2} = 1.63$). Although a reduction in use frequency over time was also found for the Smart Thermostat, the

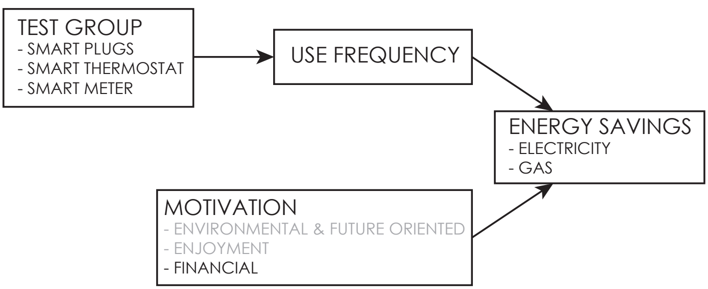


FIG.2.3 MODEL: FULL MEDIATION EFFECT OF USE FREQUENCY ON ENERGY USE

respondents still used the EMS practically daily (M_{T1} = 6.05 vs. M_{T2} = 5.90) and their partners/inmates almost every week (M_{T1} = 4.97 vs. M_{T2} = 4.72). This suggests that the Smart Thermostat had not drifted to the background and participants still actively used it to control their energy consumption after seven months.

2.3.5. PRODUCT EVALUATION

The questionnaire data were also used to explore whether the users of the Smart Thermostat and the Smart Plugs differed in their evaluation of the EMS. Independent sample t-tests showed significant differences for all evaluation measures (see Table 2.6). This suggests that in comparison with users of the Smart Plugs, users of the Smart Thermostat were more content with the EMS. Furthermore, they evaluated its ease of use, its appearance, the accessibility of information, and the gas and electricity usage information more positively.

2.4. DISCUSSION

Giving feedback about their energy consumption to households can reduce residential energy demand (Abrahamse et al. 2005; Darby 2006; Fischer 2008; Ehrhardt-Martinez et al. 2010). One of the factors that influences the effectiveness of feedback is the design of the EMS by which the feedback is given. Consequently, researchers have started to explore how the design of these systems can assist energy-saving behaviours. This research contributes to this literature by comparing two test groups provided with two different EMSs and a control group in a long-term field study. We demonstrate that just giving feedback by an EMS is insufficient for fostering energy-saving behaviours. Only one of the two EMSs resulted in energy savings that were in line with the savings found by the meta study of McKerracher and Torriti (2012). In contrast, users of the other EMS behaved correspondingly to the control group that lacked a dedicated feedback device, resulting in no acquired energy savings. The difference of the success of both EMSs relates to the reported use frequency. This is consistent with the proposition of Van Dam et al. (2010) who investigated this topic qualitatively. Only if people keep using an EMS frequently, it can provide them with feedback to influence their energy consumption on the long run, and thus use frequency serves as the underlying mechanism for the success of an EMS.

TABLE 2.6 MEAN VALUES OF PRODUCT EVALUATION

	SMART PLUGS M (SD)	SMART THERMOSTAT M (SD)	*t*	*p*
Overall satisfaction	2.97 (1.08)	3.69 (.86)	-5.81	<.05
Appearance	3.24 (1.01)	3.99 (.67)	-6.94	<.001
Accessibility of information	3.07 (1.14)	3.79 (.82)	-5.78	<.001
Gas usage information	2.81 (1.26)	3.94 (.72)	-8.60	<.001
Electricity usage information	3.36 (1.10)	4.00 (.69)	-5.58	<.001
Ease of use	3.30 (1.04)	4.08 (.63)	-7.33	<.001

Use frequency can be sustained by designing the EMS in such a way that its feedback is accessible and easy to use. The Smart Thermostat, the EMS that was perceived as most accessible and easy to use in this study, was used more often and did result in energy savings. An important, additional result was that the users of this EMS continued using the system frequently during the study. This suggests that using the EMS has become part of their daily habits and resulted in lasting energy savings.

In contrast, users of the Smart Plugs did not save energy. It is likely that this EMS is perceived as less easy to use by the abundance of options in displaying energy use. It does provide appliance-specific breakdowns, but this information may be difficult to understand for many users and, consequently, the ease of use of the Smart Plugs is probably lower. Although the Smart Thermostat does not have an appliance-specific breakdown, users may still have acquired direct feedback on the consumption of specific appliances by switching an appliance on while monitoring the difference. These results support the warnings of Wood and Newborough (2007) to keep the design simple and find a balance between the amount of options and ease of use. Our finding that an appliance-specific breakdown may be disadvantageous seems to contradict prior research (Synovate 2010; Fischer 2008; Bonino et al. 2011; Karjalainen 2011), in which feedback with an appliance-specific breakdown was proposed as the ideal way of giving feedback. Still, these results are mainly results from preference studies. It seems that people want these breakdowns, but at the same time, the breakdowns make the feedback too complex. Too much information is likely to confuse and distract the user, so choices have to be made (Wood and Newborough

2007). Otherwise, it is highly probable that users will stop using the system and do not save energy. Hence, in order to obtain good insight into the effects of specific design features, it must be tested among a group of real life users over a longer period.

Furthermore, the EMS Smart Plugs is not accessible enough, because users need to start up the computer before they can access the feedback. It is likely that these measures affect use frequency and, consequently, energy use. Accessibility of the feedback provided by an EMS can be assisted by its place and its medium. An EMS can be an application or a web portal that is accessible by another device (e.g. computer). However, an EMS can also be a dedicated display that is attached to the wall or offered as a wireless device. The advantage of an application or a web portal is that the costs remain low. Disadvantages are that users have to start up their computer to acquire feedback and that the application may be lost between all other applications. The advantage of a wireless, dedicated display is that you can walk around with it to switch appliances on and off, thereby learning about the energy use of different appliances. The disadvantage is that, over time, the display will easily end up in a drawer. In contrast, a dedicated display that is attached to the wall will remain in the corner of your eye like a reminder. In that sense, it is important to give special attention to the hardware as well. When users think the design is more attractive, it is more likely that the EMS gets a more central location in the house, which is important for habit formation (Hargreaves, Nye, and Burgess 2010). The accessibility of the Smart Thermostat was considered higher because this EMS is a central display and the user does not have to start up the computer. It gives feedback immediately when the user touches the display. We have seen in our study that these users remain using the system almost daily and save energy.

A more user-centred design approach (Wever et al. 2008) can help assessing the accessibility and ease of use for all household members in early stages of the development of EMSs and by that improving the effectiveness of EMSs. But this is possible only when designers take into account the relevant household dynamics (Strengers 2011; Hargreaves et al. 2010; Van Dam et al. 2012). Still, many EMSs are too complex in their feedback, do not make inventive use of clear visuals and are mostly used by male users. EMSs need to become accessible and easy to use for all household members to become effective.

2.4.1. FURTHER RESEARCH

Altough we have done our best to get a representative sample by randomly inviting participants, the response still caused the final sample to slightly differ from the total population. The groups of younger couples and single women in smaller residents was a minority in the sample. Hence, more research is needed in this specific group.

Our research was limited to two specific EMS designs that were different on more aspects than just one. These EMSs were deliberately selected because market-ready technology was needed to prevent many technical issues within the large sample. Future research could benefit from systematically designing different EMSs and to compare their effectiveness in the field to gain a more detailed understanding of the effect of certain design variations and interactions with different EMSs. It is especially interesting to focus on design aspects facilitating use frequency of all household members and which negotiations can and must be supported by an EMS (Van Dam et al. 2012). Design recommendations may result from these kinds of studies. However, smaller samples are most probably a result of this research set-up.

The hypothesis that we have tested in this study is that easy to use and accessible systems are important for saving energy on the long run. It increases the chances that people will remain using the Energy Management Systems over time. However, the obtained energy savings with the best of the two EMSs were less than 5%. This is in line with the savings found by the meta study of McKerracher and Torriti (2012) who found that 3% to 5% is realistic. Though 5% energy savings by all Dutch households equals a power plant, it is not enough for the maintenance of our welfare and environment. Therefore, we will investigate how households cannot only reduce demand, but also how they can change patterns of electricity demand to match sustainable electricity production more cleverly. The field studies presented in the following chapters are all investigating a shift in electricity demand to moments when supply is abundant. We start with a qualitative study in Chapter 3.

03

EXPLORING DEMAND SHIFTING

An exploration of the factors that affect households' tendency to shift their electricity demand

Besides reducing energy demand, households have to shift electricity demand to moments when electricity is locally produced to use the sustainable electricity most efficiently. The qualitative field study presented in this chapter, examined the factors that influence the likelihood that people will shift their electricity demand to match local sustainable supply of electricity. Based on the results, several recommendations are given for designing EMSs combined with smart appliances.

This chapter is an adapted version of Charlotte B.A. Kobus, Ruth Mugge and Jan P.L. Schoormans. (2013) Washing when the sun is shining! How users interact with a household energy management system. Ergonomics 56 (3) p. 451-462

Currently, the energy market is changing because electricity produced by fossil fuels is becoming more expensive, and because new energy technologies, like solar panels, are becoming less expensive. As a result of these changes, more and more households are adopting solar panels and other clean energy technologies. One of the difficulties of this sustainable, local energy production is that it is often not demand driven. Large European transmission grid expansions are planned to ensure that sustainable electricity is transported from areas where it is produced to areas where there is demand. However, sustainable, locally produced electricity is used most efficiently if it is consumed directly when and where it is produced. This research focuses on households in an effort to change household electricity consumption to a more supply driven character. Electricity demand should shift to moments when electricity is locally produced. This will reduce transmission losses and can prevent some of the biggest grid and reserve capacity investments.

Prior studies on changing household energy consumption have focused on lowering demand (e.g. Van Houwelingen and Van Raaij 1989, McCalley and Midden 2002, Abrahamse et al. 2005, 2007, Fischer 2008, Abrahamse and Steg 2009, Faruqui et al. 2010b). It is concluded that frequent, immediate feedback and goal setting helps people to reduce electricity consumption when applied well as also shown in Chapter 2. Reducing consumption is the first step towards a sustainable energy system. However, a demand reduction of electricity consumption only, will be insufficient. Shifting electricity demand to match local, sustainable supply is considered the next step. By giving feedback and feed forward, the user can schedule the use of appliances to times at which local electricity is abundant. Moreover, as a result of new technology some appliances could also operate semi-autonomous. In that case, the so called smart appliance can help users to select the most desirable time for consuming electricity, for example, by taking into account weather forecasts. In the study in this chapter, we focus on shifting electricity consumption using an energy management system (EMS) in combination with a smart washing machine.

Derijcke and Uitzinger (2006) demonstrated that people are able to shift 15% of their washing machine, dryer and dishwasher usage, to match their local solar supply. However, their research provided only preliminary results among a small and highly motivated sample (four households) and did not assist the user with technology, such as an EMS or smart appliances. Further research is needed to provide insights into the factors that influence users' likelihood to shift their electricity

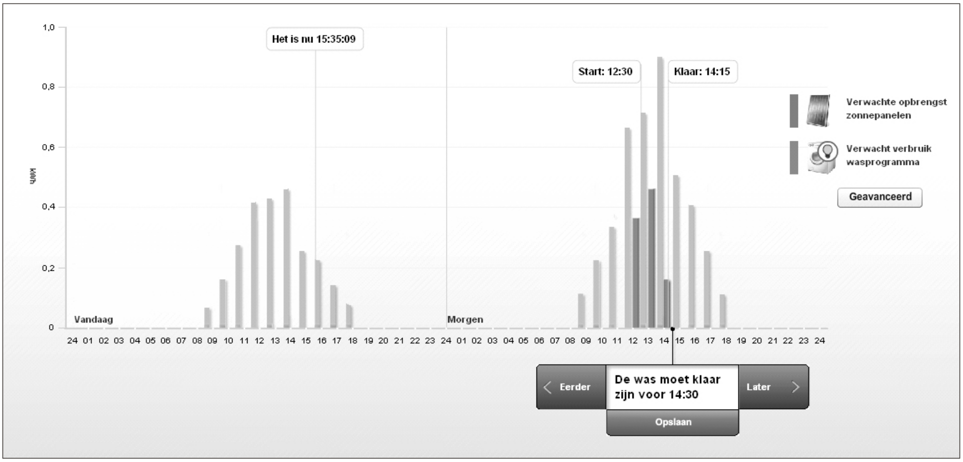


FIG.3.1 THIS EXAMPLE SHOWS THE EXPECTED SOLAR PRODUCTION (LIGHT BARS) FOR TWO DAYS. THE WASHING MACHINE (DARK BARS) STARTS TOMORROW AND IS READY AT 14:15H, WHICH IS BEFORE 14:30H AS IS PREFERRED.

consumption to moments in time where sustainable solar electricity is abundant. State of the art technologies, like EMSs and smart appliances, may stimulate households to shift electricity demand in time. However, we now lack an understanding of how people respond to and interact with these new technologies.

This research contributes to the literature by exploring how the implementation of an EMS and a smart washing machine (consuming app. 150 kWh/year on average) affects electricity consumption behaviour. In addition, participants of this study received 10 m^2 solar panels (producing app. 1700 kWh/year) and a digital electricity consumption meter. The EMS collects real-time consumption data from the digital electricity consumption meter and production data from the solar panels. These data are given real-time and in an historical overview in a program installed on a personal computer to the user. Feed-forward is given in the form of precise hourly solar radiation forecasts to an estimation of the upcoming solar electricity production over two days (see Figure 3.1). These forecasts can be used to schedule the usage of the smart washing machine, but also the use of other appliances to moments in time, where solar electricity is abundantly available. The smart washing machine can operate semi-autonomous, which implies that it can operate in an independent and goal-directed way (Rijsdijk and Hultink 2009). This washing machine functions like a normal washing machine but has additional communication capabilities with the EMS. Users can set when the washing process should be completed at the latest (e.g. end of afternoon or the day after) on the EMS, which

FIG.3.2 THE DISPLAY OF THE WASHING MACHINE TELLS THE USER THAT IT IS 'WAITING FOR THE SUN' AND THAT THEY NEED TO PRESS A BUTTON TO START THE WASHING PROCESS IMMEDIATELY

TABLE 3.1 FUNCTIONAL CHARACTERISTICS OF THE EMS

	SMART WASH
Hard and software	Program installed on a dedicated PC with 9 smart plugs, a smart washing machine, solar panels, a smart meter and a gross production meter.
Real-time feedback	Electricity consumption and production in Watts, Euro or CO_2 (refresh rate on demand) and gas meter reading (refresh rate every hour)
Historical comparissons	Electricity consumption and production in kWh and gas in m^3. Both are presented in Euro and CO_2 emissions and visually in a bar chart.
Normative comparissons	X
Feeling of achievement	Counting green wash cycles (cycles during hours with solar PV) called 'green washes'
Appliance specific breakdown	Real time and historical. Grouping of appliances for example by room is possible. The home screen of the user interface shows a house with different rooms and the amount of electricity production per room.
Control other appliances	Users can make a time-table when to shut connected devices on and off.
Feed forward	Solar radiation forecast in a bar chart with a simple weather forecast of two days.

then calculates the best time to start the washing machine based on the solar radiation forecasts and sends a signal to the washing machine when to start. A digital display on the washing machine shows its status (e.g. 'waiting for the sun') (see Figure 3.2). Table 3.1 gives an overview of the functional characteristics of the EMS used in this study.

The EMS and the smart washing machine can only be successful if users are willing and able to use them. So far, we lack understanding of how users interact with this kind of EMS and smart washing machines and which benefits and/or barriers determine the success for shifting households' electricity consumption. This chapter addresses these research questions by conducting interviews among users of these technologies.

3.1. RESEARCH OBJECTIVE

This thesis investigates how technologies can encourage households to form new habits concerning a shift in their electricity consumption. Because habits are assumed to be automatically cued by a stable context (Verplanken and Aarts 1999), the study in this chapter brings about important changes to the stable context of washing by the presence of solar panels and by persuading users to operate their smart washing machine using the EMS. By using the EMS, people acquire information about their electricity consumption and production. The autonomy of the EMS and the smart washing machine enables users to schedule the washing process to the time that sustainable supply is available and promotes the creation of a more desirable habit concerning electricity consumption. It is assumed that these changes to the context of washing induce people to rethink their actions, thereby disrupting their habits, while simultaneously promoting the repetition of the new, desired action: washing when the sun is shining. An expected side effect will be a demand reduction, because the EMS gives frequent, immediate feedback about electricity consumption. As explained, it is concluded that feedback helps people to reduce electricity consumption as well (see Chapter 2).

The primary aim of our qualitative research was to uncover the factors that influence the likelihood that users will shift their electricity consumption to match sustainable supply. We explored how the households in our study used the provided technologies, whether it helped them to become aware of their consumption patterns and to what extent new electricity consumption behaviour is likely to form into a habit. Furthermore, we investigated the degree and nature of motivation of users to shift electricity demand. We also identified specific system variables that encourage or hinder users to perform the desired electricity consumption behaviour. Finally, we took into account that the EMS is household-based and that in households all members consume electricity.

3.2. METHOD

The goal of this study was to gain rich insights regarding participants' experiences and interaction with the EMS. This research goal was fulfilled using a qualitative methodological approach. The EMS used in this study was installed at 24 households (one single person, six couples and 17 families). All households participated on a voluntary basis. Twenty-one of these households (response rate = 88%), who had been using the system for three to four months during spring and summertime, were interviewed for this research. This was considered an optimal time for the interviews, because participants had the time to form new habits, but were still able to remember the way they used to perform before the EMS.

The semi-structured interviews were conducted with users of the EMS at their homes. During the interviews, users were asked to describe their experiences and interaction with the system. First, users were asked whether and how they matched their electricity consumption to the availability of local solar electricity. Did using the system result in the formation of a new washing habit? Second, the interviewer asked users to explain how they had operated the system since it was installed. Specifically, users explained why and how they made use of the feedback and feed-forward that was provided. Also, they explained why they did (not) use the system's feature to operate the washing machine autonomously. Third, the interviewer asked why and to what extent users felt motivated to perform the new behaviour. What are the perceived benefits of performing the new electricity consumption behaviour by using the EMS? Fourth, users were asked to evaluate the system by describing the system variables that positively influenced the new behaviour and the variables that disturbed a behaviour change. Finally, various factors related to the household were discussed that influenced behaviour change. Interviews took approximately 60 min to complete and were performed in June/July 2011. The sessions were audio-taped and fully transcribed.

To analyse the results, the researchers read three transcripts and performed initial coding based on 'middle-order' categories. These are called fairly common sense categories by Dey (1993), around which the data can be organised, without implying commitment to any particular theoretical approach. A middle-order approach was attractive, because we applied semi-structured interviewing. The researchers identified broad themes after the initial coding and discussed emergent findings with each other and compared this to existing literature to categorise codes. We assigned all data from the other transcripts to codes and simultaneously revised the system of categories with this data. The final categories (with their own sub-categories) included: behaviour change and EMS usage, motivation, system variables and household-based factors.

3.3. RESULTS

For qualitative research, it is generally suggested to decide on the sample size depending on the amount of new insights (new codes) that are gained with each additional interview (Guest et al. 2006). Though, complete saturation is impossible, when repeatedly only one or two new insights are obtained in the interviews, it is not valuable enough to further increase the sample size. In this respect, we identified during analysis of the data that after the 11th interview, we gained few new insights. Our last interviews mostly affirmed insights from previous interviews and assured us that we had gained a comprehensive understanding of participants' experience and interaction with the EMS.

In presenting the results, we discuss the usage of the EMS and whether a behaviour change was experienced first. Thereafter, we illustrate the factors that influence desired behaviour.

3.3.1. BEHAVIOUR CHANGE AND USAGE OF THE EMS

Demand shifting | During the interviews, the majority of participants reported that they shifted their electricity consumption of the washing machine to the moments of sustainable supply produced by the solar panels*. The best possible result was shown by over half of the

* Later on, we also assessed the demand shift quantitatively by investigating the electricity consumption data of the washing machine over a period of two years (electricity consumption over time per household) (Klaassen et al. 2013). In the two years, the washing machine is generally turned on during hours in which electricity is locally available. Compared to the average EU household (IEEA 2008), the evening peak load of the washing machine of participants was shifted to midday.

participating households. These households did not only take the solar radiation forecasts into account to schedule their smart washing machine usage, but also to plan usage of other appliances (e.g. dryer or dishwasher). Other participating households demonstrated desired behaviour, but only when using the smart washing machine. Only a few participants did not change their behaviour at all.

Although users experienced the EMS for only a few months, they already described the creation of new associations between actions (using the washing machine) and the changed features of the context in which they are performed (using the EMS while scheduling the washing machine usage) that are necessary for the disruption of an existing and the formation of a new habit (Verplanken and Wood 2006).

> “When you have done it a few times, it is like you are washing normally... It is just an operation that you can do automatically at a certain moment.”

Although the majority of participating households shifted their electricity consumption to match their local supply, the EMS was not necessarily consulted for radiation forecasts, nor was the system's autonomy always used. Looking outside to see whether the sun is shining and knowing the most optimal hours of radiation (i.e. normally around noon) was considered a good solution to circumvent (parts of) the EMS. Some users took notice of the radiation forecasts, but did not use the system's autonomy.

Demand reduction | The change in context initiated by the EMS and the feedback it provided were explicitly recognised as factors that made the participants reconsider their prior electricity consumption. Besides the EMS, participants explained that the presence of the solar panels was also effective for becoming more conscious about electricity consumption and its effects on the environment. This did not only result in demand shifting, but also in demand reduction. This finding corresponds to the literature, where the important role of feedback on electricity consumption, demand reductions and becoming more aware of the energy consumption behaviour is explained (see Chapter 2).

> “My husband turned on the lights in the bathroom, while I was watching our energy usage. I saw it rise with 100W and I screamed upstairs to him to ask what he was doing. I think 100W is too much. I did not know that before...”

3.3.2. MOTIVATION

If people are motivated, they are more likely to demonstrate the desired sustainable behaviour over time, thereby enhancing the chance that this behaviour will form into a habit. Based on the interviews, nature and level of motivation were considered important.

Nature of motivation | The first reason for participants to use solar electricity production was the opportunity for a behavioural alternative that would help to solve *environmental* issues. Many participants expected fossil energy supply to become scarce and perceived the pollution of our energy usage. Therefore, new ways of using and producing energy were necessary. Specifically, participants reported that they would like to leave a good place to live for their children and generations following them. By changing electricity consumption and using their solar electricity directly, they felt they took their responsibility.

> “I just want to leave a good place to live, when I am not around anymore. Life goes on. And it is important to teach the children, that they use it sustainable”

The second motive was the *financial* incentive. Shifting electricity consumption to match solar production was seen as an opportunity to save electricity costs. Furthermore, some users were insecure about the financial compensation for the electricity returned to the electricity network, which made them especially eager to use the local electricity themselves.

Third, participants reported that their motivation to use the EMS to change their electricity consumption was their *interest in advanced and new technologies*. These participants can be considered early adopters of new technologies (Rogers 1995). In comparison to other users, they were indeed more tolerant towards errors and difficulties in the system and were willing to spend more time learning how to use the system correctly.

> “I am always interested in new technologies. It is just wonderful! And it never ends... trying new stuff. When it does not work? Nothing happens”

A few participants had the *dream to become self-reliant*. They do not rely on the energy system actors’ intention to maintain energy affordable, nor the intention of these actors to pursue a sustainable energy system. Using one’s own electricity production fitted perfectly in becoming independent. Lastly, the *social norm* was named as a reason for using solar electricity directly. It was just something you have to do as a citizen with social responsibility.

Level of motivation | To evaluate the level of motivation, two factors were taken into account: participants' evaluation of the invested time and effort to learn the new technology and their own evaluation of the level of motivation. Based on their responses, it was evident that participants greatly differed in their level of motivation.More importantly, the level of motivation affected users' experiences and interaction with the EMS.

Because the EMS is a new technology, the majority of users needed some time to learn to operate the system. If users are motivated, they consider this learning process normal and the perceived shortcomings of the system and potential household-based barriers do not obstruct reaching the goal of consuming the local electricity. However, if users are less motivated, one bad experience with the system or a perceived household-based barrier is enough to form a justification for not demonstrating the desired sustainable behaviour. For these users, it is essential that the system has an user-friendly interface that does not offer them an excuse for stopping its usage.

> I do not take the time for it and when I would, I most probably would find it more fun to do ”

> “I should take more time to learn it, but I do not

3.3.3. SYSTEM VARIABLES SUPPORTING AND NOT SUPPORTING DESIRED BEHAVIOUR

Participating households greatly differed in their evaluation of the EMS. While some users successfully interacted with the system, others experienced difficulties. Several system variables were reported that influenced behaviour change. First, participants mentioned the importance of *feedback*. The EMS used in this study, provides a real-time and historical overview of electricity production and consumption, which users could use to control washing machine usage. Due to this feedback, some participants felt more in control over their own electricity consumption, which enabled them to lower their consumption. Participants also used the feedback as proof for the functioning of the solar panels and to communicate this to their peers.

Besides feedback, *feed-forward* on the expected solar radiation was considered a significant system variable for shifting users' electricity consumption. By offering feed-forward on solar radiation, users are directly offered a behavioural alternative as a solution to the perceived threats caused by former behaviour (De Vries et al. 2002).

Although most users reported that the feedback and feed-forward enabled them to shift their electricity consumption, some users criticised the *complexity* of the EMS. When users considered the system as difficult to use, this disturbed their interaction, resulting in frustration and in some cases, the discontinuation of using (parts of) the system. Smart systems are easily perceived as complex because everything happens in the 'black box' (Bauer and Mead 1995, Rijsdijk and Hultink 2009, Rogers 1995). Also, it was often considered cumbersome to start up a computer to use the washing machine. It is desired to extend the interface on the washing machine, so it is unnecessary to start the EMS before washing sustainable.

The *trustworthiness* of the system was perceived as another barrier. When users do not trust the system, they may either reject its advice or not make use of its full functionalities (Muir and Moray 1996). Sometimes, the information displayed was not believed, and users rejected all information of the EMS. The technical interferences resulting from the newness of the technologies caused some users to distrust the system and thus to stop using (parts of) it. Although it provided the most optimal use of local electricity, the autonomy of the smart washing machine was not always used. Users were able to overrule the system because a completely self-regulating system is likely to frustrate them in particular situations (Rijsdijk and Hultink 2003). Especially, households with children reported a desire to maintain in control. Washing is perceived more urgent when having kids. Nevertheless, the system's ability to work autonomous was appreciated, especially by users who are not at home during the day.

> We program the washing machine. It is very easy, because when we come home from work, the washing machine is done.

> One can just use its horse sense. When it is noon and the sun is shining, you can use the washing machine

Another system variable that influenced how users interacted with the EMS was the scoring of 'green washes'. Users reported that this *feeling of achievement* for desired behaviour made the system fun to use. According to Lockton et al. (2010), people are more likely to continue desired behaviour when they feel acknowledged for their efforts. Indeed, users wanted to obtain a high score on 'green washes'. Because other appliances (e.g. dishwasher, dryer) were not counted as 'green use', participants frequently reported the desire to link these to the EMS as well.

A side effect of this scoring was that some participants felt their washing behaviour was *observed*, and therefore, they wanted to do well. These users expected that the observers of their behaviour would name those who performed best/poorest to stimulate future behaviour. If users feel observed and believe that the observer can reward/punish them, they are likely to change their behaviour according to the observer's expectations (Fogg 2003).

Observation also had a negative effect because some users perceived it as an invasion of their privacy. This is a well-known issue for the digital electricity consumption meter (Darby 2010). These uncertainties about privacy can be explained by the general public's increased awareness of their right to, and the value of their privacy (Kobsa 2002).

An unexpected effect was users' own *goal setting* to reach 'zero'. Some users balanced production and consumption precisely by turning on other appliances for which usage was already intended. This finding suggests that for participants the household electricity balance is especially important and further stimulates them to adapt their electricity consumption. We expect that participants' focus on their own household is caused by a desire of being in control and self-reliant. Furthermore, Locke and Latham (2002) argued that goal setting is important for performance. To support goal setting, the EMS should provide the appropriate feedback to reach the desired goal.

> Last weekend, we have reached zero. I thought it was amazing!
>
> It makes me feel good, because it is like consuming your own grown strawberries

A variable that users were missing in this EMS was the option to compare with other smart washers or the so called *social proof* (Cialdini 1993). The Principle of Social Proof implies that users view behaviour as correct in a given situation to the degree that one sees others performing it. Like scores, users indicated they wanted some kind of acknowledgement for their efforts.

> I just want to know how I perform compared to other participants...

3.3.4. HOUSEHOLD-BASED FACTORS

The first household-based factor that influenced how users interacted with the EMS was *available time at home*. When users are not at home during the day, flexibility in using the washing machine decreases. Then, they are more likely to use an autonomous system to hand over a part of the flexibility. Nevertheless, this limited these users' possibilities to steer ad hoc usage to times of solar electricity production.

The second factor is *self-efficacy*. Self-efficacy is defined as an individual assessment of his/her ability to perform a behaviour (Bandura 1977). When using a new technology, it is important that the user beliefs he/she can operate it. Corresponding to Rijsdijk et al. (2007), our data indicated that people with high self-efficacy regarding the use of information technology are more likely to have positive attitudes towards the smart EMS than low self-efficacy people. The technology enthusiasts judged the EMS as simple to use and planned the washing machine during sun hours, using the system. Other participants were not used to working with computers and called themselves a-technical. The majority of these participants with low self-efficacy had a negative attitude towards the complexity of the system. Nevertheless, some of the participants with low self-efficacy did use the system and evaluated it positively.

Another factor was the *number of residents* in the household. Running the washing machine is considered more urgent when having kids and the ability to overrule the system becomes more important for these households.

An interesting finding from the interviews was that most households had roles for using the system. The EMS was considered a man's toy, while the woman of the house operates the washing machine and has no interest in using the EMS besides its smart wash function. This implies that smart household appliances must appeal to different target groups in one household.

> I am operating the washing machine. The rest is not that interesting.
> (husband's reply) I do not think the washing machine is very interesting.

3.4. DISCUSSION

An EMS may help people to shift their electricity demand to moments in time, where sustainable electricity is available. The study presented in this chapter investigated users' interaction with the provided technologies: an EMS and a smart washing machine. This research offers insights in the factors that influence the likelihood that users of an EMS will shift their electricity and will persist in this behaviour. Specifically, we summarise the likelihood for behaviour change by a combination of the user's motivation, contextual factors and the design of the technology. Designers should consider the joint effect of these factors when designing future technologies. Especially when users are not highly motivated, an inappropriate system design can be a significant factor to stop using the technologies and to return to their prior electricity consumption. Because people perceive electricity as a convenience good, it can be expected that most users will only be weakly motivated to comply with the sustainable behaviour. Then, users are unlikely to overcome even minor obstacles that they experience when using the technologies. Based on our results, several recommendations are provided, which can be used to develop successful future EMSs and smart appliances. The recommendations in this section are not only applicable for a demand shift. Often, they apply for demand reductions as well.

3.4.1. PRACTICAL IMPLICATIONS

EMS | The design recommendations for the EMS are largely in line with Chapter 2. For a shift in demand, it is of course important that the EMS interface has an intuitive design that enables users to directly use the system without having a good deal of prior knowledge. Most people are not willing to invest time in learning how to use an EMS because electricity consumption has too little importance to them. Moreover, operating an EMS should take users only little additional time. For some users, this would necessitate a simple interface with limited information, others (e.g. with high self-efficacy) still desire comprehensive insights in their electricity production and consumption. Consequently, it is recommended that an EMS has several layers in its information and a distinction between 'easy start' and 'advanced' menus.

Second, the EMS should provide users with clear feedback and feed-forward that users can comprehend rapidly. Feedback is beneficial to change households' energy consumption because it provides users with information about the results of their actions (for a review, see Abrahamse et al. 2005). Only if users understand which actions are detrimental, they can change this behaviour. While designing this specific feedback for future systems, designers should consider the various motives that people have for using the system. Because people with an environmental motive are probably more positively reinforced by feedback focused on the environmental consequences of their actions, feedback concerning the financial consequences may be more valuable for people with a financial motive.

Third, designers should search for ways to engage the user while interacting with the EMS, so that he or she will consider shifting electricity demand fun to do. One way to achieve this is through a feeling of achievement. If users receive a reward emotionally (e.g. green points) or physically (financial benefit) for desired behaviour, they are more likely to continue this behaviour (Lockton et al. 2010). By receiving a positive confirmation, people feel acknowledged for their efforts, which will result in the experience of positive emotions. Subsequently, these positive emotions will encourage users to perform the electricity shifting behaviour again (Baumeister et al. 2007). If users continue to perform the new behaviour over a period of time, a sustainable habit can be formed (Verplanken and Wood 2006).

Smart appliances | In our study, users had to use the EMS to operate the washing machine. Users had to perform additional actions if they wanted to use the smart planning function, possibly even in different parts of the house, because the washing machine and the EMS were not always in the same part of the house. It would be easier if the user could operate the smart washing machine (or other smart appliance) without having to use the EMS, which is a design challenge, because the possibilities of user interfaces of washing machines are rather limited and making them more advanced, would also make them more expensive.

Finally, an overall conclusion for both EMS and smart appliance use is that users need readily available user support, also in the setting of a study. It is likely that the novel technology will produce various technical or usage problems during implementation and usage. If these problems are not solved rapidly and accurately, users will experience negative emotions with the technologies and stop using these.

3.4.2. RESEARCH RECOMMENDATIONS

The study presented in this chapter has some limitations why a follow up, presented in the next chapters, was needed. First, all participants were employees of Enexis (Dutch distribution grid operator) who volunteered to participate in the research. It is thus likely that at least one member of the participating households was motivated to change electricity consumption. This may not necessarily apply to other household members who are making use of the system. Because the interviews were also conducted with these users, variations in motivation level were accounted for in our research. Nevertheless, it is beneficial to confirm the findings concerning the shift in electricity consumption by using a larger and more representative sample.

Furthermore, the study did not entail a financial incentive. However, financially encouraging the use of electricity at off-peak moments has shown to be efficient in the past (Faruqui et al. 2009). Further research is needed to investigate the combination of these financial incentives in combination with the investigated technologies: an EMS and a smart appliance.

The main result of this qualitative research is that we gained understanding on how users interact with new technologies (an EMS, a smart washing machine and solar PV) in their everyday lives. Furthermore, we gained promising results with respect to the potential of using technology for changing habits of doing the laundry. We also discovered what motivates or inhibits residents to perform a shift in electricity demand. The results of this study and the study in Chapter 2 show the importance of good design in accomplishing the difficult task of changing habits. Both studies provided us with many useful insights to develop the follow up study on shifting demand. The follow up field study on shifting demand provides us with the opportunity to investigate long term effects in a more representative sample. The design of this large scale and longitudinal field study is described in the next chapter of this thesis.

04

DESIGNING A SMART GRID

In Zwolle and Breda, the Netherlands

Important insights from the previous chapters are used to develop Your Energy Moment (Jouw Energie Moment) in the Dutch cities Zwolle and Breda. Your Energy Moment is a large scale, longitudinal field study with households on shifting electricity demand in time. This chapter is dedicated to the design of Your Energy Moment, because designing a study of this magnitude and length with actual users needs a thorough and user-centred design approach. We have made every effort to take care that we would recruit many participants in the same district and that they would remain participating in the study, to collect as much data as possible. In doing so, we needed to make participation attractive and needed to keep participants positive during the course of the study. The results in this chapter show that our efforts paid off.

This chapter is based on: Charlotte B.A. Kobus, Bas de Jonge, Joris D. Knigge and Han J.G. Slootweg (2011) User centric design of a smart grid; a social and economical approach. Proceedings of the 21st International Conference on Electricity Distribution. Frankfurt, 6-9

Charlotte B.A. Kobus, Jaap Kohlmann, Joris D. Knigge, Elke A.M. Klaassen and Sarah Boots (2013) Sharing lessons learned on developing and operating smart grid studies with households. Innovative Smart Grid Technologies Europe (ISGT EUROPE). 4th IEEE/PES Copenhagen, 1-5

Charlotte B.A. Kobus and Elke A.M. Klaassen (2014) Electricity on sale now! Behave conference. Oxford.

In 2010, I applied for a graduation project at Enexis B.V. Back then, only the name and the goals of the study on smart grids existed. The study was called 'smart grid pilots with the consumer' and the goals were to give an example of what a smart grid could look like and to investigate the possibilities to balance demand and supply locally in a residential district with households that produce solar energy. My colleague at Enexis was still looking for partners to cooperate with. He believed that it is important to have different stakeholders involved in setting up the study, because its value increases if objectives are combined. Commercial project developers, housing corporations and municipalities were contacted if they were willing to cooperate in the field study. The idea was to operate the study in a newly built area, because it would bring efficiency gains in installing the required technology. For the corporation, it would mean that they had to adapt their building plans for the necessary technology and had to facilitate the contact with the potential participants. Energy suppliers were asked to bring in their expertise on customer relation management and billing.

Without being able to tell the potential partners what a smart grid looks like exactly, two consortia were founded to realise field study within newly developed districts: Meulenspie and Easy Street in Breda and De Muziekwijk in Zwolle. Soon, the field study name changed to Your Energy Moment (YEM). The consortium in Zwolle is a partnership between Enexis B.V., Eneco (before DONG Energy also an energy supplier), SWZ (a housing corporation), Flexicontrol (developer of in-home devices), CGI (developer of the Central Energy Management System) and Eindhoven University of Technology. The consortium of Zwolle also applied for a subsidy, that was granted, which makes the study in Zwolle part of the Innovation Program Intelligent Networks by RvO (Rijksdienst voor Ondernemend Nederland). The consortium in Breda is a partnership between Enexis B.V. and Greenchoice (energy supplier). In the consortium of Breda, the suppliers of technology were not direct partners. These suppliers were CGI for the Central Energy Management System and Technolution and I2Tech for the EMS. Both in Zwolle and Breda, Indesit, an appliance manufacturer, was the supplier of the smart washing machine and MeteoConsult the supplier of the weather data.

The houses were built with special attention to energy efficiency. All households in these newly built city blocks produce their own solar electricity and lack a connection to the gas grid. The households of

Meulenspie in Breda use electrical heat-pumps for heating their homes. The apartments of Easy Street in Breda and all households in Zwolle are connected to a heat distribution grid. These characteristics made them especially interesting for a smart grid field study. Balancing demand and supply efficiently is a bigger challenge in these districts because all households produced their own electricity and, especially in Meulenspie, the electricity needs are high. The consortia cooperated to build the smart energy technologies of YEM. Zwolle launched in December 2012 and Breda in March 2013. The two consortia included different partners, which resulted in some design differences which will be addressed in this chapter.

My responsibility in the development team was to take care that the products and services developed would be understood and appreciated by users. The role I had in setting up the field study was unique in the field of smart grid development. Often, designers are not involved, or have just little influence in such field studies. Engineers still dominate the development of smart grids (Verbong et al. 2012) and the designs resulting from these efforts are often system-centred, starting with the technical possibilities instead of user needs. A system centred approach can often count on limited user acceptance and often results in confusion and frustration during use. Because people are generally not very motivated to change patterns of energy demand, they are unlikely to overcome even minor obstacles that they experience when using the smart energy technologies (see previous chapters). If smart grid designs are meant to be used by households over a longer period of time, engineers and designers need to cooperate in a user-centered design (UCD) approach to develop systems iteratively. The needs of users need to be well represented in the final designs that belong to a smart grid study to avoid the drop-out of participants. It is a waste of effort and money when newly developed expensive technologies remain unused by a large sample because of usability issues. The smart energy technology will keep on measuring data, but the participants will not remain filling in the questionnaires and stop using the smart energy technology, by which the chance of investigating a behavioural change is wasted. This chapter is dedicated to sharing learnings and to emphasise the importance of a UCD approach in designing smart grids for households.

4.1. USER-CENTERED DESIGN FOR SMART GRIDS

In short, UCD focusses on creating useful and usable designs by understanding user needs. The method entails actively involving users in the design phase and taking care that the designs fit user needs by iteration between design and evaluation.

The first step I took in UCD for smart grids, is that I graduated on upfront input of user needs with respect to smart energy technologies. It is often stated that it is difficult to involve customers in early stages, because customers often do not know what they desire (Ulwick 2002). However, by using metaphors (Coulter 1994) and generative techniques (Sleeswijk-Visser et al. 2005), values, meanings and use visions can be acquired. The studies of Chapter 2 and 3, did not yet benefit from the insights of my graduation project, because the smart energy technology used in these studies was already developed. However, the user insights from my graduation project were combined with (literature) insights from Chapter 2 and 3 into a design brief that is presented in the next paragraph.

Besides the insights from previous research on changing energy demand in households, the Design with Intent (DwI) tool-kit (Lockton 2010), has been of great use in developing the designs belonging to Your Energy Moment. The method is aimed particularly to guide designers in creating products and services that facilitate socially and environmentally beneficial behaviour. The method aims at inspiring design solutions by suggesting influential techniques through workshop cards with a question, and an example of the technique applied. Especially in conveying behavioural theory to other team members, the DwI workshop cards have been of value to us.

As a team, we also used the UCD methods of customer journeys (Tax et al. 2013) and personas (Marshall et al. 2015) to design the user support during the study and to fine-tune the marketing strategy. With a customer journey, the possible interactions with the products and services of YEM that contribute to the user experience were explored in time from the perspective of a potential YEM participant, also called persona. The personas were based on data derived from previously held interviews. The goal of the customer journey was to figure out how to keep the participant happy during the course of the study. In these sessions, the consortia members, but also the suppliers and the installers were involved.

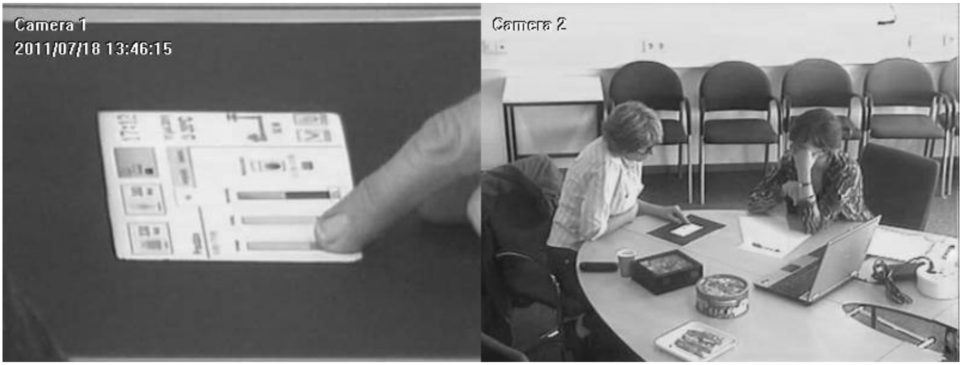


FIG.4.1 STILL FROM THE USABILITY TESTING RECORDINGS (IN THE PRODUCT EVALUATION LAB OF THE FACULTY)

For YEM participants, the EMS was expected to be the most unfamiliar and the most complex technology. Therefore, after some iterations of designing and evaluating amongst partners and acquaintances, we tested EMS paper prototypes with potential users. Usability testing during the development phase has been useful because it was hard to predict if users would understand and appreciate the design of the EMS. The main research question during these tests is: are the user tasks simple and efficient to carry out? If the user interface elements were interpreted differently than intended or when the design was not appreciated, the design had to be adapted. For both the user interface of Zwolle and Breda, 10 participants were asked to cooperate. The sessions of an hour were recorded with cameras for analysis (see Figure 4.1). The insights from this evaluation were translated into several design changes. Making design changes was still easy in this stage.

When the EMS was almost ready for launch, use cases (descriptions of all possible user tasks) were created to check whether the system was working properly. A few remaining usability issues that were found in this stage were fixed.

In Figure 4.2 on the next page, we illustrate the iterative approach of designing and evaluating by showing the several steps in the evolution of the EMS in Zwolle as an example. The design became plainer, simpler and more visual due to an iterative approach by gathering user insights during the development. The research presented in this chapter, and the following chapters, is the evaluation of the final design. The lessons learned can be used for further development of smart grid designs.

FIG.4.2 SEVERAL STAGES IN THE EVOLUTION OF THE EMS INTERFACE DESIGN OF ZWOLLE. FROM TOP TO THE BOTTOM: THE FIRST VERSION TO THE FINAL VERSION

4.2. DESIGN BRIEF OF YOUR ENERGY MOMENT

This design brief describes the requirements for the user touch-points of Your Energy Moment. The touch-points of Your Energy Moment are: the smart energy technology (EMS and smart appliances), user support and several marketing channels.

4.2.1. SMART ENERGY TECHNOLOGY

EMS | The EMS should focus on supporting households to shift energy use in time to more favourable moments. More favourable moments of energy use are times when the sun is shining or when energy is relatively cheap. Furthermore, the EMS should support energy savings.

The EMS must be accessible and easy to use to become part of daily life (Van Dam et al. 2012; Hargreaves et al. 2010). When users consider the system as difficult to use, and feel frustrated when using the EMS, it can lead to discontinuation of using the EMS. Therefore, the EMS must be easy to use by an intuitive interface that enables users to directly use the system without having a good deal of prior knowledge. The EMS must have several layers in its information and a distinction between 'easy start' and 'advanced' menus. This will make the EMS approachable for beginners, but also attractive to more advanced users. Too much information must be avoided as too much information is likely to confuse and distract the user (Wood and Newborough 2007). Moreover, the EMS should be a dedicated display that is attached to the wall and remains in the corner of the eye like a reminder to be easily accessible. The design of the hardware must be as attractive as possible, so it will get a more central location in the house (Hargreaves et al. 2010).

The EMS should provide users with clear feedback and feed-forward that users can comprehend rapidly. It must provide users with information about the results of their actions (for a review, see Abrahamse et al. 2005). When scientific terms such as Watts are used, they must be supported by visual information. Real-time consumption and production feedback (updates every 10s.) must enable the user to see the current home electricity balance directly and must stimulate self-consumption of solar electricity. The EMS must provide overviews for electricity of the past (past days, weeks, months) use so users can identify room for improvement with regard to shifting and saving electricity (Anderson and White 2009; Fischer 2008). The EMS should also provide historic overviews for electricity production. The EMS should show production and consumption side by side to enhance the use of own production.

The EMS must give forecasts on the electricity production by the solar panels. The EMS must give feed forward on the price of electricity, so users can plan when to use their appliances and to increase the feeling of being in control. The presentation of the pricing scheme should be simple and attractive (AECOM 2011) and must support quick decision making (e.g. Kahnemann 2011).

The EMS should provide credible information, give the user a feeling of being in control and the capabilities of the EMS must be reliable (Rijsdijk 2006). This means that the EMS must provide easy access feedback on the functioning of the system (Geelen et al. 2013). The user must be able to easily overrule or change plannings on the EMS. Settings must be easy to change. In case of a smart washing machine, dishwasher or dryer, the EMS should communicate when the appliance is expected to finish and if it is a good moment to use electricity. In case of a smart climate system, the EMS should communicate that the heating or cooling cycles will take place on more favourable moments. The user must be able to switch the smart planning function of the smart climate system on and off on the EMS. Lastly, it is important for trustworthiness that personal information is carefully protected.

The EMS should give the opportunity to switch between a financial profile and a sustainable profile, because people with an environmental motive are more positively reinforced by feedback and feed forward focused on the environmental consequences of their actions. Feedback and feed forward concerning the financial consequences is expected to be more valuable for people with a financial motive.

The EMS should engage the user while interacting with the EMS by giving positive confirmations and encourage users to perform the electricity shifting behaviour again (Baumeister et al. 2007). The EMS should give emotional rewards: a good feeling and a feeling of achievement (e.g. scores, levels, challenges, targets, collections, rewards [Lockton et al. 2010]). The EMS must also give feedback on physical rewards (financial benefits) for demand shifting. Negative feedback must be avoided (it is not "bad" but it could be better).

The EMS must comply to the relevant general usability requirements for an user interface (ISO 9241-11).

Smart appliances | Besides the regular user interface possibilities of a washing machine, the user interface of the smart washing machine must facilitate setting an ultimate finish time. The smart washing machine must provide a default time frame to make the user interaction more efficient. The smart washing machine has to search for the best moment to start within the time frame and communicates the expected finish time to the user (Gottwalt et al. 2011, Timpe 2009). The user must be able to accept this proposal or to start the washing machine directly by overruling the proposal.

The user interaction with the smart heat pump must be arranged by the EMS, since the heat pump itself is often hidden and has limited user interfaces. It is not worth the effort to extend this user interface, as the frequency of interaction is relatively low. The user must be able to switch the smart function of the heat pump on and off and set the temperature on the EMS.

4.2.2. USER SUPPORT

It is likely that the novel technology will produce various technical or usage problems during implementation and usage. If these problems are not solved rapidly and accurately, users will experience negative emotions and might (unofficially) drop-out (Cotter at al. 2002) and stop using the smart energy technologies. First, installers must take the time to give a short instruction when the smart energy technology is installed. For questions during use, participants must be able to consult a list of frequently asked questions and user manuals. Participants should also be able to contact a help desk. A dedicated customer service team keeps an overview of all customer contact information in a customer relations management system, because in longitudinal studies, the amount of information gathered over time can be overwhelming (Cotter at al. 2002). The customer service team must be highly approachable and manage customer expectations. The customer service team takes care that agreements with the participants are made and that all team members and suppliers adhere to the service level agreements made with the participant (Zeithaml and Berry 1985). If a promise cannot be fulfilled, the customer receives an apology and an explanation. Participants who call with problems must be cherished. These participants help to get every bug out of the system.*

* In line with philosphies on continuous improvement (e.g. Saville and Reid 2002)

4.2.3. MARKETING

The instruments for communication must be perceived approachable, personal, understandable and interactive. The customer value proposition should be clear for the participants. The main message on advantages of participating will be to increase control and save (money or the environment, it's up to you). Research goals must be integrated in the communication about the study, so that participants understand the research intentions. The innovative character must be emphasized to create tolerance for bugs in the novel smart energy technology. Next to information and instructions, storytelling must be used to motivate and inspire. It should be made clear for participants what kind of behaviours are in favour of cheaper and more sustainable electricity demand. Last, participants must get the opportunity to try and observe new technologies (Rogers 1995).

4.3. FINAL DESIGNS YOUR ENERGY MOMENT

4.3.1. SMART ENERGY TECHNOLOGY

The following hard- and software components are included in the study:

- An Energy Management System (EMS) with a wall mounted touch screen and dedicated user interface and app;
- A smart washing machine;
- A Central Energy Management System (CEMS), that provides forecasts to the EMSs and schedules smart appliances on a city block level. CEMS also collects the necessary research data;
- A smart meter and a gross production meter;
- A PV installation.

In Table 4.1 we show the functional commonalities and differences between these interfaces between Zwolle and Breda. Furthermore, by an ICT architectural decision (more central intelligence and less in the home), the EMS of Breda is a little slower than Zwolle. The home-screen of the EMS display in Breda is shown in Figure 4.3 and Zwolle in Figure 4.4. Appendix 2, provides more examples of screens. For a deeper understanding of how the EMSs work and look like, instruction videos and manuals can be found on www.jouwenergiemoment.nl.

The apps were a simplified version of the EMSs giving feedback on electricity consumption and production and feed froward on favourable

	BREDA	ZWOLLE
Hard and software	Smart electricity meter, gross production meter, EMS with wall-mounted display, smart washing machine, smart heat pump for Meulenspie.	Smart electricity meter, gross production meter, EMS with wall-mounted display, smart washing machine.
Real-time feedback	Electricity consumption and production in Watts supported by flowing visual (refresh rate every 10 s). Electricity price and costs made the past hour and so far today in Euros.	Electricity consumption and production in Watts supported by flowing visual (refresh rate every 10 s).
Historical comparisons	Electricity consumption and production in kWh in bar charts (related to energy moments). Self-consumption of solar electricity in a bar chart and a percentage.	Electricity consumption and production in kWh in bar charts (related to energy moments). Overview of the electricity taken form and delivered to the grid and the total costs of this transaction in Euros.
Normative comparisons	X	X
Feeling of achievement	Relative amounts of kWh used in favourable moments shown in coloured bars.	Users can select a goal from easy start to more advanced. If the goal is reached for three weeks in a row, a message to promote one level is send. If the goal is reached is shown by stars (zero to three stars).
Appliance specific breakdown	Historical overview electricity consumption of the heat pump.	Real time & historical overviews electricity consumption of the washing machine.
Control other appliances	Users can change planning of washing machine. Smart planning of heat pump can be switched on and off, temperature can be set.	Users can change the planning of the washing machine.
Feed forward	Favourability of energy moments (sustainable & economical) is shown in green (most favourable), light blue (less favourable), dark blue (least favourable). Solar radiation forecast is given seperately. A solar radiation forecast and a simple weather forecast of two days is given with a rain radar is given separately.	Favourability of economic moments is shown by a wallet with two coins (most favourable), one coin (less favourable), no coins (least fevourable). Favourability of sustainable moments is shown by two leafs (most favourable), one leaf (less favourable), no leafs (least favourable). Both add detail by a graph. A solar radiation forecast and a simple weather forecast of two days is given seperately.

TABLE 4.1 FUNCTIONAL COMMUNALITIES AND DIFFERENCES BETWEEN THE USER INTERFACES OF BREDA AND ZWOLLE

moments. For security reasons, these apps did not have a smart appliance control functionality. The home-screens of the apps can be found in Figure 4.5.

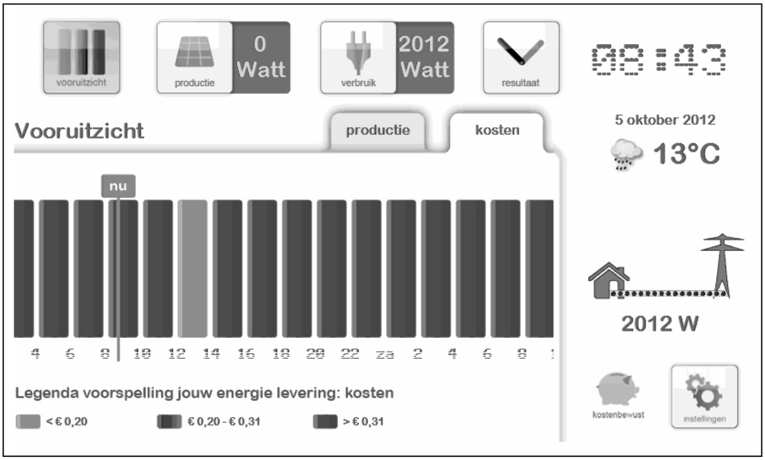


FIG.4.3 HOME-SCREEN OF BREDA

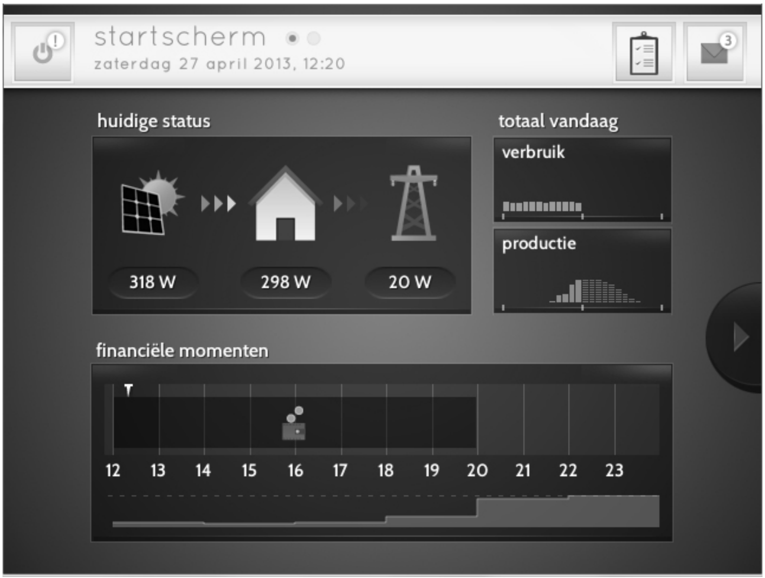


FIG.4.4 HOME-SCREEN OF ZWOLLE

At first, the plan was to provide participants with a choice between a smart dishwasher, a smart tumble dryer, and a smart washing machine. However, during the development, it was decided to focus on getting the smart washing machine to work. In the mean time, some participants were promised a tumble dryer in Zwolle. This small group of 17 households received a tumble dryer with a relatively simple postponable start and no additional user interfacing possibilities. Because the group

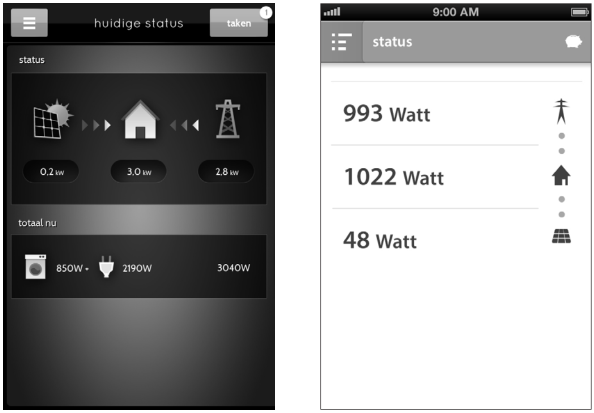


FIG.4.5 HOMESCREENS APP OF ZWOLLE (LEFT) AND BREDA (RIGHT)

is small and the tumble dryer is not really smart, this group is left out of analysis. The smart washing machine was exactly the same for both cities, because it was bought from the same supplier. The smart washing machine adheres to the requirement that the user can set the time when the laundry has to be finished (see Figure 4.6). The default is a time frame of 24h. Changing the time to start the washing machine can be performed on the smart washing machine and the EMS. However, it is easier to use the EMS.

In Meulenspie Breda, households already owned a heat pump. After a year of participation, participants received software that made their regular heat pump a smart heat pump. Users can change the temperature settings through the EMS and switch the smart planning function on and off.

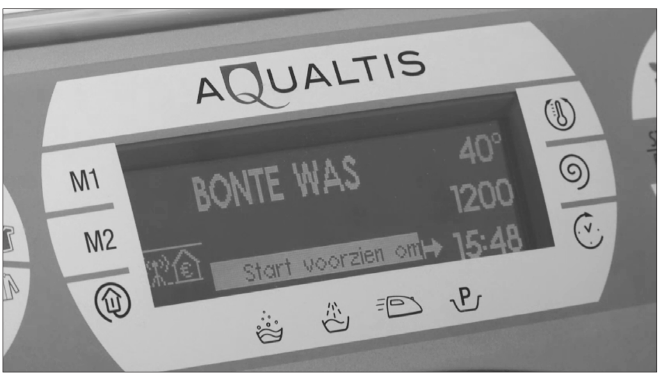


FIG.4.6 SMART WASHING MACHINE INTERFACE IN ZWOLLE AND BREDA

4.3.2. DYNAMIC PRICING

Instead of having a fixed electricity price per kWh from the electricity supplier and a fixed yearly network tariff from the network operator, the participants in this study received a dynamic tariff. This dynamic tariff fluctuates every two hours. The design of the algorithm of the dynamic price is best summarised as reducing demand during peak hours by shifting demand to moments when electricity supply is locally abundantly available. This means that in general, electricity prices are low during midday, when electricity is locally produced via the installed PV panels, and during the night, when electricity demand is low. In contrast, tariffs are generally high during the evening, when (local) electricity peaks occur. The algorithm behind this pricing scheme is described in detail by Kohlmann et al. (2011). In short, it consists of both dynamic network pricing and dynamic pricing by the supplier. First, the dynamic network pricing consists of three different levels as calculated in Formula 4.1.

FORMULA 4.1 FOR CALCULATING THE NETWORK TARIFF

$$Tariff_{network}(t) = \begin{cases} Price_{high} & \textbf{if } Load(t) > 0.83 \cdot Load_{max} \\ Price_{medium} & \textbf{if } 0.7 \cdot Load_{max} < Load(t) < 0.83 \cdot Load_{max} \\ Price_{low} & \textbf{if } Load(t) < 0.7 \cdot Load_{max} \end{cases}$$

where $Tariff_{network}(t)$ (€/kW h) is the dynamic network tariff, $Load_{max}$ (kW) is the maximum predicted load at the transformer during that day, $Load(t)$(kW) is the predicted load at the transformer during that timeslot, based on historical data and taking into account local PV production predictions and $Price_{high}$ = 0.19 €/ kWh, $Price_{medium}$ = 0.042 €/kWh and $Price_{low}$ 0 €/kWh. Furthermore, the dynamic tariff of the supplier is based on the Dutch day ahead market (the Amsterdam Power eXchange, APX) and a prediction of the local energy production shown in Formula 4.2.

FORMULA 4.2 FOR CALCULATING THE SUPPLIER TARIFF

$$Tariff_{supplier}(t) = \left(\frac{APX(t)}{APX_{average}} - sun(t) \right)^2 \alpha$$

$$\text{and: } \textbf{if } sun(t) > \frac{APX(t)}{APX_{average}}, \textbf{ then } Tariff_{supplier}(t) = 0$$

where $Tariff_{supplier}(t)$ (€/kWh) is the dynamic tariff from the supplier, $APX_{average}$ (€/kWh) is the average price on the day ahead market, $APX(t)$ (€/kWh) is the hourly fluctuating price on the market, $sun(t)$ is the predicted electricity production of the PV-panels per kWp and α is a multiplier. This multiplier is used in order to align the annual bill of the participating households to the annual bill of non-participating households (based on a fixed energy price of 0.215 €/kWh). Last, the energy tax is added (see Formula 4.3)

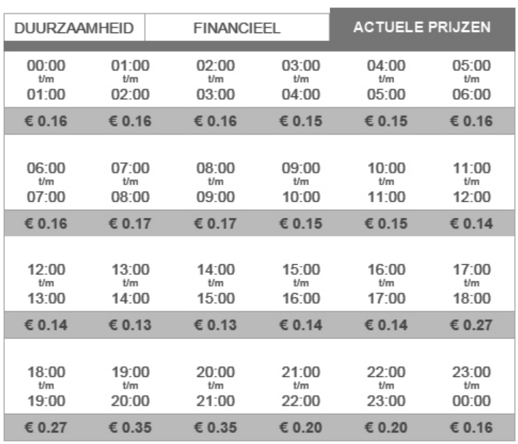
$$Tariff_{total}\,(t) = Tariff_{network}\,(t) + Tariff_{supplier}\,(t) + Tariff_{E\text{-}tax}\,(t)$$

FORMULA 4.3 FOR CALCULATING THE TOTAL TARIFF

where $Tariff_{total}\,(t)$ (€/kW h) is the total price per kWh and $Tariff_{E\text{-}tax}\,(t)$ (€/kW h) is the energy tax. The $Tariff_{total}\,(t)$ is averaged over blocks of two hours. Participants receive forecasts for the following 24 hours at noon.

The downside of dynamic pricing is that the pricing of electricity becomes even more complex. Households have difficulties with understanding energy pricing schemes already. It is argued that it is important to keep the scheme and the presentation simple and attractive (AECOM 2011). To present the dynamic tariff in an intuitive way, it was translated into three different categories in the EMS interface (high tariff > € 0.30, medium tariff € 0.20–0.30 and low tariff < € 0.20).

While the EMS gives forecasts in relative values, the dynamic tariff was presented online on the website with the exact values (see figure 4.7). The website contains the same blocks of two hours, only it is presented by hour. Last, the bill provided participants with insights about how much electricity they had used and what it costs them and what they had paid on average for a kilowatt hour.



DUURZAAMHEID | FINANCIEEL | ACTUELE PRIJZEN

00:00 t/m 01:00	01:00 t/m 02:00	02:00 t/m 03:00	03:00 t/m 04:00	04:00 t/m 05:00	05:00 t/m 06:00
€ 0.16	€ 0.16	€ 0.16	€ 0.15	€ 0.15	€ 0.16
06:00 t/m 07:00	07:00 t/m 08:00	08:00 t/m 09:00	09:00 t/m 10:00	10:00 t/m 11:00	11:00 t/m 12:00
€ 0.16	€ 0.17	€ 0.17	€ 0.15	€ 0.15	€ 0.14
12:00 t/m 13:00	13:00 t/m 14:00	14:00 t/m 15:00	15:00 t/m 16:00	16:00 t/m 17:00	17:00 t/m 18:00
€ 0.14	€ 0.13	€ 0.13	€ 0.14	€ 0.14	€ 0.27
18:00 t/m 19:00	19:00 t/m 20:00	20:00 t/m 21:00	21:00 t/m 22:00	22:00 t/m 23:00	23:00 t/m 00:00
€ 0.27	€ 0.35	€ 0.35	€ 0.20	€ 0.20	€ 0.16

FIG.4.7 EXAMPLE OF THE DYNAMIC PRICES PRESENTED ON THE WEBSITE

4.3.3. USER SUPPORT

A dedicated customer service team of two persons helps the participant when he or she encounters a problem or has a question. They are the first point of contact. This team is supported by a technical expert who pays home visits if needed to repair malfunctioning technology. Participants can call the customer service on workdays. Technical problems are resolved within 5 workdays if possible. If not, the customer service gives a prospect on the time needed to solve the issue. All customer contacts were registered in a dedicated customer relations management tool.

4.3.4. MARKETING

The customer value proposition of Your Energy Moment is put down as a certain 'lifestyle' to be integrated comfortably into daily life that helps the user to increase control over energy use. The identity of Your Energy Moment is based on the following statements: accessible, fresh, clear, calm, playful, you decide. The logo is colourful, fresh and bright and contains the hands of the clock to indicate the element of time. The colours of the logo are used in all media used for communication. The images used show that one can enjoy Your Energy Moment: 'your time, your energy' (see the title page of this chapter for an example). Texts are clear, actively written and personal.

The first moment of contact with the study participants, was mostly done by the real estate brokers by providing information on a brochure, where they were redirected to the website. All media used are described below.

- Website with dedicated platforms for the three different districts: all information can be found here. This website also serves other information seekers than participants. It provides general information on the study and news items. By the dedicated platforms it is possible to provide targeted information for each district, such as frequently asked questions, user manuals, instruction videos and the dynamic prices. These platforms also provide room for interaction between participants. Participants can leave messages and the energy production and consumption of the entire district is shown. (see jouwenergiemoment.nl)
- Digital magazines: the magazines are sent on average three times a year to the participants. The magazines mainly provide

participant-centered stories. Participants tell how they perceive participation, share their experiences and give advice to other participants. Magazines also include background articles for inspiration. (see magazines.jouwenergiemoment.nl)
- Digital newsletters: newsletters are sent to participants more often and contain more informational items than the digital magazines. The newsletters are used when there are important or interesting topics to share. Newsletters keep participants up to date with relevant information.
- Gatherings: information and demonstration evenings before the start, where participants ask their questions or share their doubts (privacy was discussed as well) and the opportunity to try and observe the new technologies (Rogers, 1995). Also includes, couple of gatherings after the start for after-care, counselling and group interaction.
- Welcome bag: bag containing booklets with relevant information and manuals. It also contains a solar charger for small portable devices in the form of a flower as a welcome present. The bag is made of durable jute with the logo of Your Energy Moment printed on it. The bag can be used for grocery shopping.

The households who did not participate were called to explain why not. Sometimes, the household would participate. The 18% of households who did not want to participate, were explaining that they could not make a decision to participate, because it was too far away in time or that they did not want to switch energy suppliers. A few households perceived privacy risks and one person reported to fear health hazards of radiation by wireless connected technologies such as the smart meter.

4.4. RESEARCH METHOD ON THE SUCCESS OF UCD

As discussed in Chapter 1, a smart grid is a technical innovation that needs user acceptance. Therefore, the research goal of this chapter is to evaluate the appreciation of YEM and the user friendliness of the EMS. This paragraph zooms in on the research method applied for providing these insights. First, we will describe the participating households. Second, we will describe the way we investigated the appreciation of YEM in general. Last, the way we evaluated user friendliness of the final EMS designs is discussed.

4.4.1. PARTICIPANTS

The recruitment strategy (and the free smart washing machine) has resulted in an unusually high participation rate of 82%. The questionnaire response rate of our questionnaires ranged from 73-100%. The number of participants that filled in all questionnaires was 67%. A usual drop-out rate of longitudinal studies is 40–60% (Bijleveld et al. 1998). Hence, the drop-out rate was low, already indicating that we managed to keep participants involved. Table 4.2, illustrates the number of respondents for each questionnaire. The first questionnaire was taken before the study, during the recruitment phase. The three follow-up questionnaires were taken with an interval of six months.

TABLE 4.2 NUMBER OF PARTICIPANTS AND NUMBER OF COMPLETED QUESTIONNAIRES

DISTRICT	NUMBER OF PARTICIPANTS STARTED	NUMBER OF COMPLETED QUESTIONNAIRES (RESPONSE RATE)			
		T_0: BEFORE START	T_1: 6 MO AFTER START	T_2: 12 MO AFTER START	T_3: 18 MO AFTER START
Easy Street	124	100 (81%)	110 (89%)	91 (73%)	97 (78%)
Meulenspie	39	39 (100%)	37 (95%)	33 (85%)	36 (92%)
Muziekwijk	77	69 (90%)	69 (90%)	60 (78%)	62 (81%)
Total	243	208 (86%)	216 (89%)	184 (76%)	195 (83%)

Easy Street in Breda is a city block with apartments where young, often single, working, and highly educated people, have bought their apartment. The residents of Meulenspie in Breda are on average slightly older, above modal earning, highly-educated couples with children. In the Muziekwijk in Zwolle, we see young couples who bought or rented a home together and started their families. Unemployment rates are quite high in this district in Zwolle. This district also includes social housing. Appendix 3 contains the extensive participant characteristics per district.

4.4.2. INVESTIGATING OVERALL APPRECIATION

A participation rate of 82% already indicates that we managed to put down an interesting proposition. The respondents of our questionnaires already accepted participation and thereby accepted the dynamic tariffs and the installation of the technology of YEM in their homes. However, an explanation of the overall appreciation of YEM before actual participation (T_0) can be useful in future efforts for smart grid acceptance, as overall appreciation is a predictor for user acceptance of smart products (Rijsdijk 2006). We used the demographic variables (age, gender, education) and

	QUESTIONS	
Overall appreciation (αT_0 = .82, αT_1 = .91, αT_2 = .93, αT_3 = .90)	'Your Energy Moment is...'	'fun' 'attractive' 'positive' 'interesting' 'valuable' 'important to me' 'beneficial'
Perceived advantage of YEM (αT_0=.78)	'By participating in Your Energy Moment, I expect to…'	'save energy' 'save money' 'use energy in a way that is better for the environment' 'control my energy consumption' 'utilize my solar energy directly'
Perceived risk (αT_0=.69)	'I think the technology of Your Energy Moment will work satisfactorily' (r) 'Little can go wrong when I start using the smart energy technology of Your Energy Moment' (r) 'I think the participation in Your Energy Moment can have a negative impact' 'I experience Your Energy Moment as an intrusion on my privacy'	
Perceived complexity (αT_0=.84) 1: 'very little' 5: 'very much',	'How much instruction do you think you need to make good use of Your Energy Moment?' 'How much knowledge do you think you need to make good use of Your Energy Moment?' 'How much help do you think you need to make good use of Your Energy Moment?'	
Perceived compatability (αT_0=.81)	'Your Energy Moment is compatible with my needs' 'Your Energy Moment fits well with the way I prefer to do things.'	

TABLE 4.3 SCALES ON USER ACCEPTANCE (MEASURED ON FIVE-POINT LIKERT SCALES RANGING FROM 1: 'COMPLETELY DISAGREE' TO 5: 'COMPLETELY AGREE', UNLESS OTHERWISE INDICATED)

the innovation attributes (perceived advantage, risk, complexity and compatibility, based on Rogers [1995]) as used by Rijsdijk (2006) for investigating overall appreciation of YEM. The scales used are based on Rijsdijk (2006), unless otherwise indicated, and are made specific for YEM (an overview of the scales can be found in Table 4.3). Overall appreciation is the degree to which participants appreciate YEM in general and is measured by seven items. The perceived advantage of YEM is the degree to which a participant believes participating in YEM will improve the way energy is used and consists of five items. We expect perceived advantage to positively influence overall appreciation. Perceived risk reflects the extent to which participants feel participation can have a negative outcome. This scale consists out of four items and does include an item on privacy, as privacy is a specific perceived risk related to the smart meter (Krishnamurti et al. 2012). We expect perceived risk to negatively influence overall appreciation. Perceived complexity relates to the degree YEM is perceived as relatively difficult to understand and use. The scale consists of three items. Higher levels of perceived complexity are expected to negatively influence overall appreciation. Last, compatibility is the degree to which YEM is perceived as consistent with the current lifestyles of participants. We measured the compatibility using a scale of two items based on Meuter et al. (2005).

We repeated overall appreciation of YEM in the follow-up questionnaires to investigate if expectations on appreciation deviate from actual appreciation during use and to investigate the effect of time on overall appreciation of YEM during participation.

4.4.3. EVALUATION OF USER FRIENDLINESS OF THE EMS

For investigating the effect of our efforts to design user-friendly EMSs, we assessed the perceived user friendliness of the EMS in the first questionnaire after introduction of the smart energy technology (T_1). We began with measuring the perceived effort required to learn and use the EMS based on the product usability scale of Nysveen et al. (2005). We extracted three items: 'The use of the EMS was easy to learn for me', 'The EMS is easy to use' and 'The use of the EMS is understandable' which formed a reliable scale (α_{T1}=.87).

Moreover, we assessed the perceived user friendliness by five single items starting with the question: 'How satisfied are you with the following aspects of the EMS?' The answers ranged from 1: 'very unsatisfied' to 5: 'very satisfied'. The aspects covered: 'access to information', 'the presentation of information', 'the functionality', 'the aesthetics' and 'the operation'.

4.5. RESULTS

4.5.1. EXPLAINING USER ACCEPTANCE

The overall appreciation of YEM before the start of the experiment was high (*M* = 3.99; *Sd*=.42), which is in line with our expectations, because the respondents already decided to participate in YEM. Furthermore,

	OVERALL APPRECIATION	PERCEIVED ADVANTAGE	PERCEIVED RISK	COMPLEXITY	COMPATABILITY
Perceived advantage	.52**				
Perceived risk	-.30**	-.19*			
Complexity	-.23**	-.07	.01		
Compatability	.45**	.29**	-.29**	-.07	
Age	.10	.00	.09	-.06	.02
Education	.02	-.03	-.06	.09	-.09
Gender	.03	.12*	.08	-.12*	-.06

TABLE 4.4 CORRELATION MATRIX APPRECIATION (*P<.05 AND **P<.001)

we found the perceived advantage to be high (M = 4.25; Sd=.45), risk perception to be low (M = 2.03; Sd=.49), perceived complexity to be quite neutral (M = 2.96; Sd=.63) and compatibility to be relatively high (M = 3.56; Sd=.58). To explore the relations between these variables, we conducted correlation analyses. As can been seen in Table 4.4, overall appreciation of YEM is related to all innovation attributes (perceived advantage, risk, complexity and compatibility) and to none of the demographic variables (age, gender, education). Answering the question on educational level was not obligatory, resulting in some missing cases. Therefore, we conducted this analysis with 196 respondents.

We also conducted a step-wise regression analysis with these 196 respondents, to further explain appreciation of YEM as a dependent variable. The innovation attributes and demographic variables are the independent variables in our analysis. For this step-wise regression, we first entered the innovation attributes (perceived advantage, risk, complexity and compatibility) and in the second step, we entered the demographic variables (age, gender, education). As can be seen in Table 4.5, the innovation attributes could explain 41% of the variance in the overall appreciation of YEM. The demographic variables were not able to explain variance in overall appreciation of YEM. These results are in line with the finding of Rijsdijk (2006) who concluded that consumer characteristics are of limited influence on smart product appreciation. Instead, overall appreciation depends largely on the perception of advantage provided by YEM. Moreover, high levels of perceived complexity and risk have a negative impact on overall appreciation and high levels of compatibility have a positive influence on overall appreciation of YEM.

TABLE 4.5
REGRESSION ANALYSES APPRECIATION ($^*p<.05$ AND $^{**}p<.001$)

		β	t	R^2	ΔR^2	ΔF
1	(Constant)		3.2*	.41	.41	33.72**
	Perceived advantage	.39	6.81**			
	Perceived risk	.28	-4.66**			
	Complexity	.18	-3.32*			
	Compatibility	.14	2.34*			
2	(Constant)		1.70	.43	.02	1.65
	Perceived advantage	.40	6.78**			
	Perceived risk	.14	-2.39*			
	Complexity	.19	-3.31*			
	Compatibility	.28	4.71**			
	Age	.11	1.89			
	Education	.08	1.47			
	Gender	-.01	-.08			

Last, we have conducted a repeated measures analysis (Bonferroni) with time as the independent variable and overall appreciation as the dependent variable to investigate the effect of time on overall appreciation of YEM. Participants were before (M_{T0} = 4.00) and during participation (M_{T1} = 3.98; M_{T2} = 3.99; M_{T3} = 3.88) very positive about Your Energy Moment. However, results show that participants were less positive in the last measurement of T_3 (F (3,483) = 3.68, p < .05) compared to T_0 (p < .05) and T_2 (p < .05) (not compared to T_1: p = *ns*).

4.5.2. USER FRIENDLINESS OF THE EMS

The questionnaire data of the first questionnaire after the start (T_1) were used to explore how users of both the EMSs in Breda and Zwolle perceive the user friendliness of the EMS. The EMSs were perceived easy to use on average (M_{T1} = 4.04) and an independent sample t-tests uncovered that users of both EMS designs found their EMSs equally easy to use (t (121.5) = -1.50, p = *ns*). Participants were also on average satisfied with the different aspects of the EMS (means of 3.5 and higher: see Table 4.3). However, by means of independent sample t-tests on the measures of satisfaction of the different aspects of the EMS, we uncovered some differences for these evaluation measures. Participants in Zwolle were more satisfied with the accessibility of information, the functionality and the operation of the EMS than participants in Breda. The reduced responsiveness of the EMS in Breda has probably a share in this effect, which has been a complaint of participants and which is in line with the findings of Alahmad et al. (2012) that even small delays can frustrate the user.

	BREDA		ZWOLLE		
	M	SD	M	SD	*t*
access to information	3.75	.79	3.96	.62	-2.07*
the presentation of information	3.81	.78	3.89	.73	-.72
the functionality	3.52	.93	3.89	.71	-3.22*
the aesthetics	3.87	.81	4.01	.64	-1.42
the operation	3.55	.92	3.94	.58	-3.85**

TABLE 4.6 USER SATISFACTION WITH DIFFERENT ASPECTS OF THE EMSS (*P<.05 AND ** P < .001)

4.6. CONCLUSIONS

This chapter was dedicated to the design of Your Energy Moment, because the design of a large scale and longitudinal study with actual users needs a thorough approach to achieve user appreciation and to prevent drop-out during participation. The results show that we have achieved user acceptance of Your Energy Moment by high participation rates, that participants appreciated Your Energy Moment and that we have developed a user-friendly EMSs by applying a UCD approach.

In line with the research of Rijsdijk (2006) on acceptance of smart products, we have concluded that the perceived advantage provided by participation has a strong positive influence on the overall appreciation of a smart grid. This means that designers should focus on understanding the perceived advantage by potential users to design products that are truly able to satisfy this advantage. This also means that marketeers should focus on understanding the perceived advantage by potential users to be able to convey the advantage. Moreover, the perceived compatibility with current lifestyles has a positive influence on overall appreciation and perceived risk and the complexity have a negative influence on overall appreciation of a smart grid concept. To increase the perceived advantage and compatibility and to reduce the perceived risk and complexity, we have performed upfront consumer research that provided valuable insights. We have made an effort to increase the perceived advantage and compatibility and to reduce perceived risk and complexity in the design of the technology by a UCD approach. Moreover, we addressed the perceived advantage and compatibility and the perceived complexity and perceived risk in our recruitment phase in which we have invited participants to information and demonstration evenings before the start. Participants were able to ask their questions or share their doubts and were given the opportunity to try and observe the new technologies (Rijsdijk 2006, Rogers 1995). We let them explain to each other how they perceived the advantages. Your Energy Moment was put down as a certain 'lifestyle' to be integrated comfortably into daily life to address compatibility.

Besides an unusually high participation and retention rate during the study, results on the overall appreciation of YEM has shown that participants were very positive. Moreover, participants indicated that the EMSs, that were exclusively designed for YEM, were easy to use.

The studies described in the next chapters, will benefit from the UCD approach described in this chapter in the sense that we have had the opportunity to collect high quality behavioural data over time for a representative sample. The next chapters will investigate residential electricity demand shifting behaviours in the long run using this data.

05

IT IS AUTOMAGIC

A real-life assessment on the effect of a smart washing machine

This chapter explores the real electricity demand shift of households in time and the role of smart appliances to bring about this shift. A longitudinal study was conducted among Dutch households in Zwolle over a period of one year. The households received a dynamic electricity tariff, an energy management system and a smart washing machine. Results show that households shift their usage of the smart washing machine mostly to midday when the sun is shining and electricity is produced by their own solar panels. Households who regularly used automation of the smart washing machine, also shifted the timing of using the washing machine away from the evening to the night. Furthermore, during the course of one year, the results remained stable, indicating a structural shift in demand.

This chapter is an adapted version of Charlotte B.A. Kobus, Elke A.M. Klaassen, Ruth Mugge and Jan P.L. Schoormans. (2015) A real-life assessment on the effect of smart appliances for shifting households' electricity demand. Applied Energy 147 p. 335–343.

The aim of this chapter is to investigate if households shift their electricity demand to times when electricity is abundantly available. To shift electricity demand in time depending on price signals, automation through smart appliances has been proposed as a promising strategy for households. Smart appliances can operate (semi-) autonomous and can thereby support users to automatically select the most desirable moment in time for consuming electricity. Prior research has investigated the effects of smart appliances on electricity demand shifting by developing statistical models and simulations (Widén 2014, Di Giorgio and Pimpinella 2012, Gaiser and Stroeve 2014, Di Giorgio and Liberati 2014). However, these models are based on assumptions with respect to the demand responsiveness of households and there is a lot of insecurity about households' willingness and ability to shift electricity demand in time (Verbong et al. 2013). In this respect, scholars have acknowledged that scientific research on the actual, everyday behaviour of households interacting with smart appliances is lacking (Geelen et al. 2013). The present research addresses this gap in the literature. Specifically, we contribute to the literature by investigating in a real-life setting the factual electricity demand shift that was achieved by a group of Dutch households while interacting with a smart washing machine over one year. We started this research with the participants from Zwolle, because of the head start of Zwolle. Chapter 6 will include both Breda and Zwolle, because the analyses of that chapter took place on a later moment in time when Breda was well incorporated. Participants in Zwolle were equipped with PV panels, an Energy Management System (EMS), and a dynamic tariff as described in the previous chapter. We evaluate self-consumption of on-site PV electricity, peak demand reductions and the effect of automation to bring about that shift in this chapter.

5.1. ELECTRICITY DEMAND SHIFTING STRATEGIES

Electricity demand shows a pattern over time, which is influenced by natural and social circumstances (Walker 2014). For example, households consume more electricity in the winter than in the summer and more in the evening when people come home from work and start using various appliances. Correspondingly, the pattern of electricity production, mostly by solar panels in residential areas, is mainly caused by natural circumstances. This brings about the problem that people are generally not at home when electricity is locally produced and create a peak demand in the evening, especially during winter. The most common strategies in the electricity sector to encourage households to use available sustainable electricity more efficiently and reduce peak demand are price signals and recently developed smart appliances. Existing research on the effectiveness of price signals has mainly focussed on peak demand reductions. These studies have reported large deviations in the peak demand reductions that households have achieved (Faruqui et al. 2010a, Thorsnes et al. 2012, Bartusch et al. 2011, EPRI 2008, Newsham and Bowker 2010, Gyamfi et al. 2013, Bartusch and Alvehag 2014). Deviations in results can be explained. First, there are several factors that cannot be influenced, such as the characteristics of the participating households. Second, designed factors, like the pricing scheme and the availability of smart appliances, caused deviations (Faruqui et al. 2010a, EPRI 2008). Most existing studies (see e.g. Faruqui et al. 2010a) on households' actual electricity demand shifting effects in combination with smart appliances make use of fully autonomous smart appliances and aim solely for a peak demand reduction. Utilities can directly lower electricity demand when peak demand is high by remotely interrupting the demand of specific appliances that use electricity (nearly) continuously, such as air-conditioners. This form of automation is referred to as fully autonomous in this thesis, because the user does not interfere with the process. The user only needs to accept the setting for electricity demand shifting to allow the utility to shortly interrupt operation. This form of electricity demand shifting has received much attention, because it is seen as the easy way to reduce the need for expensive reserve capacity. It is often applied in areas with high penetration rates of air-conditioners or electric heating.

Besides such fully autonomous smart appliances, users can shift other forms of electricity demand in time. While short interruptions of demand are mainly interesting to reduce peak demand, a shift of demand can also optimise the efficient use of (own) sustainable electricity production. The usage of wet appliances, such as dishwashers, washing machines and dryers, is in general not very time critical and therefore can be shifted. These appliances are heavy electricity consuming appliances that account for 15% of the total household demand (ECN et al. 2014), making them interesting for electricity demand shifting. The user can schedule these appliances him/herself to times at which local electricity is abundantly available. However, this form of scheduling can also be automated with a semi-autonomous smart appliance. The user defines an ultimate finish time and within this time frame, the smart appliance automatically defines the most appropriate starting time (Gottwalt et al. 2011, Timpe 2009). The few studies that have studied household acceptance of such semi-autonomous smart appliances have mostly used questionnaires to explore households' intention to shift the electricity demand of their appliances in time (Timpe 2009, Gyamfi and Krumdieck 2011, Mert et al. 2008, Stamminger et al. 2008, Broman et al. 2014). These studies show that the overall attitude towards smart appliances is positive, although respondents do perceive risks concerning safety, loss of control, technical problems and additional costs, and are sceptic about the ecological benefits (Mert et al. 2008). Especially, the smart operation of the washing machine is a sensitive issue. Although respondents reported that they were willing to shift operation, they did not want to leave wet laundry in the machine for a longer period of time. Despite that the time interval for smart operation of the washing machine is limited, these preference studies have concluded that households can shift 10–77% of the electricity demand of their washing machine (Gyamfi and Krumdieck 2011, Stamminger et al. 2008). However, when filling in these questionnaires, people respond to descriptions of smart grids, dynamic pricing tariffs, and smart appliances to form attitudes and to estimate their future behaviour. These studies can only provide limited insights in the real-life effects of electricity demand shifting for households, because many more (often conflicting) factors shape pro-environmental behaviour, so the attitude-behaviour relation is limited (Kollmuss and Agyeman 2002). The variance in prior results underline the need to measure the willingness to shift the washing machine in time in a real-life setting by studying actual, everyday behaviour of households. In Chapter 3, we investigated the willingness to shift the washing machine in time in a real-life setting, but this study had several important limitations. First of all, the study used a small sample and all participants were employees of an energy utility, thereby raising doubts about the representativeness of the sample. Second, the study did not include a dynamic tariff, which is assumed to be essential to adopt a demand shift for the majority of households (Faruqui et al. 2010a). And most importantly, as the actual usage of the automation of the smart washing machine was not measured in the study, it was not possible to investigate the role of automation for bringing about a demand shift.

A notable exception that studied a demand shift on a large scale is the German field test of three months in Mannheim where participants received dynamic pricing and smart appliances (semi-autonomous and fully autonomous) to shift demand (Kießling 2013). The results of this study showed that peak demand was reduced by 11%. Although the study concluded that the autonomy of wet appliances was often not used, because it was perceived as too complex to operate, the study did not further investigate the effect of using or not using the autonomy on the established shift in electricity demand and the study lasted too short to investigate if the change remained.

The present study contributes to the existing body of literature by investigating in a real-life setting to what extent households are shifting the moment of doing their laundry in time when interacting with a smart washing machine. Furthermore, we aim to investigate the effect of using the automation function of the smart washing machine for bringing about this shift in energy demand. The study was conducted among a representative sample of Dutch households in Zwolle. Because prior research on energy demand reduction suggests that households return to their former habits where they do not use an EMS nor save energy (e.g. Van Dam et al. 2010), we conducted a longitudinal study over a period of one year. We started this research in Zwolle, because of the head start of Zwolle. The study in the next chapter will include Breda.

5.2. METHOD

5.2.1. PARTICIPATING HOUSEHOLDS

The study took place in a newly built area in Zwolle, the Netherlands, with 77 households (96% response rate). Although the average age of the respondents was somewhat younger (M = 32), these households were a good reflection of the Dutch society with as many men as women, a modal income and an average of 2.2 occupants per household (CBS 2013). All households are located in the same city block. Households could opt-in for a smart washing machine and 56 households made use of this opportunity. However, not all washing machines functioned properly due to technical issues, which decreased the sample size to 50 households.

5.2.2. PROCEDURE

We investigated when households did their laundry by collecting data on electricity demand created by the smart washing machine by means of a metering cluster in the machine. To determine if this timing corresponded to moments of electricity production of the PV panels, we also collected data on the PV production that was measured by a separate production meter. For the analysis, we used data from March 1st 2013 till March 1st 2014, based on a 15 min resolution (35.040 samples, kW h/15 min). To define if participating households changed their laundry routines, the electricity demand of the washing machine during different time periods was compared to that of a reference group. The reference was obtained from smart plugs that were used by Dutch and Belgian households to measure the load of individual appliances in their households. This reference group was chosen, because these households are similar to our test group with respect to the cultural and natural circumstances affecting electricity consumption (and production) patterns. This dataset contained the 15 min average load (Watt) of 274 plugs from January 1st 2013 till January 1st 2014. For the analysis, the average daily load profile of each plug is used. Visually, this reference profile is in line with other washing machine demand profiles reported in literature (Gottwalt et al. 2011, Gyamfi and Krumdieck 2011, Stamminger et al. 2008, Almeida et al. 2008).

The installed technology also collected data from June 12th 2013 till March 1st 2014 on the use of automation, which enabled us to investigate the role of automation in electricity demand shifting. We counted the number of wash cycles, and classified each wash cycle either as smart (using automation) or as manual (not using automation). Subsequently, the percentage of smart wash cycles for each household is used to study the effects of using automation on the shift in electricity demand of the washing machine.

Six months after the start of the study, a questionnaire was sent to investigate the reasons to use or not use automation ($N = 55$). Next, in an open-ended question, households were asked to clarify their frequency of using the automation function of the smart washing machine.

5.3. RESULTS

5.3.1. CHANGED LAUNDRY ROUTINES

To evaluate if households changed their laundry routines, the electricity demand of the washing machine was compared to that of the reference group. In our study, households are stimulated to use electricity when tariffs are low and PV production is high. It is expected that for the participating households electricity demand will be lower during periods with a high dynamic tariff and higher during periods with high PV production. The average dynamic tariff and the average PV production during the study are shown in Figure 5.1.

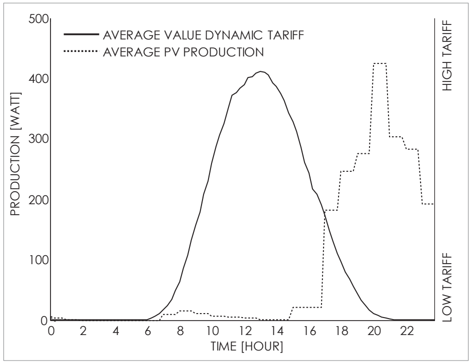


FIG.5.1 AVERAGE VALUE OF THE DYNAMIC TARIFF AND AVERAGE PV PRODUCTION DURING THE STUDY FROM 1 MARCH 2013 TO 1 MARCH 2014.

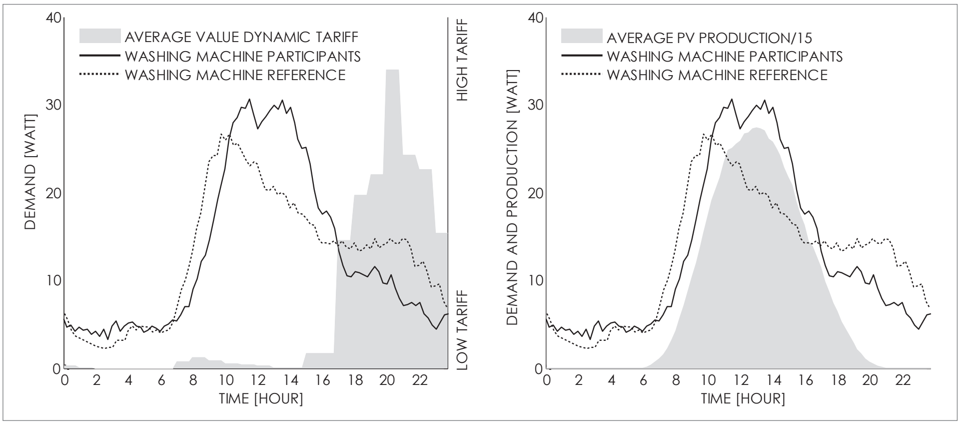


FIG.5.2 ELECTRICITY DEMAND OF THE WASHING MACHINE FOR PARTICIPATING HOUSEHOLDS AND THE REFERENCE GROUP WITH THE AVERAGE VALUE OF THE DYNAMIC TARIFF (LEFT) AND THE AVERAGE PV PRODUCTION (RIGHT)

To compare if electricity demand is higher during time periods with high PV production, the average electricity demand of the washing machine between 09:00 and 17:00 (period I) was studied. Furthermore, to compare if electricity demand is lower during time periods with a high average value of the dynamic tariff, the average demand between 17:00 and 00:00 (period II) was studied. As the objective was to investigate differences in the shape of demand, the total energy demand of all households was normalised based on the average demand of the participating households. Figure 5.2 shows the average electricity demand of the washing machine for participating households (solid line) and for our reference group (dashed line). The average profiles included both workdays and weekends. The PV production in the right figure is scaled down by a factor 15 to improve the visual comparison of the PV production profile with the electricity demand profiles of the washing machine. To determine if the shift in the electricity demand of the washing machine was significant, a two-sample t-test was conducted to compare the average electricity demand of the participating households' washing machines with that of the reference during periods with high PV production (period I: 9.00–17.00), and periods with a high electricity price (period II: 17.00–0.00), see also Formula 5.1.

FORMULA 5.1 FOR CALCULATING THE INDIVIDUAL AVERAGE DEMAND VALUES

$$\overline{P}_{wm,P_i} = \frac{1}{\Delta t} \sum_{t_1}^{t_2} P_{wm,P_i}(t),\ i = 1 \ldots N_P$$

$$\overline{P}_{wm,R_i} = \frac{1}{\Delta t} \sum_{t_1}^{t_2} P_{wm,R_i}(t),\ i = 1 \ldots N_R$$

where P_{wm,P_i} and P_{wm,R_i} are the electricity demand of the washing machine of the participating and the reference households respectively. The start and the end of the considered time period is expressed by t_1 and t_2, and N_P and N_R are the sample size of the participants and the reference. $\overline{P}_{wm,P_i}$ and $\overline{P}_{wm,R_i}$ are the individual average demand values during the considered time period, and are used as input for the t-test.

The results demonstrated that during periods when PV production is high, the average electricity demand of the washing machine of the participating households ($M_{\text{participants}}$ = 24.2 W, SD = 5.1) was 18% higher ($t\,(323) = 4.05, p < .001$) than that of the reference group ($M_{\text{reference}}$ = 20.5 W, SD = 6.2). Furthermore, during periods with a high dynamic price the average demand of the participating households ($M_{\text{participants}}$ = 8.8 W, SD = 4.8) was 31% lower ($t\,(323) = -4.18, p < .001$) than that of the reference group ($M_{\text{reference}}$ = 12.7 W, SD = 6.3). To assess if the achieved electricity demand shifting of the households was stable over time, the average electricity demand of the washing machine was studied for four periods of three months (see Figure 5.3). A repeated measures ANOVA showed that the demand did not significantly change over time (period I: $F\,(3{,}147) = 0.05, p = ns$) period II: ($F\,(3{,}147) = 1.09, p = ns$).

5.3.2. THE SMART WASHING MACHINE KNOWS BEST

To investigate the role of a smart appliance for shifting the electricity demand of the washing machine, the usage of automation was measured. The percentage of programmed wash cycles, $\overline{\%}_{cycles;P_i}$, per participant was defined, according to Formula 5.2.

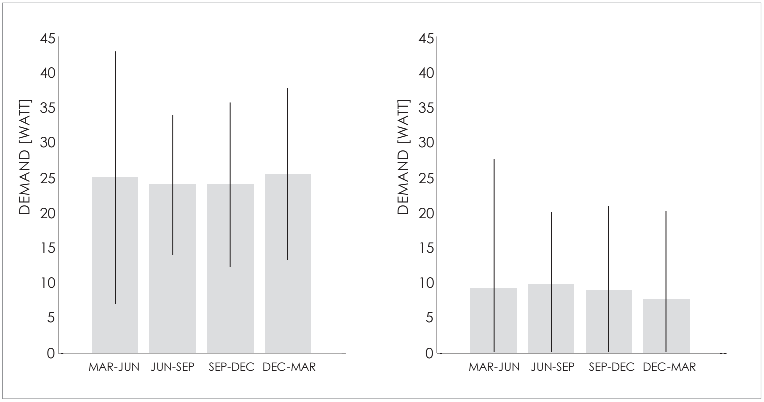


FIG.5.3 AVERAGE ELECTRICITY DEMAND OF THE WASHING MACHINE DURING TIME PERIODS WITH HIGH AVERAGE PV PRODUCTION (LEFT) AND DURING TIME PERIODS WITH A HIGH AVERAGE DYNAMIC TARIFF (RIGHT)(ERROR BARS REPRESENT STANDARD DEVIATIONS)

$$\overline{\%}_{cycles;P_i} = \frac{N_{programmed\ cycles,P_i}}{N_{cycles,P_i}},\ i = 1 \ldots N_P$$

FORMULA 5.2 FOR CALCULATING THE INDIVIDUAL AVERAGE PERCENTAGE OF PROGRAMMED WASH CYCLES

where $N_{cycles;P_i}$ is the total number of registered wash cycles per participant and $N_{programmed\ cycles,P_i}$ the total number of registered programmed wash cycles (using automation). The overall average usage of the automation for all households was 18%. This means that only 18% of all wash cycles was programmed by the households.

To judge if the use of automation influences the amount of demand shifted in time, we compared the demand profiles of the users of automation with the non-users. The households were split into these two groups, by means of a threshold of using automation at least 5% of the total amount of wash cycles. This threshold split the sample into two distinct groups of 25 households: a group that uses automation regularly (M = 35.7%, SD = 28.9), and a group that does not use automation (M = 0.9% SD = 1.6).

In Figure 5.4, the average electricity demand profile of the washing machine of both groups are illustrated. The figure shows that users of automation use their washing machine less often in the evening when the dynamic price is high and more often at night. To determine if differences in energy consumption between both groups and the reference group are significant, we conducted one-way ANOVAs with Games–Howell post hoc tests, due to the unequal group sizes of the test

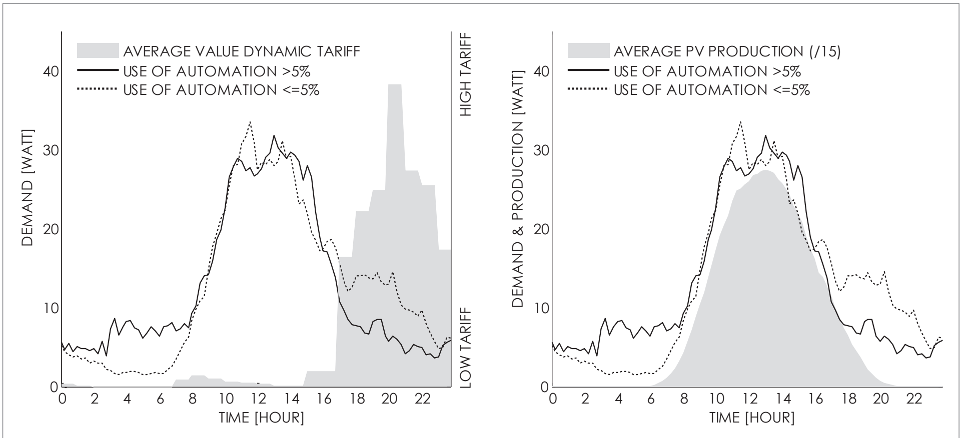


FIG.5.4 ELECTRICITY DEMAND OF THE WASHING MACHINE FOR USERS OF AUTOMATION AND FOR NON-USERS WITH THE AVERAGE VALUE OF THE DYNAMIC TARIFF (LEFT) AND THE AVERAGE PV PRODUCTION (RIGHT)

group and the reference group. The load in the two time-blocks were the dependent variables and the different groups (reference, users and non-users) formed the independent variable.

Results show that there was a significant effect of the three groups on the load during the day (F (2,322) = 8.26, $p < .001$, $M_{\text{non-users}}$ = 24.1 W, SD = 4.6, M_{users} = 24.4W SD = 5.7 and $M_{\text{reference}}$ = 20.5 W, SD = 6.2).

We also found a significant effect of the three groups on the load during the evening (F (2,322) = 12.37, $p < .001$, $M_{\text{non-users}}$ = 11.1 W, M_{users} = 6.6 W, $M_{\text{reference}}$ = 12.7 W). This time the Games–Howell post hoc tests revealed that households who used automation showed a decrease of demand of their washing machine during the evening compared to the reference ($p < .001$), and a decrease compared to the households who do not use automation ($p < .05$). For non-users of automation no significant results were found compared to the reference group (p = *ns*).

To check if the usage of automation of the washing machine remained stable, the percentage of programmed cycles was studied over time. We studied the usage of automation for every three months, generating three values per household. A repeated measures ANOVA showed that the use of automation per time period did not significantly change over time (F (2,98) = 0.02, p = *ns*).

Last, we explored why households did or did not use automation based on their responses in the questionnaire. We coded and clustered all answers into different reasons. The most important reason for using automation is saving money. Furthermore, using solar energy as efficiently as possible was named. Another mentioned reason is saving energy. The most important reasons not to use automation are that people prefer to keep control, the suggested times were not perceived convenient or they experienced a feeling of urgency of doing the laundry.

5.4. DISCUSSION

Many researchers have investigated the value of electricity demand shifting by developing mathematical models (e.g. Erdinc 2014) and the intention of households to shift demand in time with smart appliances by questionnaires (e.g. Gyamfi and Krumdieck 2011). To assess the real electricity demand shifting of households with a smart washing machine, we invested considerably in providing a large representative sample of households with state-of-the-art technology and dynamic prices over a longer period to increase the reliability of the results. This chapter presents two major contributions to the existing literature. First and foremost, the study demonstrates that households shifted the usage of their washing machine from hours with peak demand to hours in which the PV production is high. When PV production is high, the average electricity demand of the washing machine of the participating households was 18% higher than that of the reference group and during periods with a high dynamic price it was 31% lower than that of the reference group. Secondly, we found that households who regularly used automation also made use of the cheapest dynamic prices during the night and by doing so, reduced even 48% of the evening peak demand of the washing machine compared to the reference group. This makes sense, because automation facilitates using the washing machine at night when people are asleep. Over the year of testing, the observed effects did not change. From this, we conclude that shifting the use of the washing machine during the day to moments when the sun is shining, and/or to the night when prices are low by using automation, became new habits.

In previous studies, the dynamic tariff is considered an important driver for electricity demand shifting and has therefore received a lot of research attention (Faruqui et al. 2010a, Gaiser and Stroeve 2014, Thorsnes et al. 2012, Bartusch et al. 2011, EPRI 2008, Newsham and Bowker 2010, Bartusch and Alvehag 2014). A driver for change that has received far less attention is the way the EMS and the smart appliance are designed (Stromback et al. 2013). In this chapter, we learned that the participants often did not use automation (only 18% of the time) to help them schedule doing their laundry. All households used more electricity at the time it was locally produced by PV panels, but households who used automation also reduced peak demand, which means they achieved even better results. Hence, it would be worthwhile to further investigate how households can be stimulated to use automation for shifting the electricity demand of their wet appliances more often. In this respect, testing a different kind of interface for the smart washing machine would be interesting. For example, the smart washing machine in this study automatically searched for the best moment to start within a 24h time frame. Possibly, a different or adaptable default setting for this time frame may reduce the perception that the suggested times were not convenient. Another possibility would be to directly reward the use of the automation function, for example with stars, since people are more likely to continue a certain behaviour when they feel acknowledged for their efforts (Lockton et al. 2010).

This chapter has given us an answer to our most important research question. Households are shifting the electricity demand to hours when electricity is locally produced and thereby lower peak demand. Though the investigation of the electricity demand shift was limited to the washing machine, it is an encouraging result, because if households are willing to contribute this way, it is likely they will also embrace other forms of electricity demand shifting. However, it is important to further investigate households' demand shifting potential by taking other residential appliances into account. Moreover, it is important to investigate other effects on demand shifting performance than the use of automation. Last, the analyses in this chapter did not involve Breda, because of the timing. Therefore, the next chapter will investigate the electricity demand shifting habits further, takes into account other appliances besides the washing machine and includes the data of Breda to increase the sample size and improve the statistical power of the results.

06

NEW HABITS

Investigating habit formation in a longitudinal large scale smart grid study

In the previous chapter, we have focussed on changed laundry routines. Looking at the use of the washing machine, we saw relatively more demand on moments of solar PV and relatively less demand on peak moments during the evening. This chapter focusses on the established new habit formation in a broader sense. We investigate the lasting shifting behaviour of other appliances than the washing machine, the habitual use of the EMS and the motivations for change over time. In this study, we have included the data of Breda to increase the sample size. Results show that, in line with Chapter 5, participants stay shifting the use of the washing machine to favourbale moments. Furthermore, participants reported that they shift the tumble dryer and dishwasher besides the washing machine. Like for demand reduction, we revealed a positive relationship between use frequency of the EMS and the shift in demand of electricity. We argue in this chapter that giving feed forward on electricity supply besides giving feedback on patterns of demand is beneficial for higher levels of use frequency in the long run.

Chapter 4 describes the way we aimed to change routines of using electricity by changing the stable context in which people consume electricity. By introducing new technologies: a PV installation, an Energy Management System (EMS) and a smart appliance and a dynamic pricing scheme we aimed to encourage participants to shift demand. Chapter 5 has shown that households are shifting electricity demand to hours when electricity is locally produced and thereby lower peak demand. However, the investigation of the electricity demand shift was limited to the washing machine. To increase insight in the total demand shifting potential of households, it is important to further investigate the electricity demand shifting of other residential appliances too. Therefore, we investigate the reported demand shifting behaviours with appliances other than the washing machine. We include the evaluation of the fully autonomous demand shifting smart heat pump of Meulenspie Breda.

Moreover, we increase insight in demand shifting behaviours by investigating the effect of time on determinants of responsible energy use introduced in Chapter 2 and 3: motivation and use frequency of the EMS. Based on former studies on energy demand reductions, we assume that the newness of YEM wears off (Hargreaves et al. 2013). However, when households did indeed develop new habits, as concluded in Chapter 5, households continue to shift demand. Furthermore, we expect persistent use of the EMS, because households need the daily feed forward for shifting demand. This way, households will automatically receive feedback in the long run as well, which is seen necessary for persistent change in Chapter 2. Besides plain use frequency, we investigate EMS usage further, by investigating who uses the EMS when, and with what purpose, to investigate the routines that have evolved around using the EMS.

Last, the analyses of the previous chapter were limited to the participants of Zwolle due to the timing of the analyses. The study in this chapter includes both Breda and Zwolle to increase the validity of the results of Chapter 5.

6.1. INVESTIGATING NEW HABITS

Though habit formation is seen as an important topic for durable change (e.g. Van Dam et al. 2010), few researchers have been able to investigate new habit formation as a result of the introduction of new technologies in the field of shifting residential electricity demand on a larger scale.

First of all, previous longitudinal studies on shifting demand at home were small scale (e.g. Geelen et al. 2013) and previous larger field studies often lasted only for relatively short time periods (e.g. Kießling 2013). In this longitudinal set up, we investigate both actual behaviour by collecting electricity consumption data of the washing machine over a period of one year after users were familiar with using the technology of YEM, as well as reported behaviour, which includes other appliances as the washing machine as well. We investigate motivations for behaviour change over time to investigate whether the newness wears off. Also, we investigate the use of the EMS both by collecting every touch of the user on the display. For the analyses of objective behaviour, we selected a period of one year: from 1-10-2013 till 1-10-2014. Breda started in March 2013. We took the data from October on, so the households of Breda would have had sufficient time to learn to use the system. Figure 6.1 shows that the number of touches on the EMS of Breda stabilised after October 2013, suggesting that the participants of Breda had sufficient time to get used to YEM.

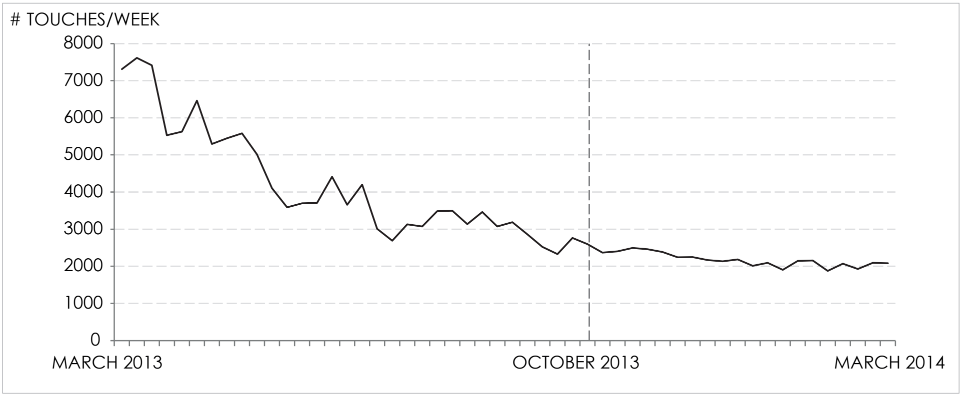


FIG.6.1 TOTAL NUMBER OF TOUCHES ON THE EMS PER WEEK IN THE FIRST YEAR AFTER THE START OF THE PARTICIPANTS IN BREDA

6.1.1. ELECTRICITY DEMAND SHIFT

First, we start by verifying the results of Chapter 5 with a larger sample. Therefore, the objective electricity demand shift of washing machine usage is measured in line with the method of Chapter 5. As explained, it was preferred that participating households would shift their washing machine usage away from the more expensive moments between five in the afternoon and midnight (see Figure 6.2) to the night or when electricity is locally produced, generally between nine in the morning and five in the afternoon (see Figure 6.3). Therefore, we have made the

FIG.6.2 AVERAGE PRICE PER KWH PER AREA FROM 1-10-2013 TILL 1-10-2014

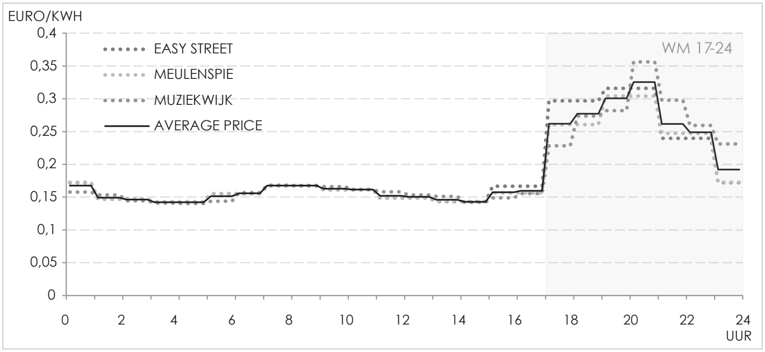
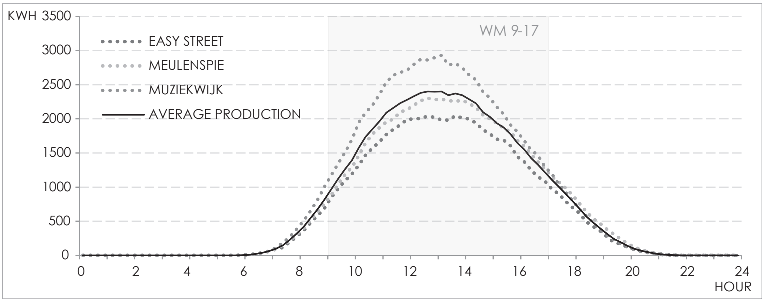


FIG.6.3 TOTAL SOLAR PRODUCTION IN KWH PER AREA FROM 1-10-2013 TILL 1-10-2014



relative washing machine usage between nine o'clock in the morning and five in the afternoon (WM 9-17) and the washing machine usage between five o'clock in the afternoon and midnight (WM 17-24) dependent measures. By 'relatively' we mean that we divided the sum of demand of the washing machine in the specific time-slot by the sum of overall demand of the washing machine. As explained in Chapter 4, not all households chose to receive a washing machine and if less than 10 wash cycles were registered in the database in the period from 1-10-2013 till 1-10-2014, the household was excluded from further analysis due to technical issues. This left us with a sample of 176 households out of the total 243, including the households of Zwolle that were part of the analyses in Chapter 5. Hence, the sample size was increased from 50 to 176 households. On average, 64% (*Sd* =.21) of the demand of the washing machine fell during the day (WM 9-17) and 26% (*Sd* = .20) during the evening (WM 17-24).

Furthermore, the questionnaires enabled us to investigate beyond the energy use data of the washing machine. In the questionnaires, respondents were asked to report which appliances or appliance groups they (intended to) shift in time. We have asked the respondents to report their intention on how often (1 'almost never' to 5 'almost always' and 'not applicable' is missing) they intended to shift the use of different appliances and appliance categories to more favourable moments in time in the T_0 questionnaire and thereafter to report their shifting behaviour in the follow up questionnaires. The appliances and appliance groups we asked for were: the tumble dryer, washing machine, dishwasher, other kitchen appliances (e.g. oven, kettle, etc.), other cleaning appliances (e.g. iron, vacuum cleaner, etc.), entertainment-related appliances (e.g. TV, game console, etc.), work-related appliances (e.g. computer, printer, etc.) and appliances that need to charge.

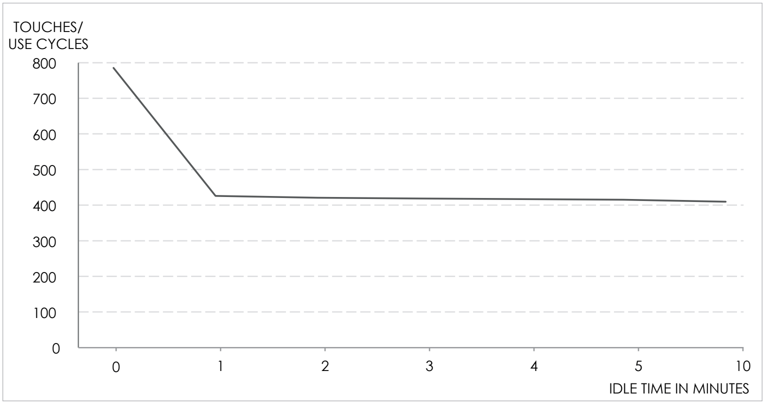
Last, we investigated the way participants of Meulenspie evaluated the fully automatic shifting of the smart heat pump to increase insight in the possible acceptance of the fully automatic demand shifting technology. First, we registered whether the smart planning function was activated. Furthermore, we asked the following questions: 'The heat pump uses a lot of electricity. Therefore it is useless to shift other appliances in time, such as the washing machine', 'It is important to me that I can switch the smart function of the heat pump on and off' and 'I believe that using the smart planning function of the heat pump is beneficial for me'.

6.1.2. EMS USAGE

Insight in how the EMS is used on a daily basis can help in finding opportunities for designing habit development around using the EMS (Van Dam et al. 2010). Concerning habits around EMS usage, we were interested in use frequency, patterns of use, use of different elements and use by different residents. To start with use frequency (UF), we registered every touch on the displays. However, if we want to define UF, we cannot use the measured display touches solely. We will need distinct use cycles that define the UF. We defined a use cycle as a cluster of display touches by defining a standard idle time. Idle time is the time between a display touch and its previous touch. For example, an idle time of one minute means that the user did not touch the display for more than one minute. By investigating the reduction of touches to use cases with idle times of one minute to five minutes and ten minutes, we discovered that an idle time of one minute is most appropriate to define a distinct use cycles. Hence, idle time is taken as 1 min (see Figure 6.3).

UF per household is the sum of distinct use cycles per household for the period from 1-10-2013 till 1-10-2014. If we examine the sum of use cycles per household, we can see that the data has some extreme

FIG.6.4 AVERAGE NUMBER OF TOUCHES PER HOUSEHOLD PER YEAR AND THE VALIDATION OF THE CORRECT IDLE TIME: AN IDLE TIME OF 1 MINUTE



values (maximum is 4970 use cycles which is over 13 use cycles a day on average). We did not delete these extreme values, because with further examination of these cases and comparing them to the reported use frequency in the questionnaire we must conclude that these are no measurement errors. Furthermore, the data is heavily skewed ($z_{skewness}$ = 20.76) and peaky ($z_{kurtosis}$ = 49.22). Hence, for further analysis with UF, we used non-parametric tests.

For gaining a deeper understanding around the routines of using the EMS, we derived the daily patterns of use by summing the use cycles per hour per day of all households. Furthermore, we investigated the use of the different screens. The use of different elements are presented in a percentage compared to the total number of touches on the screen. Insights in the use of the EMS by different residents is derived from a question in the second questionnaire: 'How often do you use the EMS?' (1 = 'Almost never', 2 = 'less than once a week', 3 = 'once a week', 4 = 'several times a week', 5 = 'once a day', 6 = 'several times a day', n.a. is missing). We repeated this question for partners, children and other members of the household. Last, we asked respondents to explain their typical moments of using the EMS in an open question.

6.1.3. SELF-REPORTED DRIVERS FOR CHANGE

To further investigate how new routines have evolved, it is interesting to investigate the self-explanation of behaviour change. We proposed different motivations to shift demand based on the motivations for change named by the participants of Chapter 3. Respondents had to indicate how important these reasons were to them on a five-point Likert scale. The answers ranged from 1: 'not important' to 5: 'very important'. We repeated this question to investigate the effect of time. However, we repeated this question only in the questionnaire of T_1 and T_3, because the list was extensive and took the respondent quite some time to complete. Moreover, we wanted to make room in in the questionnaire for the question which contextual elements stimulated the participants to shift demand, because according to Verplanken & Wood (2006), changes in the context can trigger changing habits. In the third questionnaire (T_2), respondents had to indicate the perceived influence of the several contextual features. The answers ranged from 1: 'no influence' to 5: 'large influence'. We did not repeat this question, again because we did not want the questionnaires to become too long. The items are listed in Table 6.1.

TABLE 6.1 ITEMS QUESTIONNAIRE ON PERCEIVED DRIVERS FOR CHANGE: MOTIVATIONS AND CONTEXTUAL FEATURES

MOTIVATIONS	CONTEXTUAL FEATURES
Spend less money on energy	EMS
Getting in control over my energy use	Invoice/overview
Using my own generated energy more efficiently	Smart washing machine
Feeling more independent	Solar panels
It is a challenge	Dynamic tariff
It is fun to do	Communications and user support
Trying out a new technology	
Out of curiosity	Neighbours
It gives me a good feeling	Other residents
The depletion of energy resources	
Less environmental pollution	
Secure the future for next generations	
Taking social responsibility	
Doing it together with my neighbourhood	
Doing better than other participants	

Last, we investigated the needed investment. High cost in terms of effort and time, can be a barrier for sustainable behaviour (Yeong et al. 2010). When the perceived investment in terms of time and effort is low, the reason not to perform more sustainable behaviour decreases. This scale consisted of two items that was included in the questionnaire after the introduction of YEM (T_1): 'Participation costs little time' and 'Participation costs little effort' (αT_1 =.92) with answers ranging from 1: 'completely disagree' to 5: 'completely agree'.

6.2. RESULTS

6.2.1. ELECTRICITY DEMAND SHIFTING OVER TIME

To verify our results in Chapter 5, we compared the washing machine use data of all participants, both Zwolle and Breda, with the same reference group from the Benelux as Chapter 5. An independent sample t-test showed that also for this larger sample, the washing machine use of the participants is higher when electricity is locally produced and lower during the evening ($t_{\text{WM 9-17}}(310.40) = -5.42, p<.05$; $t_{\text{WM 17-24}}(300.94)= 2.02, p<.05$) (see Figure 6.5).

FIG.6.5 AVERAGE LOAD PROFILES OF THE WASHING MACHINE FOR THE PILOT GROUP VS. THE REFERENCE GROUP

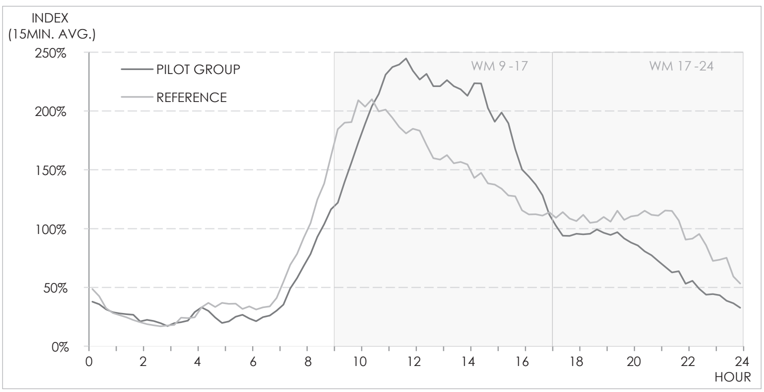
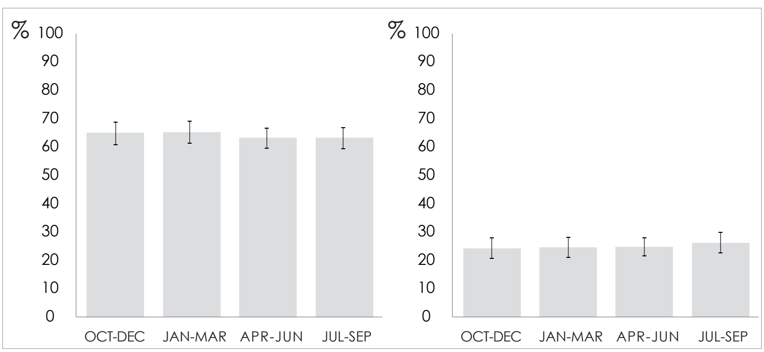


FIG.6.6 AVERAGE VALUES (WITH CI 95%) OF WM9-17 (LEFT) AND WM17-24 (RIGHT)



	F	N	MEAN			
			T_0	T_1	T_2	T_3
Washing Machine	12.78**	155	4.01	3.46^A	3.48^A	3.41^A
Dishwasher	4.35*	128	3.67	3.26^A	3.43	3.30^A
Tumble dryer	9.14**	75	3.83	3.21^A	3.12^A	3.01^A
Charging appliances	24.00**	141	2.80	2.01^A	2.01^A	1.90^A
Other cleaning appliances	17.32**	142	2.51	2.01^A	1.89^A	1.94^A
Other kitchen appliances	31.92**	140	2.13	1.54^A	1.49^A	1.52^A
Entertainment	33.76**	133	1.92	1.31^A	1.42^A	1.32^A
Work related appliances	23.37**	123	1.86	1.33^A	1.37^A	1.33^A

TABLE 6.2 REPEATED MEASURE ANOVAS ON REPORTED SHIFTING BEHAVIOUR OF T_0-T_3. * INDICATES P <.05 AND ** INDICATES P <.001. SIGNIFICANT DIFFERENCE (BONFERRONI POST HOC TESTS) WITH T_0 IS INDICATED BY ^{A}

The effect of time on this demand shift was assessed by a repeated measures ANOVAs (Bonferroni) using four quarters (1: October to December, 2: January to March, 3: April to June and 4: July to September). No effect of time was found for the demand shift ($F_{WM\ 9\text{-}17}$ (2.73, 383.55) = .91, p=ns; $F_{WM\ 17\text{-}24}$ (2.77, 384.40) = .77, p=ns), indicating a stable behaviour change (see Figure 6.6).

To investigate the demand shift of households with other appliances than the washing machine, we also asked participants to indicate if they (intended to) shift other appliances. Mostly the washing machine, tumble dryer and dishwasher were reported to be shifted (see Table 6.2).

Also for the self-reports, we have assessed the effect of time. By performing repeated measures ANOVAs with Bonferroni post hoc tests on the self-reports, we found a significant difference between T_0 measurements of all appliance shifting behaviour and the other questionnaires (except the reported shifting behaviour of the dishwasher in T_2 , which was not significantly different from the intention to shift). No significant differences were found between T_1, T_2 and T_3 (see Figure 6.7 and Table 6.2). This indicates that respondents were overly optimistic about their shifting behaviour upfront, because their intentions were significantly higher than their behaviour reports. Moreover, no effect of time was found for the behaviour reports, again indicating a stable demand shift.

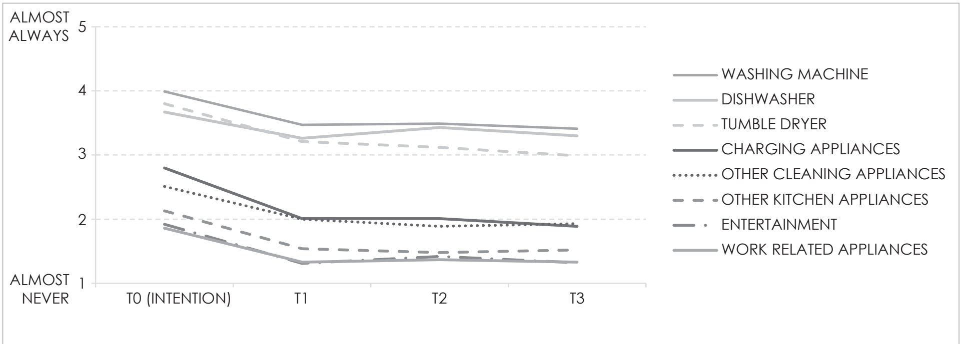


FIG.6.7 HOW OFTEN DO YOU (EXPECT TO) SHIFT (THE) ...

We investigated the value of reported intentions and the behaviour reports in our research by comparing the reported washing machine shifting with the actual timing of using the washing machine with correlation analyses. Intention to shift the washing machine (T_0) did not show a significant relationship with the washing machine demand during the day (r_{T0} = -.11, p = *ns*) nor during the evening (r_{T0} = .02, p = *ns*). Hence, no relation is found between intentions and actual behaviour. Indeed, intentions are known to deviate strongly from real behaviour (Kollmuss and Agyeman 2002).

The reported washing machine shifting was related to WM 9-17 (r_{T1} = .24, r_{T2} = .33, r_{T3} = .24, p <.01), indicating more electricity use during moments of sun when participants reported to shift the washing machine, and to WM 17-24 (r_{T1} = -.26, r_{T2} = -.42, r_{T3} = -.36, p <.001), indicating less electricity demand during the evening when participants reported to shift the washing machine. Although significant, these correlations are not strong, because it means that between 94% and 89% of the washing machine demand during the day (WM 9-17) and between 91% and 82% of the washing machine demand during the evening (WM 17-24) remains unexplained. These results indicate that the behaviour reports of this study are of limited usefulness in gaining insights in objective behaviour. This finding is in line with the finding of Kormos and Gifford (2014) who found that 79% of the variance in the association between self-reported and objective pro-environmental behaviour remained unexplained.

Last, we investigated the way participants of Meulenspie evaluated the fully autonomous demand shifting capability of their smart heat pump. The default of the smart heat pump was set on smart operation.

In October 2014, 33 out of 38 (87%) heat pumps were still operated by the smart planning function. Nevertheless, the option to switch of the smart planning function of the heat pump was highly valued ($M = 4.0$, $Sd = .95$). Participants agreed that the smart planning function of the heat pump was beneficial for them ($M = 4.24$, $Sd = .50$). Furthermore, participants indicate to find it important to continue to shift other appliances, such as the washing machine ($M = 2.35$, $Sd = .81$).

6.2.2. USE OF THE EMS

In this study, we see that the EMS is used a couple of times a week (Median = 117 use cases per household over 365 days). We investigated the effect of time (four time periods 1: October to December, 2: January to March, 3: April to June and 4: July to September) by performing a Friedman's ANOVA test on the dependent measure: use frequency. The UF did significantly change over time, $\chi^2(3) = 48.24, p < .001$. Wilcoxon tests were used for post hoc testing with a Bonferroni correction (effects are reported at a .008 level of significance). A significant difference was found between the last period and all other periods ($T_{period1} = 8995$, $T_{period2} = 7669$, $T_{period3} = 8341$). In the last period ($Median_{period4} = 31.5$), the UF was significantly lower than in the other periods ($Median_{period1} = 45$, $Median_{period2} = 42$, $Median_{period3} = 44$). However, because the first nine months showed a stable UF, it is more likely that the decline is related to the summer holiday period, in which the data of the last period was collected.

We investigated whether there is a relation between use frequency of the EMS and electricity use during favourable moments. Bivariate Spearman's correlations indicate that when participants use the EMS more frequently, they use less electricity with their washing machine peak during moments ($r_{WM17\text{-}24} = -.43, p < .001$) and use more electricity during hours of sun ($r_{WM17\text{-}24} = .34, p < .001$). This is a positive relationship between use frequency of the EMS and the shift in demand of electricity, indicating that when participants use the EMS more often, demand shifting performance improves. This result is in line with the results of Chapter 2.

Furthermore, we can derive from the data in the database on which moments the EMS was used and which screens were used. We can see in Figure 6.8 that the EMS is mostly used in the morning and in the evening throughout the week and mostly during the day in weekends.

In Zwolle, the home-screen of the EMS contained several elements, such as feed forward for the first 12 hours and simple feedback. The more detailed information was hardly used compared to the information provided on the home-screen. In Breda, users had to navigate through the interface for specific information. Therefore, the design of Breda provides us with more detailed insights in the information elements of the EMS used. We can see that mainly the feed forward is used in

FIG.6.9 USE OF THE EMS THROUGHOUT THE DAY

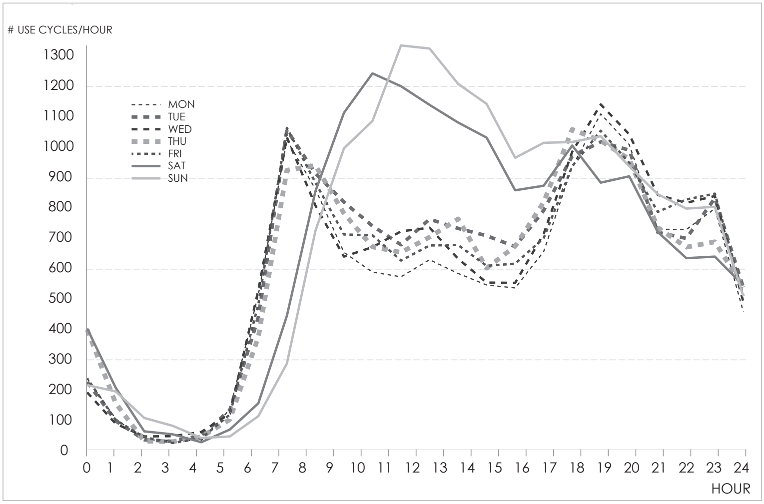
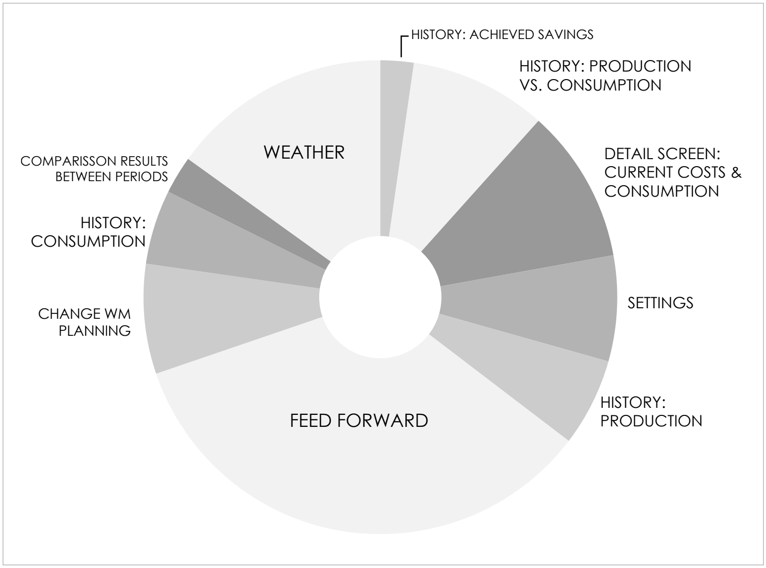


FIG.6.8 PERCENTAGE OF TOTAL NUMBER OF TOUCHES PER SCREEN BREDA



Breda and the weather screen (also providing a detailed forecast on solar production) (see Figure 6.9).

The results of the questionnaires are in line with the results from the analyses on the collected data on EMS use. When we ask participants to report about the typical moments they use the EMS (see Table 6.3 for an overview), we can see that the EMS is mostly used before using a heavy consuming appliance, to check the forecasts for planning when to use this appliance or to investigate what this appliance consumes. Other typical moments entail (1) when coming home from work to check the forecasts or the feedback on the solar production, (2) when the sun is shining to see what the solar panels are producing now and (3) when getting up in the morning to check the forecasts for the day. Hence, the feedback and feed forward on solar energy, the feed forward on dynamic prices for scheduling the use of heavy consuming appliances are the main purpose of using the EMS.

Last but not least, it is interesting to investigate who uses the EMS. In previous studies, we have seen that EMSs are mostly used by the respondents (mostly men) themselves and to a lesser extent by other residents in the households, hindering a positive dialogue around energy use at home (Van Dam et al. 2012). In this study, respondents use the EMS most often as well. Respondents report to use the EMS several times a week (M = 4.28, Sd = 1.51). However, respondents also report that the EMS is used once to several times a week by partners (M = 3.52,

TABLE 6.3 TYPICAL MOMENTS FOR USING THE EMS

CATEGORY	NAMED BY … % OF RESPONDENTS
Before/when the dishwasher, washing machine, dryer or other heavy using appliance is used	36%
When coming home	15%
When the sun is shining	14%
In the morning	12%
In the evening	11%
When passing by	7%
When leaving home	6%
To show visitors	4%
Before bedtime	4%
Other	9%

Sd = 1.92) and now an then by children ($M = 2.12$, $Sd = 1.79$), indicating that other members of the household are also using the EMS besides the respondent.

6.2.3. SELF-REPORTED DRIVERS FOR CHANGE

First, it is important to note that participants perceived that little investment in terms of time and effort was required ($M_{T1} = 4.09$, $Sd_{T1} = .61$), indicating that participants perceive that YEM is rather simple to use.

We investigated the perceived reasons to shift demand by asking how important different reasons were to the participants. First, we investigated what participants perceive as most important for a demand shift by a repeated measures ANOVA. Spending less money on energy is perceived as the most important reason to shift demand (significantly more important than all other motivations in T_1: $p < .001$ and T_3: $p < .001$). This finding is in line with the research of Watson et al. (2002), who argued that price is an important argument for behaviour change.

TABLE 6.4 MEANS SORTED FROM HIGH TO LOW ON THE VALUE OF T1. A INDICATES SIGNIFICANTLY HIGHER THAN OTHER MOTIVATIONS. B INDICATES SIGNIFICANTLY LOWER THAN OTHER MOTIVATIONS. INCLUDES THE T-STATISTIC OF A PAIRED T-TEST (DF = 187) ON THE EFFECT OF TIME ON MOTIVATION TO SHIFT. * INDICATES *P*<.05 AND ** INDICATES *P*<.001

	MEAN		
	T_1	T_3	*t*
Spend less money on energy	4.29[a]	4.29[a]	-.10
Getting in control over my energy use	3.98	3.90	1.13
Trying out a new technology	3.97	3.80	2.69*
Using my own generated energy more efficiently	3.88	3.73	2.53*
It is a challenge	3.73	3.43	4.06**
Less environmental pollution	3.68	3.73	-.88
It is fun to do	3.71	3.39	4.77**
Secure the future for next generations	3.65	3.51	2.22*
The depletion of energy resources	3.64	3.51	2.13*
It gives me a good feeling	3.64	3.51	1.98*
Out of curiosity	3.62	3.36	3.75**
Taking social responsibility	3.48	3.43	1.11
Feeling more independent	3.12	3.18	-.88
A shared effort of the neighbourhood	2.97	2.68	4.08**
Doing better than other participants	2.57[b]	2.37[b]	2.72*

Doing better than other participants is perceived least important of all (significantly less important than all other motivations in T_1: p <.001 and T_3: p <.001). Participants in Chapter 2 named a normative comparison would help them, but we did not include it in this study, because of the limited usefulness that was found in previous studies (Fischer 2008). It is possible that doing better than other participants gains perceived importance when a normative comparison is included.

We also investigated the effect of time by measuring the importance of the different reasons on two different moments in time and by performing paired samples t-tests. As expected, mostly the motivations related to fun and newness wear a bit off (see Table 6.4).

We performed another repeated measures ANOVA for exploring important contextual features (see Table 6.5). This time, it is less obvious, which contextual element was perceived most important. The respondents reported that the EMS and the solar panels are perceived most important (the EMS was perceived significantly more important than all other contextual elements p <.001, but the PV installation p = *ns*). Other people were perceived least influential (both other residents and neighbours were perceived significantly less important than all other contextual elements: p <.001).

After investigating these self-explanations, we investigate which perceived drivers make the difference, because according to Nolan et al. (2008), people are unable to explain the real causes of their energy saving behaviours. We performed correlation analyses which are presented in Table 6.6 (motivations in T_1 and T_3) and Table 6.7 (the perceived influence of the contextual features measured in T_2).

	MEAN
EMS	3,92[a,b]
My solar panels	3,88[b,c]
Smart appliance	3,61[c,d]
Tariff	3,52[d]
Bill	3,32[d]
Communications and user support	2,73[e]
Other residents	2,33[f]
Neighbours	2,20[f]

TABLE 6.5 PERCEIVED INFLUENCE OF DIFFERENT CONTEXTUAL FEATURES ON A DEMAND SHIFT. MEANS SORTED FROM HIGH TO LOW. CHARACTERS A-F INDICATE SIGNIFICANT DIFFERENCES BETWEEN MEANS.

TABLE 6.6 PEARSON'S CORRELATIONS TABLE OF DIFFERENT MOTIVATIONS IN T1 AND T3 AND ELECTRICITY USE OF THE WASHING MACHINE DURING FAVOURABLE MOMENTS

	T_1		T_3	
	WM9-17	WM17-24	WM9-17	WM17-24
Spend less money on energy	.05	-.04	.01	-.02
Getting in control over my energy use	0.13	-.06	.09	-.08
Trying out a new technology	.07	.03	-.03	.08
Using my own generated energy more efficiently	.19*	-.18*	.22*	-.23*
It is a challenge	.10	-.08	.16	-.18*
Less environmental pollution	.24*	-.23*	.10	-.11
It is fun to do	.17*	-.12	.16	-.17*
Secure the future for next generations	.15	-.16	.13	-.13
The depletion of energy resources	.20*	-.22*	.19*	-.19*
It gives me a good feeling	.22*	-.18*	.18*	-.22*
Out of curiosity	.06	-.01	-.01	.03
Taking social responsibility	.13	-.16*	.09	-.15
Feeling more independent	.07	-.10	.13	-.14
A shared effort of the neighbourhood	.05	-.03	-.04	.02
Doing better than other participants	.08	-.07	.11	-.07

TABLE 6.7 PEARSON'S CORRELATIONS TABLE OF DIFFERENT CONTEXTUAL ELEMENTS AND ELECTRICITY USE OF THE WASHING MACHINE DURING FAVOURABLE MOMENTS

	WM9-17	WM17-24
EMS	.09	-.10
My solar panels	.40**	-.35**
Smart appliance	.17*	-.19*
Tariff	.27*	-.21*
Bill	.15	-.13
Communications and user support	.24*	-.15
Other residents	.12	-.12
Neighbours	-.04	.08

We can see that some reported motivations correlate with demand shifting. The three motivations that correlate with both WM9-17 and WM17-24 and correlate in both T1 and T3 are: to use own generated energy more efficiently, that it gives a good feeling and to take care that energy resources deplete less. Regarding the perceived influence of the contextual elements, we can conclude that the presence of the solar panels is important for change, but also the communication and user support, the tariff and the presence of the smart appliance.

6.3. DISCUSSION

This study investigated the development of new habits around shifting demand and using the EMS by a longitudinal approach. In line with Chapter 5, the washing machine use of the participants is higher when electricity is locally produced and lower during the evening compared to a reference group and remained stable over time. Furthermore, we asked participants to indicate if they shifted other appliances. Participants reported that they do shift the tumble dryer and dishwasher next to the washing machine. This reported shifting behaviour was also stable over time. The behaviour reports on shifting the washing machine showed to be of limited usefulness in predicting the objective shifting behaviour by the washing machine. This finding is in line with the results of the review study of Kormos and Gifford (2014), who found that 79% of the variance in the association between self-reported and objective behaviour remained unexplained. Nevertheless, it is likely that shifting behaviour, like performed with the washing machine, is also performed with the tumble dryer and dishwasher, as participants indicated they shifted the demand of these appliances.

The intention to shift demand had no significant explanatory power whatsoever regarding the actual use of the washing machine. Participants in our study were overly optimistic about their demand shifting behaviours upfront, which is a common phenomenon (Kollmuss and Agyeman 2002). Many prior studies did not have the opportunity to measure actual behaviour and relied on intentions (Timpe 2009, Gyamfi & Krumdieck 2011, Mert et al. 2008, Stamminger et al. 2008, Broman et al. 2014). Investigating intentions seems like an affordable, but less valid, way to investigate behaviour.

Besides investigating a demand shift of the washing machine and other manual efforts to shift demand, we investigated the smart use of the heat pump. Participants indicated that the smart planning function of the heat pump was highly valued, which reflected in the finding that 87% of the heat pumps were operated by the smart planning function. Still, the option to switch the smart planning function off and on was highly valued. This means that households must have the option to switch off the smart planning function to reduce perceived risk (see Chapter 4), but when they are satisfied with the operation and can see the advantages, they will leave it switched on. Last, though the smart heat pump can shift a large share of the electricity demand of a household without any effort of the user, participants still indicated that they felt it was important to continue to shift other appliances such as the washing machine besides the heat pump. Hence, shifting a large electricity guzzler such as the heat pump automatically, does not mean that shifting electricity demand of other appliances, which requires more effort, feels useless.

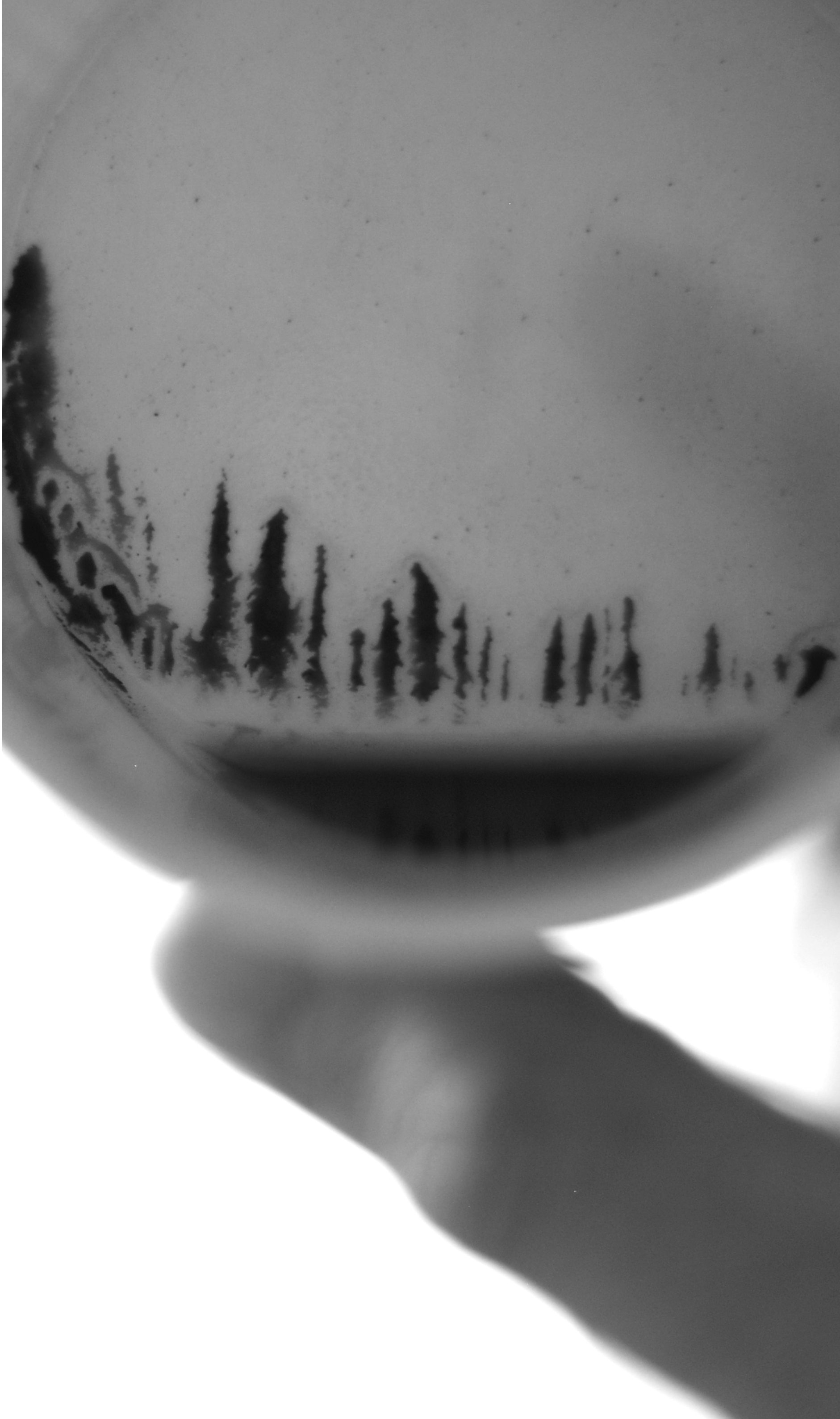
The most important reason according to participants for shifting electricity demand is spending less money on energy. Irrespectively of the true influence of a financial motive on energy shifting demand, this finding means that a dynamic tariff is indeed important for a behaviour change, because people perceive a financial advantage as most important. We do not think that people make a truely rational cost-benefit analysis of the money saved compared to the effort needed, because the amounts of money saved were limited. This finding implies that it is important that the financial incentive feels rewarding and that the price differences are presented in an appealing way. Designers should look for ways to present the pricing scheme so it can positively influence a rewarding feeling.

Furthermore, we investigated the effect of time and discovered an erosion of certain motivations. As expected, the motivations related to fun wear a bit off. Gamification is named as an important opportunity to involve users in energy saving behaviours (e.g. Geelen et al. 2012). Though gamification is a good opportunity to involve users in the first place, strategies to involve users in the long run are needed, as it is expected that fun wears off. Regarding a gaming element, we have found that doing better than other participants was perceived least important. It is possible that the perceived importance of this motivation increases when a normative comparisson is included, creating another driver for change.

A decrease of the use frequency of the EMS over time found by previous studies was related to users loosing interest in the EMS during the course of a study (e.g. Van Dam 2010, Hargreaves et al. 2013). As more or less the same routines are performed every day, chances are that people will have the feeling that they have learned to understand their patterns of demand and do not need the EMS anymore. Like the study in Chapter 2 on energy demand reduction, we revealed a positive relationship between use frequency of the EMS and the shift in demand of electricity. This means that use frequency of the EMS is both important for a demand reduction as well as for shifting demand. In contrast to the results of Van Dam et al. (2010) and Hargreaves et al. (2013), we see that the EMS is used frequently in the long run: on average several times a week. A possible explanation for the persistent use of the EMS in this study compared to studies that investigated a EMS for demand reduction might be that the EMS for a demand shift provides new information every day: a forecast on the dynamic tariff and on the expected solar production, so there is a reason to keep using the EMS. These moments of use of the EMS also provide the opportunity to give more feedback on demand.

Furthermore, we have found that residents feel highly influenced by the presence of their solar panels to shift electricity demand. This is an interesting result, because more and more households start to produce their own energy. To get householders really involved with the task of making the energy system more sustainable, it is not only important to support them to buy their own PV-installation, but it is also important to offer them insight in and forecasts on what their installation provides them. It seems that households even gain interest in abstract concepts such as kWhs when they start producing their own energy.

The next chapter, Chapter 7, will elaborate on all the findings and research implications of this thesis and includes suggestions for further research.



07

PHOTOGRAPHY:
LOOKING AT NATURE
IN 'KOFFIEDIK'

CHANGE TO RETAIN

The role of design in behaviour change for a brighter future

And finally, this last chapter summarises the main findings and implications of this thesis: the opportunities for households and energy companies and the design rules for smart energy product developers. We elaborate on suggestions for further research and discuss that the value of our research differs for possible futures. We close this chapter, and thereby this thesis, by some concluding thoughts.

The research presented in this thesis investigated how households can be encouraged to shift electricity demand away from peak moments, to moments of (local) sustainable electricity production. We focused on the way households interact with smart energy technologies and how the design of technologies influences more desirable habits regarding energy use at home. The most encouraging finding of this thesis is that households are willing and able to cooperate in demand shifting in the long run, when they are facilitated by the right designs. This is an important result, because previous research concluded that lasting behaviour change is difficult (e.g. Abrahamse et al. 2005, Van Dam et al. 2010, Hargreaves et al. 2013). The dominant conclusion of prior research is that people eventually fall back into their old energy inefficient habits. Our research demonstrates that good design can permanently change behaviour into more sustainable behaviour.

We started this research with a quantitative explanatory field study on the value of design for reducing energy demand at home. We concluded that real-time feedback given by an EMS can only be effective over time if households remain using the EMS frequently, which means that a EMS must be easy to use and accessible. Thereafter, we aplied an exploratory sequential mixed methods approach to investigate the main topic of this thesis: shifting electricity demand away from peak moments, to moments of (local) sustainable electricity production. Our qualitative field study examined the factors that influence the likelihood that people will shift their electricity demand to match local sustainable supply of electricity. Important insights from these two studies were used to develop the quantitative follow-up. In a large scale field study, we explored the electricity demand shift of households in time. We found that households shifted their usage of the smart washing machine mostly to midday when the sun is shining and electricity is produced by their own solar panels. Households who regularly used automation of the smart washing machine, also shifted the timing of using the washing machine away from the evening to the night. We also investigated the shifting behaviour of other appliances than the washing machine and the habitual use of the EMS. Participants reported that they shift the tumble dryer and dishwasher besides the washing machine. Like for demand reduction, we revealed a positive relationship between use frequency of the EMS and the shift in demand of electricity. The results remained stable, indicating a structural shift in demand. Figure 7.1 gives a visual overview of our findings.

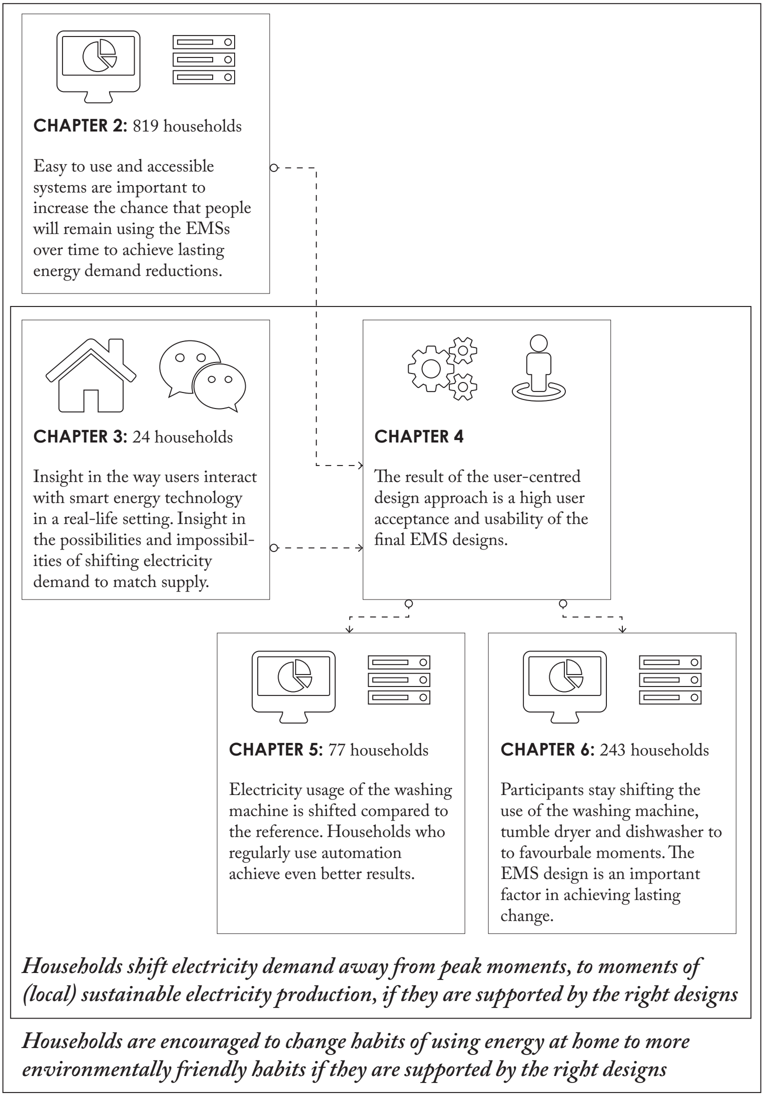


FIG.7.1 VISUAL OVERVIEW OF OUR RESEARCH FINDINGS

7.1. THE SOCIETAL AND SCIENTIFIC RELEVANCE

It is important to change the way we produce and use energy to save our environment and retain our level of welfare. Progress on energy efficiency has been striking during the course of this research. For example, solar panels came closer within everyone's reach* and there is almost no car producer left without an electric car in its portfolio. Still, energy efficiency targets are by far not met in the Netherlands. According to the National Energy Exploration report (ECN et al. 2015), the energy supply of the Netherlands is still largely based on fossil fuels and has relatively high CO_2 emissions, which have hardly reduced since the 90's. A solid long-term plan seems to be lacking. In our neighbouring country Germany, long-term goals support cooperation on shared priorities bringing them faster towards a low carbon economy. Cooperation is needed in realising major changes, which will have consequences for society as a whole.

One of the major changes needed is the way energy is used. Without changing the way energy is used, more renewable energy does not automatically result in a low carbon energy system as wind and solar energy are fluctuating and back-up production based on fossil fuels is needed. One of the main ideas behind a large-scale deployment of smart grids is the opportunity to make optimal use of renewable energy by matching demand to supply conditions. This way, smart grids facilitate the energy transition towards a sustainable society that is less dependent on fossil fuels. However, uncertainties regarding households' willingness and possibilities to cooperate in the task of making the energy system more efficient is one of the most important reasons of the growing number of smart grid initiatives in Europe (Covrig et al. 2014).

This research does not give direct insights into the economical and societal implications of smart grids, because these implications depend of other developments like the further introduction of the electric car (see par. 7.4). However, until now, researchers that did investigate these implications had to work with assumptions on the willingness and ability of households to shift demand in time. We concluded, that supported by the right designs, households have indeed shown to be willing and able to cooperate in making the energy system more efficient, even in the long run. This insight is important for the societal and scientific debate on the possibilities and impossibilities of smart grids. The research presented in this thesis demonstrated the value of good design for achieving a change in the patterns of energy demand at home in the long run.

* For example, PV panels are now for sale at IKEA

Lately, the power of design to increase desired behaviour is gaining interest of scholars. Many different applications are tested (e.g. Wever et al. 2008, Bhamra et al. 2011), design guidelines and toolkits are developed (e.g. Lockton et al. 2010, Tromp 2013, de Kuijer 2013) and ethical issues are assessed (Dorrestein 2012). Tromp (2013) argued that designers have always had an influence on how people behave. In line with her ideas, Dan Lockton was giving a presentation and claimed: "Underneath every design lies an hypothesis of how people will behave". The question arises: how can this level of influence be used to reduce the impact on our environment specifically? Applying the insights from research in a large project collaborating with several companies was needed for the further development of the field of design for sustainable behaviour specifically (Daae 2014). We have assessed the value of design in a large project collaborating with several companies by applying knowledge from the field of design for sustainable behaviour with a UCD approach in the field of smart grids. The UCD approach was considered very useful to understand the perceived benefits, risks, complexity and investments needed, and to develop products that fit user needs that are able to change behaviour. Moreover, we contributed to the literature of design for sustainable behaviour, because our focus was to achieve changes that lasted. We have had the opportunity to investigate how households use the smart energy technology over time and how more desirable habits were formed. The longitudinal approach of this large scale, real-life field test is - to the best of our knowledge - unique in the field of design for sustainable behaviour. We contributed to this research field by showing the power of its application, even in the long run. The next paragraph discusses the relevance and the implications of our findings per audience.

7.2. MAIN FINDINGS AND IMPLICATIONS PER AUDIENCE

The relevance and meaning of our findings differ per audience. Therefore, we discuss the value of our main findings for the two different sides of the value chain: for households and for energy companies. Furthermore, we argue that the value for both sides depends on good design of smart energy technologies. We provide general recommendations for good design of these technologies to successfully facilitate changes in patterns of energy demand.

7.2.1. OPPORTUNITIES FOR HOUSEHOLDS

In theory, smart grids can provide households with the opportunity to save money and/or to participate in making the use of energy more sustainable. In addition, the infrastructure gets more reliable when energy demand becomes more predictable by increased information on energy flows, so there is less chance of disruptions.

However, for many households it is generally difficult to change patterns of consumption, even when the household is motivated to do so. According to Huijer (2013), western society lives in an age of abundance and it is difficult to have the discipline to reduce consumption*. She argues therefore that people can outsource this discipline to other human beings and/or to technology.

In line with abundance and the accompanying difficulties of changing patterns of consumption, is that the Dutch energy supply system is fully designed for unimpeded access to energy (see Chapter 1). To deal with this abundance, smart energy technologies can indeed help households to change patterns of energy demand to more affordable and sustainable patterns of demand in different ways. At one side of the spectrum is the fully automatic technology: the investment in terms of time and effort to change patterns of energy demand is relatively little, hence little discipline is required. The household only decides once to invest in the technology or to install a setting. Furthermore, when designed well, the technology is the most efficient decision maker for using energy efficiently. However, the investment is often higher at this side of the spectrum. For example, fully automatic thermal or electrical buffering requires physical space in the home, the technology needed can be more expensive and the feeling of being in control reduces when everything happens fully automatic in a black box (Rijsdijk and Hultink 2003, Geelen et al. 2013).

At the other side of the spectrum, smart energy technologies can facilitate a behaviour change by disrupting the stable context in which households consume energy (Verplanken and Wood 2006). In other words, related to the ideas of Huijer (2013), smart technologies can help to consume energy with more discipline. This side requires a larger investment of the household in terms time and effort, but the household even increases control over its own energy consumption. For example,

* This might explain the success of the Japanese guru of tidiness, Marie Kondo, in our western society. More than two million copies of her book *The Life-Changing Magic of Tidying Up* (2015) are sold worldwide already.

the household receives perfectly timed and understandable feedback on patterns of demand and feed forward on the availability of energy and plans when to use appliances most optimally. This form of in between automaticity is called semi-autonomous in this thesis.

Our research has shown that when smart energy technologies are designed well, households are indeed facilitated to use energy in a more efficient way and by that have the opportunity to save money and to use energy in a more environmentally friendly manner. We argue that when the design of smart energy technologies is done right, the technologies create a natural balance between the perceived investment needed and the perceived advantages of change. To make optimal use of these smart energy technologies, households need to have confidence in the technology. Only the designs that really help households in making patterns of energy consumption more sustainable and affordable and are privacy friendly, will obtain the confidence of households.

7.2.2. OPPORTUNITIES FOR ENERGY COMPANIES

At the other side of the value chain, smart grids are able to make the operation of the energy system more affordable for the customers of energy suppliers and grid operators. However, I have noticed during my time in the energy sector that there is little confidence of energy companies in their customers' willingness to be involved in a transition towards a more sustainable energy system. The chief executive director of Good Energy, Juliet Davenport, once asked the audience at a conference, whether it was the customers who did not trust energy companies, or was it the energy companies who did not trust their customers. I believe it was her response to the complaints about a lack of trust of customers towards energy companies and complaints on the low interest in energy as a product.

Our research has given an encouraging example that customers are willing to be involved in a transition towards an affordable and more sustainable energy system. Results demonstrated a structural shift in demand. Households shifted the usage of the smart washing machine mostly to midday when the sun is shining. The big energy efficiency gains are not achieved by shifting the demand of appliances such as the washing machine (Widén 2014). Nevertheless, our research has shown the willingness and ability of households to change patterns of energy consumption in the long run. This is a valuable insight, because it gives a positive outlook for the possibilities of shifting large electricity consuming applications, such as electric cars and heat pumps that are now entering the market. The potential investment savings by shifting the electricity demand in residential areas is calculated to be running in the billions of Euros (e.g. Erdinc 2014, Veldman et al. 2013, Rastegar et al. 2012, Finn et al. 2013, Faruqui et al. 2010a). A shift in the use of relatively small electrical appliances is a good way to educate households about demand and supply balancing difficulties and to start involving households in releasing the potential benefits for both sides of the value chain. The smart meter is now installed in many European households, but on itself the smart meter only provides the opportunity to save operational costs of meter readings. As Faruqui et al. (2010a) stated, the economic potential of smart meters is much larger. When the smart meter is coupled to new tariff structures and user-friendly energy saving or shifting technologies, this potential can be unlocked.

Besides smart energy technologies, new tariff structures need to be designed by energy companies. Previous studies have demonstrated the positive effect of new tariff structures (Faruqui et al. 2010a, Gaiser & Stroeve 2014,Thorsnes et al. 2012, Bartusch et al. 2011, EPRI 2008, Newsham & Bowker 2010, Bartusch & Alvehag 2014). However, it is a difficult task to design a tariff that is both stimulating the right behaviour and at the same time, reflects the actual benefits for energy companies. Our design of the dynamic tariff was apparently able to motivate change. However, we noticed by the number of questions upfront, that the tariff structure was often difficult to explain. A first relatively simple and understandable step in an altered tariff structure is eliminating net metering. Net metering in the Netherlands entails that the supply of electricity back to the grid has the same value for households as the electricity that is taken from the grid. This step is important towards financially stimulating self-consumption of on-site generated electricity (Widén 2014). In Germany, where the feed-in tariffs changed recently, battery packs to increase self-consumption are becoming interesting.

Last but not least, stimulating customer loyalty by making a difference as an energy supplier is a hard job, as energy is a convenience good, a mean to an end (Watson et al. 2002). Energy falls under the category of dissatisfiers for which low performance (or absence) can cause dissatisfaction, yet, higher levels do not increase satisfaction (Cadotte and Turgeon 1988). Providing smart energy technology and new pricing schemes as a service for households to unlock the potential benefits (e.g. affordability) for households can be an opportunity to make the difference.

7.2.3. DESIGN RULES FOR SMART ENERGY TECHNOLOGY DEVELOPERS

The advantages named for both households and energy companies can be accomplished when the technologies that have to facilitate more energy efficient demand are designed well. As stated before, a balance between the perceived investment needed and the perceived advantages of change in the household needs to be created by good designs. As the perceived advantages of changing patterns of energy demand are often limited for households, smart energy technologies must be made attractive and user-friendly. For example, our findings of Chapter 2 demonstrated that merely providing real-time feedback by an EMS is insufficient to promote energy-saving behaviours. An EMS needs to be used frequently in order to become and remain effective. Therefore, the EMS should be designed for high accessibility and ease of use. We show in our research that a user-centred approach is necessary to achieve good designs. Moreover, close cooperation between different disciplines is essential to make the designs technically feasible, viable and desirable. This paragraph provides general design rules for smart energy technology development teams to deliver good designs. For a more specific design brief, we recommend reading Chapter 4.

Rule 1: Keep it simple | The most important design rule of all is to keep it simple. It is ironical how many products are called smart while it is impossible for many users to see how they can make good use of these products. Extra features might seem as extra unique selling points for the technology in advertisements. And indeed, research demonstrates that in the perspective of a potential user, extra features are valued (e.g. Synovate 2010; Fischer 2008; Bonino et al. 2011; Karjalainen 2011). However, the result of too much information and functionalities can be confusion and distraction, which is devastating for the user experience (e.g. Wood and Newborough 2007). As a blogger once wrote beautifully about *de Toon*, an EMS that is in my eyes one of the most user-friendly EMSs available on the market: "a product by techies, for techies." It seems that even this EMS remains too complicated because few choices have been made in terms of what functionalities to implement and what information to show.

Furthermore, we have experienced that making something easy to understand, is difficult for the development team. The possibility to collect stars in Zwolle, for example, where users could set a goal and receive stars for reaching their goal, cost a lot of time and effort. The interface element was seen valuable, because it gave users a quick and easy interpretable insight in their performance. However, it was difficult to turn it into an appropriate reward for the desired behaviour and to make it understandable.

To make sure users understand the designs, usability testing along the way is crucial. Testing does not have to imply an expensive large scale research. Just asking a few people how they evaluate and interpret the designs during the development phase can be enough. Experience shows that it is better to spend time and money on testing often on a small scale, than on testing with a large group once (e.g. Brown 2009; Ries 2013).

Rule 2: It is all about timing | Behavioural change can be achieved by well-timed and personal feedback and feed forward and by the provision of spot on behavioural alternatives (e.g. Fogg 2003, Thaler and Sunstein 2008). It is important that the EMS automatically switches on by a single touch so it can give immediate feedback and feed forward when the user asks for it. When users have to put too much effort in acquiring feedback and feed forward it is likely that they will stop using the EMS. In the studies of Chapter 2 and 6, use frequency of the EMS was found to be important for lasting behaviour change. In this respect, it is important that the EMS remains visible. Of course, the EMS will not have the same aesthetic appeal to residents like a piece of art they own. However, when an effort is made to make the EMS as nice looking as possible, it is more likely that the EMS gets a central location in the house, which is important for habit formation (Hargreaves et al. 2010).

Rule 3: One size of autonomy fits none | Different appliances in the household need different automation designs, because user needs around using these appliances are different. In Chapter 1, we have explained that different levels of autonomy are needed for different ways of using energy. We explained that fully autonomous designs are suitable for continuous energy demand and that semi-autonomous designs are suitable for non time-critical demand. However, more nuances are needed in the design of autonomy. For example, a smart washing machine will need a different design than a smart dishwasher. Both are semi-autonomous designs, but for the washing machine, the finishing time is often more important than for the dishwasher, because people do not want to leave their centrifuged clothes in the washing machine for too long. For this specific issue, a solution can be that the moment of heating the water is planned during moments electricity supply is abundant, because heating uses most electricity. Centrifuging can then take place right before the ultimate finish time.

Furthermore, different households have different needs for automation. For example, in Chapter 3, we have found different perspectives from households on automaticity. Some found it rather useless or even inconvenient to let the washing machine schedule automatically, while other participants asked for more appliances that could operate automatically. It is interesting however, to look for ways to increase the use of automation, because in Chapter 5, our findings showed that households who used automation achieved better results. However, the smart planning function was only used 18% of the time. A few degrees of freedom in the way the autonomy works for the user might help. For example, the smart washing machine in this study automatically searched for the best moment to start within a 24 h time frame. Possibly, an adaptable default setting for this time frame may increase use. We developed an option to switch this function off entirely, to offer the freedom of using the smart planning function of the heat pump. This option was highly valued by participants, though most participants did make use of the smart function of the heat pump.

Last, automation must be designed to enhance human performance and to make it easier for people to change patterns of energy consumption. It is argued by Rijsdijk and Hultink (2003), however, that higher levels of autonomy increase perceived risk. Developers can reduce perceived risk through the design, for example, by providing feedback on the status of the appliance and the option to interrupt actions of the appliance at any time.

Rule 4: Find ways to engage users in the long run | In Chapter 6, we demonstrated that the EMS was used frequently: on average more than once a day, which remained stable over time. In Chapter 2 and 6 we have seen that use frequency of the EMS is necessary for long-term changes in demand. A possible explanation for the persistent use of the EMS in Chapter 6, is that compared to studies that investigated a demand reduction, the EMS in our study provides new information every day. Feedback on energy demand is more or less the same every day, but forecasts on the dynamic tariff and on the expected solar production change. Hence, there is a good reason to use the EMS every day. Furthermore, we concluded in Chapter 6 that households seem to gain interest in an abstract concept, such as the kWh, when they start producing their own energy. Therefore, we conclude that it is essential that households get insight in and forecasts on what their PV-installation provides them.

Another possibility to engage users is the feeling of achievement and acknowledgement. People are more likely to continue a certain behaviour when they feel acknowledged for their efforts (Lockton et al. 2010). Partly, this feeling is covered by a financial reward in the field study Your Energy Moment. In Your Energy Moment in Zwolle, stars were included that gave a quick indication of reaching the self-set goal of using electricity on the right moments. Moreover, Chapter 3 puts forward that it is perceived effective to reward the use of the washing machine during hours of sun by giving points. Moreover, a Belgian field study (Vanthournout et al. 2015; D'hulst et al. 2015) rewarded the use of the automated planning function of the washing machine directly, which resulted in higher levels of using the automated smart planning function than we have found in Chapter 5. Therefore, it is likely that rewarding the use of the automated planning function of the washing machine directly, can increase the use of the automated function.

Rule 5: Respect privacy | Last, as the amount of data collected increases, privacy and data security issues start to form a risk. The increased awareness by the general public of their right to, and the value of, their privacy makes it ever more important that developers take privacy into account (Kobsa 2002). Privacy design principles abstracted from the legal code have been developed by Patrick and Kenny (2003). The principles require that users comprehend why, are aware that, and are able to control how their personal data is send and handled to realize an agreement. Chapter 4 demonstrated that the risk perception around privacy was unexpectedly low in the field study of Your Energy Moment. We expected higher levels of perceived risk, since the privacy issues around the smart meter are discussed heavily and are one of the main reasons for rejecting the smart meter (e.g. wijvertrouwenslimmemetersniet.nl). The low levels of perceived risk can be explained by the involvement of a privacy and security expert in the development phase who advocated the privacy by design method (Montes-Portela et al. 2013)*.

* The method is in a way similar to the idea of usability by design, but focusses on continuously taking into account the privacy issues instead of usability issues during development

7.3. DISCUSSION ON OUR FINDINGS

We have had the opportunity to investigate the interaction between households and the smart energy technology at their own homes. Another way to investigate the interaction with innovative smart energy technologies, that is gaining interest, is by inviting people to stay in a dedicated house equipped with smart energy technology and observing their interactions. Amongst other universities, MIT and Delft University of Technology own such houses, which are dedicated for doing research. These houses are intended as a way of doing qualitative research with smaller samples before performing a field study (e.g. Keyson et al. 2013). We argue that the follow up field study, like performed in this thesis, is necessary for valid results, because side effects of observing people in an environment that is different from their home can be expected, because the entire context of people is different from home (Verplanken and Wood 2006). We have studied participant behaviour in the context of their own home over a long period, increasing the chances of valid results.

To increase the validity of our results further, we performed both qualitative research for gaining the rich insights and large-scale quantitative research to investigate behaviour change. We have invested considerably in acquiring objective behaviour data from a large sample to investigating a behaviour change. This has shown to be of value, because the study in Chapter 6 found that the behaviour reports on shifting demand were of limited usefulness in explaining an actual demand shift. This finding is in line with the results of the review study of Kormos and Gifford (2014), who found that 79% of the variance in the association between self-reported and objective behaviour remained unexplained. With the increased possibilities of measuring objective behaviour by technological developments, we strongly recommend to shift away from measuring behaviour by questionnaires.

Regarding the representativeness of the samples, we have discussed that both the samples of Chapter 2 and 3 had their imperfections. The participants of Chapter 2 were slightly older than the average Dutch population and mostly men were involved. This deviation is more common in energy saving research (e.g. Abrahamse and Steg 2009), possibly because older people have more time or perhaps older men are more interested in energy and technology. Chapter 3 involved participants who were likely to have an above interest in energy, because they were employees from an energy company. However, for the study presented in Chapters 4, 5 and 6, we increased the representativeness of the sample by our extensive recruitment efforts. This way we achieved a participation rate of 82% in the three newly built housing districts. Another way to reduce the chance of having a biased group of highly motivated participants is to perform research on the effects within an opt-out group (effort is needed to not participate) instead of an opt-in group (effort is needed to participate). However, ethical issues arise with this form of recruiting participants.

Moreover, we have invested considerably in high-quality customer service to prevent people from dropping out during the course of the study. The downside of our efforts to get people to participate and to stay involved might be that participants were willing to do something in return (Cialdini 1993). Then again, it is less likely that people hold on to just doing something in return, every day, for a period of two years. Therefore, we argue that our longitudinal approach increases the validity of our findings.

To summarise the above, in spite of the high costs of the technology and accompanying customer service and recruitment strategy, we have been able to carry out real life field studies over a longer period of time. Therefore, we have been able to investigate objective behaviour in a setting as close as possible to a natural environment. The real life longitudinal field studies enabled us to obtain valid results on energy demand reductions and the electricity demand shifting potential of households. Moreover, our approach gave us valuable insights in the way households interact with smart energy technologies.

7.3.1. SUGGESTIONS FOR FURTHER RESEARCH

Though we have gained many valuable insights by our approach, it is important to increase insight in the way households can be facilitated to improve patterns of energy consumption by further research. Our first research limitation is that participants were all Dutch. However, preferences of diverse cultures with regard to smart energy technologies can exist (Jeong et al. 2009). For example, the smart meter was relatively easily accepted in Italy, while the Dutch population was more reluctant to smart meters because of the perception of severe privacy rights infringements (Hoenkamp et al. 2011). Hence, other results and design recommendations for smart energy technologies can be found in countries with a context and culture different from the Netherlands.

It would also be beneficial to systematically design different smart grid concepts and to compare their user experiences and effects. For example, it is interesting to investigate different designs of the forecasts on the EMS. How does the way the dynamic tariff is presented affect effectiveness? We presented the dynamic tariff in a simplified way, but the precise effects of this presentation are unclear. Moreover, in none of the EMSs, we have used a normative comparison, because of the limited effects found so far. However, it is interesting for further research to investigate new forms of normative comparisons, where households are not compared to the average, but to the top 10%. Recent research has found that this form of comparison is more effective (Asensio and Delmas 2015). The same research has also experimented with other arguments for energy saving. They found in a field study of eight months with 118 households that public health externalities of electricity production (childhood asthma and cancer) outperform monetary savings as an argument. Health-based information motivated 8% energy savings compared to the control group and were particularly effective on families with children, who achieved up to 19% energy savings. Though this argument is found effective, it is doubtful if people are willing to pay for a device with such negative feedback. Last, it is interesting to investigate some other forms of giving feedback and feed forward. For example, more abstract forms of feedback like a subtle sound (e.g. birds that sing louder when more energy is used [Lockton et al. 2014]) or an object that changes form or colour.

Future research should move beyond wet appliances, because the electricity demand shifting potential of only wet appliances is limited (Widén 2014). The acceptance and effects of electricity demand shifting for new energy efficient technologies, such as electric vehicles, are very interesting, as these can be of great value due to their large contribution to peak demand (Veldman et al. 2013, Wang et al. 2011, Verzijlbergh et al. 2014). In this respect, the most suitable form of automation (fully/semi-autonomous or manual) needs to be investigated for different applications. For example, the perceived risk of an autonomous system may differ between various applications. Heat pumps demand a large share of the residential electricity consumption and can be used to buffer thermal energy. Because people are nowadays used to heating with a self-regulating function, we argue that a fully autonomous smart technology for demand shifting is less likely to be perceived as risky for this appliance. Smart charging of an electric car, on the other hand, can be perceived more risky because of range anxiety, which must be taken into account in the design (Schmalfuß et al. 2015). More research is needed to investigate in which situations users prefer which level of automation and how the user interface is best designed.

Besides further research on these design features, some of our research limitations could be tackled by further research. First of all, it would be interesting to study before and after effects. In Chapter 2, the time needed for installing the devices in households all over the Netherlands was long and hence it was not possible to investigate the effects of the EMSs directly after installation. We were able to compare the results with a control group to investigate the effects. In Chapter 5 and 6, we investigated the degree of electricity demand shifting over a longer time period. Again, we compared our data with a reference group, which consisted of a large group of households in the Netherlands and Belgium, from which we had gathered washing machine consumption data in the same time period. In our research set-up, households were situated in a newly built area, which made the expensive installation process of the smart energy technology more efficient. The efficiency of this process made it possible to perform this research on such a large scale, but did not enable to measure before and after effects. As the aim of our research was to investigate long-term effects, and we were able to compare the results with a control or reference group, we believe that this does not undermine the value of our findings. Nevertheless, it can be interesting for future research to investigate before and after effects.

Lastly, it would be interesting to perform more long-term field studies. It is especially interesting to perform research over a couple of years to see what happens with the use frequency of the EMS and the patterns of energy demand. We found that participants used the EMS significantly less in the summer holiday period in Chapter 6. By means of more long-term field studies, it can also be investigated if users take up using the EMS after coming home from vacation for example.

7.4. THE FUTURE OF SMART GRIDS

The photography on the title page of this chapter represents the Dutch version of the saying *reading tea leaves*. The photo is dedicated to this paragraph in this chapter as no-one knows for certain what the future will bring. Nevertheless, there are some interesting trends that affect the relevance of our findings and the chance smart grids will become part of our energy system in the long run. This paragraph reflects on these trends in relation to our findings and the future of smart grids.

7.4.1. POSSIBLE FUTURES AND THE RELEVANCE OF OUR FINDINGS

First of all, the development of more renewable energy is important for the relevance of our findings, because when the share of renewable energy increases, the amount of decentralised and fluctuating production capacity increases. This development makes the need for shifting demand larger. The prices of fossil fuels have recently dropped because shale gas and oil from the USA and the persistent extraction of fossil fuels by OPEC countries are pushing the prices downwards (ECN et al. 2015). This makes the business model for renewables currently less attractive. Nevertheless, prices of fossil fuels are expected to increase in the long run, prices of renewables are expected to drop further and clean energy technologies are expected to become more easily available (ECN et al. 2015). Furthermore, the disadvantages of fossil fuels are becoming more apparent and social resistance towards the disadvantages of sustainable technologies is slowly resolved by more clever designs. For example, many people think solar panels are ugly, so they are integrated with other building materials which makes them less noticeable (see Figure 7.2 for an example).

What is also increasing the relevance of shifting demand is an expected increase of electricity demand in residential areas. Electricity is slowly replacing fossil energy carriers mainly for transport and heating. Chapter 1 already introduced graphs that illustrate this trend. Shifting demand to moments when electricity is abundantly available is needed to make efficient use of the current infrastructure (e.g. Veldman et al. 2013).

FIG.7.2 ECONEXIS DEMO HOUSE IN ZWOLLE. THE HOUSE IS BUILT TO LOOK LIKE A HOUSE WHERE PEOPLE CAN SEE THEMSELVES LIVE. INCLUDES ALL MODERN ENERGY TECHNOLOGY, WHICH ARE HARDLY VISIBLE

Furthermore, the development of in home electricity storage technologies is important. The price of storage per kWh is dropping (Nykvist and Nilsson 2015). Besides possibilities of electrical storage, innovations regarding thermal storage are being developed. For storage to take off, households must be willing to invest in storage capacity and willing to make room in their houses for storage. Innovations are responding to this last issue by making clever use of the small space that is located underneath most Dutch households. Moreover, feed-in tariffs are likely to be eliminated after 2020 in the Netherlands, making storage financially more interesting. Germany already preceded the Netherlands in eliminating net metering and are subsidising battery packs.

7.4.2. CHANCES OF SMART GRIDS TO BECOME BUSINESS AS USUAL

The chance that smart grids become business as usual depends on the urgency for smart grid solutions as described in the previous paragraph. The question remaining for this paragraph is if smart grids are feasible in the coming years by the developments of the means that are needed to realise smart grids.

First of all, smart meters are becoming part of the European household. The smart meter is an important enabler for acquiring reliable data to feed EMSs. Currently, more and more households are installing some kind of EMS or smart thermostat. A smart thermostat is a device that helps households to increase thermal comfort and using gas more efficiently. Not all smart thermostats are giving feedback on gas consumption on the display in the living room itself. However, many are giving feedback on an app that must be installed to control the smart thermostat from a distance. It is a relatively small effort to include other forms of feedback and feed forward, especially when the data is already acquired by the smart meter. Moreover, the price difference between an EMS or smart thermostat is relatively small. Currently, an EMS or smart thermostat is about 100 Euros more expensive than more simple thermostats. This might be a lot of money for some households, but many people easily spend 100 Euros extra to obtain a smart phone with the newest features*. Moreover, few people know the price of their current thermostat, because it is sold together with the much more expensive boiler, making this price difference a mere pittance. These kind of business models should be considered more often. The problem is however, that manufacturers of boilers are often different companies

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*e.g., the iPhone 6s is 110 Euros more expensive as the iPhone 6. The first three days after launching this new version, Apple already sold ten million units than the companies developing EMSs. And more generally, new smart grid technologies often have limited possibilities to cooperate with other smart grid technologies. Cooperation between different actors, or open innovation strategies, are necessary for a smooth interface between different technologies and for more clever business models.

Another development that is actually enhancing the scenario that smart grids will become real is the trend of connectedness, also called the internet of things. For example, Indesit, the supplier of the smart washing machine used in our research recently developed a connected line. Users of this line can, for example, automatically download new programs for their appliances or receive a message when an error occurs. The idea behind this last functionality is that many people do not want to leave home when their washing machine is in operation, because of the risk of a flooding. With the assurance that you will receive a message when a flooding happens, it might be more comfortable to leave home in case of the unlikely event that a flooding occurs. This product is thus not smart for shifting demand, but is already connected. Indesit calls this product line *smart grid ready*, because it is relatively easy for them to give the appliance a software update to become smart grid ready as it is already connected.

Last, a positive influence is that using smart technologies in general is becoming familiar to people. More and more, people are wearing smart devices everywhere. For example, the penetration rate of smart phones is currently 82% (Bruyckere 2015). This development improves the possibility to provide feedback and feed forward by the improved opportunities for monitoring and intervention. For example, a smart phone provides an extensive user interface, sensors, a GPS and is able to send push messages. Moreover, because smart technologies are becoming more general, people will have less difficulties in getting used to new forms of smart technology. It is likely that people will have more confidence in getting technological assistance in making their energy consumption more efficient, as they are used to getting technological assistance in performing other preferable behaviours. An example is the increased availability of and demand for fancy pedometers.

7.5. CONCLUDING THOUGHTS

A smart grid might sound like a purely technical innovation and seems to have an impact on energy our energy grids alone. However, with the implementation of smart grids, households can become involved in making the energy supply more efficient in order to positively influence the affordability of energy and to save the environment. It is important to note however, that for big changes in patterns of demand, underlying factors that have locked in the patterns need to change (Walker 2014). For example, when we can change the collective routine of driving to work in the morning and coming back home in the evening every day, serious peak demand reductions can be achieved. Interventions like smart energy technologies to change patterns of demand are less effective compared to more radical social changes like the one named above. But at the same time, interventions like smart energy technologies are also easier to implement (Daae 2014). And these smaller changes can be worth the effort. For example, only 5% of the energy demand of Dutch households is the equivalent of the production capacity of a whole coal power plant (380 PJ [CBS 2015] $\cdot$ 0.05 = 19 PJ = $5 \cdot 10^6$ MWh, $5 \cdot 10^6/365/24$ = 602 MW*). Yet, this potential can only be achieved, when households are willing and able to use smart grids. This is where good design comes in.

* The coal power plant on Maasvlakte-1 we mentioned in Chapter 1 has a capacity of 520 MW

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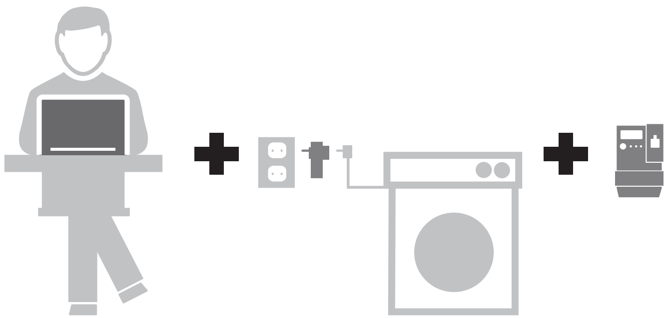
APPENDIX 1

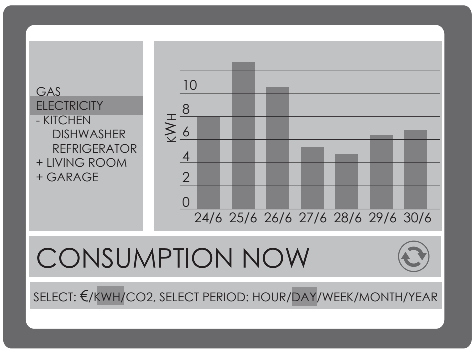
Visualised EMS characteristics Chapter 2

SMART PLUGS

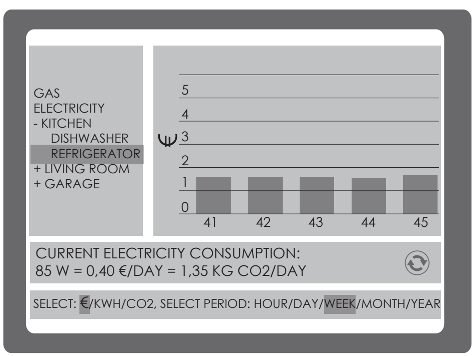
HARD- AND SOFTWARE: WEB APPLICATION WITH 9 SMART PLUGS CONNECTED TO THE SMART METER. CONTROL: USER CAN PROGRAM PLUGS TO SWITCH THEM ON AND OFF.



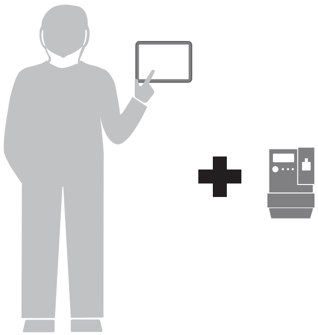
HOME-SCREEN: REAL TIME FEEDBACK (ELECTRICITY IN W, € OR CO_2 AND GAS METER READING. HISTORICAL (HOUR,DAY,WEEK, MONTH,YEAR) COMPARISONS (ELECTRICITY IN KWH AND GAS IN M^3. BOTH IN € AND CO_2 AND VISUALLY IN A BAR CHART)



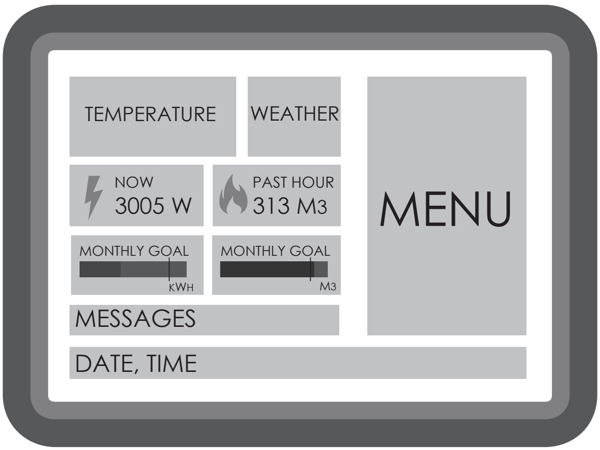
APPLIANCE SPECIFIC BREAKDOWN: REAL TIME AND HISTORICAL. GROUPING OF APPLIANCES POSSIBLE. CONTROL: USER CAN MAKE A TIME TABLE WHEN TO SHUT CONNECTED DEVICES ON AND OFF



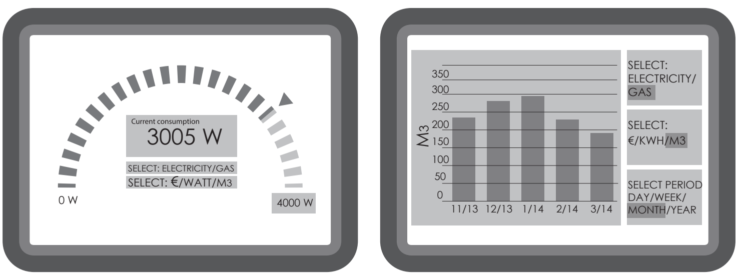
SMART THERMOSTAT



HARD- AND SOFTWARE: DISPLAY ON THE WALL, CONNECTED TO THE HEATING INSTALLATION AND THE SMART METER. CONTROL: USER CAN CHANGE THERMOSAT SETTING



HOME-SCREEN: REAL TIME FEEDBACK (ELECTRICITY IN W, € OR CO_2 AND GAS OF THE PAST HOUR IN M^3 OR €) SHOWING ENERGY USAGE IN COMPARISON TO GOAL IN GREEN, TURNING RED, WHEN TARGET USAGE IS REACHED



LEFT: REAL TIME FEEDBACK PRESENTED VISUALLY (CIRCULAR STATIC SCALE). RIGHT: HISTORICAL (DAY,WEEK, MONTH,YEAR) COMPARISONS (ELECTRICITY IN € or KWH, GAS IN € or M^3) MADE VISUAL IN BAR CHARTS

APPENDIX 2

Screen examples EMSs Zwolle and Breda

BREDA

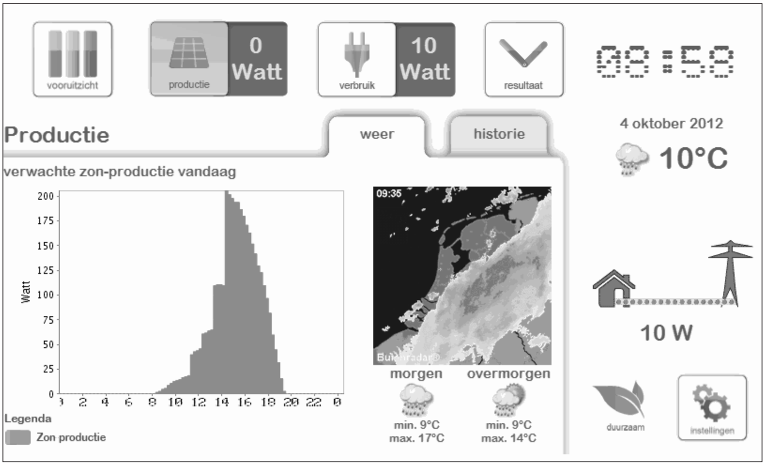
HOME-SCREEN

CURRENT ELECTRICITY USE AND PRODUCTION (REFRESHES EVEREY 10 SECONDS).

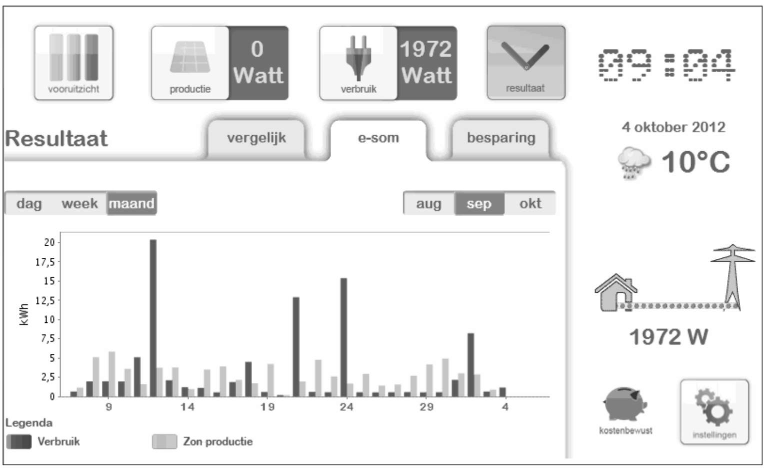
VISUAL SHOWING THE AVERAGE PRICE OF ENERGY

SHOWING THE AMOUNT OF ELECTRICITY DISTRIBUTED TO/ FROM THE HOUSE

WEATHER FORECAST WITH EXPECTED SOLAR ENERGY PRODUCTION



ELECTRICITY USE OF THE HEAT PUMP COMPARED TO THE TOTAL ELECTRICITY USE WITH INDICATION OF FAVOURABLE MOMENTS



HISTORICAL ELECTRICITY USE AND PRODUCTION SIDE BY SIDE

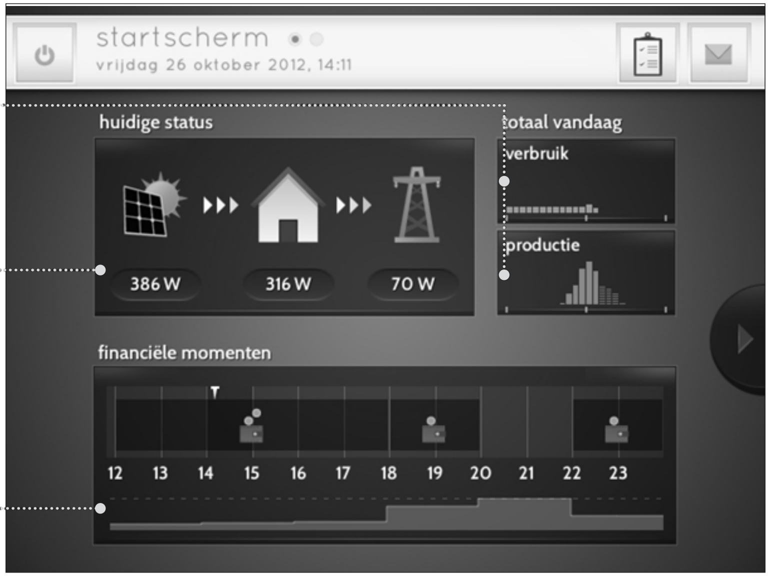
ZWOLLE

HOME-SCREEN A

PREVIEW OF ELECTRICITY USE AND PRODUCTION TODAY

CURRENT ELECTRICITY USE, PRODUCTION AND THE AMOUNT OF ELECTRICITY DISTRIBUTED TO/ FROM THE HOUSE (REFRESHES EVERY 10 SECONDS).

VISUAL SHOWING THE AVERAGE PRICE OF ENERGY



HOME-SCREEN B

PREVIEW OF THE COSTS TODAY

WEATHER NOW

PREVIEW OF GOAL ACHIEVEMENT

ELECTRICITY CONSUMPTION FOR TODAY WITH WASHING MACHINE AND SUSTAINABLE MOMENT INDICATOR

CHANGING THE PLANNING OF THE SMART WASHING MACHINE

APPENDIX 3

Household characteristics of Zwolle and Breda

As described in Chapter 4, the three participating districts of Your Energy Moment have their own characteristics. The table contains the demographic characteristics of these districts.

	EASY STREET BREDA	MEULENSPIE BREDA	MUZIEKWIJK ZWOLLE
Average floor space in m2	70	150	100
Percentage of men respondents	62%	80%	52%
Average age respondent (at the start)	30	40	32
Educational level respondent	43% lower educated, 45% middle, 12% scientific	33% lower educated, 47% middle, 19% scientific	32% lower educated, 18% middle, 50% scientific
Median household income	Modal	2 average wages	Modal
% unemployed respondent	4%	5%	15%
Respondent at home during the day (1 = never, 5 = always nearly almost)	1.9	2.2	2.3
Partner at home during the day	2.2	2.8	2.8
Family situation	70% single, 26% living together or married without children	11% single, 32% living together or married without children, 55% with children	19% single, 52% living together or married without children, 25% with children
Average number of residents per household	1.3	2.8	2.1
Percentage rent	2%	0%	30%

DANKWOORD

Jan en Ruth, jullie zijn fantastische promotoren. Het was een groot plezier om met jullie samen te werken. Ik weet dat de wetenschappelijke ‘wij’ vaak ten onrechte wordt gebruikt. In dit proefschrift niet! Jullie zijn enorm persoonlijk betrokken geweest en maakten veel tijd vrij om niet alleen inhoudelijk te discussiëren, maar ook te filosoferen over het leven. Jullie vullen elkaar ook erg goed aan. Jan, je bent het relativeringsvermogen. Je geeft aan wanneer het goed genoeg is en stelt het werk altijd in perspectief. Ruth, je bent heerlijk oplossingsgericht, brengt focus aan en hebt een briljant oog voor detail. Ik ben jullie heel erg dankbaar voor dit alles.

Elke, je bent niet voor niks mijn paranimf. Ik was vanaf het eerste moment al blij met je komst. Niet alleen omdat je me hielp die moeilijke vragen over de database te beantwoorden. Wist ik veel… Maar ook omdat het meteen gezellig was. We werden al snel het onderzoeksteam (en komisch duo, voor al uw feesten en partijen) van het project en dat beviel me erg goed.

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afstudeerders die ik heb mogen begeleiden waar ik zelf veel van leerde en die hebben bijgedragen aan dit onderzoek.

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Lieve vrienden en vriendinnen, bedankt voor de inspiratie die jullie me altijd geven. Bedankt ook voor het subtiel checken hoe het gaat met het p-woord en alle afleiding er juist van.

Kleine, zeer wijze en liefdevolle familie, bedankt: allemaal! Ook mijn schoonfamilie. Mam, bedankt voor je oneindige steun en ook nu door het zijn van mijn paranimf. Saar en Tien, lieve zussen, bedankt dat jullie er altijd voor me zijn.

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CURICULUM VITAE

Charlotte Kobus was born in 's-Hertogenbosch in 1986. After completing her secondary education at Gymnasium Beekvliet, she started her BSc program at the Faculty of Industrial Design Engineering of TU Delft in September 2004. She received her MSc degree in Strategic Product Design at the TU Delft in November 2010. She was an intern at Enexis, a large Dutch distribution network operator, during her MSc research project. That is when she started to investigate smart energy technologies by a qualitative inquiry of early stage user insights.

Enexis offered the unique opportunity to combine being part of the management trainee program and becoming a PhD researcher at the department of Product Innovation Management at the TU Delft. After the program, she was entitled innovator at Enexis where she could work further on her research and on several interesting innovation management topics. Just a few months ago, she started her own company called TINH with Phuong Ngo. TINH specialises in a designerly ways of facilitating true collaboration.

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Kobus, CBA, Klaassen, EAM & Slootweg, JG 2014. Slimme warmtepomp let op energieprijs. Energie+, 2014(December), 10-13.

SAMENVATTING

Goed ontworpen slimme-energietechnologie kan het gebruik van energie in huishoudens blijvend veranderen

Automobilisten zijn er allemaal mee bekend: de ellende van file. Voor onze te synchrone transportbewegingen zijn al verschillende oplossingen geïntroduceerd: zo werd in 1979 het dalurenabonnement gelanceerd om het treinmaterieel efficiënter in te zetten, en de piekdrukte te beperken. Een aantal grote steden in Nederland hebben daarnaast onlangs spitsmijdprogramma's geïntroduceerd (bijvoorbeeld wildvandespits.nl) waarbij automobilisten rond de 150 euro per maand kunnen besparen als zij niet achter elkaar aansluiten in de file.

Kort gezegd is het onderwerp van dit proefschrift vergelijkbaar met een spitsmijdprogramma voor het gebruik van elektriciteit in huis. Onze elektriciteitsinfrastructuur is namelijk ontworpen om de piekvraag van vandaag de dag te faciliteren. Maar enerzijds neemt de vraag naar elektriciteit toe, nu vervuilende energiedragers worden vervangen door elektriciteit, bijvoorbeeld door de komst van de elektrische auto. Anderzijds beginnen huishoudens hun eigen duurzame elektriciteit te produceren. Als veel huishoudens in dezelfde wijk zonne-energie produceren, kan de aanbodpiek op een zonnige zomerdag net zo hoog zijn als de vraagpiek op een winteravond doordeweeks. Zonder ingrijpen zou de energie-infrastructuur uitgebreid moeten worden om de piekvraag en aanbod aan te kunnen. Het probleem moet dus op twee fronten worden aangepakt: wanneer piekvraag wordt beperkt en verbruik van eigen zonne-energie wordt gestimuleerd, kunnen grote investeringen in de bestaande energie-infrastructuur worden vermeden en wordt duurzame energie efficiënter benut.

Slimme netten worden gezien als een oplossing om optimaal gebruik te maken van zowel de duurzame energie als van de bestaande energie-infrastructuur door vraag en aanbod slimmer af te stemmen. Vaak zijn slimme netten ook bedoeld om huishoudens te stimuleren om elektriciteit efficiënter en duurzamer te gebruiken. Slimme-energietechnologie en nieuwe tariefstructuren worden in deze vaak gecombineerd om een gedragsverandering te bewerkstelligen. Het is alleen de vraag of huishoudens in staat zijn hun energievraag te veranderen en slimme netten te accepteren.

Stimuleren van efficiëntere en duurzamere energievraag is niet eenvoudig: elektriciteit is bijvoorbeeld nog steeds relatief goedkoop en grote financiële voordelen, zoals die mogelijk zijn met spitsmijdprogramma's, zijn moeilijk te realiseren. Bovendien is het gebruik van energie in huis een gevolg van dagelijkse huishoudelijke routines. En routines staan er nou eenmaal om bekend dat zij moeilijk te veranderen zijn. Slimme-energietechnologie zou hier een uitkomst kunnen bieden, maar dan moet die wel zo ontworpen worden, dat het aansluit bij de behoeften van gebruikers en tegelijkertijd gewenst gedrag in de hand kan helpen. Deze uitdaging kan het beste worden aangepakt met een gebruikersgericht ontwerpproces. Door een aantal iteratieslagen van ontwerp en evaluatie worden gebruikersbehoeften betrokken in het ontwerpproces. Het onderzoek in dit proefschrift laat zien hoe een gebruikersgericht ontwerpproces wordt toegepast in het veld van slimme netten om slimme-energietechnologie gebruiksvriendelijk te maken. De kwantitatieve veldstudies in dit proefschrift laten het positieve effect van deze aanpak op duurzamere en efficiëntere energieconsumptie zien.

De inhoud van dit proefschrift | We werken de relevantie van het veranderen van de huishoudelijke energievraag in huis verder uit in Hoofdstuk 1. In Hoofdstuk 2 beginnen we vervolgens met het onderzoeken van de waarde van een goed ontwerp in het veranderen van energievraag op een bekend terrein: het stimuleren van energiebesparend gedrag. We hebben in dit hoofdstuk de variatie in de behaalde energiebesparing door verschillend ontworpen Energie Management Systemen (EMS) onderzocht. De twee systemen gaven beide terugkoppeling over de vraagpatronen van energie in het huishouden, maar verschilden in de manier waarop zij dat deden. We concluderen aan de hand van een grootschalige veldtest, dat als een

EMS gebruiksvriendelijk en toegankelijk is, de kans dat men de EMS blijft gebruiken verhoogt en daarmee ook dat men een energiebesparing realiseert. We zagen dat de ene EMS goed werd gewaardeerd en gebruikt en dat daarmee energie is bespaard. De gebruikers van de andere EMS waardeerden het systeem echter minder en gebruikten de EMS een stuk minder vaak. Deze groep heeft geen energiebesparing behaald.

Voor het verkennen van de factoren die de neiging van huishoudens beïnvloeden om elektriciteitsvraag af te stemmen op het aanbod, hebben we in Hoofdstuk 3 een kwalitatieve veldstudie uitgevoerd. Deelnemers werden gevraagd om hun elektriciteitsvraag te verschuiven naar momenten waarop zij zelf elektriciteit produceerden met hun zonnepanelen. Zij werden hierin bijgestaan door een EMS, die nu naast terugkoppeling over hun energieverbruik, ook vooruitzichten over de zonneproductie bood. Daarnaast kregen zij een slimme wasmachine. De gebruiker kon de slimme wasmachine een eindtijd geven waarvoor de volledige wasbeurt moest plaatsvinden. De slimme wasmachine kreeg een sein om te gaan draaien wanneer de zonnepanelen de meeste elektriciteit produceerden. We hebben door deze veldtest veel inzicht vergaard in de manier waarop gebruikers omgaan met een slimme wasmachine en een EMS. Ook hebben we inzicht gekregen in de mogelijkheden en onmogelijkheden van het verschuiven van de elektriciteitsvraag door andere factoren dan de geleverde techniek.

Hoofdstuk 4 bouwt voort op de inzichten uit Hoofdstuk 2 en 3, en is gewijd aan het ontwerp van een grootschalig en langdurig veldonderzoek met betrekking tot het verschuiven van de elektriciteitsvraag. In drie woonwijken in Zwolle en Breda, produceerden huishoudens hun eigen zonne-energie. Zij kregen een speciaal ontwikkeld EMS en een slimme wasmachine. Bovendien kregen zij een dynamisch energietarief. Deelnemers konden dus zelf kiezen om hun energieafname te plannen tijdens periodes dat zij zelf energie opwekten en/of periodes dat zij gebruik konden maken van gunstige tarieven. We beschrijven in Hoofdstuk 4 hoe we deze technologie gebruiksvriendelijk hebben gemaakt. In Hoofdstuk 5 presenteren wij de eerste resultaten van deze studie. We hebben ons in eerste instantie gericht op de bijdrage van het gebruik van de slimme wasmachine in het verlagen van piekvraag en het efficiënter gebruik maken van lokaal opgewekte zonne-energie. We concludeerden dat in vergelijking met een referentiegroep, deelnemers relatief vaak tijdens de zon-uren wassen en relatief minder vaak tijdens de piekuren. De huishoudens die regelmatig gebruik maakten van de planfunctie van de slimme wasmachine gebruikten bovendien nog minder elektriciteit tijdens piekuren en verschoven het moment van gebruik naar de nacht.

In Hoofdstuk 6 onderzoeken we ook de timing van het gebruik van andere apparaten dan de wasmachine over tijd. Deelnemers hebben aangegeven dat zij het gebruik van de vaatwasser en de droger ook verschoven naar gunstige momenten. Deelnemers gaven aan dat zij verschillende motivaties hadden om dat te doen. Wat opviel was dat het gevoel van een 'leuke uitdaging' na een aantal maanden afzwakte. Toch bleef de verschuiving van elektriciteitsvraag naar gunstigere momenten overeind. We onderzochten ook het gebruik van de EMS in deze studie. Wederom vonden we een positieve relatie tussen het gebruik van de EMS en het gebruik van elektriciteit op gunstige momenten. We stellen in dit hoofdstuk dat het geven van vooruitzichten over de levering van elektriciteit, naast het geven van feedback, gunstig is voor het blijvende gebruik van de EMS. Hoofdstuk 7 geeft een overzicht van de belangrijkste bevindingen en de betekenis van dit onderzoek. We bespreken de suggesties voor vervolgonderzoek en bediscussiëren de relevantie van dit onderzoek voor verschillende toekomstscenario's. Ook zijn er een aantal praktische ontwerprichtlijnen opgenomen voor het ontwikkelen van slimme-energietechnologie.

Conclusie | Dit proefschrift laat zien dat huishoudens in staat en bereid zijn om hun energieverbruik blijvend te veranderen, mits zij worden ondersteund door goed ontworpen, gebruiksvriendelijke technologie. Er zijn eerder studies gedaan naar het effect van slimme-energietechnologie en tariefstructuren om beter gebruik te kunnen maken van de beschikbare hernieuwbare energie en van de bestaande energie-infrastructuur. Maar nog niet eerder is de gewenste gedragsverandering op zo'n grote schaal en over zo'n lange tijd onderzocht en is er speciale aandacht geweest voor het ontwikkelen van gebruiksvriendelijke slimme-energietechnologie. Door zowel kwantitatief als kwalitatief onderzoek laten wij zien, dat pas wanneer mensen in staat zijn en bereid zijn om langdurig de technologie te gebruiken, deze een blijvende verandering kan bewerkstelligen. Dit proefschrift bevat daarom praktische ontwerprichtlijnen voor slimme-energietechnologie die een blijvend effect moet hebben op de manier waarop huishoudens energie verbruiken.

Propositions accompanying the thesis:

A SWITCH BY DESIGN

User-centred design of smart energy technologies to change habits of using energy at home

1. If smart energy technologies are well designed, households will change their patterns of energy demand permanently. (this thesis)
2. To change habits into more sustainable habits, the focus should be on making sustainable behaviour easier. (this thesis)
3. The trend of flexible working hours benefits energy companies in multiple ways. (this thesis)
4. In the near future, households will get used to taking into account the natural supply of energy when using it.
5. Companies and governments that extract shale gas and oil are like an nicotine addict anxiously looking for the last half smoked cigarette in the trash.
6. In the design world, it is often stated that if the design is not understood or used in the wrong way, the design is stupid, not the user. Unfortunately, this point of view remains fairly unknown outside the design world.
7. One man's deviation between intention and behaviour is another man's business model.
8. Ironically, SMART (Specific, Measurable, Acceptable, Realistic, Time-bound) goals usually result in foolish behaviour.
9. You can learn most of those who remain open to continue learning themselves.

These propositions are regarded as opposable and defendable and have been approved as such by Prof. Dr. J.P.L. Schoormans and Dr. Ir. R. Mugge

Stellingen behorende bij het proefschrift:

A SWITCH BY DESIGN

User-centred design of smart energy technologies to change habits of using energy at home

1. Wanneer slimme energie techniek goed ontworpen is, zullen huishoudens hun energieconsumptiepatronen blijvend veranderen. (dit proefschrift)
2. Om gewoontes in duurzame gewoontes te veranderen, moet de focus liggen op het gemakkelijker maken van duurzaam gedrag. (dit proefschrift)
3. Energiebedrijven hebben op meerdere manieren baat bij de trend van flexwerken. (dit proefschrift)
4. In de nabije toekomst zullen huishoudens het normaal vinden om rekening te houden met het natuurlijk aanbod van energie.
5. Bedrijven en overheden die schaliegas en olie winnen zijn vergelijkbaar met een nicotineverslaafde die naarstig op zoek is naar een restje van een peuk in een prullenbak.
6. In de ontwerpwereld wordt vaak gesteld dat als het ontwerp niet wordt begrepen of verkeerd wordt gebruikt, het ontwerp dom is, niet de gebruiker. Helaas blijkt deze stelling buiten de ontwerpwereld nog vaak onbekend.
7. De één zijn afwijking tussen intentie en gedrag, is de ander zijn verdienmodel.
8. SMART (Specifiek, Meetbaar, Acceptabel, Realistisch, Tijdgebonden) doelstellingen creëren ironisch genoeg doorgaans dwaas gedrag.
9. Je leert het meeste van mensen, die zelf open blijven staan om te leren.

Deze stellingen worden verdedigbaar geacht en zijn als zodanig goedgekeurd door Prof. Dr. J.P.L. Schoormans en Dr. Ir. R. Mugge

This doctoral thesis demonstrates that households are able and willing to permanently change their habits of using energy, if they are supported by well-designed, user-friendly technology. Previous studies have assessed the impact of smart energy technologies and new tariff structures to make optimal use of sustainable energy supply and the existing energy infrastructure. However, these studies did not investigate the desired behaviour change on such a large scale and/or over such a long time. Moreover, there has been little focus on developing user-friendly smart energy technologies. The findings from both quantitative and qualitative research demonstrate that only when people are able and willing to use smart energy technologies over time, these technologies can bring about a lasting change. Therefore, this thesis includes practical design guidelines for developing smart energy technologies that are intended to have a lasting effect on the way energy is used at home.