A valutation of electricity distribution capacity

MASTER THESIS REPORT

HUBERT SPRUIJT

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A VALUTATION OF ELECTRICITY DISTRIBUTION CAPACITY

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PREFACE

A vast interest in how our energy systems are structured and what the impact of technological developments in this field means for society is why I started the master Energy Science. After finishing most of the courses I realised that the electricity system is key within the energy transition but also that it was at the same time still undiscovered area for me. A curiosity arised of how this system works and what influence the integration of more sustainable technologies would have. It became an aim to explore this while writing my thesis. An earlier visit to GEN with our study association had shown that they had a similar interest in the future developments and that they could provide me part of the answer to how this system as whole works. I was therefore very pleased to hear that they were willing to support me during my journey, although I would be the first intern ever. During the time there I indeed learned a lot from these professionals. It also gave me a valuable insight in the pace of a consultancy firm. I'd like to thank all people at GEN and Wessel in specific for the valuable discussions, extensive knowledge of the energy sector and detailed remarks. It really helped me building this product.

Also many thanks to Wilfried for his shared interest in our future electricity system, the feedback on my work and the well appreciated discussions including both.

Vincent and Johann, inviting me over to Enschede and thinking along helped me getting focus. Also thanks to Jan for taking the time for an interview and providing me help with data later on. To Boudewijn for an economic recap and to my friends Luuk and Remco for the lively discussions about the future of our electricity systems.

Although we never met I would really like to thank Felix Claessen. His simulation data has been of great use for the analyses done and this thesis would have been very different without it.

In addition, thanks to all other people I met during this journey, all adding their piece to my puzzle.

The curiosity I started with has largely been fulfilled by everyone mentioned above and by scientific knowledge from al the readings. Now knowing where we could go, I will always be wondering of what the future will really bring us.

Hubert Spruijt

Waddinxveen,

14 August 2014

ABSTRACT

Predictions of future load developments at distribution level of the Dutch electricity network show that demands of especially electric vehicles and heat pumps rather than solar panels or micro combined heat and power have the potential to cause stability issues in the grid. Already at a low degree of penetration into the network, these technologies can require too much power. A high simultaneity of consumer behaviour worsens this problem. To prevent network outages measures should be taken by the grid operators.

A few options are available to solve the aforementioned issues. Most are aimed at increasing the supply to the consumer by grid reinforcements or by local energy supply. These are cables and transformers with a larger capacity, a micro CHP and a local battery. However, also the demand side can be used as a means to prevent the problems by decreasing high peak demands. This is called 'demand response' and often leads to shifting peak demands to other periods of the day. Many different demand response configurations are possible, but in all cases the question remains if a consumer would really benefit from them or that other options such as a battery or grid reinforcements would be better.

Consumers adapt their demand only little to price variations. One thus can consider electricity as an inelastic good. Using the investment costs of the available solutions to increase supply or decrease demand for capacity and taking into account the change in welfare, a comparison of the options is made. The outcome shows that demand response can be an attractive alternative for small peaks. However, for larger peaks the deadweight loss rapidly increases and a drop in utility will always take place. The value of electricity for a consumer is very high compared to its price. This makes that a desired change in behaviour of the consumer requires a large fee by the grid operator when financially incentivising the consumer. Uncertainties about real consumer behaviour, combined with the big effects on the cash flow of a grid operator can make investing in a demand response system risky. In the basic scenario, it results that investing in a demand response system is the least attractive option for society in this study. Due to the high indifference of consumers to react to price it will be very difficult for grid operators to guarantee a cost-effective and reliable electricity grid based on price incentivised demand response. From the other options, grid reinforcements by additional and larger cables and transformers is the most cost-effective solution for this case where only local grid investments are included. Furthermore grid reinforcements provide a high degree of certainty about the available capacity and deadweight losses are avoided.

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DEFINITIONS

APX	Amsterdam Power eXchange
CES	Constant Elasticity of Substitution
CHP	Combined Heat and Power
CPP	Critical Peak Pricing
DG	Distributed Generation
DLC	Direct Load Control
DR	Demand response
EV	Electric Vehicle
HV	High Voltage
IBP	Incentive-Based Programs
kV	kilo Volt
kVA	kilo Volt Ampère
LV	Low Voltage
MV	Medium Voltage
PBP	Price-Based Programs
PHEV	Plug-in Hybrid Electric Vehicle
PTU	Programme Time Unit (15 minutes)
RGO	Regional Grid Operator
RTP	Real Time Pricing
TOU	Time Of Use rate

1 INTRODUCTION

1.1 BACKGROUND

Electricity is key in today's complex society. Communication, computation and visualization are just some examples of many actions in our daily routine which involve a reliance on an everlasting access to a stable system providing us the necessary electrical power. After decades of a rather similar structure, part of this system is changing now, impacting the rest of it and raising questions about how to invest in a stable future electricity system.

Fed by a growing concern of global warming, depletion of resources and resource dependency, a transition to a more sustainable society has been put in motion (Sociaal Economische Raad, 2012). While the transition itself starts getting more visible, policy, innovation and markets even further add to the increase of its momentum. Governmental bodies like the European Commission have set goals in their policy as far as 80% CO_2 reduction in 2050 compared to 1990 levels and are calling for real action now (Hemicker, et al., 2010). Similarly the Dutch government with a target of 16% sustainable energy in 2023 is showing policy to change (SER, 2013). Governmental support helps driving change, but also markets create opportunities. The latter is shown by higher (primary) energy prices which lead to more investments in sustainable technologies at both the energy supply and demand side (IAE, 2012). The increased cumulative demand of these technologies leads to technological learning which drives down the costs of technologies and thereby makes it more attractive to invest in them (Junginger, et al., 2010). This innovation is important to give momentum to the transition.

The increase in application of sustainable technologies will have a major impact on the way our energy systems are structured. For the electricity sector the shift towards more sustainability leads to other routes of electricity transport and higher peaks in volume to be distributed. Looking at the supply side this is caused by an increased share of decentralized renewable electricity production (GEA, 2012). But despite higher efficiencies of electrical appliances, also the demand side has its share. Demand of electricity is expected to increase due to a replacement of fossil-fuelled technologies by more sustainable applications like heat pumps and electric vehicles (Tennet, 2010) (Alliander, 2012) (Oirsouw, 2012). To better match this supply and demand consumer participation at electricity markets is foreseen (SEC, 2012).

1.2 PROBLEM DESCRIPTION

Lack of incentive for efficient network use

The current electricity grid is not designed for the aforementioned future developments. Historically its structure and regulation is based on centralized production, leading to one-way transport (Oirsouw, 2012). Furthermore, in Dutch energy legislation, the electricity grid is defined as a copper plate, regarding transport and capacity bottlenecks as irrelevant to the grid user as the commodity price should be independent of production or consumption site (De Staat, 2011). Therefore, users do not directly experience a price increase when production has to take place at distance, while in physical terms the losses are a lot lower when a neighbour produces the electricity as a shorter transport distance and fewer conversion steps are involved. A similar situation occurs at the capacity availability. Legislation states that the grid operators have to make sure that there is always enough transport capacity available for the grid users and that the voltage (and frequency) is maintained within legally defined borders (De Staat, 2011) (Energiekamer NMa, 2012). These legal requirements result in expensive investments for small peak periods.

The costs of both the grid losses and the capacity availability are distributed over all customers by the grid operators. Often grid users pay an annual fee which is independent of the amount of kWh's transported by themselves (NMa, 2009). This way, by law the losses in the grid seem non-existent for the grid-user when he consumes or produces electricity. Therefore, the current system lacks an incentive for efficient use of production and consumption units, for efficient transport over the infrastructure and for avoiding congestion problems (Vereniging van Nederlandse Gemeenten, 2013). The facts that the transport costs are independent of the network availability and that the losses are not accounted for, take away the incentive to make optimal use of our electricity transport and production system.

Optimal electricity system investments

If the principle of having a 'copper plate' is maintained, as a result of the greater local power demand and supply, a part of the connections will face risk of overload during peaks in simultaneity of demand or supply (Lumig, 2012). Currently safety measures will interrupt the connections when overload occurs, leading to lower grid uptimes (Oirsouw, 2012). This is a highly undesirable consequence for both business and consumers for apparent economic and social reasons (Sluis, 2013). In accordance with energy legislation grid operators are obliged to make sure enough capacity is available. The prevention of lower uptimes then creates a demand for the installation of more capacity. Next to this a large part of our grids were constructed during the 1960s and 1970s of which parts also have to be replaced as they reach their technological life span (Pellis, 2013a). For these reasons investments in the current electricity system will have to take place now. And this does not only mean investing in a variety of reinforcement measures, but can also be in the form of supply and demand contracts with users at specific locations. To maximize the societal value it is important that the new system has the right dimensions in terms of reliability, affordability and sustainability since it will probably have to function for the next 50 years (Blom, et al., 2012). Therefore we should explore the best way of defining our electricity system, which means that alternatives to traditional ways of grid expansion should also be considered.

Societal impact

In the end the transport structure, or grid, is paid by society. So when the current structure of the grid has to be adjusted, society as a whole will pay the price. It is hard for grid users to avoid these costs concerning the grid, as total off-grid self-sufficiency is often more expensive and electricity has become one of the basic needs of life. In our modern society we cannot function without it and the amount of applications using electricity is still growing. In addition to commodity costs and energy taxes, the transport of electricity constitutes about 30% of the costs concerned with fulfilling a household's energy demand (see Annex 1). From a societal perspective, minimizing the societal burden is key when fulfilling this demand. Aiming for lowest transport costs will add to this goal.

Technological development

To optimize the societal impact of a transition concerning the distribution grids, nowadays new technologies as increased voltages and demand response are being developed which provide options in both a technical and an organizational manner (Kok, et al., 2012) (TNO, 2013). At the same time, we are in a phase where there is no dominant design yet since few of the novel options are yet commercially applied. The challenge is to follow the right technological path in order to prevent a lock-in effect in a societal less beneficial way. We now have the chance to redefine the structure of our electricity system, taking all the above into account. Therefore it is important to identify and compare the options available. With this in mind the following question will be answered.

1.3 RESEARCH QUESTIONS

Main question:

Which upcoming demand response concepts for electricity distribution capacity are beneficial for society?

Research questions:

- What future load developments can we expect on our electricity distribution grids?
- Which technical and organizational options applicable to the Dutch grid are theoretically possible to keep the distribution grid quality at legal service levels?
- What options have minimal economic and social costs at different developments?
    - What is the theoretical flexibility available in transport capacity over time?
    - How do customers respond to changes in price?
    - What is the annual fee for the consumers per option?
    - What is the influence of consumer participation in short term electricity markets?
    - Which option shows the best cost-effectiveness over all developments?
    - What are the most influential variables?

1.4 HYPOTHESIS

It is expected that creating an incentive for local use of electricity by a demand response system is beneficial for society as a whole, since it prevents new investments in larger cable capacity and it decreases transport losses. It should be mentioned that when implementing flexible pricing on transport capacity, this mechanism should make sure that even when the Amsterdam Power eXhange (APX) prices are low, there is enough incentive to be able to shift demand for transport capacity if needed. Maintaining such a policy throughout the year is expected to increase the costs of transport for a consumer and decrease the societal benefit of flexible pricing, but is expected to be still in advantage of replacing parts of the network.

1.5 RELEVANCE

Lowering global warming

Creating an incentive to shift peaks in demand for transport capacity will lead to shifting peaks in demand for the commodity. With lower peaks in demand on the market, power plants will face fewer adjustments in their production. They will run more efficiently and thus have less emissions per kWh electricity produced (Blom, et al., 2012). Also total grid losses will be lower and savings on the total consumption will occur, preventing generation and thus emissions.

Societal benefit

Besides lowering emissions, lowering the peaks in demanded capacity results in less necessary investments due to grid reinforcements (Vereniging van Nederlandse Gemeenten, 2013). The costs of these would otherwise be passed on to the customer in one way or another, so the society will benefit as well. This is especially important since the upcoming distributed generation might even increase the network costs (Hallberg, et al., 2013). Also, a better distribution of capacity costs over the customers can be reached by allocating a higher price to customers who are willing to pay for service during periods of high transport capacity demand.

In a future scenario where most of the energy is produced by consumers it is worth questioning what role grid operators should play and how we have to anticipate on that now. Therefore this study will give an indication to what extent congestion can be solved by the market or should be addressed by a grid operator.

The Dutch government wants to stimulate the application of new technologies within the electricity sector (Rijksoverheid, 2012). This study provides insight in directions to stimulate.

Scientific relevance

Although a report written by CE and KEMA (2012) gives an extensive overview of the possible future developments and costs, it also describes the urgent need of development of time and place dependent pricing mechanisms and regulation. This study is especially aimed at the pricing component, but an answer to this will automatically give a base for the development of regulation. In that sense it will add to the knowledge in the energy sector.

There are a few studies about the costs involved for smartening our grids which cover the system as a whole but do not focus specifically on the distribution level (Faruqui, et al., 2010) (Blom, et al., 2012). Kok, et al. (2011) describe costs for making the network EV and heat pump ready, but don’t consider smart grid options.

Although a lot has been written about smart grid concepts and all the technical mechanisms behind it, a real comparison with all alternative options has not yet been found.

However, more importantly and a prerequisite for the comparison is a quantification of the change in consumer welfare, reflected by the change in consumer surplus and deadweight loss due to adapting demand. Blom et al. (2012) state that the negative change in welfare will be largely compensated by the positive change of the tariff incentive, however they don’t prove it in any way. Many studies have been done about demand response and the peak reduction possibilities (Claessen, 2012) (Kok, et al., 2012). A lot focus on the impact of experiments, however, using elasticities with the results from a simulated future demand situation to calculate the future welfare effects is rarely done. Furthermore, different smart grid studies reveal cost savings for consumers, however if these savings are due to lower market prices, then they are not representative for peak pricing to cope with transport constraints (EU, 2012).

1.6 SCOPE

This paper starts off with the comparison of different use concepts theoretically available for the Dutch grid situation on distribution level. It focuses on options that are implemented between the production and consumption side of electricity influencing transport by either increasing the physical capacity of the grid (Figure 1), or by preventing peak demand (Figure 2). They will be implemented at or before the connection to the customer. A representative area of 275 households under a 400 kVA transformer is used for the comparison (Pellis, 2013b).

Opinions seem different when predicting the speed and consequences of rapidly emerging technologies. Although the available simulation data are assumed to be representative for 2050, we rather speak about scenarios based on a set of different technologies at both the demand and supply side of electricity instead of on a specific future year.

Since the EU policy is aimed at the installation of smart meters for every connection (EU, 2009), we assume in this study that every connection has one. This is applicable when comparing the options which include different pricing mechanisms. Therefore the costs of installing smart meters will not be taken into account.

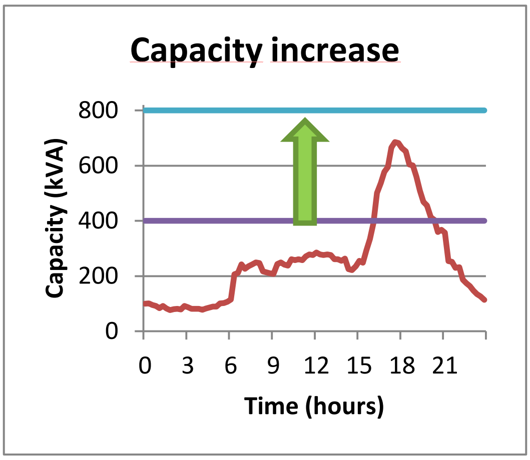


FIGURE 1

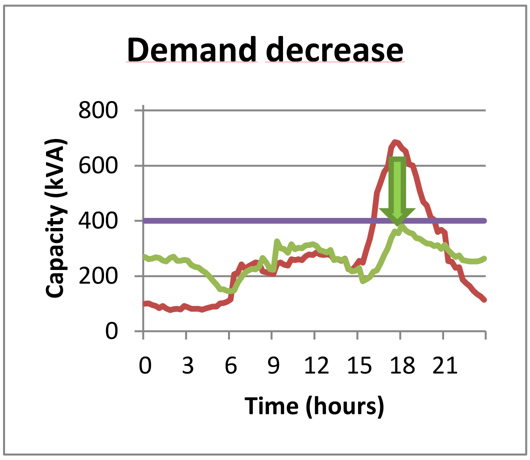


FIGURE 2

1.7 THESIS OUTLINE

In the introduction part the current situation in the Dutch grid is explained. After this chapter 2 a theoretical background will be provided including the more technical properties of the grid, the principles it is based on, and what future challenges there are. Important concepts as demand response, smart grid and consumer surplus are explained in 2.6, 2.7 and 2.8. What follows in the methodology chapter 3 is the approach taken here to compare the different options after which the consecutive results are presented in chapter 4. This chapter follows the research questions by first presenting which future developments and problems are expected on distribution level. Next, as part of this thesis was to find out about the different possible options to cope with future load developments, these will be presented next. They are split up in options which increase the network capacity and an option (demand response) for which an capacity increase is not necessary. Then the options are evaluated in the conclusion and discussion including guidelines to value and make investment decisions in electricity networks. Finally several recommendations for further research follow.

2 THEORETIC BACKGROUND

2.1 ELECTRICITY GRID BASICS

Transport and distribution

To transport electricity in an efficient manner it is desirable to keep the thereby emerging losses to a minimum. These losses are due to resistance of the cables and other components, which increases with the square of the current (Blom, et al., 2012). Increasing the voltage allows the same power to be transported using a lower current. Therefore the backbones of our grids which have to transport the most electricity all use high voltages. However, higher voltage on the cables also means a closer approach to the breakdown voltage to the surroundings and thus a need of much more insulation and safety measures. Therefore transformers are used to create several lower voltage levels when getting closer to the consumer.

Voltage levels

In the Dutch grid often 3 voltage levels are distinguished. These are the high, medium and low voltage grids. The high-voltage grid has voltages of 380, 220, 150 and 110kV (TENNET) and there are only a few large industrial customers directly connected to it. Tennet, the transmission system operator (TSO) is in charge. Other voltage levels (sometimes called 'distribution grids') are governed by Regional Grid Operators (RGO) The medium-voltage is 50, 25, 23, 20, 13 and 10kV (STEDIN KCD). Bigger companies with a high electricity demand are connected to it and also generation facilities like combined heat and power (CHP) and wind turbines use these levels. The low voltage grid used by the smaller companies (< 0.3 MW power demand) and all households is 400V, using 3 phases of 230V (Oirsouw, 2012). Legally a deviation of +/- 10% of the voltage level is allowed and a RGO is responsible for supplying this quality (Energiekamer NMa, 2012).

Frequency and phases

The voltage generated has a frequency of 50 Hertz. This means that 50 times per second the voltage changes from positive to negative and back by following the curve of a sinus. All electrical equipment is designed on this property. Power plants however, have an output of 3 different phases of the 50 Hertz frequency. These all differ 120 degrees or 1/150th second. This is because powerful equipment often demands 3 phases of this sinus at the same time. Nearly all consumer appliances work on 1 single phase and therefore many households are only connected to 1 phase, while the incoming cable of the building often still has 3 phases (Oirsouw, 2012).

Stochastics

The stochastic behaviour of customers allows the total electricity system to be designed for a smaller demand than the capacity of the actual sum of all connections. At higher levels of voltage in the electricity system the relative peaks will be lower due to the aggregation of thousands of stochastic demands. Therefore, larger simultaneous electricity use due to changing consumer behaviour could require grid reinforcements.

Structure & dimensions

Historically seen electricity was first generated in power plants supplying local grids. Later, these grids were connected and most electricity production was directly fed-in into high-voltage grids. Since almost no local distributed generation took place this has led to a system designed for a most efficient top-down transport. Nowadays the place of production is changing and thus requires adjustments in the design and dimensions (Oirsouw, 2012).

The historical emergence of the grids has left its traces in the design as well. The grid architects of the former municipal energy companies all had their own interpretation of what good governance of their grids was, resulting in differences in the dimensions of our grids. Related to these unequal grid-operating regimes are the different structures of these grids. Some might be highly meshed; others will have a radial structure which consists of unconnected strands departing from 1 point (Pellis, 2013a). However, the kind of operating regime is not the only reason for the different structures. Also the local situation might ask for specific structures. The result is that grids will face different problems and that there will be different solutions required.

After the HV backbone of the system the MV grids show different structures, of which radial is not really common in the Netherlands. The ring structure is a loop which creates the possibility to continue supply when one interruption occurs. At this structure connections to different substations can be present. Another often occurring situation is the combination of a main ring, sub ring and strand or meshed structure. Meshed has the advantage of having more possibilities to divert the power during an outage and heavy loads can be distributed over multiple strings. Especially for rural and industrial area's this can be desirable (Oirsouw, 2012).

By a ring main unit the LV grids are connected to the MV level. The LV grids often have a radial structure without a connection to another station. However, both ring and meshed do occur. There is no interruption reserve when radial structures face a breakdown. This is then first fixed by a generator car (Oirsouw, 2012).

In older rural grids meshed structures occur, however the feed-in points should be connected to the same MS-strand. Although it has advantages like better voltage levels and less grid losses, higher powers are involved in case of a short circuit which makes it more dangerous and also a more complex security is necessary. Therefore new grids are radial designed (Oirsouw, 2012).

2.2 TRANSFORMERS

Transformers can both in- and decrease the voltage level, depending on which side the demand transcends the production. They are produced in standardised sizes of which a 400 kVA model is commonly used in the Dutch grid. When this 400 kVA transformer is insufficient (in terms of capacity) an often used follow up would be 630 kVA (Apel, 2013) (Oirsouw, 2012). Consequentially the same costs are involved in case a small or a much larger upgrade is necessary. In theory, this implies that the value per kW additional capacity would be higher if the exceedance of the maximum system-capacity is only small. However, due to the possibility to temporarily exceed the maximum capacity up to 140% of the labelled capacity of the transformers a fuzzy area exists where capacity expansion is not really necessary. Furthermore, one of the RGOs in the Netherlands indicated that when installing a new transformer, as a rule of thumb its capacity will measure 40% above the annual maximum peak. This is to be prepared for future growth of demand and not having to replace it soon (Pellis, 2013b).

2.3 ELECTRICITY PRICE EXPLAINED

The electricity bill of a consumer consists out of 3 main parts: transport costs for the grid operator, commodity costs for the electricity supplier and tax for the government (see Annex 1). For Dutch consumers transport has a fixed price, depending on the connection capacity. The part of the bill which depends on the amount of kWh's used consists of the commodity price of the supplier and tax. The average price offered by suppliers in the Netherlands in 2013 was 7.5 euro cents including the commodity and the standing charge (CBS, 2014a). On top of this first an energy tax of 11.65 eurocents and a sustainable energy fee of €0,0011 is applied, after which 21% VAT is calculated over the total (Rijksoverheid, 2013a) (Rijksoverheid, 2013b). This brings the average kWh price for consumers at 23.8 eurocents in 2013. On top of this price consumers pay on average €252.91 capacity fee and get €318.62 back from the government per connection (The Bill Doctor, 2014). At an average of 3283 kWh the average annual electricity bill is €648.36 (CBS, 2014b) (CBS, 2013a).

2.4 INFLUENCE OF SOCIAL BEHAVIOUR

Social behaviour also plays a role in the potential load problems. At a local scale this is confirmed by a case study done by Geraedts (2013) who shows that it is more likely that people buy solar panels if a neighbour in their area already has installed a couple of them compared to an area where there are no people with solar panels around (Geraedts, 2013). This social behaviour is thus important when buying new technologies. It locally increases the rate of penetration of the technology and consequential the local simultaneity in the grid. When others have the solar panels installed this is the so-called 'social proof'. The social influence is more important for technologies with a clear (visible) appearance to others. Technologies like heat pumps are more individualistic and their rate of penetration will therefore be less influenced by this effect (Holger, et al., 2011).

If locally concentrated high peak demand causes load problems, this power is delivered from somewhere else in the grid. In the case of a low regional simultaneity of local behaviour, the higher grids will most likely have sufficient capacity to cope with this local demand problem. However grid operators argue that larger, regional simultaneity of behaviour could become a problem and make investments in higher regional and national grid levels necessary as these then have to be able to cope with higher loads as well (Pellis, 2013a).

However, on a larger scale social behaviour can also cause a different problem. Following Rogers adoption curve, the overall penetration of a technology follows an s-curve over time. This means that if a technology is successful, after about the first 16% developments will take off and go very fast. If the maximum penetration rate for an average local grid is rather low (e.g. EV's), RGOs will need a lot of extra grid reinforcement over a small amount of time.

2.5 SMART GRID PRINCIPLES

There are many views of what a smart grid really is, but here we will define it as a grid enabling demand response (DR). Its configuration can be done in many different ways whereby sensors and communication services play an important role to assure the quality of the electricity supply. DR is seen as both a solution to capacity shortage of the grid and a better functioning of the markets. Both of these two functions compete for flexibility in the electricity consumption behaviour of the consumer. When the availability of the commodity is also incorporated, the total price will thus be the result of two different markets. These markets can have opposing price signals. This occurs when there is a low commodity price with a highly increased local demand as a consequence. In theory this should not be a problem as long as the sum of the total decreased welfare in society over time due to the local raised transport prices is lower than the costs to install an alternative during that time. In practice laws don't allow local increases in transport price now. The characteristics of this market seem similar to perfect competition as there are many suppliers and many buyers with very low market power each.

2.6 DEMAND RESPONSE

Consumers often face fixed electricity prices and thus have no incentive to react on scarcity of supply. Enabling this is called demand response (DR) and can be done in many ways. When looking into this the first distinction to be made is the difference in Incentive-Based Programs (IBP) and Price-Based Programs (PBP). IBP comes down to rewarding a customer for a commitment to reduce his demand and involves programmes such as Direct Load Control, Interruptible Load, Emergency DR and Ancillary Services Market (Albadi & El-Saadany, 2008). PBP uses differences in electricity price to flatten the demand curve and is often more suitable for consumers.

Incentive based programs

From the IBP solutions the Direct Load Control (DLC) is also applied at distribution level. DLC is different from other smart solutions stated below since customers are basically not the ones in charge of the decision to consume. Central steering mechanisms are responsible for this. Often a rebate on the annual electricity bill is given in return for participation. Sometimes a penalty fee applies in case a customer wants to use the electricity anyway. It has mainly been applied to consumers with air conditioning or electric water heating (Sergici & Faruqui, 2011). In theory it would be worth investigating this option for the future Dutch situation too as heat pumps have similar usage characteristics as air conditioning for which this is applied. In an adapted form it would also be an option to apply to electric cars. Cohere for example is a company already offering such services for office buildings (Cohere, 2013)

Price based programs

In theory a diverse set of rates covering all varieties until a real-time market price can be made by combining the time of announcement and the size of price-similar blocks. In practice this results in a set of classifications. Among others the literature uses three main categories to describe the different DR rates (Fan & Hyndman, 2011). The first is the often used Time Of Use (TOU) rate where a pre-determined difference in price at fixed times is applied. In The Netherlands we have the option for day- and night tariffs, which in fact is a simple example of this. A second option is Critical Peak Pricing (CPP). Here a peak-price is only used during peak demand in the order of 1% of the hours per year. For the rest of the time a flat or TOU tariff is applied (Faruqui & Sergici, 2009) (Albadi & El-Saadany, 2008). Price announcement often takes place a day in advance. A form of CPP is the Extreme Day Pricing where a higher tariff is set for whole days, also announced a day in advance. Also Peak Time Rebate creates similar opportunity costs to CPP, but is announced in the form of the opportunity to gain a rebate for each unit of demand below a certain baseline. The third and last main category is Real Time Pricing (RTP). The situation on the wholesale market is reflected by hourly, quarterly or even smaller fluctuations (Fan & Hyndman, 2011). Price-information is available from day-ahead till hour-ahead or even shorter time scales.

Consumer participation

It is questionable if demand response for consumers will really be a success. There are at least three reasons why coupling Dutch consumers to the commodity market will likely not result in big changes of their electricity use and thus influence on the day-ahead till real-time market prices.

- The economic value of a kWh is much lower for industrial customers. A consumer for example is willing to pay much more for boiling 200 ml of water for a cup of coffee as what an industrial customer would be willing to pay for boiling the same amount in his thousands litres process. Electricity is seen as an input factor of the production process of which the costs should be minimized. Therefore industrial consumers have a lower elasticity, meaning they are more likely to respond on price changes (Bernstein & Griffin, 2006).

- The fixed tax per kWh for industrial customers is much lower (see annex 2). A doubling in commodity price will lead to a 41% increase in consumer price, while for big industrial customers it will also mean a nearly doubling of their total price.
- Only 21.8% (2012) of the electricity use can be attributed to households; the rest is mainly industrial (CBS, 2013b). However extra loads by EVs and heat pumps on one side and fewer heavy industry could change this figure.

When there is no business case for consumers on the commodity market, a system for residential demand response would only be constructed to prevent the network from outages. This would decrease a potential business case of such a system for the RGO.

2.7 ELASTICITY

Demand response is based on economic theory of demand and supply. For electricity and many other goods a drop in its price will lead to an increase of demand and a price rise will lead to the opposite reaction. The magnitude of the resulting change however depends on the nature of the respective good e.g. the availability of substitutes, the necessity for living and utility (usefulness) compared to price level. This consumer response to a change in its price can be expressed by the elasticity. It is a dimensionless ratio describing the relation between the relative change in demand and price (Albadi & El-Saadany, 2008).

Long term / short term

For most goods, time influences a consumer's possibilities and willingness to adjust his behaviour and therefore elasticities are only valid over a certain time interval. In general two periods are distinguished: short- and long-run elasticity. Short run elasticity is generally seen as the elasticity for a period over which a consumer does not change its inventory of electric appliances and is even taken as long as up to 5 years. Long-run elasticity is taken over even longer periods in which the inventory does change (Barnes, et al., 1981). The difference is often ambiguous and can vary per study. In this case we will only make use of the short run elasticity since adaptation of a consumer's inventory is not taken into account over the length of the simulation.

Own-price elasticity

Different relations are described by an elasticity, however the most commonly used elasticity is the own-price elasticity of demand. It describes a consumer's response to a change in the good's own price (Bernstein & Griffin, 2006) (Neenan & Eom, 2007). Other elasticities are the income elasticity and the cross-price elasticity expressing the change in demand due to a change in respectively the income and price of a different good. The own-price elasticity is calculated as

$$\sigma_d = \frac{dQ/Q}{dP/P}$$

with σ_d the price elasticity (dimensionless), Q the demand (kWh), dQ the difference in demand (kWh) between the old and the new situation, P the price (Euro/kWh) and dP the price change (Euro/kWh) between the old and new situation (Fan & Hyndman, 2011).

In case of decreasing peak load electricity the elasticity thus mainly reflects the willingness to adjust the behaviour and allows for a quantification of the loss of welfare in monetary terms. When the value of this elasticity gets below a value of -1 and thus an increase in price of 1% leads to a decrease in demand of more than 1%, it is seen as an elastic good. A value between 0 and -1 means a proportional smaller decrease in demand as the percentage rise in price (Fan & Hyndman, 2011). This is the case for electricity as shown in table 1 and 2.

The typical own-price elasticity is measured over a period of months or years, therefore within-day substitution does not affect this measure. Applying this would give a wrong image of the effect of a desired peak reduction by an increase in price. However when decreasing the time period over which the elasticity is representative to a specific period of the day, then the within-day substitution is also included in the elasticity estimate. Therefore these estimates are generally higher, but they are not often measured. For electricity, some peak-elasticities have been retrieved as shown in table 1 and for comparison also generally lower 'normal' own-elasticities are presented in table 2. Table 2 also shows that the values of elasticities differ a lot per experiment. Although the focus is on short-run elasticity, it is worth mentioning that a Suisse study reports long-run elasticities between -1.60 and -2.26 during the peak (Filippini, 2011). Furthermore, studies are not always representative, as some feature an opt-out option at which costumers with a low elasticity will opt-out, increasing the overall elasticity (Jessoe & Rapson, 2014).

TABLE 1 - ON-PEAK SHORT-RUN OWN-ELASTICITY FIGURES

Elasticity	Source
-0.28	(Faruqui & George, 2002)
-0.6	(Filippini, 1995)
-0.77 - -0.84	(Filippini, 2011)
-0.79	(Aubin, et al., 1995)

TABLE 2: ELASTICITIES OF DEMAND FOR ELECTRICITY

Price elasticity		Source
From	Till	
-0.047	-0.098 (with enabling tech)	(Faruqui & Sergici, 2009)
-0.3	-.47 (winter)	(Faruqui & Sergici, 2009)
-0.032	-0.054	(Faruqui & Sergici, 2009)
-0.042	-	(Charles River Associates, 2005)
-0.08	-0.15	(Alberini & Filippini, 2010)
-0.2	-0.24	(Bernstein & Griffin, 2006)
-0.363	-0.428	(Fan & Hyndman, 2011)

Elasticity of substitution

In the case of electricity, peak use and off-peak use could be seen as substitutes. Increasing the price of one of these goods (e.g. peak kWhs) will not only decrease the use of the good itself, but it will also affect the use of its substitute (off-peak kWhs), which also depends on its own price. A more common approach compared to the peak own-price elasticity is therefore the use of an elasticity of substitution. It is an often used single parameter to measure of the shift in demand due to price incentives in different periods (King & Chatterjee, 2003).

Equal to the relative change in demand ratio between the two substitutes, divided by the relative change in price ratio it is rather similar to the own price elasticity. The formula is

$$\sigma_s = (\frac{d\left(\frac{Q_p}{Q_o}\right)}{\frac{Q_p}{Q_o}})/(\frac{d\left(\frac{P_o}{P_p}\right)}{\frac{P_o}{P_p}})$$

with subscript p and o respectively indicating peak and off-peak.

A Constant Elasticity of Substitution (CES) model is often used to describe the demand for two substitutes under the assumption of a constant elasticity of substitution (Boisvert, et al., 2004) (Goldman, et al., 2004). Values retrieved by assuming this model are shown below.

TABLE 3 - ELASTICITY OF SUBSTITUTION UNDER CES MODEL ASSUMPTION

Elasticity	Source
0.20 – 0.33	(Braithwait, 2000)
0.07 – 0.21	(Caves & Christensen, 1984)
0.14 - 0.39	(Baladi, et al., 1998)
0.31	(Braithwait & Eakin, 2002)

Factors of influence

The price elasticity of demand is not a stable number as the consumers' ability and willingness to adapt its electricity consumption is influenced by many variables. In fact, when looking closer at the end-use one could say that many uses of electricity fulfil different needs with their own elasticity and elasticities can be made for each application. Barnes et al. (1981) already apply this by using different elasticities for different end-use categories. This implies that the availability of a heat pump and/or an electric car will have an impact on the total elasticity of a household. In practice it is shown that energy-demanding technologies as air conditioning have a big impact of up to 150% more on the response by the consumer (Faruqui & Sergici, 2009). It is thus reasonable to assume that also the possession of an EV will have a big impact on the response.

The technological properties of an electrical device and the desire to use it at the planned moment leave room for substitution of usage in time. This is a main component of the elasticity and probably the reason why technologies as air-conditioning increase the price response. A separate elasticity to describe this effect exists, but this is calculated as the rate of substitution between peak and off-peak in response to a change in the ratio of the respective prices (Charles River Associates, 2005). The exact time of substitution is not know and therefore this elasticity cannot be applied in the analysis done here.

Other variables influencing the elasticity are the hour of the day, the day of the week and the time of year. As the weather has a big influence on the heating and cooling needs of a household it is therefore also an important variable for the available flexibility in consumption. Furthermore the expected duration of the price change and the new price level can be important parameters (Neenan & Eom, 2007).

Due to all the variables and the different weights assigned to them, elasticities differ per customer. Therefore it can be useful to analyse groups of customers with similar behaviour. Industrial consumers for example have a higher elasticity (Faria & Vale, 2011). Elasticity also changes along the demand curve, which on its turn varies due to weather and consumption patterns (Charles River Associates, 2005).

Influence of enabling technologies

Enabling technologies which provide price information and own demand statistics have shown to substantially increase the price elasticity (Allcott, 2011). In the Illinois project an increase of price elasticity from -0.047 to -0.069 was found, equal to more than 47% (Faruqui & Sergici, 2009). Similar effects are expected due to technological development in the automation of demand response, an important characteristic of the smart grid concepts. Fewer involvement of the user during decisions converges his experience of the PBP to DLC. It decreases the effort of the user to respond compared to the situation without these technologies (in which a lot of research to elasticities of electricity is done). Therefore it is expected that the elasticity of users with an automatic intelligent decision system is higher as is shown in current studies.

Levelling effect

With the elasticity applied (defined here as ‘control option’), we assume a higher price during periods of load reduction and a lower price than before during periods of increased demand compared to the ‘non-control option’. As an effect, consumers with a higher willingness to pay for their electricity during peaks will have a higher bill as before and consumers who are more reactive to price will have a lower bill. Since low-income households are more price-sensitive a levelling effect could occur (Borenstein, 2010). This is not true in case of an entrance barrier to this market due to high upfront costs for an enabling device.

Demand curve

Using an elasticity, the price adjustment of a DR system can be calculated, however to understand the implications of the price adjustments, a more thorough knowledge of the economic mechanisms behind it is necessary.

In theory one could address a value in monetary terms for each individual potential use of electricity in kWh. Sorting all these values from high to low gives us the demand curve of the electricity market as represented by line D in figure 3 (Pindyck & Rubinfeld, 2007). For supply of electricity this would work just the other way around, creating a supply curve defining the price of the commodity at every given demand. At the intersection of both a price is established. In reality consumers face a predetermined price, incorporating all long term demand and supply expectations. This price is not responding to the short term supply. It can therefore be seen as a fixed price for which any demand is possible. In a future situation consumer prices could become variable per PTU. However, concerning just the commodity of electricity, a single consumer has a negligible influence on the total electricity market and price resulting from this market. Also an area of 275 households will hardly be of any influence concerning their peak of far below a MW, while the total electricity demand in the Netherlands is on average 11.6 GW (CBS, 2013c). Therefore an endless supply is faced at any price for (the group of) households as shown by the horizontal supply curve S in figure 3.

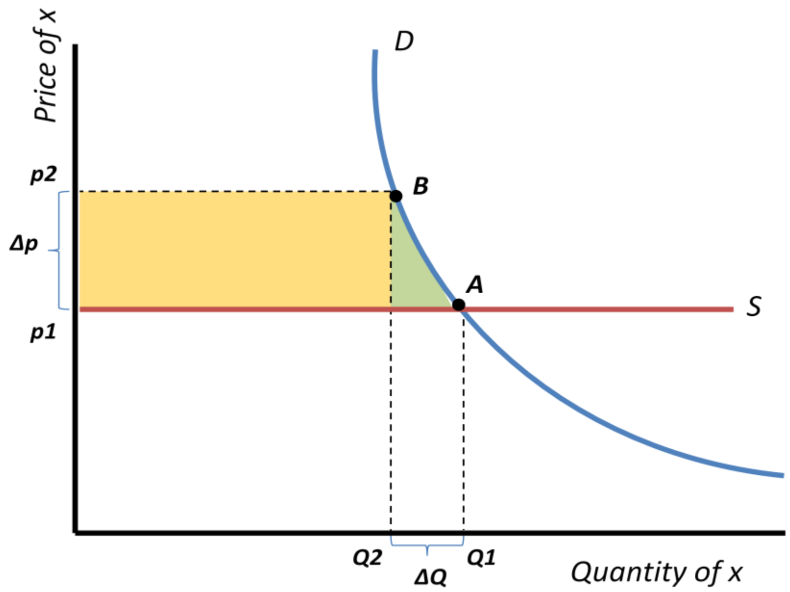


FIGURE 3 - LOCAL ELECTRICITY DEMAND AND SUPPLY IMPRESSION

The access to the electricity market is restricted by the connection capacity of the grid (Q2). To keep the demand within this capacity, price will have to be increased from p1 to p2 during peak hours.

Welfare effects

The welfare consumers gain from consuming a product is often measured by the consumer surplus. This is the difference between the price consumers pay and the actual value they are willing to pay for their consumption. It is equal to the area under the demand curve D and above the market price P_1 the consumers pay. At a price increase, the yellow surface is extra expenditure for the consumers and income for the grid operator. For society as a whole, a transfer of welfare takes place. However, the green surface is a loss of welfare at the consumer's side, which is not transferred to a counterparty. This is called the deadweight loss. It represents the 'costs' of not reaching the economic optimum and is an important measure to compare the costs of alternative options with (Pindyck & Rubinfeld, 2007).

Utility

The usefulness of a product experienced by a consumer is called the utility. At the initial situation, consumers show a preference to consume more during peak hours. They experience a higher utility during peak hours. The utility has an ordinal scale due to the preferences on which it is based, however it is an useful concept to understand and calculate effects of economic decisions.

The additional satisfaction a consumer gets by consuming one more unit of either peak or off-peak electricity is called the marginal utility. This figure diminishes with every additional unit consumed and therefore the (utility) graph is convex. From the equal marginal utility principle follows utility is maximized when the available budget is used in a way that the marginal utility per euro spend is the same for each good (Pindyck & Rubinfeld, 2007).

Indifference curves

Indifference curves, or iso-utility curves show all combinations of two goods which result in the same level of utility. Diminishing marginal utility give the resulting graphs a convex shape, when the goods are not total substitutes. An often used model is the Constant Elasticity of Substitution (CES) model where utility is described by a graph with the same elasticity at all points (Stern, 2008). The green to red curves in figure 4 illustrate increasing levels of utility.

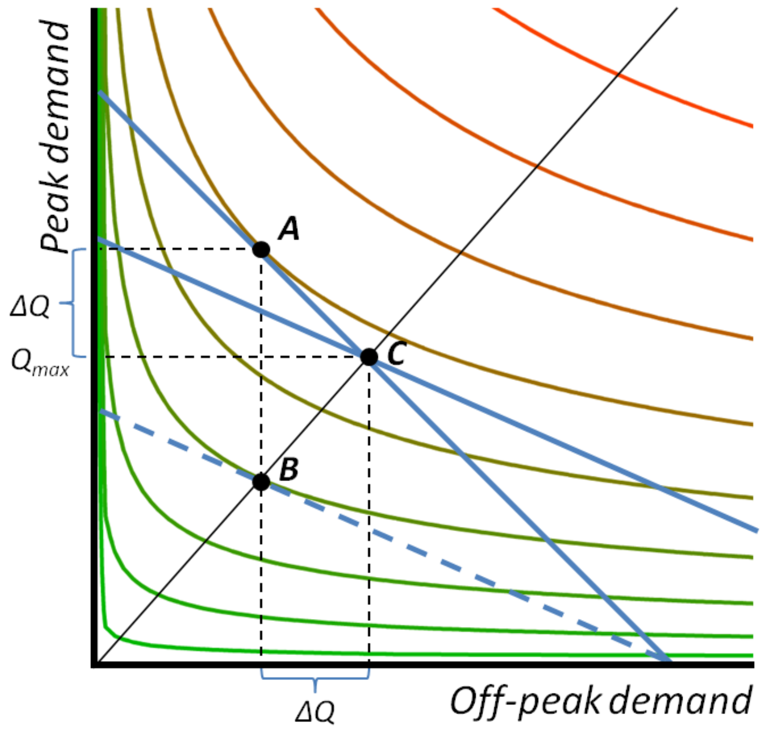


FIGURE 4 - SHIFT IN PREFERENCES DUE TO A PRICE INCREASE

Now introducing the concept of budget lines, the linear blue lines in figure 4 reveals each combination of peak and off-peak units which can be bought for the same amount of money under certain prices. As we assume that a consumer will maximize it's utility under a constraint budget, the most satisfaction will be in point A. In point A the indifference curve has exactly the same slope as the budget line. Therefore the marginal rate of substitution at that point will be equal to the price ratio between peak and off-peak units of consumption (Pindyck & Rubinfeld, 2007).

When the electricity use during peak hours is constraint to a level below the initial peak demand, then a new equilibrium, maximizing utility is only reached when the slope of the iso-budget line is equal to the slope of the indifference curve in that point. This is shown in figure 4. A price increase of peak electricity will under a constraint budget at first result in optimum B. The slope of the new tangent is equal to the negative price ratio between the two demands. Next, an equal percentage decrease in price of the two substitutes will lead to the new optimum C, having the same total consumption as in A, while spending the same budget (Pindyck & Rubinfeld, 2007).

As the demand of electricity is inelastic, the elasticity of substitution is low and the rate they face is rather flat, we can assume that current usage patterns are the most preferred and convenient. When having to adjust the pattern within the same budget, this will thus always be a sub-optimum. This is confirmed by figure 4 which also illustrates that the new optimum always results in a lower utility as the initial situation.

3 METHODOLOGY

In order to answer the research question, first an estimation of the expected problems is made. Next, the implementation of different solutions is compared using the original, uninfluenced demand pattern of a scenario of a common future situation on the Dutch grid. Special attention is paid on demand response. Then, to assess the sensitivity of the results to the influence of the peak height and the elasticity, these inputs will be varied over a range. Furthermore, APX prices will be introduced to get close to realistic variable prices and get insight in their influence.

3.1 UNDERSTANDING, PROBLEMS AND OPTIONS

A combination of literature research and interviews is performed for multiple purposes at the same time. It is used for three different goals. The first is to get a better understanding of the electricity market which is necessary to conduct this research. The second goal is to answer the first research question, which aims to explore the consequences of future developments. The last goal is to answer the second research question by investigating the possible options to keep the consequences of these developments within legal boundaries. In particular for the latter industry experts are consulted.

3.2 COMPARISON OF OPTIONS

Then, to answer the third research question the different options[1] are compared at their societal costs[2] for a 275 household area connected to a 400 kVA transformer. This is representative for often occurring situations within Dutch grids (Pellis, 2013b). The dimensions of the options will be defined by the maximum peak capacity demand in a future scenario, based on a medium penetration of the most problematic technologies as found in the answer on research question 1 in chapter 4.1. This medium degree of penetration of about 50% of the maximum penetration is chosen, because it would already be a very big difference from the current situation considering the low share in sales and the low replacement rates of these technologies. Besides, when following Roger's theory about diffusion of innovations the 50% penetration would also be the stage in which the most growth in absolute amounts can be expected (Doorman & Tuinenburg, 2012). This implies that if problems occur at or before this stage, they will rapidly keep on expanding with apparent social and economic consequences.

The dimensions of the option where the grid is upgraded by extra cables and transformers can differ a lot per situation. Thus to make this study more representative, a range is included for this option with different cable lengths and transformer capacity.

For the options which increase the grid capacity, only data about the maximum peak capacity demand is sufficient. However, to compare the costs of the option which decreases the demand, a data series about the demand of an uncontrolled and a controlled scenario over a year is necessary. Furthermore electricity prices and price-elasticity's are required to calculate the change in societal utility and the price incentive by which the consumer is stimulated to adapt his behaviour. The data series is retrieved from the Smart Grid Control study by Claessen (2012) as described in 3.4.

By using the initial investment, the economic lifespan and an interest rate of 5% an annuity for each option is calculated. As the comparison takes place on this annuity and we assume the

[1] As described in the answer to the 2nd research question in chapter 4.2

[2] Thus including a change in utility and in financial costs.

electricity price to stay equal, the outcomes over the years will remain constant. In the annual costs O&M expenses are not taken into account as these are assumed to be minor compared to the investment (Apel, 2013). Fuel costs for the option with the CHP are not taken into account as this CHP is considered to be able to deliver electricity on a cost-competitive basis during peak demand in which prices usually rise as well. Thereby, the capital expenditures are already paid for in the initial investment, which makes it more cost-competitive.

The data from Claessen (2012) is for a future situation which still seems far away concerning the high penetration rates. By assessing the sensitivity of the results for the influence of differences in peaks, it also describes how the path to the main scenario will look like. Therefore the costs and differences in possible configurations of options of a - 50% til a 50% peak are compared. In case of the options which increase the grid capacity this means that the peak of excess capacity demand is multiplied by these factors. In case of the demand response options the difference between the controlled and the uncontrolled data is multiplied by these figures and added to the controlled version to get a new uncontrolled version and use that for a new analysis.

3.3 DEMAND RESPONSE COST CALCULATIONS

To calculate the total cost for the consumers of the implementation of a DR system both the costs involved for the technology and the change in welfare, measured by consumer surplus should be taken into account. While the costs of the technology can be based on interviews and an educated guess, the change in consumer surplus depends on the scenario and assumptions made and extensive computations are necessary. In addition also a change in utility will take place which cannot be quantified in terms of money and will therefore be described qualitatively.

The quantification of the change in welfare in monetary terms requires a demand curve from which it can be deduced. The method and demand curve used depends on the assumptions made about the demand curve and the way the RGO incentivises consumers to adapt their behaviour. Initially, our most important assumptions are:

- Taking as a starting point that the RGO aims to maximize welfare, a real time pricing scheme will in theory reflect the best approximation per time unit.
- Furthermore it is safe to assume that the implementation should not lead to losses or profits on the exploitation for the RGO, keeping the costs and revenues of the total consumption at 0. This also brings some redistribution of welfare between consumers due to different individual preferences. This is in line with the 'Polluter Pays Principle', because the consumers causing the peaks will be charged the most.
- Finally, total electricity use over the day is assumed to stay equal. Temporary decreasing electricity demand by shifting it to a different timeframe is easier than decreasing total demand. Especially for larger loads as EV charging and a dishwasher load can more easily be shifted as totally removed. It is therefore that total electricity use is assumed to be equal over a day and that all avoided peak demand returns during off-peak hours. In figure 4 the most optimal use will thus always be on the initial iso-budget line, which is also an iso-quantity curve.

Two different methods have been explored, of which one is ultimately used. The other approach is nevertheless described as it gives an useful insight in pro's and con's of this methodological choice for possible future follow-up.

3.3.1 ELASTICITY OF SUBSTITUTION

From the theory about substitute goods as shown in 2.9, at an equal total demand, the equal-budget assumption can only be maintained when both peak and off-peak price and quantities are adjusted. At first sight the elasticity of substitution seems an appropriate tool, since it is a single figure describing the relation between all four of these parameters:

$$E_s = \left(\frac{d\left(\frac{Q_p}{Q_o}\right)}{\frac{Q_p}{Q_o}}\right) / \left(\frac{d\left(\frac{P_o}{P_p}\right)}{\frac{P_o}{P_p}}\right)$$

P and Q are Price and Demand and the subscripts denote a peak or off-peak situation. The elasticity of substitution however only describes the relation between two substitutes or periods. Under the assumption of keeping the total use over a day equal, each period would in theory have 95 substitutes. Therefore the assumption could be made that certain parts of a peak period are substitutes for specific parts of the off-peak period.

For small differences in quantity the d in the substitution formula is often replaced by a Δ and the changes become a subtraction of the new by the old situation. However, this does not correctly reflect the original demand curve behind the ratios. A better approach to the original demand curve is given by combining the Constant Elasticity of Substitution (CES) function with the budget constraint. The CES function describes the total utility from two substitutes under the assumption of a constant elasticity.

Some activities can hardly be replaced (like power use for a consultant's computer), resulting in a near zero elasticity of substitution. Other activities can more easily be replaced, approaching a near linear isoquant for equal utility, reflecting perfect substitution. In general most activities will not be either of those extremes, but somewhere in between with a diminishing marginal utility of substitution. Therefore a constant elasticity of substitution could be a reasonable approximation.

The standard form, developed by Arrow et al. (also called ACMS form) is (Klump, et al., 2011):

$$U(Q_p, Q_o) = C(\alpha Q_p^{\frac{\sigma-1}{\sigma}} + (1-\alpha) Q_o^{\frac{\sigma-1}{\sigma}})^{\frac{\sigma}{\sigma-1}}$$

Besides the already used units, U is the utility level, σ is the elasticity and distribution parameter α and substitution parameter C are constants: (Klump, et al., 2011)

$$\alpha = \frac{P_{p1} * Q_{p1}{}^{1/\sigma}}{P_{p1} * Q_{p1}{}^{1/\sigma} + P_{o1} * Q_{o1}{}^{1/\sigma}}$$

$$C = U_0 \left(\frac{P_{p1} * Q_{p1}{}^{1/\sigma} + P_{o1} * Q_{o1}{}^{1/\sigma}}{P_{p1} * Q_{p1} + P_{o1} * Q_{o1}} \right)^{\frac{\sigma}{\sigma-1}}$$

The partial derivatives are

$$\frac{\partial U}{\partial Q_p} = C * \alpha * (\frac{U}{Q_p})^{\frac{1}{\sigma}}$$

$$\frac{\partial U}{\partial Q_o} = C * (1-\alpha) * (\frac{U}{Q_o})^{\frac{1}{\sigma}}$$

The ratio R of the partial derivatives is equal to the price ratio at the optimum (Mittermaier, 2008), giving

$$\frac{P_o}{P_p} = \frac{1-\alpha}{\alpha} * \left(\frac{Q_p}{Q_o}\right)^{\frac{1}{\sigma}} = R$$

If we assume that the aim of the grid operator is to level out the average expenditures, to the initial level, then expenditures will always be equal to constant C.

$$P_p * Q_p + P_o * Q_o = C$$

Together this allows for the calculation of P_p and P_o.

$$P_p = \frac{C}{Q_p + R * Q_o}$$

$$P_{p2} = \frac{P_{p1} * Q_{p1} + P_{o1} * Q_{o1}}{Q_{p2} + \frac{1-\alpha}{\alpha} * \left(\frac{Q_{p2}}{Q_{o2}}\right)^{\frac{1}{\sigma}} * Q_{o2}}$$

As we assume that the total electricity use over the day stays equal, Pp2 is now a function of Qp2 and a demand curve can be constructed. Po2 is derived in a similar way. Inserting the exemplary figures of table 4 at an initial price of €0,237 and a rather high elasticity of substitution of 0.3 results in a new peak price of €0,37 and a new off-peak price of 0,037. For a low elasticity of 0.1 this would be respectively €0,395 and €0,0004. At those two elasticities, in theory a consumer is assumed to respond very different. However, in reality the peak prices could be seen as both 'expensive' and the off-peak prices as 'very cheap' and 'nearly free'. Irrespective of the elasticity, it is doubtful whether a consumer would behave different facing such low prices,.

TABLE 4 – CES TEST FIGURES

Qp1	750
Qp2	600
Qo1	250
Qo2	400

Making up the balance about all assumptions and the questionable consumer response at very small electricity prices, it is doubtful whether this approach is still giving a good representation of the reality. The theory behind it however creates some useful insights. Changing price ratio's for example always causes a drop in utility, even when the former budget and quantity are similar. Also, ordinary peak demand already causes a large volatility in price.

3.3.2 ELASTICITY OF PEAK DEMAND

Instead of changing peak and off-peak prices to change the quantity, also only the peak price can be increased to decrease the peak demand. This however increases a consumer's expenses on electricity. As explained in the theory, the elasticity of peak demand is similar to the usual own-price elasticity, but only measured during peaks. To calculate the change in welfare, the demand curve has to be constructed. A linear curve is often used to simplify economics, however it is in general not considered as the most approximate reflection of reality. Another option is the demand curve following from the assumption of a constant elasticity. This is neither a very good reflection of reality, however the characteristics are considered more applicable to the situation on this electricity market. The demand curve of a constant price elasticity will be of the form below. When P is price and b and σ are constants, σ will always be the elasticity.

$$Q(P) = b * P^{\sigma}$$

This can easily be proven by the following equations (where Q' is the derivative of Q):

$$Elasticity = Q' * \frac{P}{Q} = \sigma b P^{\sigma-1} * \frac{P}{bP^{\sigma}} = \frac{\sigma b P^{\sigma}}{bP^{\sigma}} = \sigma$$

First, parameter b is calculated using the figures from the initial equilibrium situation.

$$b = \frac{Q_{p1}}{P_{p1}^{\sigma}}$$

Then, the new price can be calculated:

$$P_{p2} = \left(Q_{p2}/b\right)^{1/\sigma}$$

Next, the integral reveals the total change in consumer surplus between P_1 and P_2.

$$\Delta CS = \int_{Pp1}^{Pp2} Q(P) = \frac{b}{1+\sigma} * {P_{p2}}^{1+\sigma} - \frac{b}{1+\sigma} * {P_{p1}}^{1+\sigma}$$

Then, subtracting the total value of the extra fee, results in the deadweight loss.

$$DWL = \Delta CS - \left(P_{p2} - P_{p1}\right) * Q_{p2}$$

The peak elasticity thus allows us to calculate the deadweight loss per PTU during peak hours. Resulting income of the fee are extra profits for the RGO. This is an exchange of welfare, and therefore not considered as a loss. As RGO's are regulated organisations, the extra revenues will probably return in society in a certain way. The 0 change in income of the RGO is thus not met, but in society as a whole it can be seen as a redistribution of welfare.

3.3.3 ANNUAL EFFECTS

The welfare effects over a year are calculated per PTU of 15 minutes by applying the peak-elasticity to the difference between the maximum allowable capacity and the peak demand. This peak demand is predicted by a year-long simulation of the usage of electrical appliances in the 275 households, which is described more extensively in 3.4. Using this data and the formula for the deadweight loss, the following formula for the annual change in deadweight loss is constructed

$$Annual\ deadweight\ Loss = \frac{35040}{34942} * \sum_{i=1}^{34942} \mathrm{DWL_i}$$

with i the index number of the PTU *i*. A compensation is needed since the available data contains only 34942 valid PTU's and the costs should be for a year, containing 35040 PTU's. This formula can be placed at the 'Deadweight loss' box in figure 5, which gives a simplified overview of how the societal costs of the DR option are calculated.

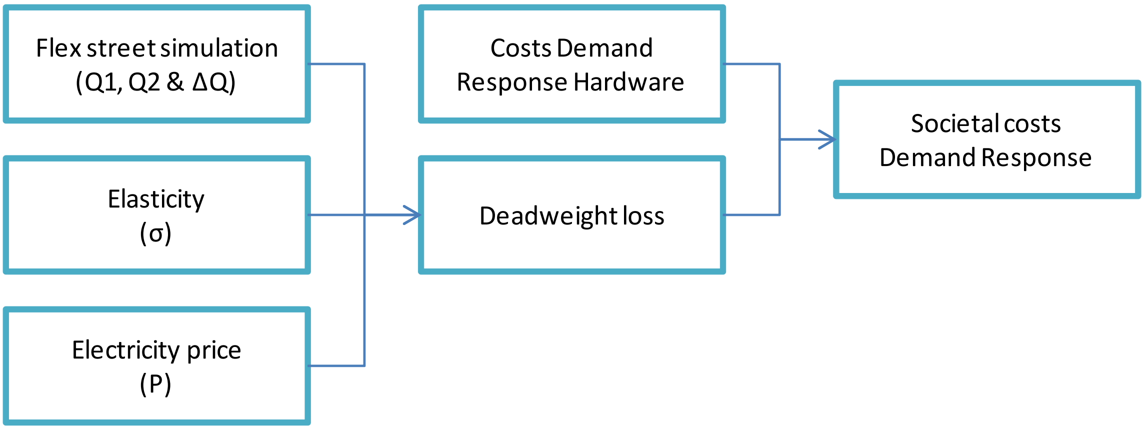


FIGURE 5: CONSTRUCTION OF SOCIETAL COSTS DEMAND RESPONSE

The analysis is done by using the part of the electricity price that varies per kWh as that is equal to the marginal costs for a consumer. This is the price of delivery plus the energy tax of €0.1165 and the VAT of 21%. (See annex 2 for an overview) The price of delivery has been around €0.079 between 2007 and 2013 and this number will be used here (CBS, 2014a). A comparable price of € 0.079 is also used for future energy studies (Koutstaal, et al., 2012). Adding the energy tax on top of the €0.079 and multiplying by 1.21 results in a fixed price of €0.238 per kWh to which a consumer responds. The energy tax deduction on the electricity bill a household connection gets each year is of no importance here since it is a fixed amount per year which does not affect the part to which a consumer will react. This shows what the effect would be in a situation of demand-response to only the capacity for access to the commodity.

3.3.4 APX TREND

Since the 'smart energy' developments also allow for a variable tariff for the consumers linked to the market prices, an estimation of the difference in consequences between the two pricing regimes is done. To simulate a situation where consumers face a tariff corresponding to the commodity price on the market a similar calculation is done using prices following the APX trend instead of a fixed tariff. A trend is used and not the direct APX price because we assume that consumers will not be able to directly purchase from the APX and pay the real price, but have to pay an intermediary organisation for their market access. The fee used is equal to the ratio between the average 2007 APX price of €0.0419 per kWh and the fixed price of €0.079 per kWh. The APX price will be multiplied by this factor to get a price series of every hour in 2007. The year 2007 is used as the Flex Street simulation uses a yearlong measurement of electricity consumption from that year as a base for the variation in electricity consumption (Claessen, 2012). The APX price and the Flex Street uncontrolled demand correlate slightly over the 34942 data points with a coefficient of .2820, having a p-value of 0. The correlation is considered as weak, which is a logical result considering all other variables involved. Furthermore, the p-value indicates this correlation is very significant, since it shows a near 0 probability of getting this correlation by random chance if the true correlation is 0. A special uncontrolled demand pattern using the APX as base is not available. However, due to the low response in demand on price (as explained in 3.5), the difference between the uncontrolled demand with and without the APX as base is expected to be very small.

For the analysis an uncontrolled demand pattern of a situation with a realistic future penetration of major-impact technologies was needed. As 4.1 further elaborates on, plug-in hybrid electric vehicles (PHEV) and heat pumps have the highest impact (Blokhuis, et al., 2011) (Lumig, 2012). The desired demand patterns were found in the simulation data from the moderate scenario of the 'Flex street model' from Claessen (2012). It contains a year-long simulation of a group of 400 houses including solar panels, dishwashers, batteries, PHEV, heat pumps, washing machines and a standard non-controllable load as shown in figure 6. The scenario used from Claessen (2012) is mainly chosen as it contains a 50% penetration of heat pumps and PHEV's. These values are assumed to be the most realistic and useful compared to other scenario's from Claessen 2012 which use either 0 or 100% heat pump penetration and 0, 10 or 90% PHEV penetration. Besides, for these technologies a near 100% percent penetration would be maximum as every household has heating and nearly every household has a car, so 50% can be called a medium penetration. The penetration rates of all technologies are shown in the table below.

TABLE 5: PENETRATION RATES ELECTRIC APPLIANCES

Technology	PV	Batteries	Heat pumps	Washer/ dryers	Dishwasher	Plug-in hybrid electric vehicles
Penetration rates (%)	15	5	50	60	60	50

Figure 6 gives an illustration of the load without any control mechanism to adjust demand to desired levels. The simulation is based on a year-long measurement of a Dutch group of houses in 2007. Therefore also the corresponding APX price of that year is used in the analysis.

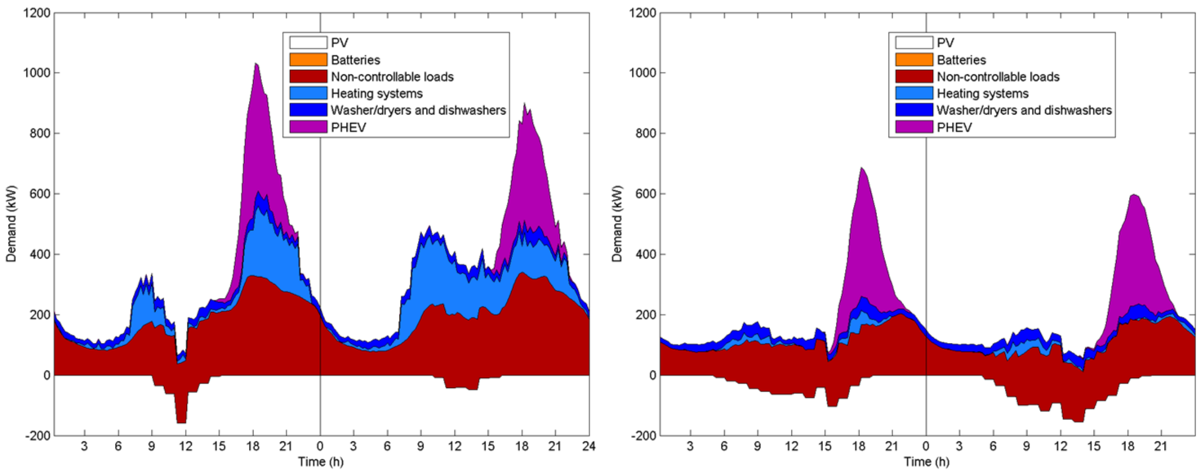


FIGURE 6: BREAKDOWN OF THE ELECTRICITY DEMAND ON A WINTER (LEFT) AND SUMMER (RIGHT) FRIDAY AND SATURDAY FOR THE NON-CONTROLLED MODERATE SCENARIO. (ADAPTED FROM CLAESSEN (2012))

The original data consists of 400 households, but the heat pumps where addressed to the last 200 households. To keep the total distribution of heat pumps at exactly 50% while decreasing the sample to 275 households, the loads of the total sample are divided by 400/275. Table 6 shows the resulting maximum load and amount of capacity-exceeding PTU's per year. The average annual electricity use per household is 5569 kWh. With a kWh price from 3.3.3 and 2013 tax deduction and grid capacity from 2.3, the total electricity bill would be €1192.18. For further information about the model and the simulation we refer to Claessen (2012).

TABLE 6: MODEL PROPERTIES

Annual peak in kVA	764.5
# of PTU's above Max. cap.	3995
% of PTU's above Max. cap.	11.12%

Although the scenario used seems very representative for a general future situation also different future situations are expected with either higher or lower peaks. Lower peaks are most likely in case of a lower penetration of EV's. Also when many consumers own electric cars, the simultaneity of their behavior could already lead to higher prices and thus lower peaks in the case of real-time commodity pricing for consumers. Larger peaks could occur if the simultaneity of use is even higher as in the simulation, or at a higher penetration of large loads as EV's.

To indicate the influence of the differences in the future scenario, the welfare effects are also calculated for a range between a 50% higher and lower peak demand. An elasticity of -0.6 will be used during this comparison, as this is a common value according to the figures in table 1.

3.5 ELASTICITY VALUES

As the price elasticity for electricity depends on many variables an upper and a lower boundary are used to give the range for the expected costs. An educated guess on the most likely value in this range is used for further analysis. In order to obtain well-founded elasticity values, different numbers from multiple studies have been used. These should however be interpreted with the acknowledgement that each experiment has its own consumption patterns influencing the elasticity. Especially in the USA different experiments have been executed. Despite the very different characteristics of the electricity markets over these experiments, in the end consumers will just be able to respond to the variable part of their bill.

The aim of the DR calculations is to give a direction of what the costs could be. Therefore a range of elasticity values is included from a very inelastic -0.1 till a unit-elasticity of -1, leaving space for an insight in what the influence of enabling technologies would be. Looking at values in table 1 we estimate that a value of -0.6 would be likely to use as an educated guess in between.

An important assumption used is that past and predicted future prices will not be included in the elasticity since the change in response to this is very hard to quantify. The effect of this on the total costs due to loss of welfare are expected to be small as there will be situations where the effect is positive and others with a negative influence. This way the sum is reduced. We also assume a very inelastic supply curve of the commodity since we are looking at a small area of only 275 households, not influencing the nationwide electricity market.

All prices used are in 2013 Euro's. As we speak about a future situation, inflation might affect the price in Euro's. We assume this effect is equal for every price given and also the income of the consumer, thus not affecting the purchasing power(Pindyck & Rubinfeld, 2007).

4 RESULTS

4.1 PROBLEMATIC LOAD DEVELOPMENTS

The dimensions of a grid depend on the expected behaviour of the consumers. Grid operators have to make an estimation of the future developments influencing this behaviour. A grid will be designed to cope with the largest expected peak load in its entire economic lifespan. This load depends on the amount of customers and their behaviour, so for both a prediction for over 30 years is made. For 1973 till 2008 the total growth in electricity consumption has been stable at 2.4 % growth per year. However for consumers the grid operators use growth rates between 0.2 and 2% a year (Lumig, 2012). Many grids are dimensioned around 1 kW per household and till recently new grids were often dimensioned at 1.1 to 1.3 kW a household. Now 1.3 kW is taken as lower boundary for the design, already taking some extra future growth into account (Pellis, 2013a).

In their extensive study of the future developments influencing the Dutch grid Rooijers & Leguijt (2010) speak about an inevitable expansion of the grid capacity for all considered scenarios. The technological developments determine the extent to which the expansion is needed. This is not all in the scope of this study, but for an understanding of the expected problems the consequences of some major technological developments will be described in short.

When heat pumps are installed, their peak demand will already be responsible for an increase in peak demand of 2 till 2,5 times compared to the current situation (Rooijers & Leguijt, 2010). Heat pumps have a rather high load with power capacities up to 11 kW when electric heating is included (Vaillant, 2011). Thereby, they show rather high simultaneity, especially after an outage or during a cold winter evening. The new peak capacity can be 9 to 10 times higher as the current peaks with which the grids are designed when the electric heating is included. Without electric heating the peak reduces to a factor 3 to 4 of the current situation. First the transformer will be overloaded, but even the cables will by far not be thick enough when for example all houses at a strand of 10 switch to a heat pump (Oirsouw, 2012) (Rooijers & Leguijt, 2010).

Solar power has a simultaneity value of 1. Especially in areas where households have a lot of roof space compared to the number of people in that area problems in voltage levels are expected. The autonomous demand of around 0.5 kW will be much lower as the production by the solar panels (Au-Yeung, 2013). The remainder of the production will cause a slight increase in voltage when this is put on the grid. Since the voltage levels are steered for grid areas of about 10 km^2 the differences inside that area can become too big and capacity increase of the network is needed.

The daily electricity consumption of an EV will be about 6.3 kWh a day. To load them the connection capacities start at 3.5 kW up to 11 and even 22 kW (EV-BOX, 2013). The standard plug is designed for up to 40 kW, in line with the trend of faster charging. In the worst case simultaneity is close to 1 when all cars are plugged at the beginning of the evening which could result in an additional peak load up to 10 kW per household (Oirsouw, 2012).

Micro CHPs generate both electricity and heat at the same time, so when the heat demand peaks also a peak in electricity production will occur. Their electricity output will be between 1 and 2 kW of which the autonomous demand should be subtracted. Taking simultaneity into account, an increase of the maximum peak by about 0.5 kW is expected (Rooijers & Leguijt, 2010).

The potentially largest effects on the necessary grid capacity occur due heat pumps and EVs. But when these are both successfully adopted, the combination will cause even bigger problems.

Obstacles also occur when looking at the solutions. Increasing the capacity of the grid can be difficult in city hearts where streets have to be opened and where space for new transformers is lacking (Rooijers & Leguijt, 2010).

4.2 CONCEQUENCES FOR THE ELECTRICITY NETWORK

An increase in the installed capacity of appliances at both the demand and production side also increases the chance of reaching the maximum capacity of the network as defined in its weakest component's specifications. Depending on the duration and size of this capacity exceedance there are two situations to distinguish. In the first situation a smaller and short-lasting peak occurs. Since a breakdown of components is often caused by melting parts, the system can handle short peaks if they do not generate too much heat. This of course depends on the time, the size of exceedance and the properties of the weakest component. A disadvantage however is that the warming and cooling of a component will reduce its lifespan, which implies a quicker replacement and thus extra costs. Therefore a reduction in economic lifespan can also be seen as one of the options in this situation. This however is not the focus of this research and is therefore not taken into account.

In the other situation there is an immediate reduction in lifespan to 0 (or just simply a 'breakdown'). It often causes an outage, but also in a situation with a loop-wise construction this will very likely lead to a breakdown on the other side of the ring as this part has to process a lot more power. Therefore other solutions than reducing economic lifespan will be needed. This is investigated next.

Both from literature and interviews different options to prevent an overload on cables arise. Most options come down to an adjustment of the infrastructure which increases the maximum capacity available. There the supply thus increases, but the demand for capacity by either production or consumption of electricity stays the same. However, another approach is lowering this demand itself during peak consumption, also called 'peak shifting'. In the following chapters both directions will be further explored.

4.2.1 INCREASING NETWORK CAPACITY

These options come mainly down to an increase in hardware applications installed by the grid operator. The options prevent the user to have to adjust his behaviour as they secure the supply of sufficient power. Usually the grid operator uses an economic lifespan of 30 years for their investments in extra capacity. Thereby they aim to prevent replacements during this economic lifespan. So the capacity of their new investments will be equal to the maximum expected peak load during this lifespan, which is 764.5 kVA in the Flex Street moderate scenario.

Extra cables

Installing extra cable capacity is a way to increase the capacity. One could expect that the cables will be replaced or extra cables will be laid near the other. However, due to the stochastic characteristics of the necessary capacity, increasing the amount of connections between cables will also result in an increased capacity. It lowers the impact of simultaneity, since the power can flow in multiple directions. In practice, at the Dutch RGO's this impact is often calculated with the Strand-Axelsson equation (Au-Yeung, 2013) (Phase to Phase, 2006). Just closing the loop at the end of two strands [3]in a grid, or connecting them somewhere along the way will result in an increased capacity. Another option is laying an extra cable from a transformer to the middle or end of a strand (Pellis, 2013a). This can be the same transformer or another one, as long as these are connected to the same MV network. The latter has the advantage of spreading the load (and stochastics) between the transformers. In practice this option is not applied at the moment as it has higher short circuit currents and needs more sophisticated safety measures.

Installing extra cables is a costly option. Roughly 80% of the costs are related to the costs for groundwork. Less than 20% is for the cables themselves. Together they come down to about €83,- per m (Pellis, 2013b). The economic lifespan of these investments is 30 years.

Larger transformer

Installing a new transformer is an option most likely to be used since the thickness of the cables often allows for higher power flows as needed during the highest annual peak demand. This is due to the fact that the cables have standard thicknesses and from a precautionary principle they will often be over-dimensioned and thus able to handle more power (Pellis, 2013a) (Au-Yeung, 2013). The costs of replacing an old transformer by a new one of 400 and 630 kVA are respectively about €7800,- and €11.000,- (Pellis, 2013b) (Apel, 2013). For a whole additional 400 kVA unit to be build these costs are about €30.000,-. Also here an economic lifespan of 30 years applies.

Increased voltage

Increasing voltage on the distribution grids will allow for higher powers to be transported over this grid. Each household will then get its own transformer, allowing for 230V. This concept is still in development phase (Au-Yeung, 2013). An amount of 800 V was mentioned in personal communication. Especially in older cables such an option could lead to a quicker breakdown when power leaks trough weak spots in the mantle due to the high voltage (Oirsouw, 2012).

When increasing the voltage over the low and medium voltage grids an increased amount of power can be transported over the same infrastructure. The principle of this solution lies in Ohm's law, which states that the total resistance of a power flow depends on the current trough a cable and its specific resistance. However, due to

Since most household applications are made to work on 230V, an increase of the voltage at the grid they are connected to has the direct implication that a transformer is needed for every household. It is a concept still in research and therefore no real-life results have yet been retrieved. It would however also mean the installation of other MV/LV transformers with a lower conversion factor as before, hence cheaper.

Households with a single phase connection only need a transformer for this single phase, capable of transmitting at least the full connection capacity (often 16 Ampère and thus 3.8 kVA). When multiple phases are used, they will all need the possibility to be transformed to at least the maximum capacity. This increases the costs, however especially in older city hearts where the ordinary solution of opening the streets is expensive households are smaller and probably fewer connections use multiple phases. Despite inquiries at the regarding RGO, no further information was retrieved about the technical details or costs, therefore this option cannot be compared on costs.

[3] Strand: often used term for a cable in the street to which the houses are connected

Micro CHP

A micro Combined Heat and Power plant produces both electricity and heat at the same time. It is fired on methane. When using 10 CHPs of $20kW_e$ / $35kW_{th}$ it would be an alternative compared to replacement of a transformer. A series of these units producing power at strategic points in the grid would be able to keep up the voltages and prevent overload of the transformer. They could be operated on a cost-competitive basis by a third-party where the RGO pays most of the initial investment and the third-party agrees to fulfil demand when shortages appear. The third party will pay for the fuel costs as described in the methodology. In this case the costs are €30.000,- per unit and the economic lifespan is 30 years (Apel, 2013).

Battery

The placement of batteries at strategic places in the grid to fulfil the peak load demand peak is also an often heard option. A constraint to this system is the energy content of the battery pack which should be large enough to supply all electricity in the hours during a peak. Also enough time to recharge is needed afterwards. Therefore a battery is chosen which is able to cope with the largest necessary generation and storage capacity from the simulation of respectively 365 kW and 1281 kWh, calculated from the simulation results for the 100% moderate Flex Street scenario. For the analysis a rather low future price prediction of €160,- per kWh is derived from a promising technology start-up, in line with predictions from Hensley, et al. (2012). The batteries will have an economic lifespan of 30 years (Eos Energy Storage, 2013).

4.2.2 DECREASING PEAK DEMAND

Smart grid investments

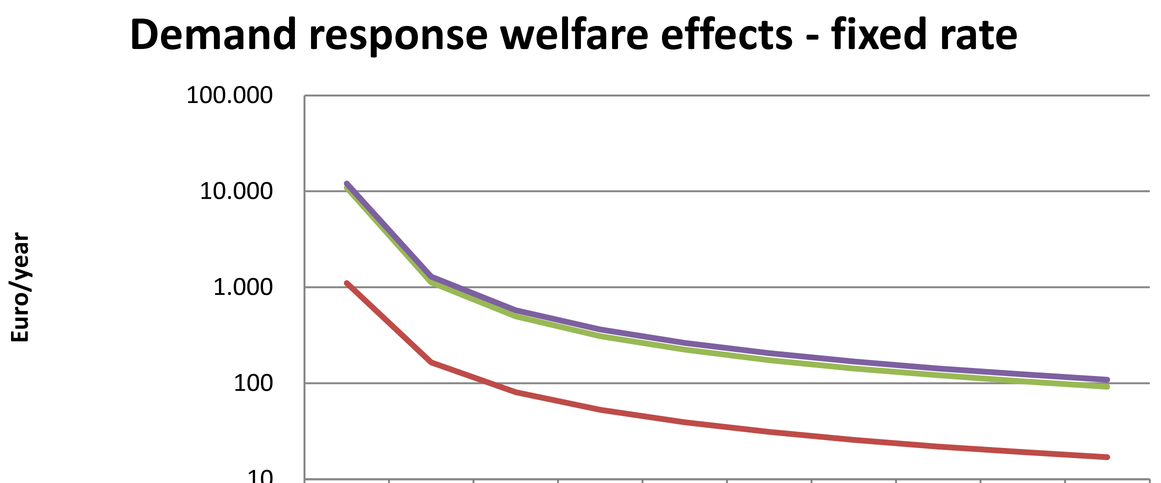
A smart grid is suggested as a promising solution as well, however there are many different configurations of this concept. What they all have in common is that communication technologies and sensors are used. Communication can be done in many ways but there is no dominant design yet. Sensors are needed to make predictions and measurements. It can then be determined whether peak demand occurs and if measures should be taken. The measurements could be done at all customers and then aggregated, or a measurement device can be installed at the transformer. When doing measurements at each consumer, the aggregated amount can be used to determine the transformer performance. Extra calculation steps are necessary when dealing with meshed structures (Oirsouw, 2012).

With the sensors and communication of the measurements a grid operator can act upon a situation of overload by taking measures himself or by incentivising the customers to lower their demand for capacity. The costs of this technology are between €2.000,- and €3.000,- per 400 kVA transformer of which the upper boundary is used for analysis (Apel, 2013). Considering technological learning we assume an additional €100,- for the enabling technology per household. Due to the high rate of technological development and higher complexity of the components, an economical lifespan of 10 years is taken for the DR technology.

Smart grid operation

Besides the direct costs for the technological equipment, welfare effects are also of major importance for a demand response solution. As shown in the methodology, an RTP scheme at which the additional income for a RGO is equal 0, is difficult to apply and brings a lot of uncertainty. Assuming that a RGO aims to minimize its own financial risk and aiming for an easy applicable scheme, the approach is to use RTP for only peak hours. In fact this is rather similar to most Critical Peak Pricing schemes, with the difference of more different rates during the peaks.

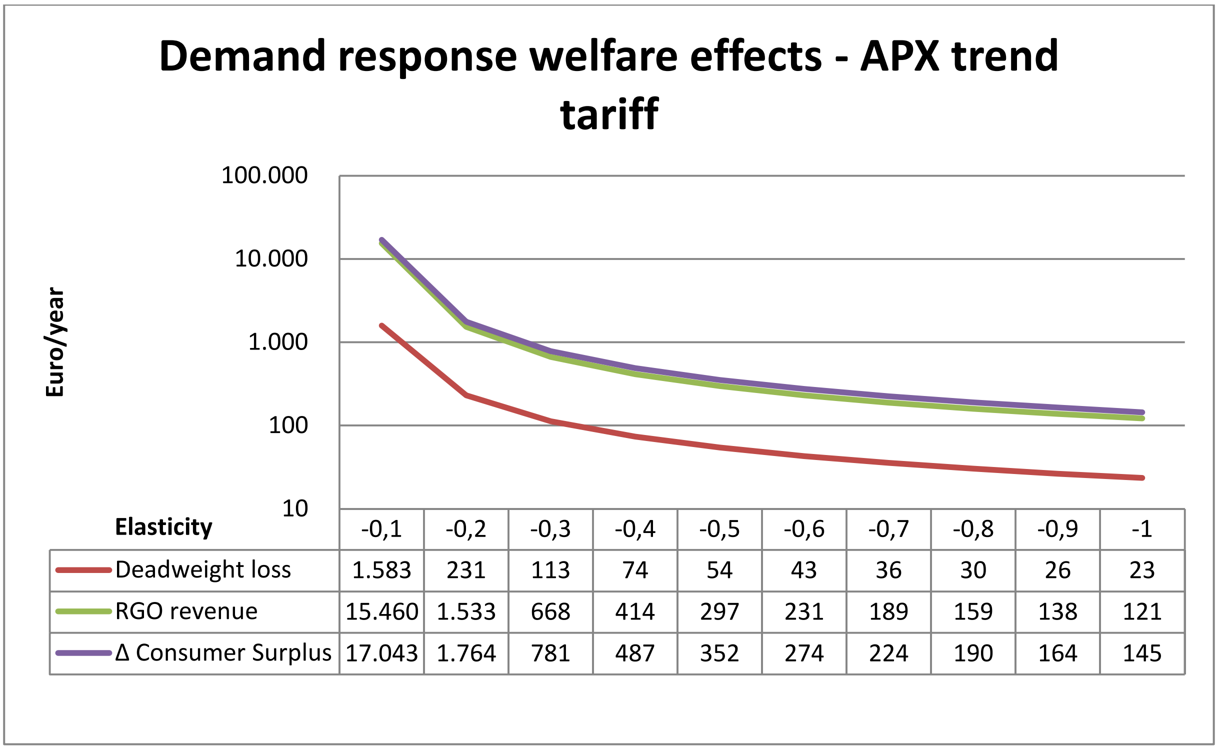
Below, the welfare change due to a financial incentive by demand response is shown in figure 7. The y-axis has a log-scale to also include the results of the lower elasticities. A lower price response increases the deadweight loss and costs for the consumers. At the lowest elasticities, the change in surplus and deadweight loss are extremely high. It is a result of the theoretical approach. However most studies show elasticities around -0.6 and for these figures the welfare effects have plausible values.



Elasticity	-0,1	-0,2	-0,3	-0,4	-0,5	-0,6	-0,7	-0,8	-0,9	-1
Deadweight loss	1.110	165	81	53	39	31	26	22	19	17
RGO revenue	10.912	1.121	496	310	224	174	143	121	105	92
Δ Consumer Surplus	12.022	1.286	577	363	263	205	168	143	124	109

FIGURE 7 – ANNUAL WELFARE EFFECTS OF DR PEAK PRICING PER HOUSEHOLD UNDER A FLAT RATE

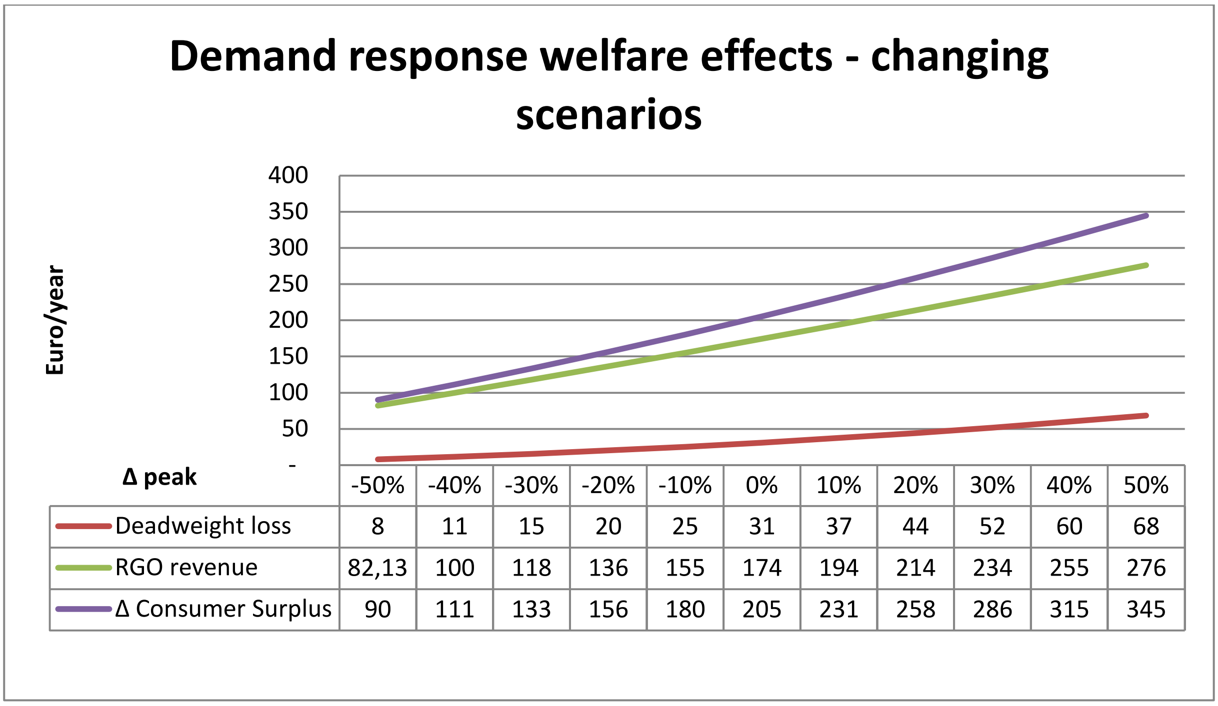
Involving market prices, while keeping the average price constant, leads to an increase of the surplus and the deadweight loss as shown in figure 8. Demand response under variable rates could thus be less attractive as under fixed rates. The influence of different elasticities is rather similar as at a fixed tariff.



Elasticity	-0,1	-0,2	-0,3	-0,4	-0,5	-0,6	-0,7	-0,8	-0,9	-1
Deadweight loss	1.583	231	113	74	54	43	36	30	26	23
RGO revenue	15.460	1.533	668	414	297	231	189	159	138	121
Δ Consumer Surplus	17.043	1.764	781	487	352	274	224	190	164	145

FIGURE 8 - ANNUAL WELFARE EFFECTS OF DR PEAK PRICING PER HOUSEHOLD UNDER A VARIABLE TARIFF

Figure 9 illustrates the effect of a change in peak demand on the welfare for a fixed rate and a peak elasticity of -0,6. 0% is equal to the original scenario. The other percentages reflect the in- or decrease of the original excess of the demand. As one could expect, welfare effects increase with an increasing peak.



Δ peak	-50%	-40%	-30%	-20%	-10%	0%	10%	20%	30%	40%	50%
Deadweight loss	8	11	15	20	25	31	37	44	52	60	68
RGO revenue	82,13	100	118	136	155	174	194	214	234	255	276
Δ Consumer Surplus	90	111	133	156	180	205	231	258	286	315	345

FIGURE 9: CHANGE IN WELFARE BY CHANGE IN PEAK PERHOUSEHOLD AT ELASTICITY -0.6

Influence on the supply side

Effects on the supply side are more difficult to quantify. In general, a forced decrease in demand would decrease the amount of operational units within the merit order and therefore decrease the market price. Increasing demand would have the reverse effect. However, the merit order has a steeper slope at large market volumes during peak hours than during off-peak hours with small market volumes. Therefore the average market price will drop when peak demand is substituted by the same amount of off-peak demand.

An other effect is that when the average market price drops, also the fixed price consumers pay will drop and decrease the necessary price increase by the RGO. These two prices thus influence each other. The resulting changes are not taken into account as they are assumed to be of minor importance for the outcome of this research.

When consumers still pay their fixed commodity price, profits for electricity suppliers would go up. Due to competition, the average fixed prices will drop, again affecting the necessary price change by the RGO; thus influencing each other. Furthermore, when peak use and restrictions correlates at large scale, the volatility of demand decreases. As an effect, cheaper electricity production can take place.

4.2.3 FINAL COMPARISON OF OPTIONS

Table 7 shows the final costs of all options per household per year compared for different peaks, with 100% being the reference case. Besides of the original sources, the input data has also been reviewed by an expert from a RGO (Bongaerts, 2013). Only cells representing a combination of an option with a peak percentage containing a value are considered as possible solutions to the respective peak. When installing an additional transformer new cables are necessary for the connections, but also when replacing the transformer by a larger one also new cables are necessary to deal with the high peaks. Therefore the option 'Cable & transformer' adds those costs together. Although cables have an economic lifespan of 30 years, practice shows that many are much older. It would be questionable if other options could get an extended lifespan after their economic lifespan as well. This can also be seen as additional value. An other advantage is that creating extra capacity by heavier components like the cables also creates a kind of guarantee for the availability of capacity for a certain price over 30 years. For a DR solution the figures will vary from year to year depending on consumption patterns and trends.

The CHP is a relatively expensive solution compared to the others. A battery is a lot cheaper, however it is still more expensive than grid reinforcements. Nevertheless there is potential for actual application. The costs for grid reinforcements differ per situation and the figures used can have a large variation, which could approach the costs of a battery.

The smart grid costs are equal to the investment costs of a smart grid plus the variable expenditures for the incentivising fee by the RGO. The investment costs are very low compared to the alternatives, however the societal impact is a lot higher. The annual electricity expenses of a consumer are approximately €1192,18 for an average of 5569 kWh as shown in 3.4. Compared to this figure, the additional expenses of a consumer (or additional RGO revenues) in the major DR scenario are about 15%. The deadweight loss is in the order of 3 %.

It could be questioned where all the money should go to, as the grid operators will have a large revenue stream. As RGOs are regulated, it is very likely that regulation will require this money to be returned in society, e.g. by decreasing a tax. When people are compensated by such a tax reduction in other goods, there might be a chance that society will accept a change in their electricity bill.

In a real situation the costs of the same option to solve a capacity issue of a similar size will differ per situation. Therefore the range of expected peaks is included. Although the options are all based on different assumptions, this study gives at least a good order of magnitude of the differences. One of the major assumptions is the elasticity of the DR, therefore the deadweight loss for other elasticities and a higher and lower expected peak can be found in annex 3. Similar to figure 7 and 9, deadweight loss increases a lot at low elasticities and even more at high peaks.

Rising electricity prices will change the figures somewhat, but are not expected to change the preferred outcome a lot due to the large differences between the options.

The influence of the interest on a preference is expected to be small. The rate can be higher or lower than 5%. However, changing the annuity interest to 2% or to 8% will result in a relative change of – 19% and +19% of the 30 year annuity's compared to the 10 year annuity figures. This does not change the order of preference for a certain alternative.

TABLE 7: ALL OPTIONS COMPARED ON AN ANNUAL COST BASIS USING A PEAK ELASTICITY OF -0.6

Option	Size	Unit	Investment costs	Economic lifespan	Annuity per house	Peak 50%	Peak 100%	Peak 150%	Source
New transformer	400	kVA	€ 7.800	30	€ 1,85				(Pellis, 2013)
New transformer	630	kVA	€ 11.100	30	€ 2,63	€ 2,63			(Apel, 2013)
Additional transformer	400	kVA	€ 30.000	30	€ 7,10		€ 7,10		(Rooijers & L
Additional transformer	600	kVA	€ 33.300	30	€ 7,88			€ 7,88	
Extra cable	300	m	€ 24.900	30	€ 5,89	€ 5,89			(Pellis, 2013)
Extra cable	1000	m	€ 83.000	30	€ 19,63		€ 19,63		(Pellis, 2013)
Extra cable	2000	m	€ 166.000	30	€ 39,27			€ 39,27	
Cable & transformer						**€ 8,52**	**€ 26,73**	**€ 47,14**	
CHP	**20**	**kW**	**€ 30.000**	**30**	**€ 7,10**	**€ 63,87**	**€ 127,74**	**€ 191,61**	(Apel, 2013)
Battery	**1281**	**kWh**	**€ 204.960**	**30**	**€ 48,48**	**€ 24,24**	**€ 48,48**	**€ 72,73**	(Eos, 2013)
Smart grid transformer			€ 3.000	10	€ 1,41	€ 1,41	€ 1,41	€ 1,41	(Apel, 2013)
Smart grid device consumer			€ 100	10	€ 12,95	€ 12,95	€ 12,95	€ 12,95	
Smart grid direct costs						**€ 14,36**	**€ 14,36**	**€ 14,36**	
Smart grid Δ consumer surplus						€ -90,08	€ -205,41	€ -344,52	
Smart grid revenue RGO						€ 82,13	€ 174,37	€ 276,11	
Smart grid dead weight loss						**€ 7,94**	**€ 31,04**	**€ 68,40**	

5 DISCUSSION

5.1 METHOD

The methodology used for the calculation of the costs for DR aims to put a realistic price on the available electricity within a constraint part of the electricity grid by using observed consumer responses (elasticities). Literature shows that elasticities increase with time. Furthermore, the elasticities in a future situation with enabling technologies and relatively easy switchable large loads as EV's and heat pumps are expected to be larger than the elasticities from the literature, often based on current technology. The used values have a range from -0.1 till a maximum value of -1 with -0.6 as the best estimate for the short term peak elasticity. If the elasticity turns out to be a lot larger, then the results are quicker in the advantage of demand response.

Elasticity of substitution connects the peak and off-peak prices and demands and therefore it seems a very appropriate measure to use. However it is difficult to apply as it is unknown which demand is replaced to which other period and many assumptions have to be made for it's application. The elasticity is more suitable for a situation of only two periods.

As the simulation data contained only 364 days for the most appliances and some outliers in the last two quarters, during analysis these are not taken into account, but the results are extrapolated to the value for a full year by multiplying by 35040/34942, as 35040 is equal to the amount of quarters in a full year of 365 days. Also at the very start an outlier in the load of the dish washer was found and therefore deleted.

One might argue that volatility at the electricity markets will go up due to a higher share of renewables (GEN, 2013). In that case the 2007 market data might not be representative. On the other hand, demand response on the commodity markets could decrease volatility and therefore we argue that the 2007 APX prices might indeed be a good reference for future market behaviour.

The APX prices were per hour, while the simulation has been done per quarter. All quarters in the same hour where given the same APX price instead of unique quarterly prices. Consequential positive and negative deviations in costs are likely to cancel each other out. However, it could have had a negative influence on the correlation. Furthermore the value of hour 2016 was missing and therefore the average value between the former and latter hour was taken. Compared to the amount of data points this will not be of influence on the results.

The analysis with the elasticity is based on the price per kWh of electricity. Since we speak about a future situation there is a big change of changing prices. The tax regimes for electricity might change and the feed-in of renewable could lower the average market price due to a shift down the merit order of generation capacity (GEN, 2013). That of course also largely influences the outcome of the analysis with the elasticities.

For none of the options the costs O&M is included. While there might be some differences between technologies, it is expected that in the end it will stay in the range of a couple of euro's per household per year to add per option. That will not result in big differences in the preference of an option.

The downscaling of the simulation data from 400 to 275 households gives a more average result of the change in surplus, but this will probably be a bit lower due to decreasing relative peaks by larger samples when dealing with stochastic behaviour. Therefore all necessary capacities will be a bit higher. For the analysis this only influences the costs of the battery system directly. For other systems this small change will not impact the costs of the option.

When decreasing the amount of electricity in one peak-PTU, other peak-PTU's can be seen as substitutes and therefore they could face a higher demand as predicted by the un-controlled Flex Street model. The method used does not account for these effects. However, the physical components of the grid can withstand higher power as their guaranteed capacity. Therefore the resulting incentive from this method would in a real situation probably also be sufficient.

This study is based on a set of technologies with certain penetration rates. For PV, PHEV and heat pumps the penetration rates are rather high compared to the current situation. It is not very likely that the exact scenario, with the same penetration rates, will occur. However it is much more probable that future demand curve will take similar shapes and then results are comparable. Economic calculations are not directly based on technologies, but on the resulting demand. To make the results more robust for different shaped demand curves, a range between 50% higher and lower peak demand is included. This also gives insight in the period before and after the main scenario.

The welfare effects calculated here are only representative for a consumer. Producers however also experience welfare effects. The supply curve, reflected by the merit order is for the rather flat compared to the demand curve, except for peak hours. Shifting peaks is the major aim of the applied DR system, so when this happens on a large scale with a high degree of simultaneity, there could be a significant welfare effect on the producer's side. The other way around, prices increase during peaks and when consumers face similar changes in rate, they could already have an incentive to lower their peak electricity use. As a result, the price increase by the RGO will be lower, also decreasing the welfare effects in society.

5.2 RESULTS

Smart energy systems are in a conceptual phase in The Netherlands. It is not yet clear what the dominant design will look like, how the social acceptance will be and whether the amount of participating consumers will be enough to really make a difference. Due to those uncertainties we do not know yet where we are going, but due to this study we have a better sense what additional welfare effects it will cause. How to bring these welfare effects - which mainly depend on consumer preferences - down would be a recommendation for further research.

Elasticity

As mentioned in the theory section, the elasticity is under influence of a lot of variables. One could even determine the elasticity per appliance and these elasticities are expected to differ: a consumer will value heating a cup of coffee probably higher than heating the house using the same amount of electricity in kWh. It is therefore recommended to do further research in how elasticities differ due to variables and among appliances using self-deciding systems which react according to user preferences as this is a common future vision of demand-response.

Enabling devices

In the study of Neenan and Eom (2007) about three quarters of the demand response was attributable to one quarter of the participants. This underpins that the elasticity also differs per consumer and raises the question about the distribution of welfare effects amongst different consumers. This is an important aspect of research before implementing a DR system. Reasons for the differences in response can be explained by the different utility of money per consumer and different abilities to shift demand due to work, sports and other occupations. An enabling device is therefore expected to increase the amount of participants attributing to the major part of the demand response, lowering the financial incentive in the results of this report.

Cables

As every part of the grid differs in amount of connections, sort of loads, dimensions and more, the used distances for the cables can differ a lot. The corresponding values can thus be seen as rough "guestimates". When better data is available, it can be used to compare to other options.

Legal issues

Aside from tax, in theory the commodity price and the transportation fee together determine the total electricity price. These however originate from two different markets. Given the fact that the commodity price is decided on a national level, solving local problems on distribution level by a financial incentive then asks for a local transportation price. There a problem arises as these local prices for transport will result in discrimination in price between different areas, which is currently against the law.

Rational behaviour

Looking at the switching behaviour of consumers, there is a big reluctance in switching to another supplier for getting a much lower bill. Although reasons like distrust for other suppliers also play a role, it is still questionable if it is not the incentive that is not big enough to overcome the burden of hassle when switching.

Influence of commodity markets

At first sight the change in welfare could be completely contributed to the scarcity in distribution capacity. In a situation of fixed kWh prices this will be true, however when consumers are able to respond to the market prices they will already have an incentive to reduce demand as the simultaneity of demand will cause scarcity at the electricity market which will lead to higher prices. In that situation the change in welfare of the original calculation includes both an influence of the transport scarcity and the scarcity of supply. The sensitivity analysis about reducing smaller peaks cannot be used to describe this effect since the rise in commodity price is not taken into account in these calculations. However it can be seen as a lower boundary for an equal drop in peaks due to higher commodity prices.

Influence of generation constraints

One could doubt the occurrence of huge peaks in demand due to heat pumps or EV's since the generation capacity in the Netherlands will likely not be able to cope with this at a large scale. Neither neighbouring countries could help out since they would probably face the same simultaneity peaks. Consequentially, due to this constraint incentives to prevent peaks could be expected. The drop in consumer surplus and utility then still holds, but should be split into a term for generation constraints and one for the transport constraints.

Tariff structure

Looking at the current tariff structure, the incentive for a consumer to adjust his behaviour according to differences at the electricity market is largely reduced by the big share of fixed tax of 59% upon the variable part. It could possibly partly explain the small difference between the analysis with the fixed and the variable tariff. Further research into the influence of different tariff structures is therefore recommended when aiming at the implementation of a DR system.

6 CONCLUSION

Considering future load developments at distribution grids, mainly peaks in demand due to simultaneity in use of heat pumps and electric vehicles may lead to capacity shortages of the cables and transformers. Using a simulated penetration of 50% for both of these technologies for an average area of 275 households under one 400 kVA transformer leads to a transformer capacity deficit of 364.5 kVA.

In search of ways to cope with the peaks causing this exceedance, only as little as 4 realistic options were found. Grid reinforcements can be done by cable- and transformer investments, installation of a local CHP or the use of a battery. An alternative is to decrease the demand by demand response.

Comparing different options to increase grid capacity with the demand response concept reveals that the costs for the additional equipment of setting up a DR system are low, but the extra fee on top of the electricity price makes this option more costly to the consumer. A peak elasticity of -0.6 is representative for electricity, meaning that a 1% price increase will lead to a 0.6% decrease in demand. The fixed costs for a consumer are €14.36 and the deadweight loss is €31.04. The fee consumers pay to the RGO is even higher with€174.37, but the impact is lower as it could lead to cost savings at other public expenses of a consumer. RGO's are regulated and therefore it is likely that additional profits will (in)directly be returned to society.

The results are sensitive for the value of the elasticity. In literature a range between -0.28 and -0.84 is found. Although the higher elasticities are more likely, demand response can become an expensive option for the consumer when elasticities appear to be low in reality. This increases the risk associated with implementing DR. Furthermore, the true consumer response to price changes in the future is very hard to quantify.

In the most responsive case calculated using an elasticity of -1 at the original peak, the impact on the consumer is not that high anymore with a deadweight loss of €16.93 and an extra payment of €92.20. As can be seen in table 8 this is always more advantageous as the CHP costing near €127.74 per year. As the next option, a battery system costs about € 48.48 a year. These two options are unlikely to be used as the replacement of cables will almost always be cheaper at €26.73 a year. Considering the other advantages, it is not only a very cost-effective option, but it also a risk averse, long-term option with a very large technical lifespan.

Grid reinforcement with heavier cables and transformers will be even more advantageous in the situation where grid replacement has to take place anyway due to bad conditions of the cable. 80% of the costs are for opening the street.

The hypothesis that demand response systems using financial incentives would be beneficial for the society as a whole is only true in the case of low peaks or high elasticities. Currently other options are often preferred. This is only valid for a distribution grid level as costs for higher-level system investments are not taken into account.

Considering the difference between the total costs during a fixed tariff and a variable tariff based on the APX, the influence of consumers participating in short term electricity markets could increase welfare effects by roughly 30%. On the other side, simultaneity of behaviour would increase the market price, decreasing demand and resulting in a lower fee by the RGO. The influence of variable tariffs for consumers is therefore not likely to have a large influence on the welfare effects.

Households pay a high fixed amount (59.6%) of energy tax, which decreases the impact of a variation in the commodity price on their kWh price. It could be a reason to reconsider the current tax regime. This large share of tax also means that the difference could be higher for more energy intensive customers of the distribution grid like SME's as a larger part of their tax depends on the commodity price.

This research has tried to provide a different way to take investment decisions in the social-economic context of smart energy systems by taking a valuation for adjustment in behaviour into account. It gave an insight in the possible negative effects of demand response and in that sense it contradicts other smart-grid studies. Till now the deadweight loss and utility seem underexposed externalities of the data presented about smart grid concepts.

TABLE 8: ANNUAL COSTS PER OPTION

Option	Peak					
		50%		100%		150%
Cable & transformer	€	8.52	**€**	**26.73**	€	47.14
CHP	€	63.87	**€**	**127.74**	€	191.61
Battery	€	24.24	**€**	**48.48**	€	72.73
Smart grid direct costs	€	14.36	**€**	**14.36**	€	14.36
Smart grid dead weight loss	€	82.13	**€**	**174.37**	€	276.11

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ANNEX

1. ELECTRICITY PRICE

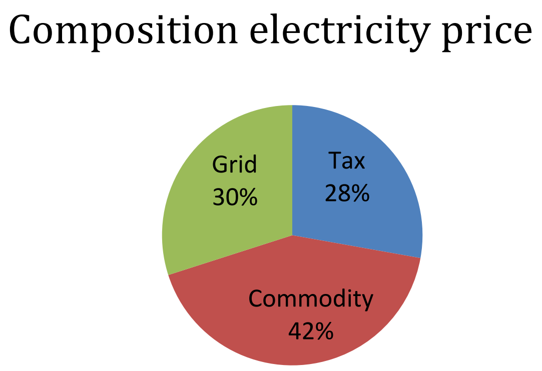

FIGURE 10 AVERAGE ELECTRICITY PRICE HOUSEHOLDS 2.5 - 5 MWH/YEAR IN 2012 (CBS, 2013D)

2. ELECTRICITY TAX

Electricity per kWh	2013, excl. VAT
0 - 10.000	€ 0.1156
10.001 - 50.000	€ 0.0424
50.001 - 10 mln	€ 0.0113
> 10 mln non-commercial	€ 0.0010
> 10 mln commercial	€ 0.0005

TABLE 9 ENERGY TAX (RIJKSOVERHEID, 2013B)

Sustainable energy fee 2013	€ 0.0011

TABLE 10 SUSTAINABLE ENERGY FEE (RIJKSOVERHEID, 2013B)

Energy tax deduction household 2013	€ 318.62

TABLE 11 TAX DEDUCTANCE (RIJKSOVERHEID, 2013B)

VAT	21%

TABLE 12 VAT (RIJKSOVERHEID, 2013A)

3. DEADWEIGHT LOSS FOR DIFFERENT SCENARIOS

Change in peak	Elasticity: -0.2	-0.4	-0.6	-0.8	-1
-50%	€ 31.77	€ 12.75	€ 7.94	€ 5.77	€ 4.53
0	€ 164.91	€ 52.91	€ 31.04	€ 21.92	€ 16.93
+50%	€ 478.75	€ 123.13	€ 68.40	€ 47.14	€ 35.91

TABLE 13: ANNUAL DEADWEIGHT LOSS IN € PER HOUSEHOLD FOR DIFFERENT LOADS AND ELASTICITIES