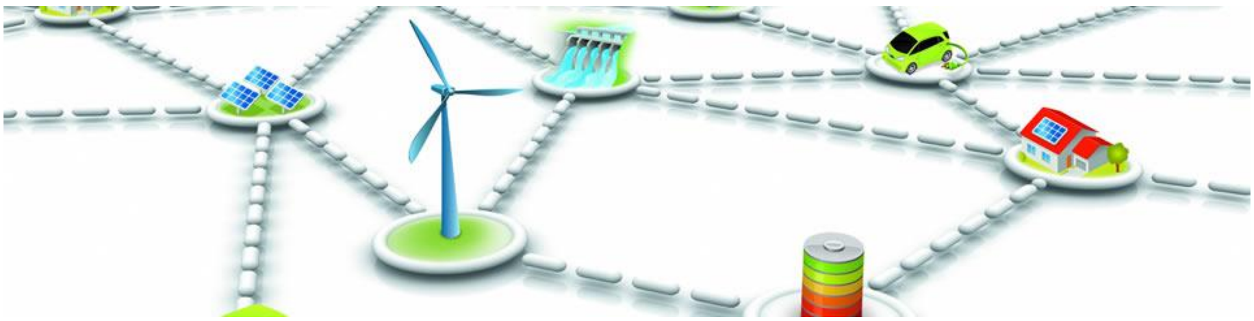
Master Thesis

Dynamic Electricity Management -

Flexibility of demand in the Dutch electricity market



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Bart Gombert

Utrecht University

Universiteit Utrecht

Colophon

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Author	Bart Gombert
Student number	3118029
E-mail	bart.gombert@gmail.com
University	Copernicus Institute of Sustainable Development
	Utrecht University
	Heidelberglaan 2
	3584 CS UTRECHT

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External Supervisors	Maarten van der Kloot Meijburg, Ruut Schalij

Abstract

This research has investigated the potential for demand response for use in a changing electricity market. Demand response (referred to as Dynamic Electricity Management or DEM in this research) can have various purposes for TSOs, DSOs and electricity suppliers. The current and future technical potential was researched for each actor and depends on the ability to use load interruptible or load shiftable appliances. Whereas current potential can have a small positive contribution (especially to TSOs and DSOs),the current DEM systems are not capable to make Demand Response work for current appliances. With future DEM systems and smarter appliances more potential can be unlocked and the distinction between load interruptible and load shiftable appliances will disappear. However, progressing energy efficiency of household appliances reduces electricity usage of suitable household appliances in the order of 50%. Increasing penetration rates of tumble dryers, dishwasher and especially heat pumps and electric vehicles will also increase the potential for Demand Response.

Keywords: Demand Response, Demand Side Management, intermittent renewable energy, electricity usage household appliance, tumble dryers, washing machines, refrigerators, freezers, dishwashers, electric vehicles, heat pumps

A Word of thanks

Having written my bachelor thesis two years before, I knew that in the end the hardest part was not in the writing itself. The hardest part, I had learned, was choosing a topic that would capture my interest for a long enough period to write my master thesis. I always have had a special interest in the energy sector, mainly because of its major role of importance in just about every aspect of modern live. Yet my knowledge of the energy sector would not escape the level of the next in-depth article of a magazine or newspaper.

During a discussion forum I came into contact with the e-Risk Group, a small consultancy firm run by two senior partners with a career in the financial and energy industry. They explained to me the challenges the energy sector is facing and interested me for writing my thesis on a topic that could possibly solve some of these challenges: dynamic electricity management. A topic was chosen!

I want to express my appreciation for the opportunity Maarten van der Kloot Meijburg and Ruut Schalij have given me for writing this thesis with their support. I was always given their full confidence and freedom, something I value. They have learned me a lot about the energy sector and especially about the electricity market. I have enjoyed our many discussions about energy and other totally unrelated topics. The time they invested is invaluable. Although there is still many more things to learn some good things do come to an end.

Also I would like to thank my supervisor Wilfried van Sark and the second reader Eva Niesten for providing me with sharp and detailed comments on early drafts. The more comments I got, the better I would enjoy. The many literature references were helpful and provided the depth I was looking for.

Finally I have to thank my family and friends and Steven Vester in particular for proof reading my thesis as an outsider with helpful suggestions on structuring the story. During two years of the pilot I have been (too) busy combining work and study and an internship. Yet every week we would have our moment to enjoy having fun. My parents have been very supporting to get where I am today, especially so in the last demanding year. Thank you all, I will never forget!

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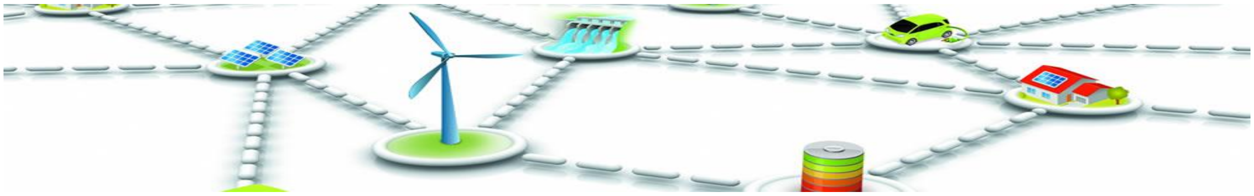

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1. Introduction

1.1 Background

Any amount of electricity demanded at any given time must be met by an equal supply to maintain an alternating current of about 50 Hz. Vice versa, all produced electricity at any given moment must be consumed almost that same instant. If supply and demand in the electricity market are out of tune, the grid will become unstable leading to potential brownout or even blackout (Green and Newberry, 1992). Examples of this incongruity are e.g. when many people switch on their water boilers simultaneously during half time of a popular sports match. The electricity market is therefore defined as a "demand following market" (Eemflow Energy, 2014).

In an ideal electricity grid, demand and supply are evenly spread throughout a 24-hour day to make the best use of network capacity (Laborec, 2013). From an ideal market model perspective based on marginal costs, demand of electricity would increase as soon as '*extra*' electricity supply comes available, e.g. when the sun shines (Borenstein, 2008; Green and Newberry, 1992). Currently neither is possible because demand is not responsive to supply changes (CE Delft, 2012): only supply can respond to demand, not vice versa. Due to the physical characteristics of electricity, supply always has to meet instantaneous demand. Storage of electricity could solve this problem, with two major drawbacks: electricity storage is expensive, and current storage options do not have the capacity to store enough electricity or for longer periods of time (MacKay, 2009).

These inflexibilities make the electricity market and the grid that facilitates it less dynamic. Moreover, the production of electricity is more or less fixed for an assumed peak demand and so is the maximum network capacity. This means that the installed peak production capacity and available peak network capacity are only used for a limited amount of hours annually. Most of the time the system is over-dimensioned and thus not optimally utilised (Laborec, 2013). Maximum network capacity could be better utilised if there were more or other options to manage the use of the (maximum) capacity of the grid, i.e. spread the load.

1.2 Trends

A number of changes in our society are currently transforming the electricity markets.

First of all, the **electrification of society** means that more technologies are driven by electricity. The development of electric cars and the ongoing trend of ever more (small) electric devices is clear evidence in this case. This is not to be taken lightly: for instance, current estimates about further adoption of the electric car show this product alone has the potential to double domestic electricity usage (ECN, 2013). Also in the longer run, relatively new technologies such as heat pumps and/or other means of electric heating are expected to increase domestic electricity usage.

A second, more fundamental, change to the system is the rise of **intermittent renewable generation** (ECN, 2014)**.** This type of power supply, spanning predominantly solar and wind power, will change the entire game of the energy markets (Schleicher, 2012). Key challenges are (1) matching demand and supply of electricity, as the current market structure for electricity trade has not changed adequately to deal with ongoing development of intermittent generation (ECN, 2014); and (2) facilitating intermittent generation. This type of generation is, unlike centralized large power plants, usually more distributed - meaning bi-directional electricity transportation must be facilitated (TenneT, 2010). This is challenging, as currently operational electricity grids were designed to carry current from high voltage to low voltage and not vice versa. This has implications for Distribution System Operators (DSOs) in the near future. And (3) the influx of intermittent supply has (price) effects on the wholesale strategy of electricity suppliers (the buying and selling of large chunks of electricity between businesses).

In conclusion: electrification and renewable electricity will have a major impact on electricity markets in the next five years. The following problem definition will elaborate on the consequences these trends have for three key actors in the electricity market: the Transmission System Operator (TSO); in The Netherlands this is TenneT, the DSOs and electricity suppliers.

1.3 Problem definition

The current trends in the electricity market show that the electricity market model and the electricity grid might not be well enough equipped to deal with these changes. As Schleicher (2012) put it: *"The consumption-production balance may trigger massive innovation and investment in energy management technologies involving different kinds of storage and controls".* This paper will describe and research a novel way of managing and investing in electricity grids. This different kind of controls could be what is called a smart grid. A smart grid uses ICT to continually gather data on the electricity grid; the idea is that the electricity grid can be operated more efficiently based on the continuous stream of data. A smart grid should therefore be able to support the adoption of the abovementioned trends in a novel way. In a nutshell: by leveraging ICT capabilities, smart grids are able to bring measurement techniques used in the higher voltage parts of the grid to the lower voltage parts, allowing leeway for better and autonomously matching of supply and demand. A smart grid can enable consumers to play a more active and prominent role in the electricity market. The demand side of the electricity market becomes dynamic as opposed to its current passive role (CE Delft, 2012).

This research paper will use the following smart grid definition by Ofgem as a guide, which was dubbed precise yet easy to understand (Frontier Economics, 2012):

"A smart grid is part of an electricity power system which can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies."

Earlier studies of smart grids have concluded that they have a positive societal cost benefit (Faruqui, 2010; CE Delft, 2012; KEMA, 2010). CE Delft concludes that the benefits of the smart grid are mainly attributed to the middle and low voltage network, the grid level at which households are connected. However, it is remarked that currently there are no exact numbers: households are not currently metered (near) real time. This is the key weakness in their study: their conclusions were based on educated guesses by expert opinions rather than actual data. This is precisely at the heart of the current problem for smart grids and a reason for the Ministry of Economic Affairs to instigate several pilot projects (EOS, 2011).

Indeed, collecting real world data about potential smart grid performance is a tricky endeavour for at least two reasons. For one, it is necessary to have an accurate estimate of the benefits of a smart grid before people will participate in large numbers. If the benefits can be established, households may be expected to participate in **Dynamic Electricity Management** (DEM). DEM is an application of the smart grid and its aim is Demand Response (DR). It allows optimization of matching demand and supply, by actively altering electricity demand.

Second, in order to successfully implement, operate and measure the effectiveness of a DEM system, experience is quintessential. It remains currently unknown what the precise impact of DEM is, and what the effect of actively altering electricity demand is (Frontier Economics, 2012). Accurate figures on the potential of smart grid applications are necessary for further development of smart grids. Both the necessary hardware and software are still under development; no one system is currently completely capable of enabling DEM. In other words, further development of smart grids is slowed by the timeless chicken-and-egg story. As a means of overcoming this, a pilot project could be launched to gain the much needed experiences with current technology, the customers (providers of DEM) and other actors. As demonstrated, the potential benefits of smart grids and DEM are not yet sufficiently made clear to the general public.

1.4 Research question

This research will be based on one of the instigated pilot projects for smart grids in the Netherlands. The pilot Smart grid Rendement Voor Iedereen, has started in 2011 and its aim is to gain valuable experiences with smart grids and to stimulate the development of business cases based on smart grids. More specific the application of DEM will be tested. It will be researched if and to what extent Dynamic Electricity Management has an effect. This research will assess the technical potential of electricity demand available for demand steering in the smart grid pilot that takes place in the city of Amersfoort. The main research question is formulated as follows:

'*What is the present and future technical potential in electricity use for Dynamic Electricity Management based on households in the smart grid pilot Smart grid Rendement voor Iedereen?'*

Technical potential is defined as the maximum power load and summation of electricity demand not constrained by economics (e.g. costs of equipment) or behavioural aspects of the consumer. I.e. it is assumed that devices are (semi)-automatically operated.

To structure the answer towards the main research question, several sub questions are formulated. The sub questions funnel towards the use and potential of DEM in a smart grid.

1) How can an energy supplier use Dynamic Electricity Management to improve its electricity wholesale strategy?

2) How can a Transmission System Operator use Dynamic Electricity Management to improve grid stability?

3) How can a Distribution System Operator use Dynamic Electricity Management to improve capacity management?

4) What are some current experiences with Dynamic Electricity Management systems?

5) What are typical penetration rates for suitable smart grid appliances?

6) What is the typical electricity usage of appliances in the pilot and how will it change over time?

2. Relevance of Dynamic Electricity Management

2.1 Link to Master Sustainable Development

The master Sustainable Development is a program facilitated by the Copernicus Institute, University of Utrecht. "The mission of the Copernicus Institute is "...*to understand and communicate the dynamics of emerging technologies and innovations that are relevant for societal problems*." Smart grids clearly resonate well with that vision, as it will shake up the incumbent, rigid electricity system.

The "research group Energy and Resources of the Copernicus Institute has the mission: "*to investigate which contributions science and technology can make to a sustainable development of society. This is done by both reactive and pro-active research in the area of, amongst others, energy*."

Dynamic Electricity Management is a relevant subject for the Copernicus Institute, mainly through its direct relation with the following themes:

- Dynamics of emerging technological innovation systems
- User – producer interactions in technological change
- Coordination through visions and expectations
- Strategies and collaborations in emerging technologies

Especially the first and last theme relate particularly well to the development of a smart grid. A smart grid requires interaction with its users, who have always taken 99.99% availability of electricity for granted. This makes for tricky waters to navigate, as any dent in this near flawless track record will damage the public image of the smart grid's potential. Building smart grids is much more than installing smart meters. The user interaction necessary in a smart grid requires the users to be educated of its purposes.

2.2 Scientific and societal value of this research

The field of smart grids has seen sizable (academic) research interest (e.g. Eurelectric, 2013; Faruqui, 2010; Seebach, 2009). However, as touched upon before, most of these research projects are bounded in the sense that they are only able to estimate or model the effects of smart grid implementation. In contrast, this research aims to contribute to a better understanding of the potential and possibilities of a smart grid by using empirical (near) real time measurements. Conclusions by CE Delft (2012) can only be given within limits of their sensitivity analysis. This indicates the need pilot projects to estimate the effect of time and location specific, variable, electricity tariffs. The European Commission (2012) remarked: *Especially at the early stage of smart grid development, consumer participation and response are still uncertain and relevant behavioural information (e.g. load profiles) is often not (yet) accessible to utilities*".

This research will add to the existing body of scientific literature by using consistent measurements over a longer period of time on the low voltage grid. The electricity usage of individual appliances is measured. That allows even greater precision than the current smart meters that are being installed over the next few years. The (monetary) benefits of a smart grid can be related more precisely to the received data. These results can be applicable to the TSO TenneT (improving grid stability), the DSOs (avoiding peak demand), and energy suppliers (complementing their wholesale strategy). This could for example lead to new load profiles or new ways of network management by the utilities.

3. Theory

3.1 State of the art literature

The growing relevance of DEM is clearly stated by Pöyry (2011). The study mentions the following three trends that will alter the current electricity market:

1) Electricity generation will become more inflexible due to increasing amounts of solar and wind power. This places a greater premium on having load that can follow generation, assuming there is no large storage alternative.
2) Electricity demand could become more variable with larger peaks, which underlines the benefits of shifting load away from peak periods. This assumes network capacity will more or less remain equal and limited.
3) Electricity demand may have much greater potential for flexibility in the future through the electricity usage associated with heat and transport (electrification of society).

Development of these trends and ultimately their impact cannot be estimated with full certainty. For example, a study by Budischak et all (2013) concludes that least-cost combinations of wind power, solar power en storage could entail excess generation from renewable sources. Renewable energy supply over capacity by a factor of 290% of normal load could substantially require less storage. DEM is by its nature storage of electricity in the form of time (shifting the power load) or in the form of heat (interruption of the power load). With massive overcapacity the need for 'storage' in the form of DEM would decrease similarly.

The second trend assumes that the future electricity market and its networks are still run in a fashion similar to today. Distributed storage in combination with solar panels at home, as is now subsidized in Germany (KfW, 2013) could take away the necessity for demand to follow (intermittent) supply. This thesis assumes some form of DEM is needed, albeit with or without large-scale electricity storage in e.g. batteries. DEM and batteries do not necessarily exclude each other, but to some extent they do compete as alternatives for coping with supply and demand mismatches.

The third trend will only be of growing importance when penetration rates of new appliances start to rise quickly. Although more electric vehicles and heat pumps may seem likely, it is not yet the case. Increases in energy efficiency partially negate the increase in electricity use. If the trend of electrification would discontinue, together with energy efficiency, the potential of DEM would be reduced and DEM may stay an insignificant application of smart grids.

State of the art literature mentions certain prerequisites necessary for Dynamic Electricity Management (Kim et al., 2011). Consumers often have a lack of knowledge of the structure of the electricity market and lack up to date relevant information or the ability to efficiently evaluate costs versus rewards. When action on their part is required, they can show response fatigue. Energy suppliers can have wrong incentives for their employees (e.g. promoted for increased profits). Structurally, there can be a wrongly incentivized tariff structure, demographic or geographical reasons influencing electricity use and lack of policy and regulatory measures to support DEM. For a more elaborate description on '*Common failures of demand response'* please read Kim et al (2011).

This thesis assumes that DEM will become more important. DEM can yield different benefits to the three different key actors in the energy market: TSOs, DSOs and energy suppliers. The usefulness of DEM to these actors can be delineated along five dimensions (Pöyry, 2011):

1) Magnitude (in MW terms)
2) Duration (in minutes or hours)
3) Timing (time of the day) and frequency (daily, weakly, seasonal)
4) Notice period (minutes, hours, days)
5) Location (i.e. where and at what level of the Transmission and Distribution network)

Appliances will be measured on the first three dimensions. The dimensions 'Notice period' and 'Location' are constraints as given by the prevailing electricity market model. The constraints are specific for each actor. In the current Dutch electricity market, DEM will generally serve the following three purposes:

1) Improving grid stability, which is beneficial to the TSO (TenneT).
2) Defer network capacity upgrades by avoiding peak demand, which is beneficial to DSOs.
3) Facilitate additional trades on the electricity market as an option to complement the wholesale strategy, which is beneficial to electricity suppliers.

The level of the electricity grid at which an actor could use DEM according to their needs can range from local (i.e. neighbourhood) to the national level. It is important to note that the needs or uses of DEM with more actors can conflict with each other. An aggregator could solve this problem by acting as an intermediary between parties. It generates revenues by servicing and providing flexibility and ancillary services to any of the three mentioned actors.

Figure 1 shows the conceptual idea of dynamic electricity management to be used for various purposes. In order to recoup the necessary investments (regardless they are done by the consumer or another party) several tariff structures are possible. Commonly used in the Dutch electricity is the flat-(two) tiered tariff structure. Another options is Time of Use (ToU), which is essentially an elaborate multi-tiered tariff structure depending on the time of the day. Critical Peak Pricing (CPP) aims to make the busiest hours so expensive that only necessary appliances are run during that period and other demand is shifted to cheaper hours. Real Time Pricing (RTP) is a dynamic version of ToU pricing, changing electricity prices throughout the day based on real time information (e.g. market prices, electricity supply and demand, etc.) PowerCentsDC (2010) notes that the tariff structure is of large influence on participation rates in case of voluntary sign up.

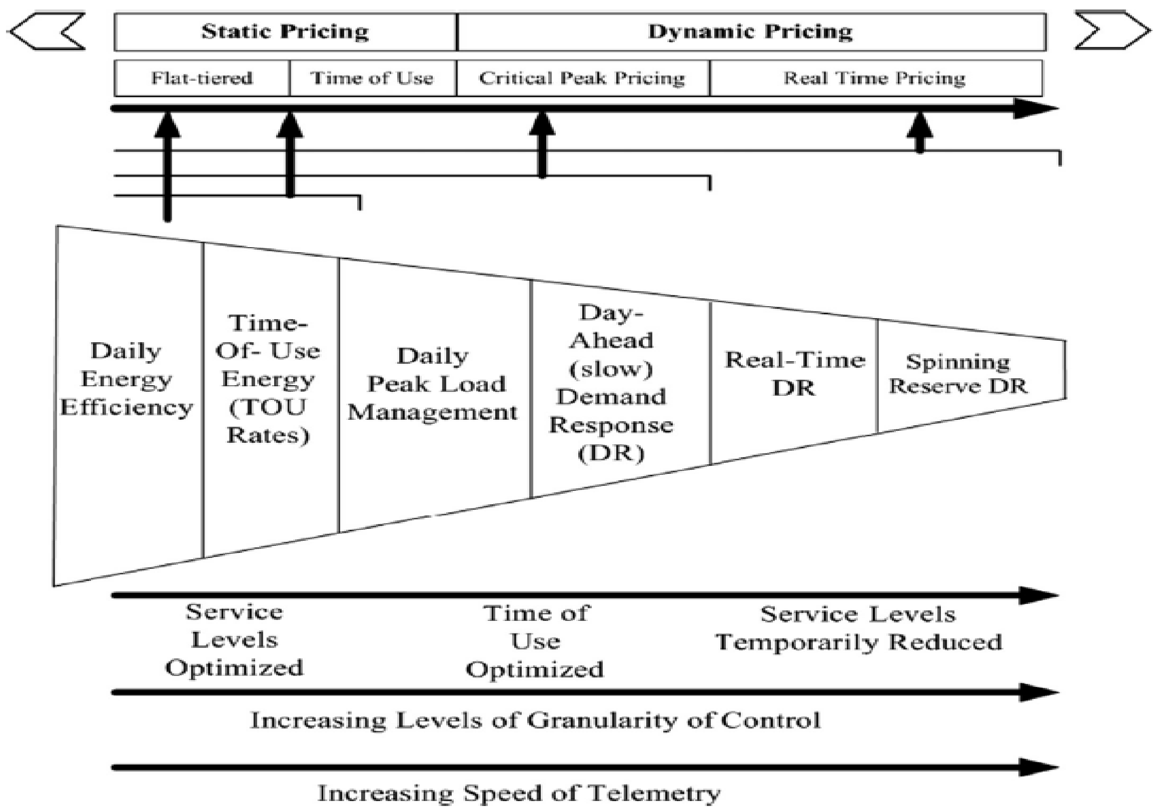

Figure 1: Conceptual perspective of efficiency and dynamic electricity management (Source: Siano, 2014)

4. Research Method

4.1 Pilot

This thesis was written as part of a smart grid pilot in Amersfoort Vathorst. This particular neighbourhood was selected because of the abundant presence of solar panels on the roofs of households. It is a perfect example of a future neighbourhood. As a note of caution however, this also means that this neighbourhood was not sampled randomly and is therefore not necessarily representative for all households in The Netherlands. The pilot is carried by 12 companies and research institutes that each contribute and collaborate from their own specific backgrounds. The aim of the pilot is to develop several business cases that are based on the use of a smart grid. The aim of this research was to validate one of the business cases, namely Demand Response (DR). In Amersfoort 100 households were recruited to participate in the pilot. The households were selected for their fit with DEM. Type of appliances to be used in a smart grid were selected by 1) their likely presence in an average Dutch household and 2) for their ability to change their electricity demand, and 3) size of the appliance load. Therefore measuring appliances was limited to the following appliances: refrigerators, freezers, dishwashers, washing machines and tumble dryers.

4.2 Research demarcation

This research is confined within the context of the current Dutch electricity market. Countries with a similar Energy Only market model include the United Kingdom and Scandinavia. The research question is demarcated to the technical potential of DEM. Technical potential assumes that only rational factors are of influence. In practices there are at least three factors that can motivate a customer to participate in DEM (Pöyry, 2011) 1) costs (i.e. reduce electricity costs), 2) convenience and commitment (i.e. minimal impact on the consumers preferences for electricity use), and 3) complexity (i.e. lack of complexity and easiness of engaging in).

The pilot limits the research on DEM to households, for two main reasons. First of all, the adoption of smart meters by all Dutch households will allow for a different electricity market model (Van Veen, 2008). Other pricing mechanisms to incentivize more efficient use of electricity, e.g. through peak pricing (EDF, 2011), Critical Peak Rebate or Time Of Use tariffs (PowerCents DC, 2010). Second, several developments will shape future electricity demand of households. These developments are: electricity savings, distributed generation, electric vehicles, and heat pumps. How these developments turn out will have important consequences for electricity suppliers with regard to their wholesale and retail strategy and for TSOs and DSOs managing the electricity grid. DEM can play a, yet to be determined, role in managing these developments.

4.3 Qualitative approach

The research method of this study is first based on a qualitative approach. There was no fixed sequence of steps in conducting the qualitative part of the research. This allowed for more flexibility necessary in the pilot project. Semi-structured interviews and desk research was conducted to explore the possibilities of DEM. The current electricity market model does not specifically take into account the possibilities of DEM. DEM has to confine within the system boundaries of the current model. Therefore it is important to explain how and in what conditions DEM might be used by an actor. Firstly in this research, actors in the electricity market are described in four steps:

1) The first step describes the function of an actor, taking into account the notice period and location of demand.
2) The second step describes trends in the electricity market affecting the function of an actor.
3) The third step describes how DEM can be used by an actor.
4) The fourth step describes how beneficial DEM can be for an actor.

A study by KEMA (2012) is used to compare the pilot to a global inventory and analysis of smart grid projects; PowerCentsDC (2010) is used to compare the process and experiences of the participants as stakeholder; Pöyry (2011) is used to compare the integral approach of an electricity market comprehending TSO, DSO and electricity suppliers; a joint study by D-Cision and TNO (2012) highlights the many implicit and underlying assumptions with regard to DEM in the Dutch electricity market.

Secondly, several DEM hard- and software systems were researched and tested during the pilot. Current state of the art literature is usually based on modelling of data (e.g. Claessen et al., 2013; Niro et al., 2013; Stadler et al., 2008), assuming the DEM system has no influence. Experiences gained are the first results documented, as the specifics of each DEM system do have implications for further quantitative data analysis and results. In the pilot project the inherent uncertainty of modelling was replaced by real life measurements of a high resolution. However, it should be noted that these measurements have their own inherent flaws induced by the way equipment is installed and the possibility of a biased sample.

4.4 Quantitative data analysis

The DEM systems for the pilot are installed at households that are equipped with a smart meter. The DEM system consists of a smart bridge and several smart plugs (from supplier Net2Grid, www.net2grid.com). The smart plugs can measure the electricity usage of appliances and are placed between a socket and an appliance. The smart bridge receives the measurements from the smart plugs and from the smart meter and uploads the data to an online database.

Data is collected on electricity usage measured in Wh on a 15-minute time resolution for smart meters and all plugs. The measured period ran from week 2 to week 20 of 2014 (6^{th} of January to 18^{th} of May). All the data was converted to kWh. Three indicators of DEM (Pöyry, 2011) are distilled from the electricity usage data: magnitude (in terms of kW power), duration (in minutes or hours) and the timing (time of the day). The frequency with which a certain power load occurs (e.g. daily, weekly or seasonal) should also be measured, but due to time constraints this was not possible. Quantitative findings were compared to earlier studies by Stamminger et all (2008) for comparing load profiles of appliances; and a study by Kling et al. (2012) for its resemblance with the aim in this thesis. Only measurements of weekdays were used for the following reason. More economic activity takes place during weekdays, resulting in more electricity usage, which is therefore more likely to bear important results for actors. Note: it may well be that daily electricity usage in the weekend is higher for households than during weekdays. In appendix 1 data quality check is described.

4.5 Quantitative results

The first step was comparing the penetration rates of the appliances to earlier studies. Seebach et al (2009), Stamminger et al (2008) and ECN (2000) derive results for potential of DEM based on penetration rates and standardized load profiles of appliances. Deviations in penetration rates are an important factor in the technical potential for DEM.

In a second step, the selected data was normalized for each type of appliance by taking the averaged performance of all appliances. This shows the continuous load profile of each type of appliance over time. The normalized profile was compared to the load profiles assembled by the University of Bonn (Stamminger et al., 2008).

In a third step, annual electricity use of appliances was derived. For refrigerators and freezers the average daily usage over the measured period was multiplied by 365 days. For dishwashers, washing machines and tumble dryers the average was multiplied by the EU reference amount of cycles as used in calculating the energy efficiency label of an appliance. The EU energy efficiency labels take into account standby usage and involve a mix of programmes, with partial and full loads and high and low temperatures. A dishwasher is based on 280 cycles a year, a washing machine is based on 220 cycles a year and a tumble dryer is based on 160 cycles a year. In this calculation it is assumed that the mix of programmes is reflected in all the measured cycles.

In the fourth step, the normalized continuous load profile for each type of appliances was multiplied by the penetration rate found in this study. Smart meter data was used to measure the total electricity usage of each household. The electricity usage of all appliances is compared to the total power load of all households over time. This shows the present potential of DEM as percentage of total electricity use by a household.

Fifth, the energy efficiency was determined. Electricity use for dishwashers, washing machines and tumble dryers can differ each cycle, depending on the program settings used in that particular cycle. The specific use depends on the temperature setting, kilograms of load and length of the program set. Electricity use for refrigerators is highly dependent on the size of the appliance and constitutes a similar problem. Lowest energy use of a refrigerator is therefore not a sole indicator of high energy efficiency. To circumvent the problem of lack of specific appliance information, appliances were divided into two equal sized groups: one of low electricity use and one of high electricity use. It is assumed that this averages out different sized appliances, programs settings and partial loads. The future potential of DEM is calculated as the difference between the high and the low electricity using groups. The difference of the electricity use between the high and low group was taken as an indicator for energy efficiency over time and compared to estimates of electricity use by 2025 as studied by the University of Bonn (Stamminger et all, 2008).

Sixth and final the technical potential for DEM as gathered from the measurements are discussed as results for each actor. The results are put in context of the current electricity market model.

5. The current electricity market model

5.1. Energy suppliers

5.1.1 Responsibility

Energy suppliers deliver electricity to their retail customers. They have the obligation to submit electricity programs (E-programs) detailing the expected use by their customers. Households are profiled using a standardized profile that factors in e.g. the day of the week and the season. E-programs have a resolution of 15 minutes and have to be submitted to the TSO one day ahead. Alterations are only allowed up to one hour before the timeslot is due (gate closure time as set by the TSO) (TenneT, 2010). Energy suppliers are incentivized to make the most accurate prediction of electricity use by being penalized for any deviation between predicted and measured electricity use.

Energy suppliers may use trading and/or own generation for supply. Energy suppliers trade on a variety of markets ranging from longer term of several years ahead to day-ahead and intraday markets (Edenhofer, 2013). Base load, a bare minimum an energy supplier expects to need at 24 hours a day, is procured in vast quantities and may be contracted years ahead. The APX-Power Spot Exchange (former APX-Endex market) enables trade in electricity for the day ahead. These trades are settled in blocks of one hour. The intraday markets use shorter timeframes of 15 minutes and are usually traded over the counter (OTC) between suppliers. The OTC market has more volume than the APX market (figure 2) but lacks transparency. It can be assumed that the settled APX are a good proxy for trades settled in OTC markets. The ongoing energy transition has already caused more uncertainty in electricity trades, which is in turn reflected in more short term trades as seen in figure 3 (e-Risk Group, 2014; ACM, 2013).

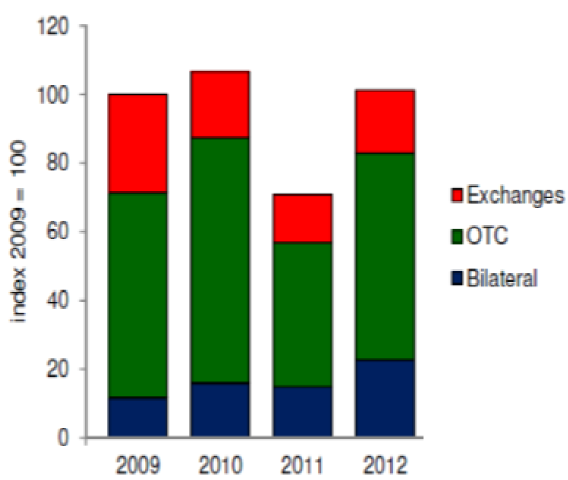

Figure 2: Division in trading places (Source: ACM, 2013)

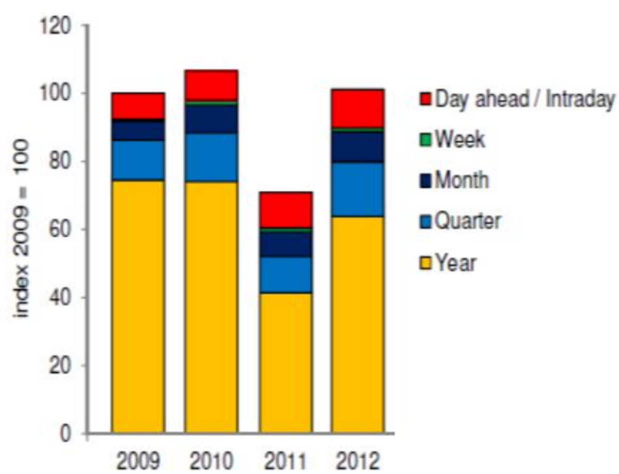

Figure 3: Division of volumes traded on short term (Source: ACM, 2013)

5.1.2 Trends

As a result of market coupling the APX prices on average have become lower since 2007 (Schuman, 2010). The APX spot prices has averaged around €50 / MWh for the last two years (see Figure 4). Distribution of prices has slightly changed over the years towards a few higher extremes.

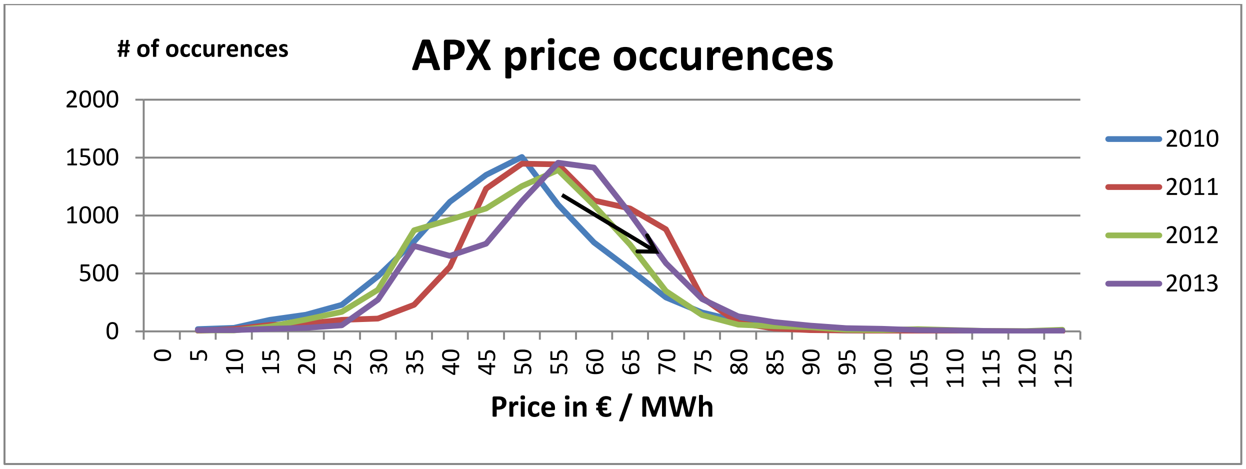

Figure 4: Indication of market prices: APX price occurrences (Source: Energymarketprices.com)

Prices on the electricity market might develop differently in the near future mainly due to the trend of growing intermittent generation (ECN, 2014). Figure 5 shows simulated generated renewable energy in 2013 and 2030 in The Netherlands using the same weather data over the period 13th to 26th of March 2010. Green shade portrays electricity supplied by renewable generation and grey shade is all (other) electricity supplied by conventional (base load) fossil fuel power plants or imports. Two trends are visible. First is that electricity consumption has grown and is more volatile by nature. Second and more important is that traditional base load is being eroded by the renewable generation (e-Risk Group, 2014). Conventional power plants in an *Energy Only* Market rely only on operational surpluses to cover their initial investment costs. Due to renewable generation the merit order is changed (*merit order effect, see figure 6)* causing the '*missing money problem*' for conventional power plants by 1) lowering the wholesale price of electricity, and 2) creating a more volatile (price) pattern increasing the risk of operating these plants.

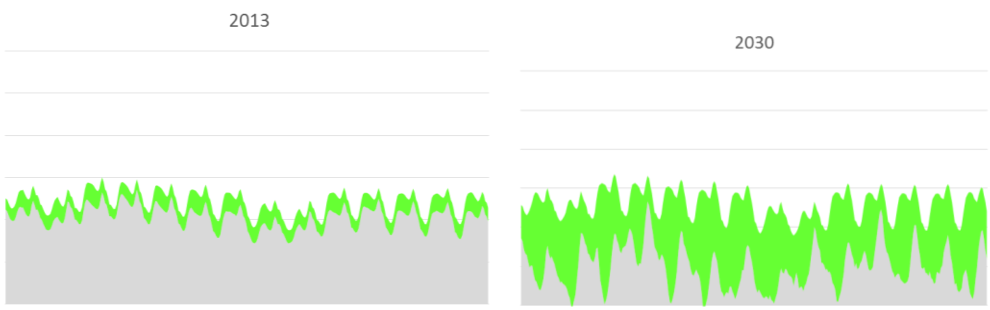

Figure 5: Simulation intermittent generation in 2013 and 2030 (Source: e-Risk Group, 2014)

Figure 6 shows what happens to the marginal price ladder of electricity generators in the case of low wind power and the case of high wind power. Low wind (Price A – dashed supply line) is settled at a higher price for a given amount of demand. In the case of high wind (Price B – solid lid) the settled price is lower, because there is more supply of low marginal cost of wind power. The line moves to the right and, hence for a given amount of demand the price is lower.

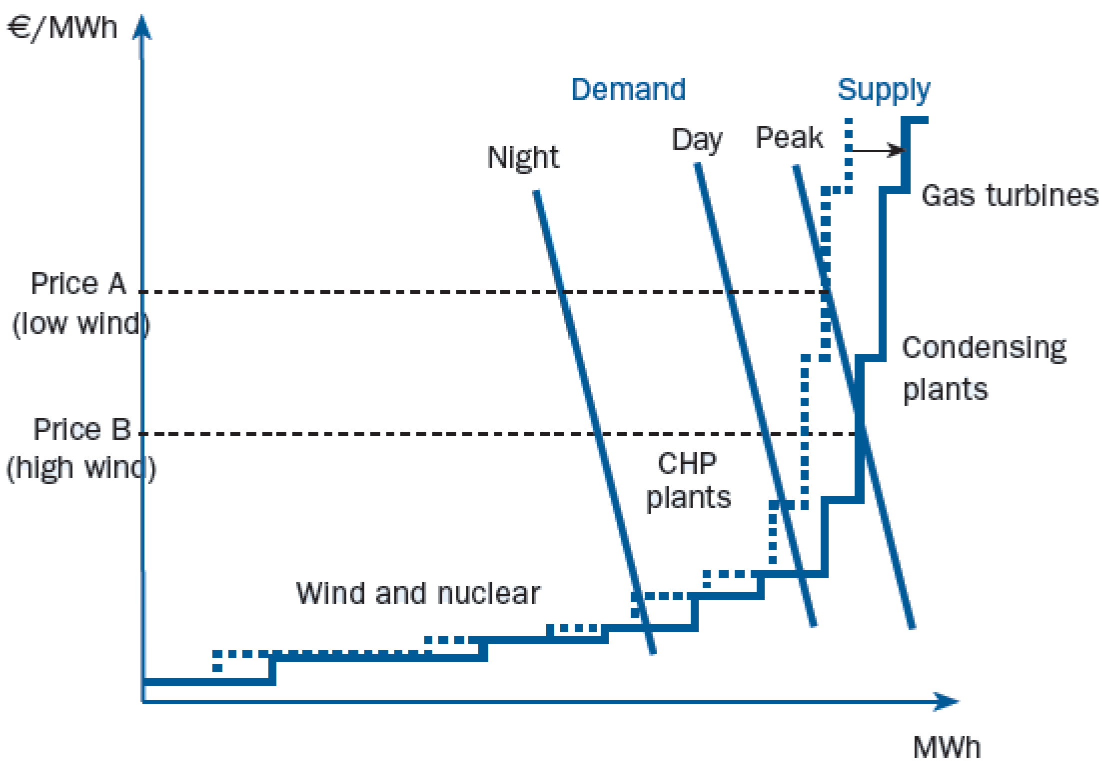

Figure 6: Merit order effect (Source: EWEA, 2012)

5.1.3 DEM

DEM would allow an electricity supplier extra options for trading and balancing predictions in the E-programs vs actual electricity demand. The electricity market is characterized as a demand following market: supply follows to match demand. DEM can do the opposite and make demand follow and match (intermittent) supply. It allows moving demand towards hours with a lot of supply of electricity (i.e. windy and sunny hours). Vice versa DEM could alter demand to move away from moments of low supply of electricity. In a demand and supply curve the two curves meet at an equilibrium price. In the traditional electricity market the equilibrium price is set mainly by demand. With growing intermittent generation the price of electricity is more and more set by supply with marginal costs of nearly zero.

In figure 7 at P1 a high price is illustrated with a low (inelastic) demand. When the electricity price is lower at P2, demand should theoretically increase.

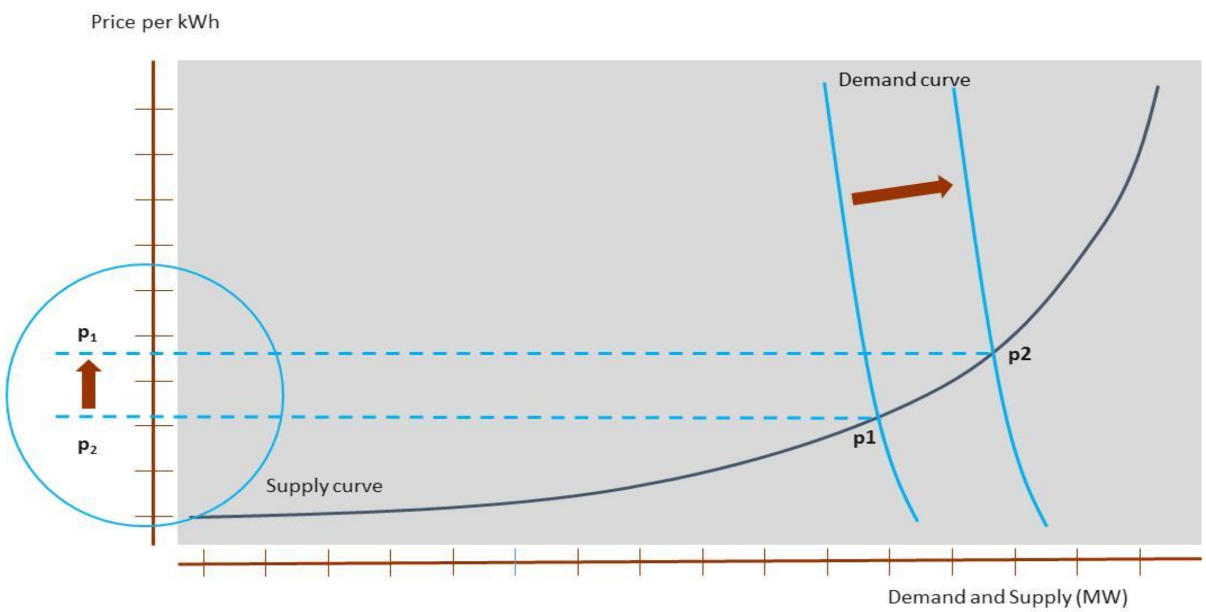

Figure 7: Schematic explanation of demand elasticity in market prices due to demand response (Source: e-Risk Group, 2014)

5.1.4 Benefits

Energy suppliers could use DEM to complement their wholesale positions as submitted to the TSO. Their uses of DEM could be (Pöyry, 2011):

1) Energy balancing in terms of energy use (MWh per settlement period) and reducing exposure by optimizing contracted position or physical position after final deadline of submitted energy programs (after gate closure by the TSO)
2) Capacity management to avoid building or running peaking generation which is more expensive
3) Manage CO2 emissions by avoid running fossil generation in reserve

Benefit 1 refers to the additional ability to trade on any of the markets an energy supplier is active, e.g. the APX-Endex market, OTC market or the imbalance market. Veeken (2014) and others (Gottwalt et al., 2011; Slootweg, 2013) have modelled savings of DEM to be in the order of €15 annually per household traded on the APX-Endex market. As stated in an interview with the e-Risk Group, similar price savings can be assumed in the OTC market as APX-Endex prices are a reflection of this market.

Benefit 2 would provide another way to cope with peak demand and avoid building higher marginal cost plants that typically cope with peak demand (usually gas fired power plants). DEM could provide relieve by avoiding peak demand and therefore avoid scarcity of supply.

Benefit 3 refers to the need to keep conventional power plants in spinning reserve. In the spinning reserve mode, power plants burn fossil fuels to keep electricity production readily available. When intermittent generation decreases (i.e. transient cloud or no wind) the spinning reserve can immediately take over production of electricity. In an energy only market, where plant owners are only paid for generated electricity and not for ancillary services, this is more costly as operational expenses are made (fossil fuels), but operational surpluses are not guaranteed (wholesale price effect and volatility effect). It suffices to say here that DEM could provide an additional source to match the predicted and real electricity use to match the E-program, especially after gate closure. The following chapter will elaborate on savings on the imbalance market from the perspective of the TSO.

5.2 Transmission System Operators

5.2.1 Responsibility

When many appliances are switched on at the same time, e.g. during half time of a popular sports match, the TSO has to maintain the stability in the electricity grid around 50 Hz (TenneT, 2010). TenneT is responsible for the balancing zone in The Netherlands and is connected to other European balancing zones. Below 110 kV the DSO is responsible for maintaining the network. TenneT is still responsible for maintaining system balancing, also on the local distribution level. Milligan et al. (2010) differentiate responses by, 1) type of event (e.g. contingency, forecast errors), 2) time scale of the response, 3) type of required response (e.g. instantaneous frequency deviations, readiness to start a power plant), and 4) the direction of the response (either upward or downward). Across European balancing zones it is agreed that frequency control is used as primary regulating power. All generation plants have to provide 1% of their generation capacity to respond to frequency changes. It is used automatically by sending an electronic signal, the Load Frequency Control. Power plants across the grid have to adept power supply just so to maintain 50 Hz alternating current. Within the balancing zone of The Netherlands TenneT has several ways to reach its goal of electricity system stability. The imbalances are met with secondary regulating power, reserve power and emergency power. These types of power are used in escalating steps to respond to the situation at hand (see figure 8). The costs of these powers are reflected in the imbalance market that Tennet operates. Owners of generation capacity above 60 MW have to make compulsory bids in the Transmission program (T-program). On the basis of the E- and T-program TenneT is able to 1) manage congestion in the network (T-program), and 2) allocate the deviation from the predicted E-programs.

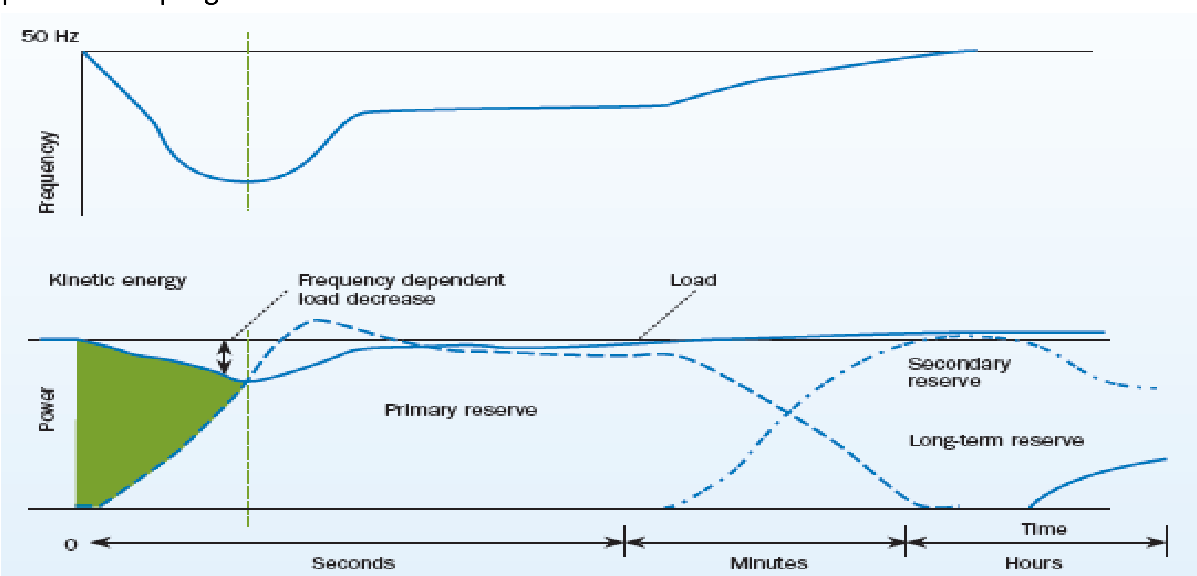

Figure 8: Balancing services time frame activation (Source: EWEA, 2012)

Energy suppliers are incentivized to make the most accurate prediction in their E-programs. They have to pay the imbalance price for each settlement (period of 15 minutes) multiplied by the deviation in electricity usage. Niesten & Jolink (2013) show that although the current imbalance market does actually constitutes absence of a market due to high investments in specific assets. They refer to dynamic electricity management as an opportunity to reduce the need for these large investments. This could increase the participation of small players in the imbalance market, thereby creating a better market.

5.2.2 Trends

The imbalance market is based on quarterly hour prices on 35040 hours annually. High supply of electricity is indicated in figure 9 by the negative prices. Renewable generation has priority on the electricity grid. When renewable generation provides more electricity than anticipated, an excess of supply is provided to the market. Prices settled in the imbalance market might develop different in the near future mainly due to the trend of growing intermittent generation (ECN, 2014). Quarter hour imbalance prices may tend to become more extreme. In the same meta study by ECN (2014) it is estimated that with increased levels of intermittent generation, imbalance costs will increased in the order of several EUROs / MWh[1] depending on the penetration levels of wind and solar power. At the same time, more intermittent generation increases the short-term volatility of wholesale prices, enhancing the risk of power generation as a business.

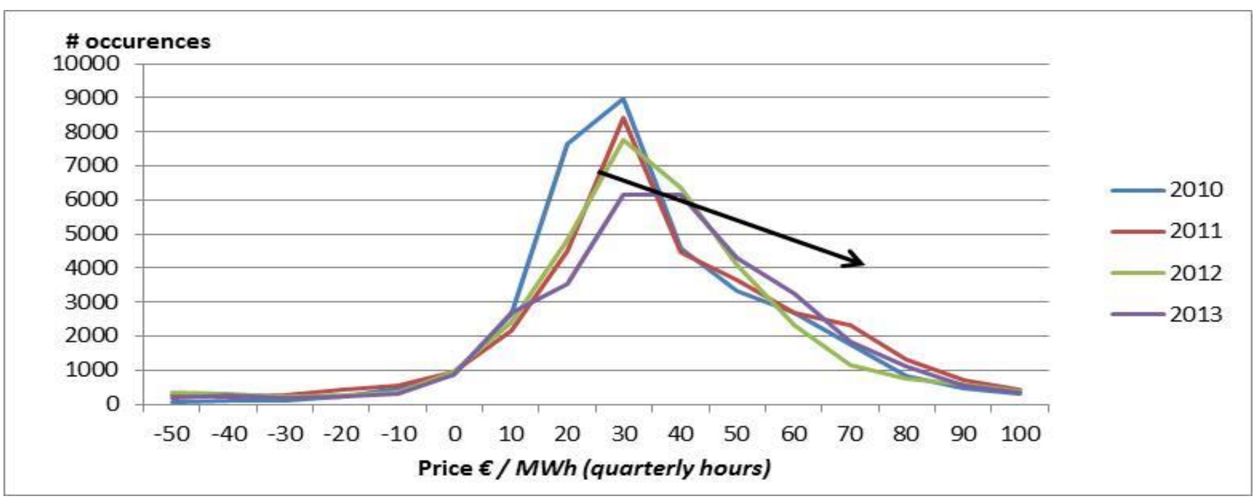

Figure 9: Distribution of number of same price occurrences on the imbalance market over the years 2010 to 2013, prices capped at -50 and 100 and interval of 5 (Source: e-Risk Group, 2014)

[1] Balancing costs are generally the lowest component of total variable renewable energy system integration costs, ranging from 1-6 €/MWh, i.e. 5-15% of total integration costs. The largest component consists of either grid related costs or adequacy costs, depending on the specific case or study considered

5.2.3 DEM

Regulating power might have different requirements in the future to deal mostly with forecast errors of intermittent generation (Holttinen et al., 2011). DEM could complement grid stability and imbalance market by following decentralized generation. I.e. enable a more supply driven market as opposed to the traditional demand following market. DEM is currently useful for negative power, i.e. to avoid electricity demand by switching off load interruptible appliances when necessary. Future DEM equipment could also actively use more electricity when necessary (e.g. by pre-cooling a refrigerator). Future regulating power could very well entail different requirements such as high ramp rates, shorter gate closure times, shorter settlement periods, and smaller bid sizes (Veen, 2007, Holttinen et al. 2011). Some of these requirements may very well better fit the characteristics of DEM than traditional plants used for regulating and reserve power.

5.2.4 Benefits

A TSO could use DEM to complement their primary goals. Their uses of DEM could be (Poyry, 2011):

1) Power balancing operation on a minute by minute basis
2) System balancing in the hour after gate closure time

Benefit 1 refers to the ability to better match demand with the given (intermittent) supply with the use of DEM. It has been shown that DEM systems can respond fast enough to respond to ramp (down) rates of e.g. solar panels and wind power output (Kok, 2013). Benefit 2 refers to the predicted and actual (allocated) electricity use by each energy supplier in each settlement period of 15 minutes. TenneT may use the ability of DEM as an additional way to balance the system in conjunction with the (compulsory) bids of conventional power plants. In a modelling study by the e-Risk Group (2014) it is estimated that an average household can generate savings in the order of €26 annually on the imbalance market. However, Veen (2007) has concluded that shortening the gate closure time would significantly reduce the need for system balancing. This is in line with the fact that more recent predictions of intermittent generation significantly reduce the forecast errors (ECN, 2014). Another benefit due to the use of smart meters is that it allows for an exact allocation of electricity usage for each household[2]. DEM will allow to (near) real time match real electricity usage with predicted electricity usage. DEM theoretical enables a possibility: an energy supplier could *pay* its customers to use more electricity at those moments, thereby avoiding penalties for deviating from their E-program.

[2] Currently this is done using standardized profiles per type of connection and all induced costs are socialized.

5.3 Distribution System Operators

5.3.1 Function

DSOs have two main responsibilities according to Netbeheer Nederland, 1) to maintain the electricity (and gas) infrastructure on the low voltage (low pressure in case of gas) networks and 2) to facilitate a (better) working electricity market. While the first responsibility is obvious, the second responsibility refers to the role the DSO has in the current model of the electricity market. A DSO has a subordinate role by being legally obliged to make available enough transport capacity, i.e. a DSO has to facilitate the '*copper plate assumption*' (D-Cision, TNO; 2012). Current reliability is 99.99% uptime with an average discontinued network connection in the order of 27 minutes a year per household (Netbeheer NL, 2013). Network reliability and capacity is managed and monitored using multiple indicators. Examples of indicators are: maintenance logs, static network capacity, power load logs, new power connection requests (Stedin, 2011). These indicators make sure that the distribution network is always over-dimensioned to a certain extent.

5.3.2 Trends

As scarcity is a basic economic function, the lack of the scarcity incentive makes efficient investments in the electricity network more difficult and maybe more expensive (D-Cision, TNO; 2012). The current used 'fit-and-forget' approach implies that all issues are resolved for a long term upfront at the planning stage. The shift towards more (distributed) intermittent generation may mean that this approach is no longer cost effective (Borenstein, 2008). The fit-and-forget approach is inflexible in the short term to accommodate the two trends in the electricity market.

Network capacity use is typified as '*camel back*' shaped by two distinct moments (figure 10): one in the morning at around 8 or 9 am and a second in the evening between 17 and 20 pm. The trend of electrification could be a major concern for DSOs. Space heating in The Netherlands is predominantly based on gas, but this need not be the case in the future. The ongoing trend of electrification could mean that space heating could become based on electricity, which is already common in e.g. France (EDF, 2011). This would have implications for the necessary network capacity as peak demand will become even more pronounced at the two mentioned distinct moments (as is also illustrated by the two coinciding graphs of the power and heat demand in figure 9). It will also have implications for balancing of electricity on the local networks for which TenneT is responsible. The altering and increasing amounts of electricity (demand and supply) at local levels might imply more local balanced markets instead of one national balancing market.

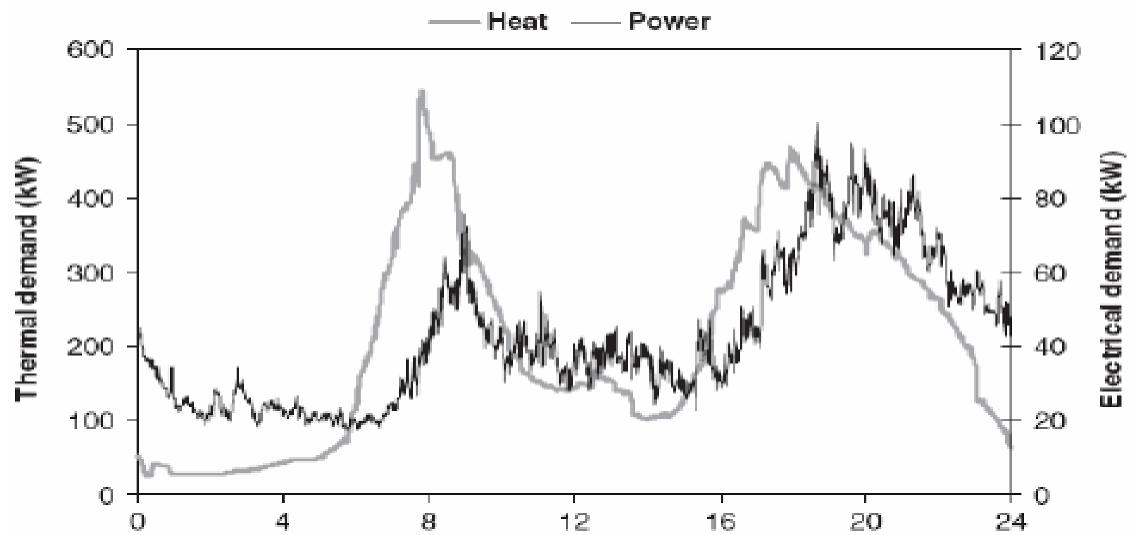

Figure 10: Typical aggregate heat and power demand (50 houses) in a distribution network over 24 hours (Source: Peacock and Newborough, 2006)

The trend of growing intermittent generation need not necessarily have to become a capacity issue. In several studies by Dutch DSOs it was found that in the order of 50% penetration levels of solar panels could be absorbed in the distribution network, depending on the age of the network and the peak capacity installed (with an average of 1 kWp per connection) (Laborec, 2013; Paatero, 2006). It is remarked that the voltage regulation could change, but this is also depending on the orientation of the panels and the quality of the inverters installed (Paatero, 2006; Eltawil, 2010). Wind power is usually connected at a higher voltage level than households and therefore a responsibility of TenneT and does not pose a capacity problem for DSOs. Currently, some uncertainties do exist regarding the peak capacity at the local scale (Smit, 2005). Although households never use all the same appliances at the same moment, solar panels in the same neighbourhood do generate electricity at the same moment. Also, future appliances such as heat pumps and electric vehicles are more likely to simultaneously use electricity. Due to their high electricity usage, this may cause local networks to reach their limits.

A benefit of distributed generation such as solar panels is that it may reduce network losses. Electricity is generated on site and transportation of electricity is avoiding, avoiding network losses that are paid for by DSOs. However, generation close to consumption does not necessarily reduce distribution network costs, but may in fact increase them (Eurelectric, 2013). Network capacity still has to be based on peak demand and solar panels do not necessarily generate (a lot of) power on the moments of peak demand. Also, other types of protective and control systems for DSOs are necessary to cope with a bi-directional flow of electricity.

5.3.3 DEM

The following illustration shows the effect of energy trends and the possible applications of DEM.

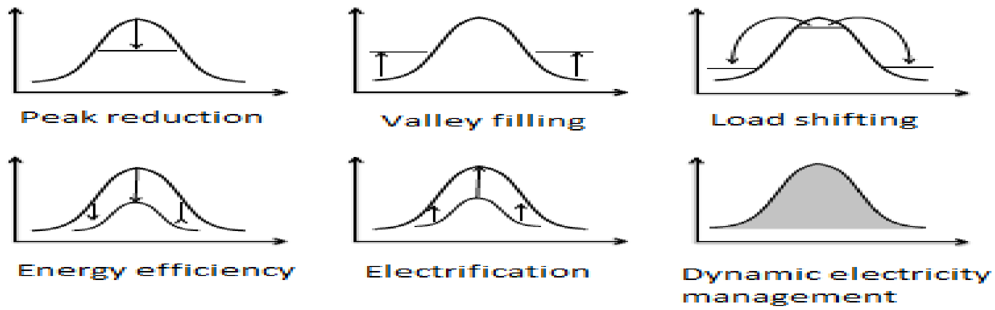

Figure 11: DEM applications (Source: adapted from Chuang and Gellings, 2008)

The six pictures are explained as follows.

1) Peak reduction at common hours of peak demand can avoid over-dimensioning grids
2) Valley filling can be a consequence of avoiding peak demand (or in the case of an energy supplier it is used to match the supply of intermittent generation)
3) Load shifting can be used to match demand with supply
4) Energy efficiency has a positive limiting effect on (peak) demand, but decreases the potential for DEM
5) Electrification has a negative effect on (peak) demand, but increases the potential for DEM
6) DEM is the (perfect) matching of demand and supply

5.3.4 Benefits

A DSO could use DEM to complement their two main tasks. Their uses of DEM could be 1) Avoiding peak demand by moving electricity demand to another time, and 2) Optimize capital costs of investments by avoid or defer network upgrades (Poyry, 2011).

Research on benefit 1 shows encouraging results: DEM has the potential to reduce peak electricity demand in the order of 5-30%. Participation by consumers depends on the price incentive used, e.g. critical peak pricing, critical peak rebate or hourly pricing (PowerCentsDC, 2010). Newsham et al. (2010) find that critical peak pricing in combination with automated response by households reduce peak demand by 30%. Two-tier tariff systems reduce peak demand at most by 5 %. Other research, e.g. Torriti et al. (2010) finds that peak demand in the winter can be reduced by 5 to 6% in Denmark. DSOs that are actively trying to alter (peak) demand can encompass more local (renewable) electricity generation in their networks and postpone investments (e.g. Breuer et all, 2007 and McDonald, 2008).

Benefit 2 refers to network investments carried out by DSOs. Network investments consider long term planning in the order of 40+ years (Uneto Vini, 2008). However, parts of the network may be overdue for replacement and are currently overcharged (Stedin, 2011). Overcharging increases the wear and tear and it increases the chance of malfunction. Smit (2005) expects a large increase in network upgrades by the year 2020. There are no exact figures for avoided or postponed network investments. Network investments can only be postponed (up to several years), but never fully be deferred. Postponements should therefore be expressed in terms of € / kW reduced demand / year. Many sources lack this detail, e.g. CE Delft (2012) estimates deferred network investments at € 1200 / kW reduced demand. Smart Grids Model Region Salzburg p7 states: "*In the medium voltage network, there will be, for example, a benefit in the range of € 22-104 per kilowatt of successfully reduced demand*", but lacks to mention that these figures are probably per postponed year of network investments. Calculations by Alliander estimate the initial investment and annual interest component to be €130 / kW / year - which is in the range of the Salzburg pilot[3]. Stedin has a similar figure[4]. Alliander notes that a household pays about € 200 annually for a connection. Keeping in mind the ongoing trend of electrification, the necessary average peak capacity is likely to increase. However, the assumption of 1 kW average (peak) capacity for a household is a lower bound. Laborec (2013) researched the impact of distributed generation and found that DSO's use values in the range of 1 – 2 kW per connection. Furthermore it was mentioned that peak demand is measured once every two years on the level of the distribution transformer. This may indicate that peak demand is not yet a pressing issue, or simply that DSOs still have a long way to go.

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[3] Alliander (2013) provides an insightful back-of-the-envelope calculation in the costs of network upgrades. It uses the following rules of thumb:

- each grid connected house requires an average (peak) capacity of 1 kW
- each grid connection to a house requires an investment of €2500 in capacity of the grid
- regulation prescribes the investment to be amortized over a period of 40 years
- the amortization rate is estimated at 6% (fluctuates, depending on market interest rates)

[4] Stedin calculates the cost of a connection based on three parts: 1) 2.5m medium voltage network cable, 2) 12m low voltage network cable, 3) transformer for the distribution net, which can connect 275 homes. These three parts costs €993.84 + €210.58 + €28.44 and add up to €1232.86 (Stedin, 2013). However, Stedin notes that maybe not all parts have to be replaced at once.

6. The pilot smart grid

6.1 Dynamic Electricity Management systems

The pilot examined a wide variety of energy monitoring systems available (for a full list, see appendix 2). Three systems were tested from the following suppliers: Plugwise, Fifthplay and Net2Grid. A fourth system, Powermatcher, was examined in a workshop and in an interview with Alliander (2013).

This section will answer the following sub question: "*What are some current experiences with Dynamic Electricity Management systems?*".

State of the art literature that model scenarios for demand response, assume that the quality and the workings of the equipment to have no influence on the results. In practice there is a wide variety of systems available and their hard- and software designs provides both opportunities and limitations to DEM. One important limitation for example was illustrated in Chapter 4.2 on the latency of the signal required. The following part will describe this and other important aspects of current available systems and especially those that were tested in the pilot.

6.2 Current available systems

Before the three systems were chosen, a Request For Proposal (RFP) was put together on the basis of requirements set by the twelve collaborating companies and research institutes. Main requirements were set as follows, 1) quality and functionality of the hardware, 2) plug and play like installation, 3) user friendliness of the software, 4) privacy protection, 5) online data management tools, 6) price. (For a full list of requirements and scoring, see appendix 3). Equipment consists of a separate plug for each appliance and a central host that measures the smart meter and communicates the data to the online database.

After testing, it was decided in December 2012 that the system of Net2Grid best suited for the purpose of the pilot. Net2Grid is a small start-up company in the area of smart grids and DEM tools (See appendix 5 for details on Net2Grid equipment). Part of the software had yet to be developed, which allowed the pilot to request extra functionality.

Criteria	Plugwise	Fifthplay	Net2Grid
Hardware	Stored measurements (+), short wireless range (-)	High latency data (-), no smart meter data	Open standard (+), long wireless range (+)
P&P	Yes	Yes	Yes
Software	Standard	Customized	In development
Privacy	As enforced by privacy law	As enforced by privacy law	Cannot access individual data
Data	1hr resolution, proprietary online portal	15min resolution, proprietary online portal	1min resolution, open source online portal
Price	€ 300 / household	€ 300 / household	€ 200 / household

Table 1: DEM systems criteria overview

During the pilot several issues were discovered, three of which are:

1) Net2Grid uses a high resolution of electricity usage, but has no option for local data storage and therefore some of the data gets lost in the case of no wireless connection of the plugs or an offline Internet connection. It was found that a central database with measurements is necessary and logical when analysing for example the potential of DEM such as in this thesis.

2) Another related problem in a central database is the data collection and labelling of the complementary appliance it measures. As the appliance cannot be digitally identified by the plug, this induces uncertainties about the measured data. Also, the database did not allow for interactively selecting the right data, increasing the time necessary for data analysis.

3) The received data had to be checked thoroughly for errors, such as resets by the plug and lost data due to lack of internet connection.

Net2Grid built an online portal of database for the purpose of analysis and feedback to the households. However, a central database is not a requisite for a smart grid. Currently systems do not (yet fully) offer the possibility of real time control of appliances. Fully dynamic prices require autonomous operation by the appliances, to avoid overburdening the user. This aspect will remain important for developing a fully functioning DEM system. In the future it is more likely for each appliance to be connected via USB or WIFI, enabling a far more sophisticated approach to a smart grid.

6.3 Selecting suitable appliances

In theory every electric device is capable of matching supply and demand, simply by turning the appliance on or off. In practice however, not all devices are effective and require user interaction or not-using them would decrease comfort. An example of the latter is a lamp that simply has to provide light when the user requires light.

There are two types of appliances suitable for DEM: load interruptible and load shiftable appliances. Load interruption refers to the ability to immediately switch off the appliance without direct consequences. Interruptible load involves a type of storage of electricity, usually converted into a form of heat. The operation of these appliances is a continuous pattern of running and pauses. Load shifting refers to the ability to postpone the use of the appliance. It involves appliances that have to meet a certain deadline before which their operation has to be finished. The start of the operation can usually be postponed and this allows the operation to be planned on an efficient moment to use electricity. The operation of these appliances is characterized by a stochastic use pattern and a short period of high peak power load (Stamminger, 2008). Knowing the typical stochastic use pattern is useful information when analysing or modelling the potential of DEM.

Main requirement for appliances to be useful in a smart grid is to have a (relatively) high power rating and/or electricity use. These two characteristics do not necessarily have to coincide. A few factors of influence on electricity use are: number of occupants, user behaviour and preferences. Appliances that fulfil these criteria are: refrigerators, freezers, dishwashers, washing machines and tumble dryers. Appliances that will be more common in the near future are: electric vehicles, heat pumps, air conditioners and storage. (For a full list of appliance and the likelihood to be present in households see appendix 4.)

Table 2 shows our assessment of the applicability of each appliance for each of the three purposes DEM can be used for. The purposes are 1) improving grid stability (IGS), 2) avoiding peak demand (APD), and 3) complementing wholesale strategy (CWS). The ratings range from low, medium to high depending on the (maximum) power rating, energy use of each appliance and ability to load shifting or load interruption. I.e. the speed with which the appliance can react to a request for demand response is an important determinant. Power ratings are based on: own measurements, literature and research in consumer guides and (price) comparison websites such as www.kieskeurig.nl. Electricity use is based on a European study 'Energy Use of Products' (2005), comparison websites with information on labels and verified with the product websites of several producers.

Appliance	Load Shiftable	Load Interruptible	User interaction	IGS	APD	CWS
Refrigerator	Low	High	Once	Medium	Low	Medium
Freezer	Low	High	Once	Medium	Low	Medium
Dishwasher	High	Low	Always	Low	High	High
Washing machine	High	Low	Always	Low	High	High
Tumble dryer	High	Low	Always	Low	Medium	Medium
E-vehicle / storage	High	High	Sometimes	Medium	High	Medium
Electric boiler / heat pump / air conditioner	High	High	Sometimes	High	High	High

Table 2: Applicability of appliances for DEM purposes

Current typical household appliances have a shortcoming that they are either suitable for load shifting or load interruption. Furthermore, load shifting appliances always require user interaction and cannot be operated fully autonomous. Load interruptible appliances are well suited for improving grid stability (IGS) and complement wholesale strategy (CWS), but their total energy use is low and therefore their impact is rated medium. They cannot be switched off long enough to be useful for avoiding peak demand (APD). Load shiftable appliances are well suited for avoiding peak demand. New and more efficient tumble dryers have a dramatically lower power rating (around 1000W compared to 3000W for older appliances), which is the reason for a medium rating. Load interruptible appliances should also be suitable for CWS as a large part of their energy use is concentrated in a short period at the beginning of a cycle. Tumble dryers are rated medium again because newer more efficient appliances are characterized by a more continuous level of energy use.

Future household appliances hold more promise for DEM. Their power ratings are higher than current appliances and so is their total electricity use. Electricity use of an electric vehicle is stored in a battery to be used later. An electric boiler and a heat pump store electricity in the form of heat that slowly dissipates over time. Storage in either a battery or in the form of heat is extremely useful for all DEM applications. The electric vehicle is rated medium for IGS and CWS because it is not necessarily to be always connected or ready to be charged.

6.4 Penetration rates

The likely presence of an appliance in a household is another factor of the technical potential of DEM. The following sub question will be answered: *"What are typical penetration rates for suitable smart grid appliances?"*

Modelling energy use and modelling the potential of DEM requires a careful examination of the resources. That is, the penetrations rates of appliances in the pool of households determine the technical potential for DEM in a pool of households. Composition of appliances in household changes over time, and penetration rates are likely to increase for reasons of comfort (ECN, 2013). In table 3 the penetration rate of the selected appliances found in the pilot project is compared with other research. Stamminger (2008) used a sample of 250 households. Holsteijn (2008) is based on an annual survey across Europe, with an unknown sample size for The Netherlands. The pilot project selected 101 participants and each participant had to indicate which appliances they owned. Three households indicated measuring an electric boiler. Due to this small number, it was decided not to include electric boilers in this study.

Appliance	Stamminger (2008)	Holsteijn (2008)	(VROM, 2010)	Pilot (# and %)
Number of households	250	Not mentioned	4700	101
Refrigerator	>100%	100%	94%	97 (96%)
Freezer	52%	30%	47%	39 (39%)
Dishwasher	50%	59%	54%	66 (65%)
Washing machine	95%	98%	94%	93 (92%)
Tumble dryer	61%	70%	64%	68 (67%)

Table 3: Penetration rates appliances

Overall the rates are comparable and seem justified when compared with the earlier studies. Lower rate in the pilot for refrigerators can be explained by the labelling of the participant. Consistency in labelling is not guaranteed and the participants might see freezers and refrigerators as interchangeable. An earlier study has shown that in 100% of the households a refrigerator (freezer) is present and in 21% a second refrigerator (freezer) is reported (EUPs, 2007). When added together, refrigerators and freezers sum up to a total of 135% in the pilot and are comparable. The higher percentage of dishwashers in the pilot project may be explained by a five year time difference between the earlier studies and the current pilot. It is very likely for dishwashers to have become more common. Washing machines and tumble dryers show lower figures, which may be caused by the biased pilot participants. In interviews it was indicated that some participants do not have tumble dryers due to environmental concerns due to (perceived) high electricity use of the appliance.

6.5 Energy efficiency

Energy efficiency of an appliance is indicated by an energy label based on a relative system. Appliances are compared amongst the same sort of appliances. A high energy efficient appliance of one sort can very well consume much more energy than another inefficient appliance of another sort. The relative system may be deceptive for consumers. The specific electricity usage for load interruptible appliances and load shift able appliances is illustrated in tables 4 and 5.

Label	A+++	A++	A+	A	B	C or higher
Refrigerator/freezer annual consumption (kWh/L)	0.85<1.0	1<1.5	1.5<1.85	1.85<2 Existing stock	Not allowed	Not allowed

Table 4: Energy efficiency labels for load interruptible appliances (source: EUP, 2007)

Labelling of refrigerators and freezers is based on total annual consumption under standardized conditions. The labelling takes into account the size of the appliance (Litres of food it can contain). Labels less efficient than A are not allowed anymore, but could very well be part of the sample in the pilot. Table 5 shows the amount of electricity usage for an average cycle of a load shiftable appliance filled with a specific volume. For dishwashers this is 12 sets of dishes, washing machine 5 kg of dirty laundry and the tumble dryer is based on 4 kg of laundry.

Appliance / label	A+++	A	B	C	D	E
Dishwasher (12 dishes)	<0.74	<1.06	<1.25	<1.45	<1.65	<1.85
Washing machine (5 kg)	<0.65	<0.95	<1.15	<1.35	<1.55	<1.75
Condense dryer (4 kg)	<1.55	<2.2	<2.56	<2.92	<3.28	<3.64
Ventilated dryer (4 kg)	<1.43	<2.04	<2.36	<2.68	<3.0	<3.32

Table 5: Energy efficiency labels (in kWh/ cycle of 4 or 5 kg) for load shiftable appliances (source: EUP, 2007)

European Union efficiency labels for washing machines are set using a weighted mix of cycles. For washing machines it consists of 42% full load cycles at 60°C, 29% partial-load cycles at 60 °C, and 29% partial-load cycles at 40 °C (EU, 2010). To derive annual consumption for energy efficiency labels, the electricity use is multiplied by a determined amount of cycles. The cycle of washing machines are multiplied by 220 times, tumble dryers are multiplied by 160 times and dishwashers are multiplied by 280 times.

Older appliances consume much more energy, which make them more valuable for DEM. Appliances have an average life span in the order of 9-11 years. It can thus be expected that the majority of older appliances will be removed or replaced over the course of 10 years, although this may change (i.e. become lower) (Cooper, 2004). Current best performing appliances are a good indicator of average performance within the next 10 years. Current and future total electricity use of current appliances with trend of energy efficiency is illustrated in figure 12.

The graph shows that the majority of demand by households is already suitable for DEM. In the future absolute demand of current appliances suitable for DEM will decline, but as a percentage of total household demand it increases. This could become a relevant fact if it is decided that the current electricity market model should change towards an (even) more DEM favourable system. If a large part of the demand were not suitable for DEM, this would hamper a transition to such a model. Current and future energy demand including the trends of electrification and energy efficiency is illustrated in (Figure 13).

The graph shows final energy use with the input of fossil fuels for heating and mobility converted into units of kWh. Electricity is a higher grade energy (in terms of exergy) than fossil fuels. Electricity based motors are far more efficient in converting energy than combustion engines. This explains the dramatic reduction in final energy consumption by households when demand of energy is far more electrified by the year 2030. However, the graph of 2030 depends on the conversion efficiency of primary energy (fossil fuels) into electricity. For example, when conversion efficiency drops to 50%, final electricity demand would only reduce to 16000 kWh (e-Risk Group, 2014). Future electricity demand for heating (heat pumps) and mobility (electric cars) will increase total electricity demand in comparison to figure 13. It is expected that these appliances are suitable for DEM, increasing even more the percentage of total household demand suitable for DEM.

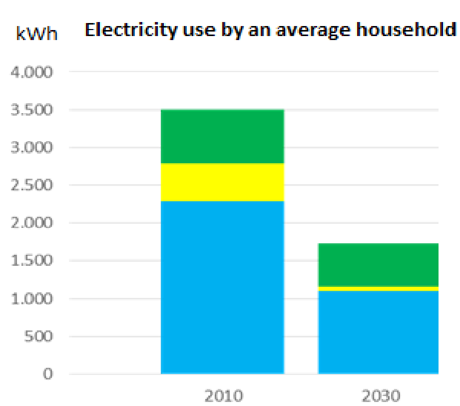

Fig 12: Electricity usage by average household in 2010 and 2030 (Source: e-Risk Group, 2014)

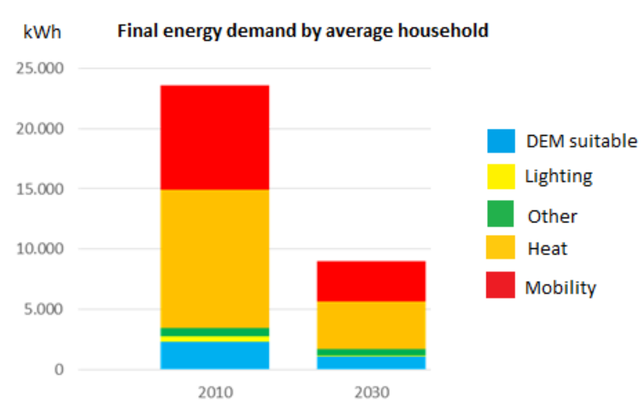

Fig 13: Final energy demand average household in 2010 and 2030 (Source: e-Risk Group, 2014)

6.6 Results

Suitability of an appliance is defined as the flexibility and the ability to address any of the three purposes of DEM as stated in the problem description. In short they are: improve grid stability, avoid peak demand, and complement wholesale strategy. The extent to which an appliance is able to address one of the three issues is dependent on the characteristics of its energy use. The following section will answer the sub question:

What is the typical electricity usage of appliances in the pilot and how will it change over time?

Electricity use is subject to change and one of the drivers (amongst other important factors such as behaviour) is technological progress in energy efficiency. The following part will show graphs of typical electricity usage as measured in the pilot. Two types of graphs were constructed:

1) A continuous normalized load profile of one appliance
2) A future continuous normalized load profile of a more energy efficient appliance

A continuous normalized load profile is the average load of each appliance as if it were operating the whole day. It shows the electricity usage pattern for one appliance, which can then be scaled to any number of appliances. The future continuous load profile is the normalized average of the 50% most efficient cycles.

Using penetration rates for the appliances as found in this pilot, three types of graphs were constructed:

1) Total electricity usage of all load interruptible appliances (current and future)
2) Total electricity usage of all load shiftable appliances (current and future)
3) Total electricity usage of all households over time (current and future)

6.6.1 Results - refrigerators and freezers

In research by Stamminger (2008) it was found that on average only 10% of the electricity use is induced by the user (e.g. opening the door). It can be concluded that the base power load curve is not significantly influenced by the user, which is an important fact for using load interruptible appliances for DEM. Figure 14 shows the average continuous electricity usage of this load interruptible appliance to be 30-35 Watt and 20 Watt for high efficiency appliances, resulting from measurements in the pilot.

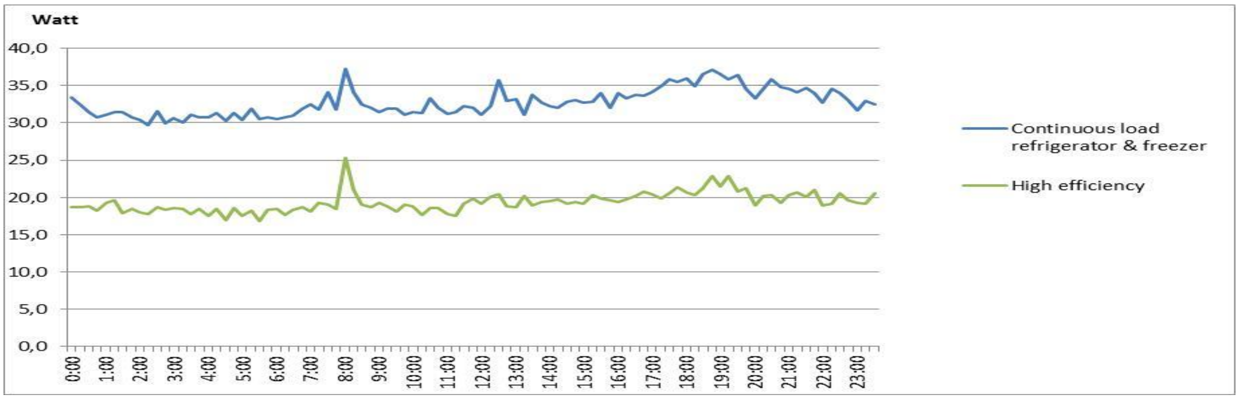

Figure 14: Current and future continuous load profile of load interruptible appliances

6.6.2 Results – dishwashers

Figure 15 shows continuous electricity usage of dishwashers at two distinct moments during a weekday. One is right after dinnertime, between 19:00 and 20:00. Another peak occurs in the late evening between 22:30 and 0:30. This peak may be induced by specific consumer behaviour (e.g. avoid noise, lower night tariffs). Energy efficient appliances do not make a major difference. Rather peak demand seems foremost a result of the specific times of use of a dishwasher and penetration rates. The incidental higher load for high efficiency appliances is assumed to be the result of these factors.

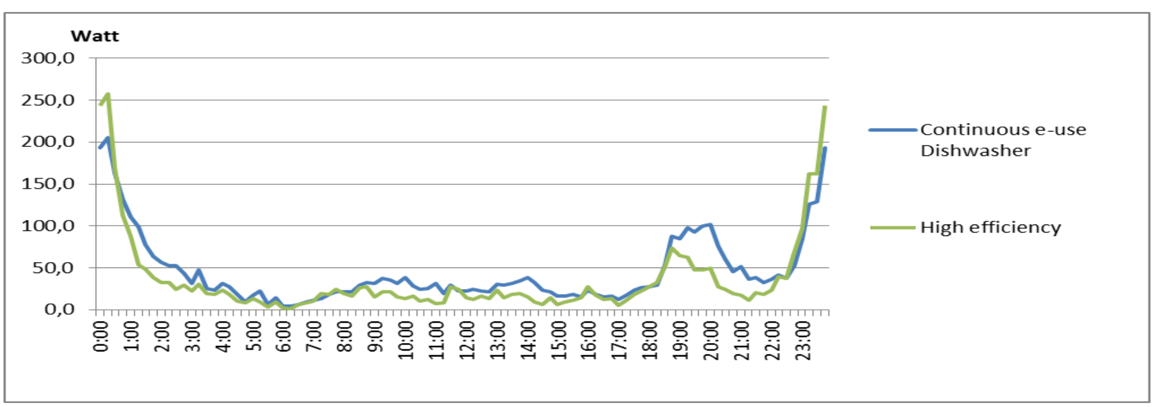

Figure 15: Current and future continuous load profile of dishwashers

6.6.3 Results - washing machines

Figure 16 shows continuous electricity usage of washing machines for one longer period of use between 8:00 and 13:00 and after that a decline in use. The pattern may be best explained by part time working people or household assistance during the day. Energy efficiency gains can be substantial by up to 30% around 10:00. Peak demand will still largely depend on time of use preferences by the user, but there is potential for DEM throughout the day.

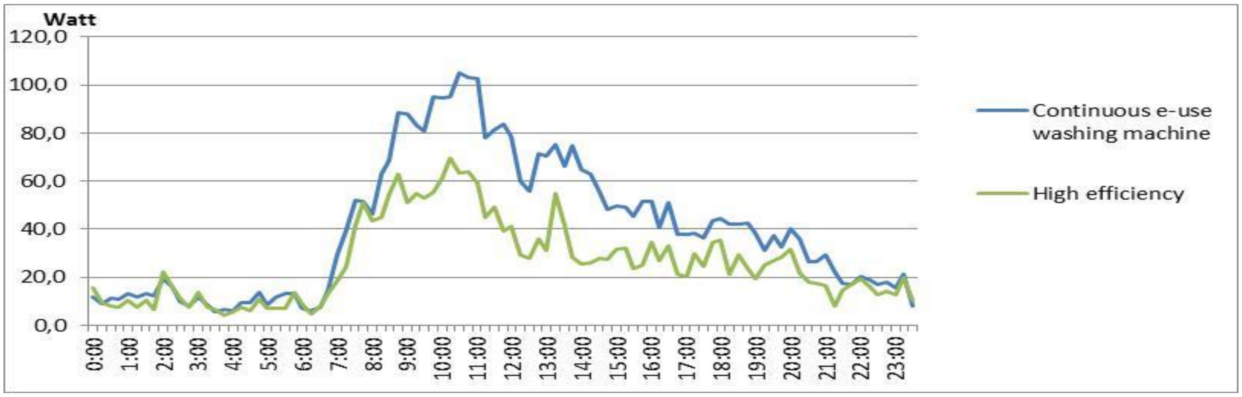

Figure 16: Current and future continuous load profile washing machines

6.6.4 Results - tumble dryers

Tumble dryers have a rather similar pattern to washing machines. Figure 17 shows continuous electricity usage for one longer period of use throughout the day between 9:00 and 22:00 with a peak in the early afternoon. A correlation between the continuous electricity usage of washing machines and tumble dryers might be present, but was not investigated. The longer period of use may be explained by the workings of a tumble dryer, which has a longer operating cycle. The graphs are based on a relatively low number of unique appliances (38) and a far smaller amount of cycles (738), which may decrease the validity of the results.

Figure 17: Current and future continuous load profile of tumble dryers

6.6.5 Current and future electricity usage of appliances

Current and future annual electricity usage as measured in the pilot are shown in table 6. Annual electricity consumption is based on the method of energy efficiency labelling. Stamminger (2008) and European Union (2010) were used to compare the results to literature. The following results were found in the pilot. Refrigerators with a low efficiency consumed 1.07 kWh per day and with a high efficiency 0.45 kWh per day (based on 70 unique appliances and 5341 measured cycles). Freezers with a low efficiency consumed 1.11 kWh per day and with a high efficiency 0.46 kWh a day (based on 27 unique appliances and 2013 measured cycles). Dishwashers with a low efficiency consumed 1.25 kWh per cycle and with a high efficiency 0.77 kWh per cycle (based on 49 unique appliances and 1603 measured cycles). Washing machines with a low efficiency consumed 1.28 kWh per cycle and with a high efficiency 0.61 kWh per cycle (based on 65 unique appliances and 1738 measured cycles). Tumble dryers with a low efficiency consumed 2.46 per cycle and with a high efficiency 1.23 kWh per cycle (based on 38 unique appliances and 738 measured cycles).

All results on energy efficiency as measured in the pilot are more or less in line with what was expected in literature, except for washing machines. Using the method in this research is only a proxy for energy efficiency. The higher energy efficiency as measured in the pilot may very well be the result of energy saving campaigns or commercials on laundry detergent promoting benefits of lower temperature washing. A solid registration of program settings for each cycle is necessary in order to make a truly accurate prediction of energy efficiency over time.

Appliance	Energy use (kWh) – high	Energy use (kWh) – low	Delta energy use – pilot (kWh)	Delta energy use – literature (kWh)
Refrigerator	393	164	229 (58%)	150 (50%)
Freezer	405	167	238 (59%)	80 (50%)
Dishwasher	350	216	134 (38%)	102 (30%)
Washing machine	282	134	148 (52%)	39 (20%)
Tumble dryer	373	170	203 (54%)	197 (50%)

Table 6: Results annual energy use (high and low) and energy efficiency

6.6.6 Results – total electricity usage load interruptible appliances

Figure 18 shows the result of all power loads of refrigerators and freezers combined (a total of 136 appliances over the first 20 weeks in 2014). Also is shown the impact of energy efficiency with a reduction of electricity use by 58%. The load is constant between 4 and 5 kW. The future load is constant between a range of 1.8 and 2.1 kW.

Figure 18: Total electricity usage load interruptible appliances

6.6.7 Results – total electricity usage load shiftable appliances

Figure 19 shows the total load of shiftable appliances in the pilot (based on 101 households). Also is shown the impact of energy efficiency with a reduction of electricity use by dishwashers (-38%), washing machines (-52%) and tumble dryers (-54%) combined. Note that the future graph assumes a similar penetration rate. It is possible that penetration rates of dishwashers and tumble dryers will grow slowly over the years. This will (partially) offset the gains in electricity usage reduction.

Figure 19: Total electricity usage load shiftable appliances

6.6.8 Results – total electricity usage households

Figure 20 shows total electricity usage by all households. Total load of households is the average gross electricity demand of all 101 households. Total net load of households is the gross electricity demand minus the average electricity generated by the solar panels over the first 20 weeks in 2014. This method had to be used as a consequence of smart meters only measuring the net electricity usage (which already discounts the consumption of self-generated electricity by solar panels). Furthermore, the data output of the solar panels turned out to be hourly data, which explains the volatile blue graph. Therefore a trend line was fitted in order to show a more smooth and realistic pattern.

Using the total electricity usage of households, DEM can be expressed as percentage of (peak) demand. Average total electricity demand of a household in The Netherlands is 3300 kWh per year (CBS, 2012). Peak demand on a normalized weekday is in the order of 80 kW. Load interruptible appliances consume in the order of 5 kW throughout the day. As a percentage of (gross) peak demand this is about 6%. Load shiftable appliances consume no more than 20 kW. As a percentage of (gross) peak demand this is about 25%. As percentage of total demand load interruptible appliances consume 12% and load shiftable appliances consume about 17% (taking penetration rates into account).

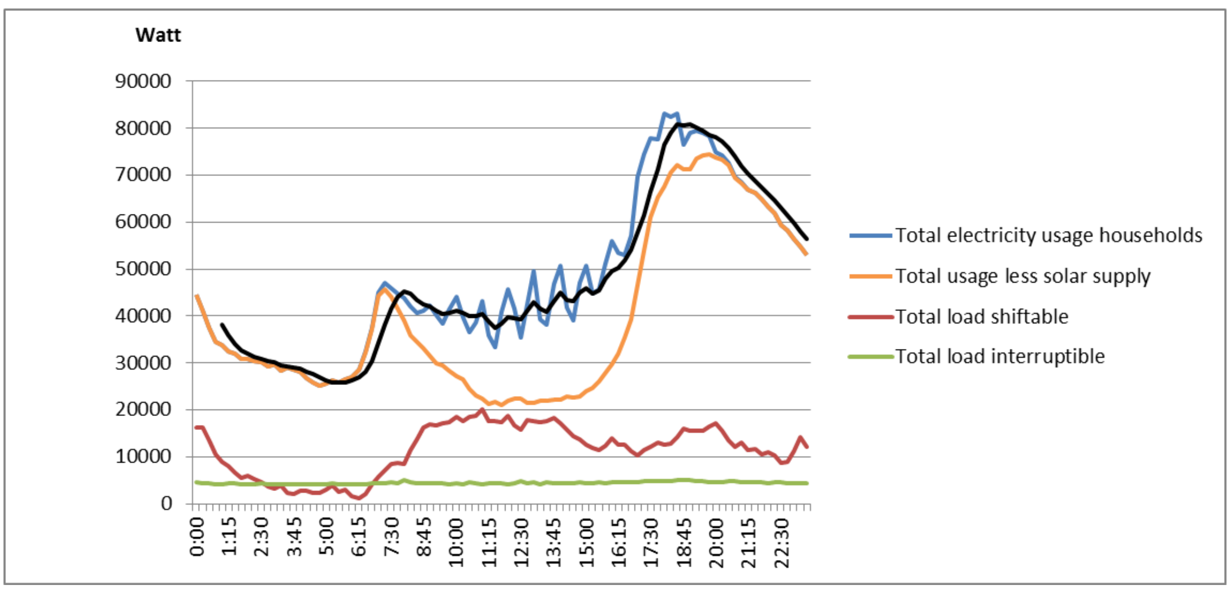

Figure 20: Total current electricity usage 101 households compared to potential for DEM

Figure 21 shows future total electricity usage by all households and for load interruptible and load shiftable appliances. Only electricity usage reduction by appliances measured in the pilot were taken into account: other non-smart grid appliances may be expected to become more efficient, notably lighting, but on the other hand more and more electronic devices may increase total electricity usage. The graph especially does not take into account electric cars or electric heating.

Also the graph displays a net electricity demand accounting for self-generated solar power based on current solar panels. In the future solar panels may become even more efficient, altering the net electricity demand of households.

Gross total peak demand is in the future estimated at 71 kW for 101 households. Future load interruptible appliances consume about 2 kW or 3% of peak demand. Load shiftable appliances consume no more than 10 kW or 14% of peak demand. These values are a lower bound when taking into account that energy efficiency measures for other appliances will also lower demand. As percentage of future total demand load interruptible appliances consume 8% and load shiftable appliances consume about 12% (assuming current penetration rates). This is in contrast with chapter 6.5 and the difference is explained by the neglecting of other energy efficiency measures that will decrease total electricity usage of households.

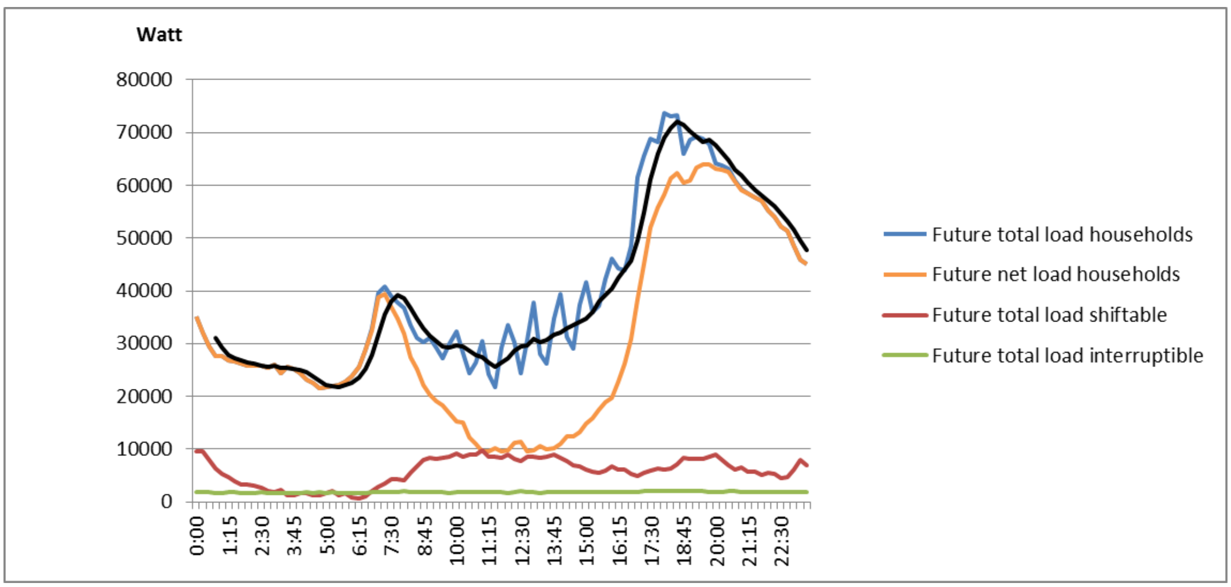

Figure 21: Total future electricity usage 100 households compared to potential for DEM

7. Interpretation of Results

7.1.1 Literature comparison

The limited sample size of 101 unique households and smaller numbers for appliances may make the results less reliable. Therefore the results will first be compared to results found in literature. Second, the results for each appliance and their usability will be discussed in the context of the three actors.

7.1.2 Literature on load interruptible appliances

Figure 22 shows a load (and temperature) profile for a refrigerator (similar for freezers). In the example the load varies between 140 Watt and 0 Watt, whereas in the pilot no such static behaviour was found. A pool of load interruptible appliances should show overlapping load profiles resulting in a consistent base line of electricity consumption. The order of the load is on average comparable to that found in the pilot.

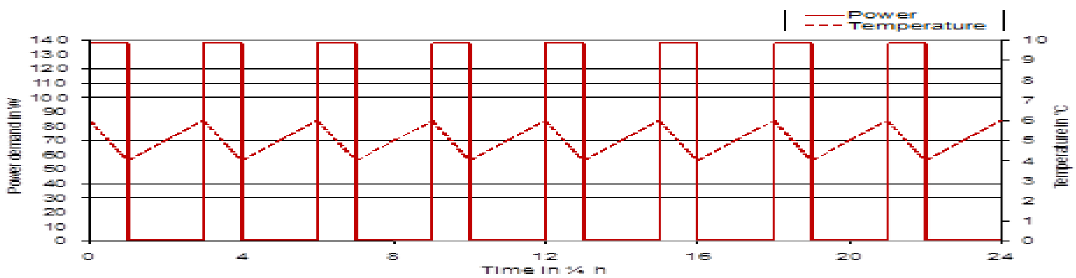

Figure 22: Continuous load profile and temperature range of a refrigerator or freezer (source: University of Bonn, 2009)

7.1.3 Literature on dishwashers

Figure 22 shows the load profile of a dishwasher. Dishwashers are rather efficient already as the found results and literature indicate one of the lowest reduction in electricity usage. The University of Bonn expects the maximum power load of dishwasher to decline by 25% and the total electricity use per cycle to decline by 30%. While maximum power load was not investigated in this research, an energy efficiency rate of 38% was found in the research. This is comparable to values found in the literature.

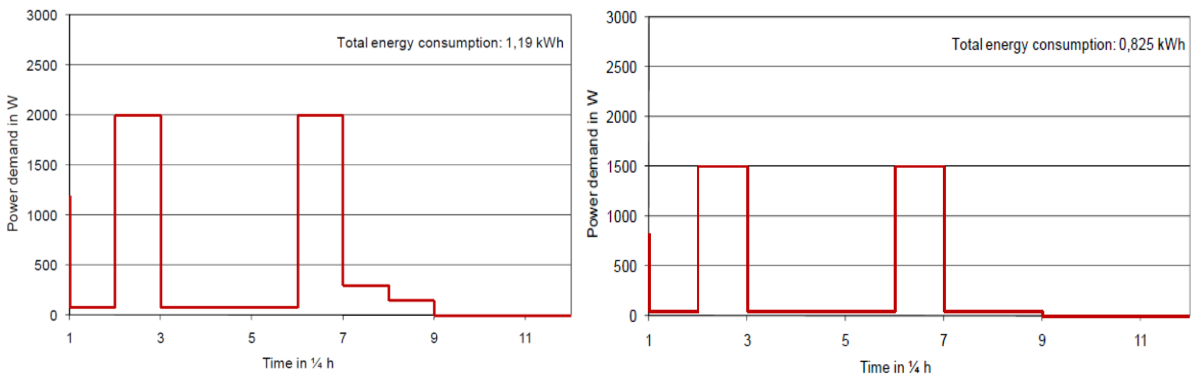

Figure 23: Illustrated current and future (year 2025) load profile of an average dishwasher in (source: University of Bonn, 2009)

Figure 24 shows the continuous load profile of dishwashers as found in literature. The results found in the pilot differ with respect to the moment in time of peak demand. In the pilot throughout the day a similar electricity usage of 50W was found. The literature suggests one peak in the evening of 90W, but the pilot found two higher peaks of 100W and 200W (cf. Fig. 15). The second peak in the late evening may be caused by a start delay function. The difference may be explained by the higher penetration rate in the pilot. This might also indicate that future continuous electricity usage by dishwashers might be different as found in literature or in this pilot due to (still) growing penetration rates of dishwashers.

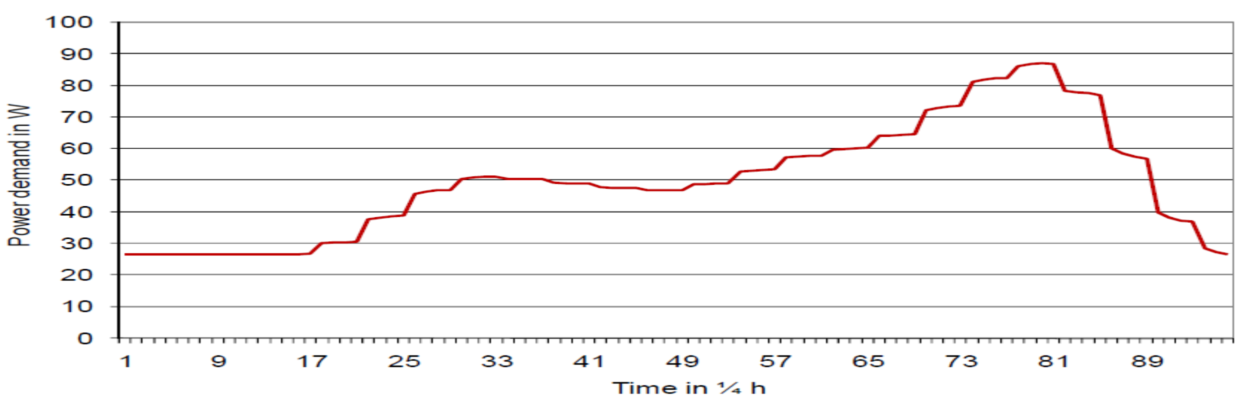

Figure 24: Continuous load profile of a dishwasher (source: University of Bonn, 2009)

7.1.4 Literature on washing machines

Figure 25 shows the load profile of current and future washing machines. The University of Bonn expects the load profile of washing machines to change to one with a lower peak demand. Total electricity use during a cycle is expected to drop by 20%. In the pilot a far higher energy efficiency rate of 58% was found. The difference may first of all be explained by the method used to calculate energy efficiency in the pilot and second by changed user behaviour washing on lower temperatures.

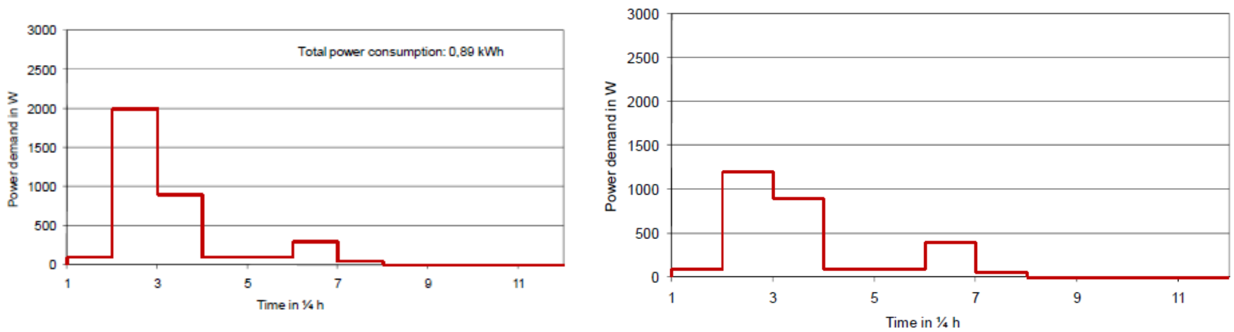

Figure 25: Illustrated current and future (year 2025) load profile of a washing machine (source: University of Bonn, 2009)

Figure 26 shows the continuous electricity usage of washing machines as found in the literature. Throughout the rest of the day continuous electricity usage is similar around 50 Watt and declining towards the evening. The result of the pilot is more or less similar, except for a peak in the late morning found in the pilot. Penetration rates are similar in literature and in the pilot. It is not likely for the penetration rates to change by much in the future, as there is little need for more than 100% penetration rate of washing machines. Any differences might therefore be best explained by (changed) user behaviour or a biased sample in the pilot.

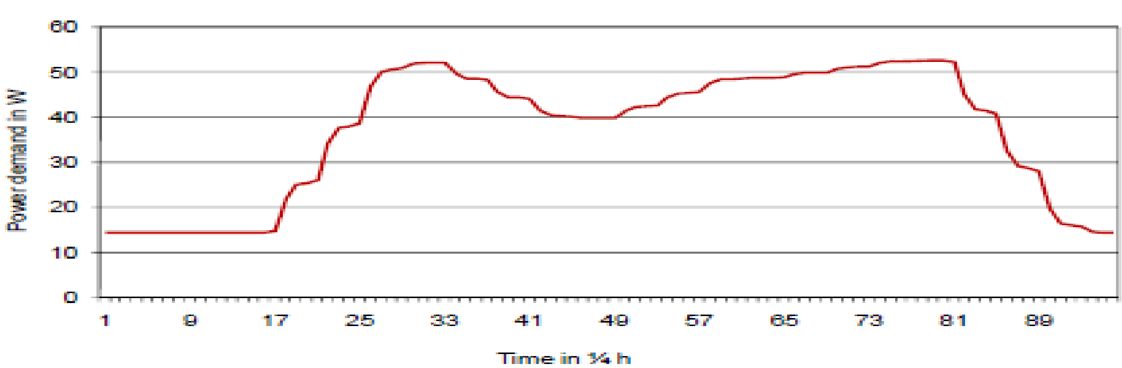

Figure 26: Continuous load profile of a washing machine (source: University of Bonn, 2009)

7.1.5 Literature on tumble dryers

Figure 27 shows the current and future load profile tumble dryers. The University of Bonn expects the power load of future tumble dryers to drop by 50% and the cycle to last slightly longer. Electricity use is expected to drop by 50%. This is more or less in line with the findings in the pilot, which show that electricity usage is estimated 54% less.

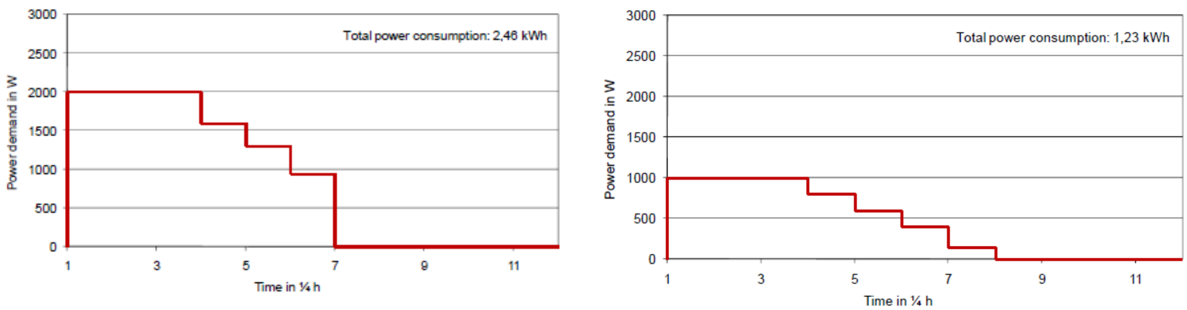

Figure 27: Illustrated current and future (year 2025) load profile of a tumble dryer (source: University of Bonn, 2009)

Figure 28 shows the continuous electricity usage of tumble dryers as found in the literature. It shows a slightly different pattern than found in the pilot. The results are similar for the rise from the early morning to the late morning to settle for a rather constant electricity usage. The results in the pilot are less smooth in the afternoon, which may be explained by the small sample size of 38 unique appliances and far less measured cycles. In comparison to the other appliances, about half the amount of cycles was measured, making the graph more volatile.

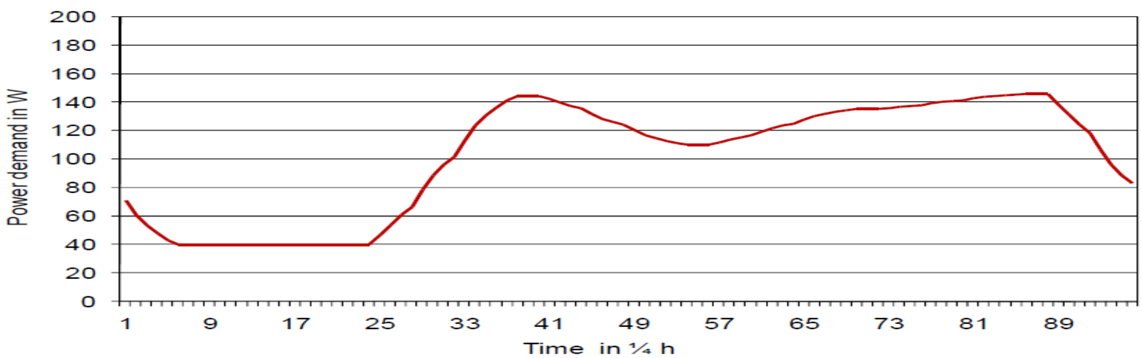

Figure 28: Continuous load profile of a tumble dryer (source: University of Bonn, 2009)

7.2.1 Technical potential for TSOs

In chapter 5.2 it is argued that with current DEM systems only load interruptible are suitable for TSOs. Therefore load shiftable appliances are estimated for current technical potential, but only taken into account for future potential. Current technical potential of load interruptible appliances is estimated to be on average 30 Watt per appliance. TenneT contracts about 300 MW of control power (TenneT, 2010). Based on 7 million households in The Netherlands all load interruptible appliances would be able to provide 280 MW. In theory DEM could provide the majority of control power, doing away with conventional power plants. Current minimum bid size required for Tennet is 5 MW, which translates to more than 160,000 appliances. With a penetration level of 135% this is about 123,500 households, which provides a major practical hurdle if DEM was to be used.

Future potential for load interruptible appliances reduces by more than 50%. On top of that it is argued that in the future more contracted control power is necessary to match increasing volatile intermittent supply. Future technical potential for load shiftable appliances is in this research estimated 1.5 times that of future load interruptible appliances. In theory DEM could also in the future provide the majority of control power, assuming 100% participation rate of households.

7.2.2 Technical potential for DSOs

Chapter 5.3 argues that the most important application of DEM for DSOs is avoiding peak demand. Results show peak demand to average around 750 Watt per household. Due to averaging out this result found in the pilot is only an indication of the real peak demand, which should by definition be higher (and indeed is). The result of 750 Watt will be used here to estimate the technical potential. In the case of DSOs appliances are required that can postpone their operation for more than 2 hours, i.e. the duration of the peak demand. Therefore current load interruptible devices are not deemed suitable, only future ones are.

Current load shiftable appliances make up about 26% of peak demand. Assuming 50% response rate (100% response rate would induce another peak) peak demand can be reduced by about 13% or 98 Watt per household. In terms of investments in peak capacity this translates into 0.1 kW * € 130 / kW / year = € 13 annually (Alliander, 2013). Future electricity usage by load shiftable appliances is estimated at 16% of peak demand or 68 Watt. In a similar calculation this results in € 8 annual savings per household. Load interruptible appliances only consume about 3% of peak demand and their contribution is estimated negligible.

Due to the trend of electrification it can be assumed that the result of peak demand reduction is only temporary. It is difficult to estimate the number of years DEM would allow network investments to be postponed. The number of years network upgrades are postponed determine the total returns over the years.

7.2.3 Technical potential for Energy Suppliers

Chapter 5.1 argues that energy suppliers are better off when they have more options for trading. Current load interruptible appliances are more suitable for trading than load shiftable appliances. Therefore load shiftable appliances are not deemed suitable, and only future potential is estimated.

Results show that on average a load interruptible appliance consumes 0.005 kWh every 15 minutes. Assuming a load interruptible appliance can be switched off for a quarter hour every 2 hours this allows 12 trading options a day. Assuming a price difference of € 50 / MWh between a low and high price the value is roughly calculated to be € 1.10 annually[5]. However, this calculation does not take into account the risk of a rebound effect of cooling right after the period the appliance was switched off, which may start in more expensive settlement period.

[5] Based on 0.000005 MWh * 12 trading options a day * 365 days * € 50 / MWh price difference

Future potential for load interruptible appliances is reduced by 58% although volatility and short-term electricity prices may tend to increase compensating the result. Future load shiftable appliances consume a maximum of 0.025 kWh every 15 minutes. With a program length of 1.5 hours and assuming both 220 as the average number of annual cycles and an average price difference of €50 / MWh during each cycle the value is roughly calculated to be € 1.65 annually. The calculation is based on many assumptions and therefore the found result is only indicative of the order of size.

7.2.4 Future appliances

In a more distant future electric vehicles and heat pumps can also be added to the (technical potential for DEM. Due to their physical properties they can both shift their load (somewhat) and both theoretically interrupt their load instantaneously. This makes them extremely suitable for DEM. It is expected that the growing penetration rates of electric vehicles and heat pumps will increase especially grid related costs (EURELECTRIC, 2013). If and to what extent the potential benefits of DEM outweigh the extra costs has currently not been solved.

8. Conclusions

It was argued in this thesis that the need for DEM may become very real in the near future due to the trends of electrification of society and increasing intermittent renewable generation. Electricity usage data on appliance level was used to answer the following research question:

‘*What is the present and future technical potential in electricity use for Dynamic Electricity Management based on households in the smart grid pilot Smart grid Rendement voor Iedereen?’*

The technical potential of DEM depends on the specific use of an actor. Current suitable appliances are either load interruptible or load shiftable. This distinction is important to the actors especially with the current DEM systems. Energy suppliers can therefore only use load interruptible appliances, for they require to settle trades at the last minute. TSOs can only use load interruptible appliances, because it requires 100% reliability. DSOs can only use load shiftable appliances because it requires demand to be shifted up to two hours.

As a first result penetration rates were found to be generally equal or higher than earlier studies. One might expect the penetration rates of dishwashers and tumble dryers to increase. Tumble dryers especially will become more energy efficient, taking away the image of an environmentally unfriendly appliance.

The results have shown that in the current electricity market DEM is able to generate revenues in the order of several euros annually per household in the case of the energy supplier. Load interruptible appliances can deliver about 280 MW on a total of 300 MW contracted control power by TenneT. In the case of DSOs load shiftable appliances are able to avoid demand by 13% of total peak demand. Future technical potential is estimated to be of similar order, assuming new DEM systems and appliances do away with the difference between load interruptible and load shiftable appliances.

It is foreseen that future DEM systems with smarter and newer appliances more flexibility is unlocked by more plug and play functionality. However, by the time these systems are fully developed progressing energy efficiency has reduced technical potential. The reduction for load interruptible appliances is estimated between 50% and 59% percent and for load shiftable appliances between 30% and 54% percent. It is unlikely that the current suitable appliances will play a role of importance in DEM. DEM will foremost concentrate on heat pumps and electric vehicles, possibly in combination with local storage.

9. Discussion

Current market model

The current electricity market model is caught in a legacy structure. Energy suppliers have made long term investments that have become more risky to operate and have little incentive to stimulate energy efficiency. TSOs have to accommodate more intermittent generation with the same tools and DSOs are obliged to facilitate inefficient network expansion. Ideally, an alternative electricity market structure would incorporate solutions for these flaws. The rules are designed specifically for a centralized system and not for a large decentralized generation capacity. E.g. costs for transportation are independent of time and transported distance for the historic reason to facilitate competition between geographic dispersed market parties. As mentioned throughout this thesis, there are a few sensible arguments to make some changes. The two trends identified are the major reason that may make the current model unsuitable to address the issues of matching demand and supply and grid capacity.

Future market model

In the future the goals of DSOs and TSOs may become more intertwined. High penetration of intermittent generation on a local scale may require the need for local balancing markets (Kok, 2013). A smart grid also allows, in theory, better allocation of costs to those who induce the (extra) network and balancing costs (D-Cision, TNO, 2011). Due to the historic need for collective character and organisation of the electricity network this was not possible. If DEM is to be used in a future electricity market model some regulation by the government is required to prevent conflicting interests of actors and to prevent gaming the system. If smart grids with DEM are seen as an effective solution then model changes are necessary to make investments worthwhile. Some of these changes include for example:

- Changing bid size and requirements for offered control power to TenneT, to better accommodating the characteristics of DEM
- Do (partially) away with the copper plate obligation of DSOs allowing more efficient investments in grid capacity
- Allow investments by DSOs in smart grids and allow to appropriate revenues for these investments in DEM in the regulated tariffs
- Make the price of electricity location dependent relative to where it is consumed, stimulating self-consumption of locally generated (solar) electricity
- Make the price of electricity dependent on the time of consumption, which increases the effectiveness of avoiding peak demand

DEM systems

Current DEM systems are not yet fully capable of delivering all smart grid capabilities. One major drawback in this research was that program details of load shiftable appliances were not (and could not easily be) recorded. For research purposes a central database is needed to analyse the data. The Powermatcher system is based on real time decentralised data on electricity demand of a household (See appendix 6 for a description of the Powermatcher system). No data on exact electricity usage itself is transmitted. In the future an appliance could use sensors to measure weight and water use to estimate the exact electricity usage over time of that particular cycle and transmit the information to a DEM system. Also, future DEM appliances will be able to dynamically create more demand (e.g. decrease temperature of the refrigerator in advance). Advanced DEM systems possibly in combination with local storage (on appliance level) will thus allow and create more flexibility, increasing the potential of DEM. It is likely that future appliances will include smart hard- and software to communicate via WIFI, eliminating the need for separate smart plugs. Several initiatives such as Thread (used e.g. by Google, Nest and Samsung) make it possible for appliances to communicate using a standard protocol. This trend is likely to eliminate the need for (the development of) separate DEM systems such as researched and used in this thesis.

Future research

This thesis is based on the premise that DEM can become more important due to two trends identified in the electricity market. Other alternatives versus DEM should be investigated in order to establish which is most convenient of cost effective. E.g. local storage in batteries is continually becoming cheaper. New studies on this trend can give insight in the learning rates on storage opportunities in the coming decade. In combination with analyses of self-consumption of locally generated electricity by solar panels an optimum storage size can be determined.

Future research on the topic of DEM should focus on constructing continuous load profiles for new appliances such as heat pumps and electric vehicles. As indicated in this thesis, these appliances have a much higher potential for DEM than current appliances do. Especially load profiles of electric vehicles will need (more) empirical research as they are inherently more dynamic (due to user behaviour) than heat pumps. Load profiles of heat pumps can more easily be constructed using a method based on heat degree days, which is much less determined by user behaviour.

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Appendices

Appendix 1 - Data quality check

Data had to be checked for consistency and faults in measurements. It is expected that practical errors could occur due to the following reasons:

- Internet disconnection
- Incorrectly installed plugs or smart bridges
- Malfunction of the dynamic energy management system or software

In order to ensure that erroneous data is excluded from the final analysis the electricity usage data is first checked. One of the weak elements in the process was the labelling of type of appliances by the participants themselves. This could result in data being labelled as a different appliance and corrupt the results. The following steps were taken for checking the electricity usage data.

1) Electricity usage was totalled on a daily basis for each appliance
2) All sums of zero were discarded (standby power is still measured)
3) All labels of type of appliance in the dataset were checked against a second database compiled during installation containing registered plug codes and type of appliance. All inconsistencies (i.e. the database of labels and the labels in the online database don't match) and non-labelled appliances were discarded.
4) Only appliances deemed suitable for use in a smart grid were selected (for a full list of typical household appliances deemed suitable and not suitable, see appendix 2).
5) All appliances were checked for the direction of the electricity flow. Household appliances should have the code Instantaneous Demand Delivered and solar panels should have the code Instantaneous Demand Received. All invalid references were discarded.
6) The data were divided in two groups of appliances: 1) continuous electricity usage (e.g. refrigerators and freezers) and 2) cycle based electricity usage (e.g. dishwashers, washing machines and tumble dryers).

The following steps were taken to ensure the quality of the data. Electricity usage for appliances was checked with energy efficiency labels as described in Chapter 5.3. Appliances were discarded for any of the following reasons:

- no consecutive electricity usage data during the pilot (for refrigerators and freezers only)
- too low or too high total electricity usage for refrigerators and freezers (minimum of A+++ label containing 75L results in 60 kWh annually and a maximum of C label containing 300L results in 1000 kWh annually)
- too low or too high total electricity usage for dishwashers (minimum of A+++ label results in 0,7 kWh per cycle and a maximum of a maximum of D label with a usage of 1,65 kWh))
- too low or too high total electricity usage for washing machines (minimum of A+++ label with 3 kg of laundry results in 0,4 kWh per cycle and a maximum of C label with 8kg results in 2,16 kWh)
- too low or too high total electricity usage for tumble dryers (minimum of A+++ label with 2 kg of laundry results in 0,7 kWh per cycle and a maximum of C label with 5kg results in 3,35 kWh)

Appendix 2 – List of DEM systems

Supplier	Name Product
DSO	Smart Meter
Plugwise	Plugwise
Fifthplay	Fifthplay
Net2Grid	Computime plugs
Flexicontrol	Wendy
ECN / Alliander	Powermatcher
SMA	Sunny home manager
Eneco	Toon
Nuon	E-manager
Essent	E-thermosstaat
CurrentCost	Energeniaal
Qurrent	Qbox
Nedap	Mygrid: powerrouter
Smart Dutch	?
iNRG	?
Perfomance.com	Wattminder
Wattcher	Wattcher
Zjools	Zjools energiemeter
Cuculus	Cuculus
Xanura	?
Homewizard	Energy kit
Youless	Youless
Flukso	Flukso
Wattson	Wattson

Appendix 3 – List of suitable smart grid appliances

			Demand response		Preferences	
Prio	Appliances	Penetration rate	Load shift	Load interupt	Instant on	0-3hr shift
1	Koel-vries combinatie	100%	low	high	n.a.	n.a.
2	Vriezer	52%	medium	high	n.a.	n.a.
3	IJskast	100+%	low	high	n.a.	n.a.
4	Vaatwasmachine	50%	high	low	80%	20%
5	Droger	61%	high	low	95%	5%
6	Wasmachine	95%	high	low	90%	10%
7	Electrische boiler	10%	medium	high	n.a.	n.a.
8	Cv pomp	80+%	low	medium		
9	Electrische auto	2,4-%	high	high		
10	Warmtepomp	6%	medium	high		

Appendix 4 – Criteria Request For Proposal

Supplier	% weging	Mark	Fifthplay	Mark2	Plugwise	Mark3	Net2Grid
1. Kwaliteit van het product	30%						
1.1 Kwaliteit hardware geleverde hub en smart plugs		4	Niko group producent	4	Afmontage Eindhoven	3	Buitenlandse hw leverancier
1.2 Hardware uitbreid mogelijkheden (DEM)		3	Wasmachines	3	IJskast en vriezer	4	Open standaard (ontwikkeling)
1.3 Kwaliteit datacommunicatie: bereik pluggen	No go	4	Ster netwerk: RF 868 Mhz freq	1	Mesh: Zigbee 2.4 Ghz freq	5	Zigbee goed bereik 2.4 Ghz freq
1.4 Kwaliteit Software (computer en smartphone)		2		4		5	Portal en app in ontwikkeling
1.5 Snelheid van schakelen	No go	1	15s (via internet)	5	<1s lokaal	5	<1s lokaal
1.6 Portal mogelijkheden; eigen functionaliteit toevoegen		3	Leverbaar, in ontwikkeling	3	Leverbaar, in ontwikkeling	4	Aangeven bij ontwikkeling
1.7 Leveringstermijn hardware		4	Binnen een maand	4	Binnen een maand	3	1,5 maand
1.8 Demonstratie product (@ Lombok test centrum)		2	P1 poort leest niet makkelijk uit	4	Product werkt aardig	5	Product goed voor pilot doelstelling
gemiddeld gewogen cijfer x weging onderdeel		0,9		1,1		1,3	
2. Gebruiksvriendelijkheid van het product consument	30%						
2.1 Installatieproces		3	Plug and play	4	Plug and play	4	Plug and play
2.2 Communicatie met computer en app		3	Web inlogportal en app is mogelijk	4	Software en app nog in beta	3	Portal en app in ontwikkeling
2.3 Bruikbaarheid setup (ook zonder internet)	No go	1	Met hw en sw aan/uit knop, via inet	4	Met sw aan/uit knop	4	Met sw aan/uit knop
2.4 Customizability (hoe ziet het eruit)		3	Uitgangspunt is customizability	1	Vormgeving ligt bij Plugwise	4	Veel ontwikkel mogelijkheden
Gebruiksvriendelijkheid partners: data management							
2.5 Dynamisch energie management (data export, overlay)		3	Extern, buiten portal, custom	4	Intern in portal, vast format	5	Open source database
2.6 Duidelijkheid grafieken		4		3		4	
2.7 Data frequentie uitlezing en export		4	15 min uitlezen	3	60 min uitlezen	5	5 min uitlezen
2.8 Privacy (procedures binnen bedrijf)			Wettelijke eisen		Wettelijke eisen		Wettelijke eisen
2.9 Uitlezen P1 poort	No go	3	Portal en app	5	Portal en app	5	Portal en app
gemiddeld gewogen cijfer x weging onderdeel		0,9		1,1		1,275	
3. Prijs	30%						
3.1 Hardware set van 5 plugs en energie router		3	338 (onderhandelbaar)	3	339 (onderhandelbaar)	5	172,5
3.2 Servicekosten / jaar / huishouden		4	48 (Electrabel: 3,50 per maand)	4	21	3	120
3.3 Prijs extra hardware/software		3	Na specificaties	4	60-125	4	60+
3.4 Prijs extra ontwikkelingskosten		2	100 euro / uur	3	80 euro / uur (50% korting)	5	50 euro / uur (50% korting)
3.5 Helpdesk		1	?	3	?	5	Persoonlijk
gemiddeld gewogen cijfer x weging onderdeel		0,78		1,02		1,32	
4 Leverancier - kenmerken	10%						
4.1 Kredietwaardigheid		4	KvK of op navraag	3	KvK of op navraag	2	KvK of op navraag
4.2 Aandeelhouderstructuur		3	Onderdeel Niko groep	3	Alliander, Management	2	Dochter van Shinto B.V.
4.3 Personeel - kennisniveau, kwaliteit en potentieel		3		3	Net de goede persoon nodig	4	Persoonlijk
4.4 Strategie		5	Gateway solution	3	Energy only solution	3	Roadmap Net2grid
4.5 Ervaring in andere projecten en referenties		5	Meerdere grote projecten	5	Meerdere grote projecten	3	Kleine ontwikkeling club in NL
4.7 Bereidheid ondersteuning in de pilot		3	Commerciele basis	3	Commerciele basis	4	Legt toe, commerciele basis
4.8 Locatie		1	Antwerpen	3	Sassenheim	5	Zeist
gemiddeld gewogen cijfer x weging onderdeel		0,34		0,33		0,33	
Totaal gewogen beoordeling	100%	2,9		3,4		4,2	
Mate waarin de offerte voldoet aan de RFP			Vragen duidelijk beantwoord		Vragen duidelijk beantwoord		deels open

Appendix 5 - Details Net2Grid equipment

	Plug	**Smart bridge**
Power measurement		
Time resolution	10 seconds	10 seconds
Measurement resolution	1W	10W
Accuracy of power measurements	+/- 3% at power above 90W resistive load*	+/- 3% at power above 90W resistive load*
Minimal measurable power	5W	10W
Power rating		
A/C power	230VAC +/- 10%, 50/60 Hz	Not available
Standby power consumption	Not available	<1W
Communication		
Communication protocol	ZigBee™ with home automation profile – supports simple meter cluster	ZigBee™ with home automation profile – supports simple meter cluster
Radio frequency	2.40 GHz license-free band	2.40 GHz license-free band
Receive sensitivity	98dBm	98dBm
* Comply with IEC 62053-21 accuracy requirement		

Appendix 6 - Future DEM systems

Kok (2013) defined six requirements for a DEM system (such as Powermatcher developed by himself). The requirements are: 1) protect privacy 2) scalability, 3) openness for DEM, 4) trade & supply functionality, 5) active distribution functionality, and 6) renewable energy supply (intermittent generation) integration.

One of the most important characteristics of a DEM system should be its transparency and privacy protection for the end user (Enernoc, 2009; KEMA, 2012). Reasons of privacy are often cited as an argument to be sceptical about smart grids. Prevailing Dutch law is strict in protecting privacy with regard to energy data. Transparency in the DEM system is necessary to allow its users to perceive the benefits of participating.

Current DEM hardware and software is in an infant state and their designs require high rates of data transfer and storage. While this is not an unsurmountable problem, well-designed systems may not need this requirement. This would make them more scalable and resilient. Centralized dispatch signals for demand response require much computational power. Secondly, centralized systems need a baseline against which the effect of dispatch signal on DEM is measured. Enernoc (2009) provides an overview of challenges that come with measuring against a baseline in order to avoid over- or undervaluing DEM.

Simplicity should increase usability, while making the system also more fool proof (e.g. the labelling of appliances). Future DEM systems and household appliances could very well use new USB standards. USB was principally designed for information exchange, but later versions also can carry (increasing amounts of) currents. In a truly plug and play fashion, USB automatically recognizes the type of appliance and can exchange valuable appliance information such as program settings (Powermatcher, 2008; Alliander, 2013). Appliances could register e.g. door openings to estimate lost energy or recognize partial loads, program length, and temperature setting and use this information for a more accurate forecast of electricity use.

Requirements 4, 5 and 6 refer to functionality that is now provided by several actors. Trade & supply is provided by energy suppliers, (active) distribution functionality is necessary to fulfil the future role of a DSO in managing peak capacity. The final requirement of integrating intermittent generation is reflected in the current primary goal of grid stability of TSOs. These requirements are not relevant in this thesis on estimating the potential of DEM. They will become important when DEM is part of an alternative electricity market model.

The decentralized character of DEM at households has to be taken into account with regard to response time. Kok (2013) has developed and studied the ways in which a decentralized system can place bids and be controlled for the purpose of DEM. In his dissertation he demonstrates the ability of the Powermatcher system on a mass scale. Results on latency tests showed that all agents (over 1 million simulated households) could be reached within a maximum of 279 seconds or less than 5 minutes with artificially introduced latencies. When corrected for these artificial latencies all 1 million agents can be reached in about 30 to 60 seconds. Mills et al. (2009) estimate that (large) scale solar power plants can potentially change output (up or down) by 70% in a time frame of minutes. Guatam et al (2009) and Alegria etal. (2004) show that modern wind turbines are quite capable of quickly reacting to dispatch instructions of TSO. Especially in larger balancing areas (>1000 km^2) sudden changes in wind have a lower correlation on small time scales (Holttinen et al, 2008). This shows that DEM has the ability to react to prevailing weather conditions that are influencing intermittent generation in the case for a TSO.