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REVIEW PAPER

Review of barriers to the introduction of residential demand response: a case study in the Netherlands

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SUMMARY

Demand response, defined as the shifting of electricity demand, is generally believed to have value both for the grid and for the market: by matching demand more closely to supply, consumers could profit from lower prices, while in a smart grid environment, more renewable electricity can be used and less grid capacity may be needed. However, the introduction of residential demand response programmes to support the development of smart grids that includes renewable generation is hampered by a number of barriers. This paper reviews these barriers and categorises them for different demand programmes and market players. The case study for the Netherlands shows that barriers can be country specific. Two types of demand response programmes have been identified as being the most promising options for households in smart grids: price-based demand response and direct load control, while they may not be beneficial for market players or distribution system operators. © 2016 The Authors. *International Journal of Energy Research* Published by John Wiley & Sons Ltd.

KEY WORDS

demand response; load shifting; renewables integration; barriers; smart grids

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1. INTRODUCTION

The growth of renewable power generation has been strong in recent years: since 2006, the pace accelerated to 5.5% per year [1]. In order to reach the goal set by the European Union (EU) of 20% of renewable energy in 2020 [2] and at least 27% in 2030 [3], this growth has to continue and some challenges regarding renewable electricity must be resolved. Besides high costs, the main barrier to large-scale implementation of renewable electricity from sources such as wind and solar energy is the variability of these sources, which poses challenges for integration in the grid [4]. In the current electricity system, supply follows demand: electricity is produced by utilities and distributed by network companies when users need it using centralised usually fossil-fuel-based power plants. As the generation of electricity by wind turbines and photovoltaic (PV) systems depends on the weather, supply is variable and difficult to control, which may lead to imbalances in the electricity system. The variations in production and risk of imbalance between supply and demand lead to fluctuating electricity prices, which sometimes become even negative [5], and to higher costs to the system. Because demand and supply of electricity have to be balanced at all times, variation of the electricity price over the day may create an incentive for producers and consumers of electricity to either adapt production or demand to changing circumstances. Dynamic network tariffs have been introduced already in the 1930s to address peak-load issues [6].

A significant part of the growth of renewable energy can be attributed to local electricity production, such as PV energy at households [7]. This adds a second challenge to the system: historically, electricity is produced in a centralised way and transported to households via the high-voltage, medium-voltage and low-voltage transmissions systems. Nowadays, a large share of renewable electricity, including wind and solar PV energy, is produced locally and directly inserted in the low-voltage distribution system [8]. Large electricity peaks are created on the grid when large amounts of PV systems are installed in a district, especially in the summer. In addition, the increased deployment of electric vehicles (EVs) and heat pumps by households leads to a higher electricity demand, especially in winter [9]. The use of electricity for transport and heating is part of 'the electrification of everything' [10] and will lead to much higher electricity peaks on the network. Smart energy management including accurate forecasting of supply and demand is necessary to support the development of decentralised power generation in smart grid environments [11–16].

The combined increase in local electricity production and higher electricity demand could force large investments in distribution networks to create additional grid capacity [17]. Because these developments mainly take place at households, this problem is especially relevant for the residential sector and less for the commercial or industry sector. Electricity storage could solve both problems, as a storage device such as a battery could either supply or take up electricity and thereby balance demand and supply and reduce peaks, but present high cost prohibits this [18].

Another solution would be to let demand follow supply, which is termed 'demand response'. In general, it supplies consumers 'with control signals and/or financial incentives to lower or adjust their consumption at strategic times' [19], meaning that consumers are encouraged to either increase or decrease their electricity demand, depending on whether there is an abundance or shortage of electricity, respectively. Demand response programmes can reduce fluctuations in electricity flows and price and thereby reduce costs for the system as a whole. Concomitantly, through the reduction of the peaks in electricity demand, demand response programmes can reduce electricity peaks in the (distribution) grid, which leads to lowering the risk for overloading the network. Also, because the electricity peak in the grid determines the maximum capacity of the electricity grid, a lower peak could mean that a lower grid capacity is needed. If the needed maximum capacity of the network is kept lower, investments by distribution system operators (DSOs) to enlarge the capacity by the owners and operators of the grid can be deferred. Hence, demand response can be beneficial to electricity producers, DSOs and consumers, because it stabilises and lowers prices.

Model studies in smart grid environments show different results for the ability of demand response programmes to reduce the demand peak: peak reduction has been estimated to be 5% [20] and 20% [21] and for some local areas even between 35% and 67% [22]. Real-life cases show similar varying outcomes: sometimes the reduction is between 3% and 6% [23], 10–14% [24] and 35% [25], and in some cases, it can be as high as 50% [26]. The decrease depends strongly on the chosen programme [27].

Demand response programmes in residential areas have been offered in the USA to hundreds of thousands of consumers [28,29]. In the Netherlands, development of demand response directed to consumers is lagging behind compared to that in the USA, while day and night tariffs existed since the 1960s, which was meant to shift day loads to the night in order to leave coal-fired power plants running. Some experimental tariff systems have been tested in practice, even some already in the 1980s related to wind power [30], but were never adopted [31]. In some of the smart grid field experiments in which Dutch network companies, energy suppliers and information technology companies work together to advance the development of smart grids, demand response is tested. Only limited research has been carried out so far to identify potential barriers for demand response introduction in residential areas in the context of smart grid development.

An overview of some categories of barriers specific to the United States has been reported [32,33]. Research has been performed on barriers to demand response in Europe as well, but only on programmes organised by aggregators, and those studies either have a European perspective [34] or focus on other European countries [35] or only give a short situation overview [19]. An in-depth analysis of what obstructs the introduction of demand response programmes is lacking.

In this paper, we thus add to the present state-of-the-art in that we perform an in-depth analysis of the barriers to the introduction of demand response programmes in support of smart grid development in residential areas. Identification and review of the barriers is carried out in an original way: we formulate the barriers as hypotheses, and a distinction is made for different demand response types and stakeholders. First, a thorough document review has been performed to identify a global overview. Second, these barriers have been discussed with Dutch experts from the energy sector, linking them to the situation in the Netherlands.

Note that different stakeholders may conceive barriers in a different way. In fact, a barrier for one stakeholder may be beneficial for another. Rather than identifying barriers as arguments against introduction of demand response to accommodate smart grids, one could argue that social acceptance [36] is crucial, especially considering the 'problem' that demand response should solve, namely variability in supply and demand by decentralised power generation and consumption from systems owned by consumers. In fact, consumers are becoming 'prosumers' (producing consumers) of electricity, and they can respond at will to the surplus of electricity generated, perhaps focusing on direct use of PV power to increase their self-consumption, which will become economically interesting with decreasing feed-in tariffs or abolishment of net metering.

This paper is further organised as follows. Section 2 provides an overview of demand response programmes, while Section 3 describes the barriers found in more detail, and hypotheses are formulated. Section 4 presents results, which are discussed in Section 5. Section 6 closes the paper by drawing conclusions. Recommendations are formulated as well, such that a faster development of demand response in smart grid environments for households can be realised, in particular in the Netherlands.

2. DEMAND RESPONSE PROGRAMME OVERVIEW

2.1. Categories of demand response

Many demand response programmes have been described in literature. In order to create an overview, a categorisation method is needed. Even though multiple classifications have been proposed [37–42], the categorisation of demand response by the US Department of Energy [43] is the most widely used. It makes a distinction between tariff options and programme options, where the former is also described as price-based demand response and the latter as incentive-based demand response [43]. Based on this classification, shown in Figure 1, an overview of demand response programmes is given in the following, including some information from model studies and real-world experiments about their performance. A further subdivision is shown as well, which will be discussed in subsections that follow.

2.2. Price-based demand response

Price-based demand response includes dynamic pricing programmes, in which the price of electricity is not fixed but varies in time. The most important options are time-of-use (TOU) rates, critical peak pricing (CPP) and real-time pricing (RTP) [43]. These programmes all have the same goal: to reduce electricity use during certain periods. This is performed by setting a higher-than-normal price during these periods. In a centralised electricity supply system, TOU pricing has been introduced to increase overall demand at certain low-demand times (e.g. to let electric water heaters run at night) to create higher base load, and not to reduce peak demand.

2.2.1. Time of use

Time-of-use rates work by dividing a day in multiple periods and making the electricity price different for each period. In periods in which electricity demand is high, prices are set higher than normal. In periods in which demand is low, the electricity price is set lower than normal. This creates a financial incentive for consumers to shift their electricity use from a period with a high demand (and therefore high price) to a period with a low demand (and therefore low price). An example of TOU rates is given in Figure 2.

Time-of-use rates are the most widely applied demand response method. In the USA, over two million customers had TOU rates [39,44]. The majority of customers enrolled have been offered TOU rates as a default option, while the opt-out rates are low [28]. TOU rates are also offered to consumers in other countries, ranging from China to many European countries including France, Italy, Spain and the UK [34,45,46]. In the Netherlands, the widely used option to have a separate electricity price for the day and the night (albeit with minimal price difference of about 0.01 €/kWh) is a price-based demand response measure.

The results of implementing TOU rates vary. Model experiments show a decrease in peak use from 50% to 7.6%, without benefits to consumers: instead, the cost for consumers increased [41,42]. This is caused both by higher (average) prices and by a larger electricity use. The latter is induced by the lower tariffs during the off-peak period. The effect of demand response programmes

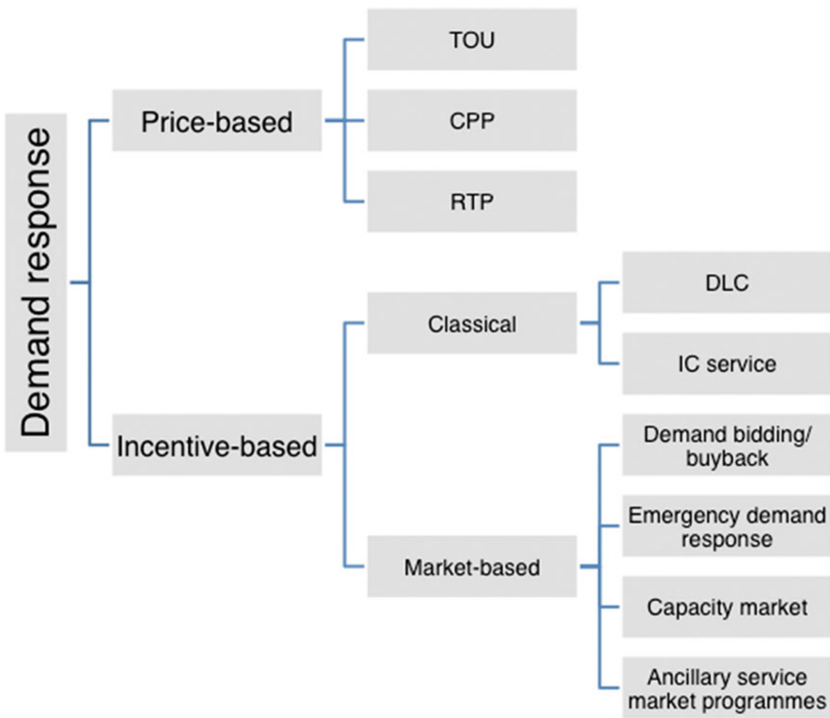

Figure 1. Overview of two categories of demand response and further classification (based on [40,43]). [Colour figure can be viewed at wileyonlinelibrary.com]

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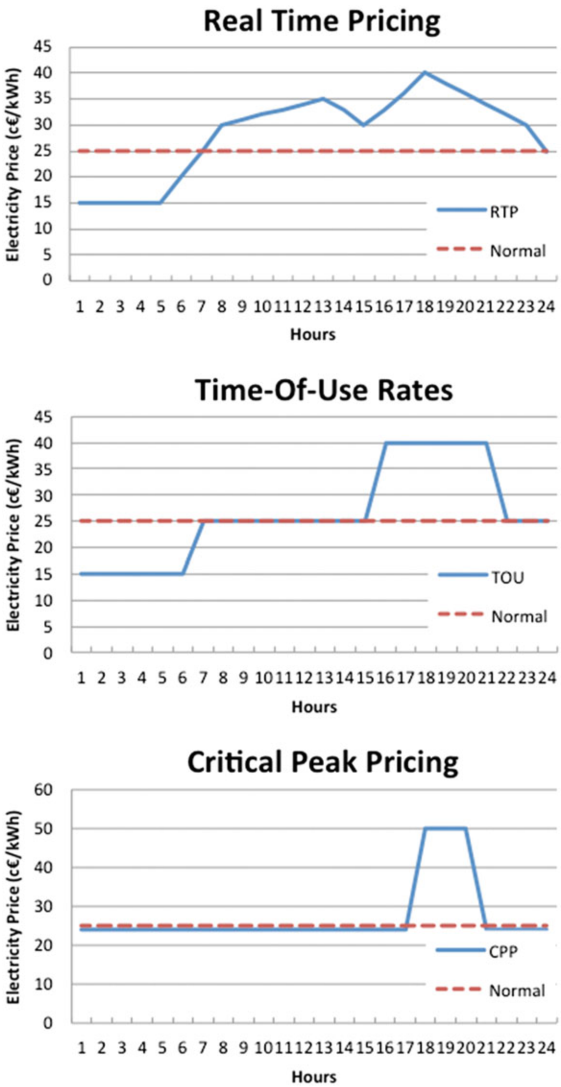

Figure 2. Price-based demand response examples: price in eurocents per kilowatt-hour per day. [Colour figure can be viewed at wileyonlinelibrary.com]

on total electricity use is uncertain regarding its overall energy savings potential [46]. Furthermore, the outcomes of these models are very dependent on price responsiveness, that is, the reaction of consumers to the higher or lower prices. This includes both *price elasticity* (the change in electricity use due to changes in the electricity price) and *substitution elasticity* (the shifting of use to a different period) [47]. The price responsiveness of consumers to variable electricity prices also differs on the time horizon: for example, in the long run, users can improve their responsiveness with automation of appliances [48]. It furthermore varies per consumer class and region [38]. For all price-based demand response programmes, price elasticity is an important parameter. However, its real value is not only not constant and very dependable on other factors but also unknown. Earlier research showed values ranging from −0.05 to −1.1, meaning a 10% increase of price can lead to a decrease of the electricity use between 0.5% and 11% [49]. Experiments in the real world showed TOU rates leading to a reduction in peak use of 3% to 6% [50].

2.2.2. Critical peak pricing

Critical peak pricing works by raising the price of electricity strongly during certain peak periods with an intended effect to reduce demand. These events are not known beforehand: in most programmes, these periods are communicated to the users shortly in advance. However, the duration and (maximum) number of these periods are determined in advance and known to the end user [26]. Users are compensated for the temporary higher tariffs by offering them a lower base tariff. An example of CPP is given in Figure 2. It is stated that CPP is the most suited pricing method to reduce peaks [26].

Model outcomes depend strongly on the chosen price responsiveness, but real experiments have proven CPP is far more efficient than TOU rates in reducing peak demand. However, the exact amount of reduction varies greatly, ranging from 13% to 20% without automation and of at least 30% with automation [50,51]. Even values of 50% have been reported in practice [26]. But it should be noted that peak reduction obviously happens only during the peak periods, while TOU rates reduce the peak every day [27]. Furthermore, model studies have indicated that the cost for consumers can be high, because some electricity use cannot be shifted to another period and the electricity price during the peak period is usually much higher [41,42]. Finally, CPP and TOU rates can be combined [50], which is used on a large scale in France and could be a promising option for the Netherlands [26].

2.2.3. Real-time pricing

Real-time pricing is similar to TOU in the sense that it includes both periods with a lower-than-normal price and periods with a higher-than-normal price; however, the exact timing of the periods and the prices are not known in advance [52]. Only a maximum price and a minimum price are set in advance, and the price can vary continuously between these limits. An example of RTP is given in Figure 2. In some RTP programmes, a price period with a fixed duration (for example of 1 h) is included, and the tariffs are communicated to the customer 1 day in advance, creating a form that has some characteristics of TOU rates and is known as quasi-RTP [53]. Models showed RTP is more efficient in peak-load reduction than TOU rates and leads to a higher economic benefit for both consumers and producers [54,55], but results depend strongly on the elasticity of demand [47]. However, it is found that even when customers are highly responsive (e.g. by using automation) monetary savings can be low [53,56,57]. Furthermore, it is noted that consumers are usually not enthusiastic about RTP [58]. Real-life studies in the United States show load reduction ranging from 12% to 33% of consumers' aggregate peak demand [59].

2.3. Incentive-based demand response

Incentive-based demand response is described as 'an agreed fixed rate payment for customer participation that reflects the savings associated with switching off during peak price events' [38]. Most authors follow the distinction of the US Department of Energy [43] and include six programmes under this name. These six programmes can be roughly divided further into two types: classical and market based (Figure 1) [40]. In classical forms of incentive-based demand response programmes, consumers are paid for their participation. Classical programmes include direct load control (DLC) and interruptible/curtailable load. The other programmes can be considered market based. In the USA, incentive-based demand response involves over five million customers [28] and is responsible for around 90% of the available flexibility [60].

2.3.1. Direct load control

Direct load control gives an electricity supplier or system operator the possibility to reduce load by remotely shutting down household appliances on a short notice [43]. A distinction can be made between controllable load, which does not impact consumer lifestyle, and critical load, which cannot be controlled [61]. The former includes space cooling and heating and appliances such as washing machines and water heaters, but charging of EVs could also be possible [16]. The most commonly used appliances in these programmes are air conditioners, water heaters and swimming pool pumps [62]. DLC programmes can also include an override option to consumers, which gives them the option to keep using their appliance, although this is seldom used by consumers [51].

Direct load control is mostly offered to small-scale users, such as households or small businesses [38], especially in the USA. The largest example is the On Call programme from the Florida Power & Light Company, which has more than 800 000 participants [63]. Many other utilities offer similar programmes [43]. Often payment is done in the form of a fixed reward, which is independent of the number of events in which the utility makes use of its possibility to control an appliance. In Europe, many experiments are underway with DLC (e.g. [64,65]), but it is not applied on a large scale (yet).

2.3.2. Interruptible/curtailable service

Interruptible/curtailable service is a programme in which users get rewarded for reducing their load to a certain, predefined level for a short period of time, such as an hour. Users that do not comply may be fined or removed from the programme. This type of programme has usually been offered only to large electricity users [43]. Interruptible/curtailable service has been applied on a large scale in the USA, where it was the most important source of demand response when measured by peak-load reduction in the USA, with a potential of over 10 GW [43]. But the number of entities offering this type of demand response programme is decreasing [39]. It has also been applied in China and Europe, but on a much smaller scale and mostly to industry [45,46].

2.3.3. Market-based demand response

Market-based demand response programmes include demand bidding/buyback, emergency demand response, capacity market and ancillary services market programmes [40]. These programmes offer users the ability to sell their flexibility on a market. Users are paid for their performance, thus receiving a price per amount of load reduction (per unit of power (kW) or energy (MWh)). The price is determined on the market, so this type of demand response will mostly be used during critical periods in which the price is high. Market-based programmes vary in multiple ways, such as on which market the flexibility is sold, if a capacity tariff is paid and whether fines are levied for non-compliance.

3. BARRIER SELECTION METHODOLOGY

All electricity consumers, whether these are residential, commercial or industrial, can make use of demand response programmes. However, not all programmes are suitable for demand response at households.

Our methodology therefore was designed in the following manner. We first made a selection of various demand response options as reviewed in Section 2 and selected only those that were suited for the Dutch case.

Second, a deductive approach based on literature research leads to the identification of 17 barriers that would obstruct the introduction of the two selected categories of demand response options for Dutch households. The barriers in each category were further classified based on whether the barrier was applicable to the situation in which the demand response programme would be organised by a market player, a DSO or both. In the latter case, the barrier was classified as a general barrier. An overview of the classification is given in Figure 3. Finally, every barrier has been labelled based on the classification of barriers by Greening [32] and Hirst [33] and are related to customers, regulatory, technical or institutional.

The third step in our methodology consisted of conducting interviews with experts in the field, based on a questionnaire. This was considered necessary as although various authors had identified barriers to demand response, many of these demand response options are not yet applied on a large scale but only tested in experiments and field studies. Expert interviews have been performed to validate the outcome of the literature study by discussing these with experts. A semi-structured interview was held with 13 selected experts from the Dutch energy sector, as in this way, it was possible to test the outcomes of the first part as well as to give room for extra input from the experts. The selection of interviewees has been based on the goal to get a broad spectrum of experts, from multiple backgrounds and

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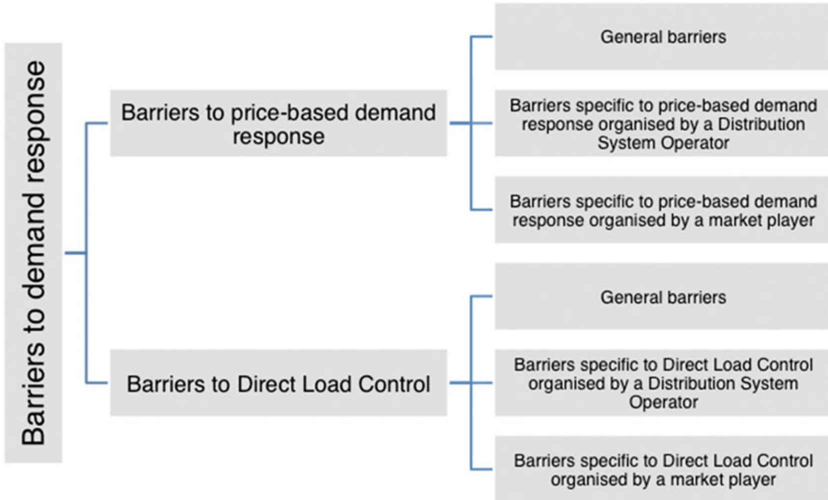

Figure 3. Classification of barriers. [Colour figure can be viewed at wileyonlinelibrary.com]

multiple organisations. A list of the organisations at which the interviewees were employed is given in Table I. Note that consumers were not interviewed, as this was not deemed necessary at this stage of the research. Also, no consumer organisation exists that specifically targets electricity issues.

An interview questionnaire was made in which the selected barriers were formulated as hypotheses and discussed to test their validity. The hypotheses are developed and described in Section 4.2. Interview transcripts were made, and all relevant statements of experts made in the recorded interviews were coded; that is, labels were attached to bits of text to distil it and to give a handle for comparing text [66]. The categories to which a statement has been coded are either one of the earlier identified barriers or, when a problem or barrier that was not yet covered was brought up by an interviewee, a new category. Coding was performed using NVIVO 10 software [67]. The coding categories are called 'nodes' in this software and are defined as 'a collection of references about a specific theme, place, person or other area of interest' [68]. Analysis of the nodes (barriers) was performed and in the end has led to either acceptance or rejection of specific hypotheses; results are presented in Section 4.3.

Table I. Overview of companies of at which interviewees were employed.

Company	Type of organisation
Alliander	Distribution system operator
CE Delft	Consultancy
E.D. Mij	Electricity supplier
Eemflow Energy	Consultancy
Eneco	Electricity supplier
Enexis	Distribution system operator
Greenchoice	Electricity supplier
NL Noodvermogenpool	Aggregator
Stedin	Distribution system operator
TenneT TSO	Transmission system operator
TNO	Research institute

4. RESULTS

4.1. Selection of demand response programmes

In Section 2, demand response programmes have been identified and described. Not all demand response programmes are equally suited for households. Two categories, that is, market-based demand response and interruptible/curtailable service have inherent disadvantages that make these programmes unsuited for household demand response, as will be discussed here.

Market-based demand response rewards the consumer per amount of demand reduction provided. For example, when a consumer receives a signal to reduce electricity use, he or she is rewarded for the amount of kilowatt-hour not used. But this amount of electricity not used is difficult to determine. Because the electricity use of a household varies strongly over time, and comparing with the moment before the signal is received is not a suitable way to determine the reduction. A better way would be to determine what would have been the electricity use without the signal: by subtracting this from the real use, the amount of reduction becomes clear. If the electricity use would be relatively constant, for example, in the case of a factory with a continuous industrial process, this could be fairly well estimated. But for an individual household, this is almost impossible. Electricity use varies per minute, per hour, per day, per month and per year and is subject to random actions, which makes the prediction of an individual consumer's baseline (i.e. the reference curve showing the expected electricity use of the customer in time without the influence of any signals or incentives) unreliable [55]. Furthermore, even if a baseline is created, the consumer can try to manipulate this baseline to increase the rewards he or she will obtain for reducing demand, for example by creating an artificially increased baseline.

Field experiments to determine how much consumers have reduced their electricity use after they received a signal to do so confirmed the difficulty of establishing a baseline on the individual household level [64]. These experiments also showed that when the experiments are continued over a long time, the baseline itself is also influenced by the experiments. Furthermore, even if a reliable baseline could be developed, it would be necessary to make a personal baseline for each participating household. Because of these reasons, market-based demand response is considered unsuited for households.

Interruptible/curtailable service has mainly been used for large industrial electricity users [43], because it has some intrinsic properties that make it less suited for household demand response programmes. As explained before, customers get rewarded for decreasing their electricity use to a predefined level. For a household, this is much more difficult than for example for a factory with several continuous processes. First of all, most households are not aware of their current power use. Secondly, this power use is highly variable and strongly influenced by events, such as electrically heating drinking water. It would be quite an effort for a household to keep electricity use below a certain threshold. Therefore, interruptible/curtailable service is considered unsuitable for households.

In conclusion, because of the inherent disadvantages of market-based demand response and interruptible/curtailable service for households in smart grids, these two programmes are not considered to be realistic options for (Dutch) households. Therefore, only barriers to price-based demand response and DLC will be examined.

4.2. Overview of barriers

Multiple barriers to the large-scale introduction of price-based demand response and DLC to households in smart grid environments have been identified. These barriers are presented below and formulated as hypotheses that have been tested in the interviews. First, barriers to price-based demand response are discussed. A classification is made between three types of barriers: barriers specific to situation in which a market player initiates the programme, barriers specific to the situation in which a DSO runs the programme and general barriers (Figure 3). General barriers are barriers that apply to the situation in which the programme is organised both by a market player and by a DSO.

4.2.1. Barriers to price-based demand response

Price-based demand response can be organised either by an electricity supplier or a DSO, as these two parties influence the electricity bill of consumers (via the electricity price per kilowatt-hour and the network tariff, respectively), and both have an incentive to use price-based demand response: an electricity supplier can use price-based demand response for example to have a lower demand when prices on the market for electricity are high, leading to lower average procurement costs. This financial benefit can be partially or wholly transferred to the consumer, via lower electricity prices. A DSO can use price-based demand response to reduce peaks in the grid.

An electricity supplier can introduce price-based demand response by making the electricity price per kilowatt-hour dynamic. A DSO can do this by making the presently fixed network tariff dynamic, that is, per kilowatt-hour and different per time period: a dynamic network tariff. An important difference between the dynamic electricity price from the electricity supplier and the dynamic network tariff from the DSO is that, when introduced, the latter would be mandatory for all consumers. This then prevents that only small electricity users would choose this option to pay per kilowatt-hour while the large users would choose the option of a fixed amount independent of the electricity use.

So because an electricity supplier is the only market player able to influence the electricity price, the distinction between a market player and DSO is replaced by a distinction between an electricity supplier and DSO in the case of price-based demand response. This has influence on the barriers: some barriers are only applicable to the case in which the DSO organises the demand response programme (dynamic network tariffs), while other barriers are only applicable to situations in which an electricity supplier is responsible for the programme (dynamic electricity prices). Therefore, a further classification of barriers is made: first, general barriers are discussed, which are barriers that are independent of the organiser of the demand response programme. Hereafter, barriers that are specific to dynamic network tariffs or specific to dynamic electricity prices are discussed. For each barrier, a hypothesis is formulated. The hypotheses related to price-based demand response are given the letter P and numbered from 1 to 12. They are shown in Table II and are further discussed in the following.

4.2.1.1. General barriers

4.2.1.1.1. Barrier 1: benefit to consumers uncertain. While the benefits of price-based demand response to the electricity market and system are clear, it is essential for its success that consumers also benefit from the programme. However, many researchers have described possible negative aspects or consequences of dynamic tariffs, and it is doubted if the financial benefits from price-based demand response would be enough to persuade customers. Not only may savings be limited, they are also uncertain [52].

Furthermore, while research showed that most customers benefit financially from dynamic tariffs, this is not the case for all customers. Customers who use a larger share of their electricity use during high-price periods than the average customer and do not change their usage pattern may have to pay more than they did before [69]. This can be especially problematic for low-income households that have difficulties to change their consumption pattern [58],

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Table II. Overview of barriers to price-based demand response.

Number	Barrier	Label
General barriers		
P1	Benefit to consumers uncertain	Customer
P2	Uncertainty in forecasting and balancing	Technical
P3	Smart meter required	Technical
P4	New system required for consumer billing	Technical
P5	New system required for allocation and reconciliation	Regulatory
P6	No access to data due to privacy concerns	Customer
P7	New demand peaks	Technical
P8	Different interests electricity supplier and DSO	Institutional
Barriers specific to dynamic network tariffs		
P9	Higher costs for large users	Customer
P10	Not allowed by regulation	Regulatory
P11	Uncertain income distribution system operator	Institutional
Barriers specific to dynamic electricity prices		
P12	Consumers are not interested	Customer

and this redistribution across customers may be the most difficult barrier to the roll out of dynamic pricing [69]. Thus, as the electricity price becomes variable, the benefit to consumers of price-based demand response is uncertain. This creates a barrier to the introduction of price-based demand response, as formulated in the following:

Hypothesis P1. The uncertain benefit to consumers forms a barrier to price-based demand response for households in the Netherlands.

4.2.1.1.2. Barrier 2: uncertainty in forecasting and balancing. At the moment, balance responsible parties (BRPs) and the transmission system operator (TSO) are able to make a reliable forecast of the electricity demand of households over the day using standard demand profiles. Demand forecasting does not take responsiveness to short-term price variations into account [70]. The introduction of price-based demand response will change this situation. It is thus argued that demand forecasting has to change to include price-responsive demand [57].

Without this improved forecasting, price-responsive demand will create an imbalance between supply and demand, because household demand will be different than expected. Predicting the changes due to price-based demand response in demand is difficult because the demand function is unknown [71]. This uncertainty in forecasting and balancing forms a barrier to DSOs or electricity suppliers to introduce price-based demand response. Therefore, Hypothesis 2 is formulated as follows:

Hypothesis P2. The negative consequences for demand forecasting and balancing form a barrier to price-based demand response for households.

4.2.1.1.3. Barrier 3: smart meter required. Dynamic pricing programmes require a smart meter to be able to determine the electricity use in each separate tariff period, as many authors noted [32,52,62]. In the Netherlands, the large-scale smart meter rollout has started in January 2015 and should be completed by the end of 2020 [72], meaning it will take 6 years for all households to have a smart meter installed. If a consumer would choose to have a dynamic tariff before 2020, while a smart meter has not yet been installed, a fee of around €70 is charged for meter replacement, while the financial benefits of price-based demand response to a consumer are uncertain as noted before. This forms a barrier to electricity suppliers and DSOs to introduce demand response in the Netherlands as formulated in the following:

Hypothesis P3. The limited number of households with a smart meter and the cost for installing a smart meter form a barrier to price-based demand response for households.

4.2.1.1.4. Barrier 4: new system required for consumer billing. At the moment, calculating the final electricity costs of a household is easy: because the network tariff and the electricity price per kilowatt-hour are fixed, only the yearly electricity use is needed. A dynamic tariff that can vary per day, per period or per hour requires new billing systems that are able to determine the final network or electricity costs for the consumers for each period and in total [9,62,73]. The cost of creating such a system forms a barrier to the party organising the price-based demand response programme; hence, we hypothesise the following:

Hypothesis P4. The need for new billing systems forms a barrier to price-based demand response for households.

4.2.1.1.5. Barrier 5: new system required for allocation and reconciliation. In the current system, a BRP has to make sure enough electricity is bought to meet the expected electricity demand of its customers for each 15-min period (known as programme time unit (PTU)) of the day. Afterwards, this is compared with the actual electricity use of its customers as measured by the DSOs, which can be higher or lower than expected. The difference is calculated for each of these periods, and the BRP either has to pay (in case electricity use was higher than expected during that period) or receives money back (in case electricity use was lower than expected during that period). Note that for each period the electricity price can be different, because the price that is used in this process is the one determined on the Amsterdam Power Exchange [74], the Dutch electricity spot market. This process is called reconciliation. The difficulty is that the actual electricity use of a household in each PTU is not known. Instead, the actual electricity use is estimated based on profiles, which is called allocation. An example of such a profile is shown in Figure 4 for a day in January.

In case an electricity supplier introduces price-based demand response, it will buy less electricity in advance for the peak periods and more for non-peak periods, because it expects its customers to shift electricity use from peak periods to the non-peak periods. However, if allocation is still based on the standard household profile, in which the reaction of a consumer to a dynamic tariff is not included, the electricity supplier will in the end (wrongfully) have to pay extra during reconciliation, because according to the allocation based on the standard profile, electricity use was higher during peak periods and lower during non-peak periods than the electricity supplier expected. In other words, with the current allocation process, the electricity supplier will not see any financial benefit from price-based demand response. This forms a barrier to electricity suppliers to introduce price-based demand response; hence, we hypothesise the following:

Hypothesis P5. The current allocation and reconciliation process forms a barrier to price-based demand response for households.

4.2.1.1.6. Barrier 6: no access to data owing to privacy concerns. The introduction of smart meters in the Netherlands has led to concerns and discussions about privacy [75,76], and this issue might resurface when dynamic tariffs are introduced. In order to create a correct bill for the customer, the electricity supplier or DSO needs access to the data from the smart meter. At the moment, a consumer needs to give explicit permission to make this possible [72]. Introduction of dynamic tariffs may be hampered, as consumers might not be willing to share a smart meter for privacy reasons. Thus, it will be impossible for the DSO or electricity supplier to create a correct bill. This forms a barrier to price-based demand response for households to DSOs or electricity suppliers, as formulated in the following:

Hypothesis P6. Privacy concerns about data sharing form a barrier to price-based demand response for households.

4.2.1.1.7. Barrier 7: new demand peaks. One of the most important goals of demand response is to reduce peaks in electricity demand. Dynamic tariffs do reduce peak demand, but research also revealed that dynamic tariffs could create new peaks in demand, potentially because of automatically operating load-shifting appliances [53,57,62,77]. As electrification in households is expected to strongly increase, new demand peaks may be expected in the future [77]. These new peaks can cause problems on the grid and higher prices on the market. This forms a barrier to price-based demand response for an electricity supplier or DSO, as stated in the following:

Hypothesis P7. The creation of new demand peaks forms a barrier to price-based demand response for households.

4.2.1.1.8. Barrier 8: different interests of electricity supplier and distribution system operator. Even though both a DSO and an electricity supplier could profit from price-based demand response, this does not necessarily mean that both would benefit at the same time [9,32,42]. An example of a situation in which such a

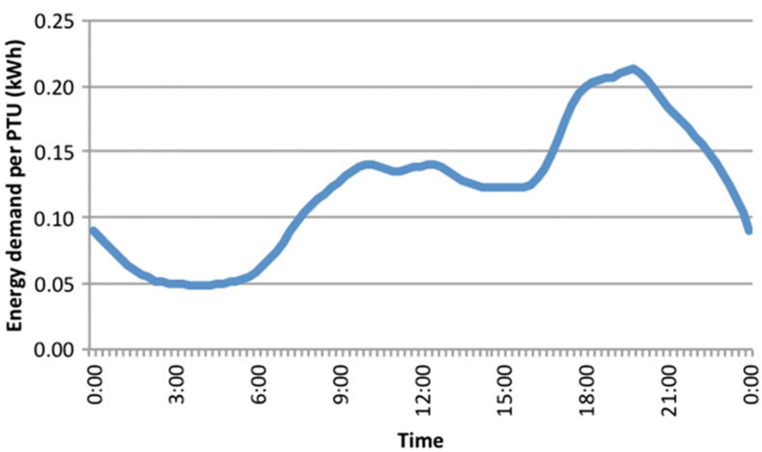

Figure 4. Profile of a household on 5 January 2015; daily use of 11.8 kWh is 0.33% of annual use. [Colour figure can be viewed at wileyonlinelibrary.com]

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conflict could arise is when the load on the grid is very high because of a high demand. If consumers are on an RTP programme and at the same time wholesale electricity prices are decreasing, an electricity supplier would lower its prices. This lower price could lead to even more consumer demand and aggravate the grid problems for the DSO. Furthermore, a situation could arise in which both parties have a price-based demand response programme: not only would a complex situation for the consumer arise when for example one party chooses to use RTP while the other chooses CPP, but as interests differ, a situation could arise in which one party tries to increase demand while at the same time the other party tries to decrease demand. The fact that a programme from an electricity supplier could have negative consequences for a DSO and vice versa creates a barrier to electricity suppliers and DSOs; hence, we hypothesise the following:

Hypothesis P8. The different interests of DSOs and electricity suppliers form a barrier to price-based demand response for households.

4.2.1.2. Barriers specific to dynamic network tariffs

4.2.1.2.1. Barrier 9: higher costs for large users. At the moment, all households have to pay the same fixed network tariff. Introducing a dynamic network tariff based on the amount of kilowatt-hour used would change this situation and would create a situation in which large differences per household arise [9]. Large users would end up paying much more than small users. While this would reward energy savings and small users would profit from this new system, it has negative consequences. First and foremost, because there is a large spread in electricity use per household [78], many households with a relatively large electricity use would end up paying much more.

Furthermore, at the moment, adding extra electric appliances to a household has no influence on the network tariff, as it is fixed. Because of a new dynamic tariff per kilowatt-hour, large electric appliances will become much more expensive to use. Estimates showed that a new tariff would lead to an increase in annual electricity costs for a heat pump of around €600 [9]. This will have a negative influence on for example the diffusion of heat pumps and EVs, while at present especially EVs are strongly supported by the government [79,80]. This barrier to DSOs to introduce price-based demand response programmes is stated in the following:

Hypothesis P9. The negative consequences for large electricity users of an increase in the price per kilowatt-hour form a barrier to dynamic network tariffs for households.

4.2.1.2.2. Barrier 10: not allowed by regulation. European Union legislation creates some room for price-based demand response. The EU directive 2012/27/EU demands that '…member states shall ensure the removal of those incentives in transmission and distribution tariffs that (…) might hamper participation of demand response' [81]. In addition, a recent report prepared for the European Commission states that 'network tariffs should promote peak demand management and aim to reduce infrastructure cost for peak demand' and 'tariffs should encourage system flexibility, e.g. distributed generation, demand response and energy efficiency' [82]. This was already advocated by EURELECTRIC (Union of the Electricity Industry), who wrote 'alternative pricing options that allocate the additional costs of network reinforcement and grid losses to the network customers responsible for creating those costs (more closely following marginal costs) should be explored' and therefore argued for 'network tariffs that penalise energy use at peak hours' [83].

However, a variable network tariff is not allowed for Dutch consumers at the moment [84]. Since 2009, the Electricity Act demands that the tariffs of a DSO should be based on capacity [85]. The main reasons are that a capacity tariff reflects costs adequately, because users with a larger capacity have to pay more and that a capacity tariff is simple to administrate [9,83]. But the Act leaves no room for a dynamic network tariff. So even though developments on the European level create room for demand response, the Dutch law prohibits it, at this moment. This forms a barrier to DSOs to introduce price-based demand response as described in the following:

Hypothesis P10. Dutch law forms a barrier to dynamic network tariffs for households.

4.2.1.2.3. Barrier 11: uncertain income distribution system operator. Dutch DSOs are paid a fixed amount per consumer, based on the capacity of the consumer. This creates a stable annual income for the DSOs. If a DSO would introduce a dynamic network tariff per kilowatt-hour, the income for the DSO would become dependent on the annual electricity use and also on the amount of electricity used per period. This creates uncertainty for the DSO and may lead to lower revenues than expected which possibly may not be enough to cover DSO costs. Because revenue adequacy is key to DSOs [83], this uncertainty in income forms a barrier to the introduction of dynamic network tariffs by DSOs. Therefore, the following hypothesis has been formulated:

Hypothesis P11. The uncertainty about the income of a DSO forms a barrier to dynamic network tariffs.

4.2.1.3. Barriers specific to dynamic electricity price

4.2.1.3.1. Barrier 12: consumers are not interested. Electricity is considered a low-interest good, abstract, invisible, untouchable, not consumed directly but rather indirectly via various energy services [86]. Consumers regard electricity as a necessity while they expect security of supply, and its costs usually are an important share of the budget of a household. It has been noted that this lack of interest to electricity could form a barrier to dynamic electricity prices [32]. As consumers presently lack experience in dynamic pricing schemes, they would not like to see the flat rates changed. Also, if costs would constitute a small part of the budget for residential and small commercial customers, no one would consider trying to understand dynamic pricing schemes [32].

To overcome this barrier and increase the number of consumers with a dynamic electricity price, it would be an option to offer it by default instead of letting consumers choose for dynamic electricity prices, while offering an opt-out possibility. This has been carried out in the USA, and results show the opt-out rates are low: for example, results from a study in California revealed that only 2–7% of the default customers opted out before the start of the programme and only 4–8% dropped out of the programme in the first 2 years [29]. However, there is no retail competition in the electricity market of the USA, meaning consumers cannot leave their utility [50]. In the Netherlands, however, the electricity market is liberalised and consumers can easily switch to another electricity supplier. So electricity suppliers might not dare to offer all their customers a new dynamic pricing plan as default option, because they fear some of their customers will switch to another electricity supplier. This could mean that customers would need to actively choose for a dynamic tariff, while they are not interested in electricity [50]. Therefore, we hypothesise the following:

Hypothesis P12. The lack of interest of consumers forms a barrier to dynamic electricity prices for households.

4.2.2. Barriers to direct load control

Similar to the situation in Section 4.2.1, barriers are divided in general barriers and barriers specific to either DLC organised by a DSO or by market players. The latter category includes all parties that could use this flexibility on a market, such as electricity suppliers and aggregators. Again, for each barrier, a hypothesis is formulated. The hypotheses regarding DLC are labelled with the letter D and numbered 1 to 5. An overview of all identified barriers to DLC for Dutch households is given in Table III, with labels added. Details are described as follows.

4.2.2.1. General barriers

4.2.2.1.1. Barrier 13: lack of large suitable appliances. The most common household appliances used for DLC are water heaters, air conditioners and swimming pool pumps [62]. Because of the large electric load, these appliances have a much larger impact on peak use than small appliances. In the Netherlands, electricity use of households is relatively low compared to other Western countries [87], because there are not many large electricity-using appliances. Not many households use large air conditioners, electric water heaters or swimming pumps, nor do many households use other large electric appliances. This could form a barrier to the introduction of DLC by DSOs or electricity suppliers in the Netherlands.

Some electric appliances that are widespread in Dutch households have been identified to be suited for DLC, such as tumble dryers, dish washers and washing machines [10,53,88]. But recent research showed the potential of these appliances is limited [23]. Besides the fact that the electricity use of these appliances is lower than the use of for example air conditioners or water heater, these appliances have two other important drawbacks. First, they have been found to be highly asymmetrical [65], meaning that when these appliances are controlled, it is much easier to suddenly increase demand than to decrease demand. This is caused by the fact that appliances are not often switched on all at the same time, so neither can they be all switched off at the same time. In other words, the coincidence factor described by Strbac is low [62]. Also, these appliances are not designed to be switched off during their use, and doing so could have negative consequences. This asymmetry limits their usefulness for demand response. The second limitation is that because of energy efficiency demands and technical improvements, newer versions will have a much lower electricity use than older versions. As a consequence, they will be less suited for demand response because of their lower electricity use. This will create a barrier to organisations that want to organise DLC programmes. Another interesting appliance could be the refrigerator/freezer, but the latter limitation also applies to this appliance.

However, in recent years, two types of large appliances have become more popular to households: heat pumps and

Table III. Overview of barriers to direct load control.

Number	Barrier	Label
General barriers		
D1	Lack of large suitable appliances	Technical
barriers specific to direct load control organised by a distribution system operator		
D2	Value to the distribution system operator uncertain	Institutional
D3	Regulation obstructs the distribution system operator	Regulatory
Barriers specific to direct load control organised by market players		
D4	Not enough value to market players	Institutional
D5	Unsuited for the regulating market	Regulatory

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EVs. These two types of appliances have a large electricity use and can be controlled. In the Netherlands, the number of installed heat pumps using air was around 30 000 units per year in three consecutive years, 2011, 2012 and 2013, and the number of installed heat pumps using water was almost 6000 per year in 2011 and 2012 but decreased to around 3000 in 2013 [89]. The number is expected to increase further: the Dutch Heat Pump Association set a target of 500 000 heat pumps in 2020 [90]. The number of electric cars in the Netherlands increased rapidly in recent years and was around 35 000 in the first half of 2014 [7], of which the majority was a plug-in hybrid or included a range extender. In 2020, this number is estimated to reach 200 000, which is the target of the government [79].

It would be very beneficial for DLC if these expectations are met and these two types of appliances become widespread in the Netherlands, but this is uncertain. So at the moment, the lack of appliances might form a barrier to DLC for DSOs or market players. The first hypothesis about DLC for households in the Netherlands is therefore as follows:

Hypothesis D1. At the moment, the lack of suitable appliances forms a barrier to DLC in the Netherlands.

4.2.2.2. Barriers specific to direct load control organised by a distribution system operator

4.2.2.2.1. Barrier 14: value to the distribution system operator uncertain. The fact that in the USA many utilities offer DLC programmes shows that a viable business case can be made for this demand response programme. However, DLC has value to these companies not only because of the effect on the grid but also because the reduced demand lowers the amount of electricity these companies have to buy for their customers during these (extremely) high-price periods. Because in the Netherlands the operation of the grid is split (by law) between production and distribution of electricity, Dutch DSOs do not have this second incentive. Therefore, Dutch DSOs will benefit less from demand response.

The monetary value of a lower household peak use was estimated for the New Zealand grid to be less than a €100/year [91], but it is unknown how these outcomes apply to the Dutch case. A study by the Dutch consultancy Ecofys estimated the value of peak reduction to be between €200 and €740/kW per household for the Dutch situation [92], showing that it is highly dependent on local differences in the capacity of the current grid and the household density. A DLC programme only has value to the DSO if the cost of the programme, including the installation of control equipment and the payments to participants, is less than the cost of the current solution, that is, enlarging the capacity of the grid. It is reported that in 2050 DLC with heat pumps and EVs can be cheaper than enlarging the capacity, but only between €5 and €23 per household per year, assuming customers participate for free and without taking inflation into account [92]. Therefore, the financial benefit of DLC is uncertain, which creates a barrier to Dutch DSOs, as formulated in the second hypothesis about DLC for households:

Hypothesis D2. The uncertainty of the benefit to the DSO forms a barrier to DLC in the Netherlands.

4.2.2.2.2. Barrier 15: regulation obstructs the distribution system operator. Dutch DSOs are regulated by the state, and some regulations have implications for DLC. Dutch law states that a DSO should abstain from any form of discrimination between consumers [85]. This could imply that the DSO is not allowed to reward some consumers (for example, with a fee or via a discount on their bill) for participation in a DLC programme if this offer is not extended to all consumers. However, most consumers will not be living in areas with possible grid constraint, so the DSO has no incentive to offer DLC to those consumers. If it would be mandatory to offer it to all consumers, the DLC programme would become much larger and much more expensive, while having no extra benefits to the DSO. This regulation forms a barrier to the DSO:

Hypothesis D3. Regulation forbidding Dutch DSOs to offer DLC only to some consumers forms a barrier to DLC in the Netherlands.

4.2.2.3. Barriers specific to direct load control organised by market players

4.2.2.3.1. Barrier 16: not enough value to market players. For an electricity supplier or BRP, DLC could be interesting if the flexibility could be used on a market, for example, the imbalance market organised by the Dutch TSO TenneT [93]. Instead of increasing electricity production to balance the system (upwards regulation), DLC could be used to decrease demand, and vice versa. Research showed that this imbalance market is a highly interesting market for residential demand response because of the relatively high potential revenues [94]. However, the business case is uncertain. The price paid by TenneT on the imbalance market for downwards regulation is usually less than €100/MWh [95]. In the past years, the price has been more than €300/MWh only around 20 times per year [95]. TenneT pays more often for upwards regulation, so more money can be earned here. For example, during 12% of the periods in 2012 and 2013, TenneT paid more than €100/MWh for extra electricity production. But prices never exceeded €600/MWh. Furthermore, the number of times TenneT had to use regulating power decreased over the last 5 years, irrespective of upward or downward regulation.

Even when it is taken into account that because the increasing share of renewables in the energy system imbalance could increase and prices could become higher in the future, the price paid for flexibility in the Netherlands is low compared to the 23 eurocents a household usually pays or receives per kilowatt-hour (in the present net metering scheme). The average price in 2014 was €69/MWh for upward regulating power and €19/MWh for downward regulating power. These price differences are low compared to the 23 cents/kWh, which forms a barrier to DLC for market players; hence, we hypothesise the following:

Hypothesis D4. The low prices on the balancing market form a barrier to DLC programmes of market players in the Netherlands.

4.2.2.3.2. Barrier 17: unsuited for the regulating market. In the USA, DLC can be used on electricity markets, including the regulatory market, via aggregators called Curtailment Service Provider [48,96]. In the Netherlands, TenneT controls the balancing market and is the only buyer on the market. TenneT contracts 300 MW of regulatory power in advance, but regulatory power can also be offered on the spot. If an electricity supplier wants to use its DLC programme to offer regulating power on this market, there are requirements that must be met, such as a minimum amount of a single bid of 4 MW [97]. In order to compare this scale with a household, it should be noted that the peak use of an average Dutch household is 0.8 kW on an average winter day and its night use is 0.2 kW [9]. However, peak use and the load available for flexibility are expected to increase in the coming years because of the introduction of heat pumps and EVs. Still, in order to actively participate in this market, aggregators controlling appliances of thousands of households will be needed.

Furthermore, regulating power must be able to be directed by the national frequency power regulator of TenneT, and TenneT demands that regulating power can be continuously regulated in discrete steps of 1 MW [97]. Finally, there are requirements for the minimum regulating rate and reaction time. If the electricity supplier contracts enough appliances, it might be able to conform to these requirements. However, it is unknown if TenneT accepts households DLC on the imbalance market, which forms a barrier to market players to introduce DLC. Thus, we hypothesise the following:

Hypothesis D5. The criteria of the imbalance market form a barrier to DLC programmes of market players in the Netherlands.

4.3. Assessment of barriers

The analysis of the interview data revealed that the experts recognised some of the barriers, while other barriers were not considered to be relevant to the Dutch situation. Expert opinions are summarised below and are used to accept or reject hypotheses, while detailed transcripts can be found elsewhere [98]. The results are discussed for each barrier; results are summarised in Tables IV and V.

Table IV. Overview of accepted and rejected hypotheses about price-based demand response.

Number	Hypothesis	Accepted/ rejected	Category
P1	The uncertain benefit to consumers forms a barrier to price-based demand response for households in the Netherlands.	Accepted	Dynamic electricity prices
P2	The negative consequences for demand forecasting and balancing form a barrier to price-based demand response for households.	Rejected	N/A
P3	The limited number of households with a smart meter and the cost for installing a smart meter form a barrier to price-based demand response for households.	Rejected	N/A
P4	The need for new billing systems form a barrier to price-based demand response for households.	Accepted	Dynamic network tariffs
P5	The current allocation and reconciliation process forms a barrier to price-based demand response for households.	Accepted	Dynamic electricity prices
P6	Privacy concerns about data sharing form a barrier to price-based demand response for households.	Accepted	Dynamic network tariffs
P7	The creation of new demand peaks forms a barrier to price-based demand response for households.	Accepted	Dynamic network tariffs
P8	The different interests of distribution system operators and electricity suppliers form a barrier to price-based demand response for households.	Rejected	N/A
P9	The negative consequences of an increase in the price per kilowatt-hour for large electricity users form a barrier to dynamic network tariffs for households.	Rejected	N/A
P10	Dutch law forms a barrier to dynamic network tariffs for households.	Accepted	Dynamic network tariffs
P11	The uncertainty about the income of a distribution system operator forms a barrier to dynamic network tariffs.	Rejected	N/A
P12	The lack of interest of consumers forms a barrier to dynamic electricity prices for households.	Accepted	Dynamic electricity prices

N/A, not applicable.

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Table V. Overview of accepted and rejected hypotheses about direct load control.

Number	Hypothesis	Accepted/ rejected	Organiser
D1	At the moment, the lack of suitable appliances forms a barrier to direct load control in the Netherlands.	Rejected	N/A
D2	The uncertainty of the benefit to the distribution system operator forms a barrier to direct load control in the Netherlands.	Accepted	Distribution system operator
D3	Regulation forbidding Dutch distribution system operators to offer direct load control only to some consumers forms a barrier to direct load Control in the Netherlands.	Accepted	Distribution system operator
D4	The low prices on the balancing market form a barrier to direct load control programmes of market players in the Netherlands.	Accepted	Market player
D5	The criteria of the imbalance market form a barrier to direct load control programmes of market players in the Netherlands.	Rejected	N/A

N/A, not applicable.

4.3.1. Barriers to price-based demand response

4.3.1.1. General barriers

4.3.1.1.1. Barrier 1: benefit to consumers uncertain. The majority of experts believed that the uncertain financial consequences of a dynamic tariff for a household would form a barrier to price-based demand response. Consumers might not like the inherent uncertainty of a dynamic electricity price, as it could mean people will have to pay more than they do in the current system. Savings result from changing behaviour and reacting to the prices. When consumers do not react properly, they might have to pay more. One expert added that this barrier was not properly understood, as in most pilot projects either the price was virtual instead of real or consumers were protected by a maximum tariff, making sure they could not lose money.

Two out of the 13 experts did not consider the uncertainty to be a barrier, referring to the large number of people in the Netherlands who uses the so-called day and night tariffs. The price difference between the day and night tariffs is small (about 1 eurocent/kWh), and the system is simple: consumers know in each moment what the electricity price is and what it will be later. Economic benefits are doubtful, or at least minimal, as the fixed tariff for night use is lower than that for day use.

Two other experts, both employed at an electricity supplier, brought up another argument against this barrier: in the current system, the consumer has a fixed price so is protected from possible price increases. In exchange, the consumer has to pay a "fee," which is included in the price. Because in dynamic pricing this risk is transferred from the electricity supplier to the consumer, the consumer does not have to pay this fee and receives on average a lower price. This reduces the chance that consumers end up paying more than they did before with their fixed price. However, it is uncertain if the financial benefit resulting from the on average lower price is large enough to compensate users who use more than average during higher-price periods. It is also not known if it is enough for consumers to compensate for the uncertainty.

Another argument against this barrier was the possibility of introducing a cap: a maximum price. This could protect consumers against high prices in case a real-time tariff would be introduced. However, even though it somewhat reduces the risk, consumers who use more than average during higher-price periods could still end up paying more.

Finally, an expert added that this might not be a barrier to all people: some will most likely not have problems with the uncertainty, as influencing a certain percentage of the consumers may already lead to a large impact on the network and on electricity production. However, this percentage is uncertain and even when the uncertainty is not a problem to all consumers, the uncertain benefit to consumers forms a barrier to price-based demand response organised by an electricity supplier for most households in the Netherlands. For price-based demand response organised by a DSO, it does not form a barrier because the tariffs are regulated and consumers have no possibility to choose. Therefore, we conclude that Hypothesis P1 is accepted, while it is not a general barrier but rather a barrier to dynamic electricity prices.

4.3.1.1.2. Barrier 2: uncertainty in forecasting and balancing. Experts on this subject agreed that dynamic prices for households have an effect on forecasting and balancing by BRPs, which at the moment is based on a standard profile for all households. Because dynamic pricing will make consumers change their electricity use, BRPs must change the way they make predictions. However, the experts did not consider it to be a barrier, as they believe the BRPs are very well able to adapt. One expert, employed at a TSO, explained that a BRP will experience large imbalance at first, after which the BRP has to change its estimations, thus quickly gaining experience, leading to good predictions of electricity demand.

Another expert, employed at an electricity supplier, suggested that when RTP is introduced, the extra costs incurred for creating imbalance could be made part of the dynamic electricity price. In other words, the consumers could pay the real costs, including the price paid for creating imbalance. In this situation, the consequences of the wrong predictions would be attributed to the consumer. Thus, it would not form a barrier to the BRP, while the consumer would be compensated with lower prices, as explained earlier.

So the negative consequences of price-based demand response for demand forecasting and balancing are limited, because BRPs are expected to be able to adapt and make new, better projections, and the possible costs can be passed on to the consumer. Therefore, it does not form a barrier to price-based demand response for households and Hypothesis P2 is rejected.

4.3.1.1.3. Barrier 3: smart meter required. The interviewed experts had different opinions about the statement that the lack of smart meters in the Netherlands forms a barrier to households demand response. While multiple experts believed that today not enough smart meters are installed, two experts, both employed at an electricity supplier, stated that there are already enough smart meters. One of them noted that between 10% and 15% of his company's customers has a smart meter already and because he did not expect electricity suppliers to offer the product straight away to every customer, this will be enough to start offering dynamic tariffs. Another expert, employed at a consultancy, added that because it is possible for consumers to buy a smart meter right away instead of waiting until it will be installed for free, he did not consider it to be a barrier at the moment.

The large majority of experts noted that the lack of smart meters would disappear in a few years, and therefore, they did not consider it to be a barrier to dynamic tariffs. An expert employed at a DSO noted that even though public opinion could turn against the smart meter (possibly because of privacy concerns), obstructing its diffusion, in the most likely scenario, every household will have been offered a smart meter by 2020, meaning there will be enough smart meters. One of the experts added that because he expected it will take some years to change the allocation and reconciliation process, which is essential as described at barrier 5, there will be enough smart meters by the time it is even possible to offer dynamic tariffs on a large scale. Thus, because of the planned large-scale rollout of smart meters, a large majority of experts stated that the requirement of a smart meter is not barrier; Hypothesis P3 is rejected.

4.3.1.1.4. Barrier 4: new system required for customer billing. Not all experts agreed with each other on the subject of the need for a new billing system. While some agreed that the difficulty of creating a system capable of working with dynamic electricity prices forms a barrier, others stated that some companies already had developed a billing system able to work with dynamic electricity prices and dynamic network tariffs. It thus would not be a problem to calculate the average price that the customer would have to pay for the electricity used, based on the electricity use of a customer in each different pricing period. Some issues remain, such as required computational power, in case dynamic electricity prices would be applied on a large scale, and missing smart meter data.

However, in case a DSO introduces dynamic network tariffs, more is needed for consumer billing than just a new system to calculate the final price for a consumer. At the moment, the DSO has no direct contact or contract with households. The network tariff is a fixed amount that is collected by the electricity supplier and passed on to the DSO. The fact that the DSO has no direct contact with consumers could be problematic when the bill is different for each consumer or for example when the consumer disagrees with the bill he or she receives via the electricity supplier. Experts considered this system to be much more difficult than the current system, while two other experts, both employed at a DSO, referred to the cost of implementing a new system on such a large scale, which could be in the range of tens of millions of euro.

Overall, even though not all experts agreed on this subject, the need for a new billing system for an electricity supplier is not considered to be a barrier because multiple experts who are working or have worked with dynamic electricity prices claimed to already have such a system. However, because of the extra system changes needed, it is considered a barrier for a DSO that wants to introduce a price-based demand response programme. Consequently, Hypothesis P4 is accepted as a barrier to dynamic network tariffs, and not as a general barrier.

4.3.1.1.5. Barrier 5: new system required for allocation and reconciliation. All interviewed experts considered the current allocation and reconciliation process to be a barrier to price-based demand response. This means that even if households move part of their electricity use to cheaper periods, the electricity suppliers cannot profit from this development. They cannot buy less electricity during expensive periods because in the end, it is still assumed that households followed the standard profile, meaning according to an expert 'that it is impossible to make money'. To prove the household is behaving differently, allocation based on the smart meter is essential. An expert, employed at an electricity supplier, explained that customers should not be included in the profile if they take part in a dynamic tariff scheme.

One expert denoted price-based demand response as 'useless' without this change in the allocation and reconciliation process. It should be noted that change is in progress, regarding abolishing the reconciliation process and using data from the smart meter instead for direct allocation on the household level [99].

Using the data from the smart meter means the smart meter is essential not only for billing, as described at barrier 4, but also for the allocation process. Consumers that do not want a smart meter or do not want to share their data cannot participate in a price-based demand response programme. This is discussed in more detail at barrier 6.

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While DSOs are involved in the allocation and reconciliation process, the way of allocating electricity use is irrelevant for dynamic network tariffs. For a DSO, it would be enough to collect and process the data as described earlier at barrier 4. So the current allocation process does not form a barrier to dynamic network tariffs.

So based on the fact that electricity suppliers cannot make a profit with dynamic pricing as long as the electricity use of households is allocated using the standard profile, the current allocation and reconciliation process is considered a barrier to price-based demand response organised by an electricity supplier. Therefore, Hypothesis P5 is accepted as a barrier specific to dynamic electricity prices, not as a general barrier.

4.3.1.1.6. Barrier 6: no access to data owing to privacy concerns. The interviewed experts more or less agree that privacy concerns form a barrier to consumers to share the data collected by the smart meter and thereby form a barrier to dynamic tariffs. However, the experts believe this is not an issue for the majority of households. Some experts noted that they believed the attention that was given to this issue in politics or in the media does not reflect the opinion of the majority of the general public. Nevertheless, in order to get the collection of data accepted, multiple experts mentioned two issues that would be critical. The first is to offer a clear benefit in exchange, while the second is to be transparent to the consumer on the use of the data.

However, many believed there still would be a small group objecting to the collection of data. One expert suggested independent trusted third parties to take over the billing process. Another expert suggested that, because an electricity supplier needs the data for billing but does not need real-time data, the data from the smart meter could be transferred with a delay of for instance 1 week. This could remove the fear that the data reveal whether the consumer is at home or what he or she is doing at the moment. Another expert added that opt-out possibilities should be offered as well. The downside of this is that it would lead to ‘gaming’: users would pick the cheapest tariff. For example, households with a lower electricity use would opt for a tariff based on the amount of kilowatt-hour used, while large users would pick the fixed tariff. This would lead to a loss of income for the DSO.

Because of the aforementioned reasons and because not every household is needed, privacy concerns about data sharing do not form a barrier to price-based demand response programmes organised by an electricity supplier. But in case the programme is organised by a DSO, it does form a barrier because these tariffs are regulated and all households have to participate. Therefore, Hypothesis P6 is accepted as a barrier to dynamic network tariffs, not as a general barrier.

4.3.1.1.7. Barrier 7: new demand peaks. The majority of experts acknowledged that dynamic tariffs could create new demand peaks. One expert explained that they already found such a situation in a pilot project with an industrial company. Most experts came up with suggestions to overcome this problem. In the case the dynamic tariff would be combined with DLC, the experts expected it would be possible to prevent new demand peaks by letting a central system take this effect into account and start appliances one by one instead of all together. However, in case dynamic tariffs are introduced without DLC, so without central coordination, the majority of the experts considered the creation of new demand peaks not only to be a possibility but also a problem, at least in case consumers introduce automation in their home.

Two experts suggested the possibility of introducing different tariff structures for different households in the same neighbourhood. But introducing multiple programmes and making sure customers in the same neighbourhood choose differently would make introducing demand response much more difficult for electricity suppliers or DSOs. Another expert proposed adding a random function into smart appliances, so the appliance would not react instantly to a price signal but only after a random period of time. But this would require the producers of smart appliances to collaborate on implementing this.

It has become clear that the creation of new demand peaks is a problem. For an electricity supplier, creating new peaks is not a problem, because the electricity supplier is not responsible for the grid. Furthermore, it would be unlikely that these new peaks are so large compared to the total national electricity use that they would have a significant impact on the electricity market. It is therefore unlikely that this problem would form a barrier to the electricity supplier to introduce dynamic tariffs. However, for a DSO, reducing peaks in the grid is the main reason to introduce price-based demand response, and therefore, the creation of new peaks does form a barrier to introducing dynamic network tariffs. It is thus concluded that the creation of new demand peaks only forms a barrier to price-based demand response for households in case it is organised by a DSO. Therefore, Hypothesis P7 is confirmed as a barrier to dynamic network tariffs, not as a general barrier.

4.3.1.1.8. Barrier 8: different interests of electricity suppliers and distribution system operators. While all interviewed experts recognised that a price-based demand response programme by an electricity supplier could work against the interests of a DSO and vice versa, only two experts considered this to be a barrier. Even though conflicting situations could arise, for example, when an electricity supplier wants to increase electricity demand while at the same time a DSO wants to decrease it, this would happen only occasionally. Furthermore, it was expected that when an electricity supplier would try to lower the price while a DSO would try to raise, it this would lead to a sub-optimal outcome for at least one of the parties, but this would not be problematic: as long as the price incentive of the DSO would be strong enough to prevent demand reaching the maximum capacity of the grid, the consequences would be limited. It could even be argued that for the system as a whole, an optimal price is reached, as the interests of both parties are included in the final price. So even though the interest of an electricity supplier and DSO could be conflicting, the consequences would be limited and most likely it would seldom happen. Therefore, it is concluded that the different interests of DSOs and electricity suppliers do not form a barrier to price-based demand response for households. Consequently, Hypothesis P8 is rejected.

4.3.1.2. Barriers specific to dynamic network tariffs

4.3.1.2.1. Barrier 9: higher costs for large users. The interviewed experts all recognised that a dynamic network tariff based on the amount of kilowatt-hours would lead to higher costs for large users but disagreed whether this is a barrier to price-based demand response. For most experts, the subject was strongly related to the question of whether this would be fair or not. Some of the experts did not consider a higher tariff for large users to be a problem, stating that this would be fairer than the current system in which almost every household pays the same amount. Two other experts added this higher price per kilowatt-hour would create a stronger incentive for energy efficiency. On the other hand, two experts, both employed at a DSO, noted that the costs for a DSO are based on the peak use in kilowatt because this determines the maximum capacity needed. So the number of kilowatt-hours used is less relevant to a DSO, making it not a fair base for the tariff.

However, even if it would be fairer than the current system, this does not mean it would not be a barrier, because it is likely households that would have to pay more would protest. Another expert expected less protest, and a third expert concluded that even when some people would protest, this would only be a minor problem. This claim is supported by the fact that the system has been changed without problems before: in 2009, the network tariffs were changed from a system based on the number of kilowatt-hours to a system based on the size of the needed capacity. An expert, employed at a DSO and who was involved in the change of systems in 2009, added another perspective. He explained that when the system was changed, much effort was put into making sure the transition would not have a large financial impact on many consumers. Therefore, the structure of the energy tax was also adapted: by changing the tax per kilowatt-hour and the fixed tax deduction, large increases were prevented for many consumers while keeping an incentive for energy efficiency. If the system is changed again, the energy tax could again be used to prevent large negative effects for some users.

It is likely that when dynamic network tariffs would be introduced, measures would be taken to prevent large price increases for some households. Furthermore, while even in that case the dynamic network tariff can be negative for some households, it is not considered to be serious enough. Because of these reasons, the fact that dynamic network tariffs would lead to higher costs for some, that is, large users, is not considered to be a barrier to price-based demand response organised by a DSO, and Hypothesis P9 is rejected.

4.3.1.2.2. Barrier 10: not allowed by regulation. The current system, in which the network tariff is capacity based, is not part of the Electricity Act but part of a by-law, a so-called ministerial order, according to an interviewed expert working at a DSO. While changing such a by-law should be possible, the interviewed experts believe changing the current network tariff system will be a difficult process, which can take years. So the current regulation forms a barrier to dynamic network tariffs. But according to the experts, the principles on which the current system and regulation is based and the reasons why this system was chosen are the most important causes for this barrier, more than the time and effort it would take to change regulation as such.

An important principle here is that DSOs have to work in a non-discriminatory way towards anybody who wants access to the grid. This principle could prohibit DSOs from introducing price-based demand response only in certain network areas or only for certain connections, such as EV charging points. While offering dynamic network tariffs to all households could be possible, it is not necessary because in most network areas there are no problems with peak capacity.

Since the current capacity-based system was introduced in 2009, the reasons and arguments to choose this system are highly relevant when attempting to change the system again. One of the reasons for the choice of the current system was the fact that it is easy to administer (as discussed at barrier 4) while a new system would be more complex. Secondly, the current capacity-based tariff matches more with the costs of the DSO, which are determined by the capacity, not the amount of kilowatt-hours. Finally, privacy is safeguarded more in the current system, creating another reason not to change regulation.

So the current regulations, especially the principles behind it and the reasons why this system was introduced in 2009, form a barrier to dynamic network tariffs. Therefore, Hypothesis P10 is accepted.

4.3.1.2.3. Barrier 11: uncertain income distribution system operator. All interviewed experts confirmed that the introduction of dynamic network tariffs by a DSO would create uncertainty in the income of a DSO, with one expert noting that 'energy savings by households would lead to higher network tariffs' because DSOs would compensate for the loss of income by raising tariffs. However, most experts did not consider this to be a barrier to dynamic network tariffs. An expert, employed at a DSO, explained that the loss of income in 1 year would allow increasing tariffs the following year, provided the DSO is financially strong enough to handle those fluctuations in income. Because in the current system the tariff in a given year is based on the situation in

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three earlier years, the latter expert is correct in stating that this can be compensated in later years, even though this might not be directly and fully compensated. Also, the credit ratings of the largest three Dutch DSOs (Alliander, Enexis and Stedin) confirm his statement about the strong financial position.

Based on the possibility for Dutch DSOs to compensate for missed income in later years by raising tariffs and the strong financial position of the DSOs, the uncertainty about the income of DSOs due to a dynamic network tariff is not considered to be a barrier to price-based demand response and Hypothesis P11 is rejected.

4.3.1.3. Barriers specific to dynamic electricity prices

4.3.1.3.1. Barrier 12: consumers are not interested. All interviewed experts confirmed consumers are not interested in electricity. Several experts referred to the relatively low price of electricity. It was also stated that the complexity of dynamic pricing and the effort needed to move electricity demand to other pricing periods would be an extra reason why consumers would not be interested.

However, two experts added that even though the majority of consumers are not interested, a smaller group is. One of the experts, employed at an electricity supplier, stated that a critical size of 25% of consumers would be enough to realise dynamic pricing. Besides the financial benefit, he considered the benefit to the environment to be a strong argument to reach this group. Another expert, employed at a consultancy, was more specific and considered people who invest in an electric car, in solar panels or in home automation to form an interesting niche market. A third expert added that more people might become interested when the benefits of a dynamic electricity price would become clearer to consumers, owing to a virtuous circle. However, it remains uncertain how strong this effect will be, as well as how much of the people in these niche markets are really interested.

Because these niche markets are relatively small and uncertain and all interviewed experts confirmed the lack of interest of consumers, Hypothesis P12 is accepted.

4.3.1.4. Summary of barriers to price-based demand response. Based on the interviews, five out of the 12 hypotheses have been rejected. Seven hypotheses have been accepted, of which five partially, in the sense that these hypotheses have been reclassified. Three have been reclassified as barriers to dynamic network tariff instead of general barriers. Two have been reclassified as barriers to dynamic electricity price instead of general barriers. Therefore, no general barriers remain. An overview is given in Table IV.

4.3.2. Barriers to direct load control

4.3.2.1. General barriers

4.3.2.1.1. Barrier 13: lack of large suitable appliances. Almost all interviewed experts confirmed that at the moment not many large suitable appliances were available at households. Experts were sceptical about the wet appliances (tumble dryer, dishwasher and washing machine) as well as refrigerators and freezers and considered the available flexibility to be insufficient. In order to have a meaningful impact, either on the grid or on the market, controlling a very large number of these appliances would be required. Experts also referred to energy efficiency improvements, meaning the available load for DLC at households will decrease even further.

Many experts believed the situation would improve as heat pumps and EVs will bring a large amount of flexible load. This statement is supported by the fact that at the moment, more than 100 000 heat pumps [89] and 50 000 EVs [100] are available in the Netherlands. However, besides the already mentioned uncertain diffusion of these appliances, there are other limitations, such as availability of flexibility. Nevertheless, heat pumps and EVs offer a substantial controllable load. One company already had started offering DLC of EVs, albeit in combination with dynamic electricity prices.

One expert, employed at a DSO, explained that for DLC organised by a DSO, a lack of suitable appliances does not form a barrier, as in that case the DSO does not worry about peak electricity demand. Appliances such as the heat pump or EV can be controlled; hence, because the problem is caused by the same appliances that form the solution, for a DSO, a lack of suitable appliances does not form a barrier to DLC by a DSO.

Based on the fact that a lack of suitable appliances does not form a barrier to DLC by a DSO and the large number of heat pumps and EVs, Hypothesis D1 is rejected.

4.3.2.2. Barriers specific to direct load control organised by a distribution system operator

4.3.2.2.1. Barrier 14: value to the distribution system operator uncertain. The interviewed experts do not agree on whether the value to the DSO of using DLC instead of enlarging the capacity of the grid is high enough to justify the introduction of DLC. While some experts are convinced using DLC is cheaper, citing for example the high costs involved in enlarging the capacity of the grid or referring to studies that indicate DLC might be cheaper, others believe this is not the case.

Another issue is highly relevant for the value to the DSO: reliability. One of the main arguments of the experts who believe DLC is not a viable option is the uncertainty about the reliability of DLC, for example, because of uncooperative consumers in a neighbourhood. An expert, employed at a research company, refers to the large media attention a DSO receives when the grid fails and concludes that DSOs rather enlarge cable capacity. Creating a pool of appliances, to reach a larger capacity than necessary, to compensate for moments some appliances are unavailable could reduce this uncertainty, at an increased cost though. Thus, based on the uncertainty on whether DLC is cheaper than the conventional solution of enlarging the capacity of the grid, Hypothesis D2 is accepted.

4.3.2.2.2. Barrier 15: regulation obstructs the distribution system operator. The interviewed experts considered the current regulation to form a barrier to DLC programmes organised by the DSO. Besides the fact that adapting laws and regulation is a long and difficult process, two main difficulties were emphasised: (1) the interviewees confirmed that the principle to work in a non-discriminatory way hinders not only price-based demand response, as described at barrier 10, but also DLC programmes. This requirement obstructs the DSO to offer DLC only in certain areas, while offering DLC to all households is expensive and unnecessary; (2) experts confirmed that at the moment a DSO is not allowed to do anything 'behind the meter', as that is part of the household, thus making it impossible for DSOs to control household appliances.

Because of these two regulatory demands and the difficulty of changing regulation, it is concluded that regulation obstructs the DSO and forms a barrier to DLC in the Netherlands. Therefore, Hypothesis D3 is accepted.

4.3.2.3. Barriers specific to direct load control organised by market players

4.3.2.3.1. Barrier 16: not enough value to market players. Almost all interviewed experts agreed that at the moment, the monetary value of flexibility is too low. However, most experts believed the value will increase as more solar PV and wind power will be installed, as these two sources of electricity are intermittent and difficult to predict. However, it is not sure that the increase of wind and solar PV power will automatically mean the value of flexibility will increase significantly. Besides the already observed trend that even though installed solar PV and wind power increased, the use of regulating power by TenneT has decreased in the last 5 years; three extra arguments have been made.

First, an interviewed expert employed at a TSO referred to the International Grid Control Cooperation (IGCC), in which the TSOs of each country exchange current power imbalances occurring in their control zones [101], thus avoiding counterbalancing, and instead of activating regulating power, power imbalances are 'netted' (compensated) by a power imbalance in the opposite direction in other regions. This greatly reduces the need for regulating power and has a downward influence on prices. Nowadays, the IGCC includes, beside the Dutch TSO TenneT, TSOs from Germany, Denmark, Czech Republic, Switzerland and Belgium [102]. Further European expansion and deeper cooperation of the TSOs could mean the trend of less use of regulating power continues.

Second, the imbalance created by wind and solar PV power is mainly due to errors in prediction. But predictions, such as wind forecasting, have improved strongly in recent years [8]. For example, in Spain, the day-ahead errors in forecasting of the output of wind power plants have been reduced by one-third between 2008 and 2012 [103]. If predictions continue to improve, this will lead to lower prices on the balancing market.

Third, if other options, such as storage or regulation of the output of gas turbines, are cheaper to use for balancing than DLC at households, these options will be preferred. This reduces the need for TenneT to set high prices. Multiple experts also referred to demand response at the industry and commercial sector, with one expert explaining that this is preferable over households. Relative to the amount of flexibility gained, the cost at households might be higher. These costs include the costs for metering and controlling appliances, also marketing campaigns and visiting customers are expensive, which is often not taken into account.

Overall, the interviewed experts considered the value of flexibility to be too low but expected it to increase in the future because of the increase of solar PV and wind power. However, considering the decrease in the recent years, IGCC, better prediction and other options for flexibility, this is no guarantee the value will increase enough to make DLC at households possible. Therefore, the low prices on the balancing market are considered a barrier to DLC programmes of market players in the Netherlands and Hypothesis D4 is accepted.

4.3.2.3.2. Barrier 17: unsuited for the regulating market. The interview with an expert working at a TSO revealed that household demand response using DLC is not suitable for use by a TSO. In the Netherlands, the national TSO TenneT makes use of three types of reserves to balance demand and supply: regulating power, reserve power and incident reserve.

Using DLC for regulating power is not possible because it needs to be directed by the automatic frequency power regulator, meaning it should be controllable on a 4-s basis. Furthermore, it should be possible to prove that the requested power was delivered, meaning real-time metering on a 4-s basis is necessary. This is beyond the capabilities of the smart meter, so it would require extra measuring equipment. The cost needed to fulfil these requirements for control and measuring do not outweigh the benefits.

Using households for reserve power would be possible, as it does not have to be controlled directly by TenneT and a longer reaction time is permitted. However, reserve power is only used 2% or 3% of the time. Furthermore, the cheapest option is chosen first. Also, a market player would need to control hundreds or maybe thousands of appliances to reach the minimum amount of megawatts. Because of these reasons, it is highly unlikely that a market player can make a viable business case out of this.

Incident reserve is also not possible. First of all, even though it is not directly controlled by TenneT, fines are levied when the reaction of the aggregator is too slow or incomplete. Second, a minimum amount of 20 MW is required. Aggregators combining various household appliances could reach this threshold, but another interviewed expert, employed at an aggregator, added that an individual connection smaller than 500 kW was not viable to use as

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incident reserve, as the costs for control and metering of each separate connection are higher than the benefits.

Multiple other interviewed experts confirmed that household demand response is not of interest to TenneT. However, TenneT is not the only party that tries to balance the system. In fact, BRPs perform the actual balancing. TenneT has 300 MW of regulatory power to control 15 000–20 000 MW; the rest is controlled by the BRPs. In this process, the price paid by TenneT is crucial. This price is paid not only to the parties that supplied regulating power but also to each party whose personal imbalance counters and thereby reduces the national imbalance. One of the interviewed experts, employed at an electricity supplier, explained that they were already using the flexibility of industrial companies to create imbalance in their own portfolio in the opposite direction of the national imbalance. This way, the BRP helps to balance the system and is paid by TenneT. So the system is largely balanced 'passively' by the BRPs, instead of 'actively' by TenneT.

So the criteria of TenneT make the use of DLC at households for 'active' balancing impossible, but BRPs can still use the flexibility for 'passive' balancing. Therefore, the criteria and regulation do not form a barrier to the use of DLC on the imbalance market and Hypothesis D5 is rejected.

4.3.2.4. Summary of barriers to direct load control. Based on the interviews, three out of the five hypotheses about DLC have been accepted. Two hypotheses have been rejected. An overview is given in Table V.

4.3.3. New barriers

Many experts considered the technology needed to control appliances to be a barrier to DLC. At the moment, smart appliances are scarce: almost all household appliances cannot be controlled. In most experiments, the appliances are controlled with smart plugs, but the experts involved in pilots with these plugs are not content with their quality. Not only the quality of hardware forms a barrier but also the cost of installing the hardware, as well as the software needed to control the appliances and a clear lack of standardisation. Based on the arguments of the experts as well as the fact that more than half of the experts brought up the lack of hardware and software needed to control the appliances in the interviews, the technology is considered to be an extra barrier to DLC, both for a DSO and for a market player.

4.4. Overview of results

Based on the interviews, several hypotheses formulated after the literature study have been rejected. In total, seven out of the 17 hypotheses have been rejected. Furthermore, an extra barrier has been added. Finally, two hypotheses describe similar barriers: Hypotheses P10 and D3, which were both accepted, described how regulation obstructs a DSO to introduce demand response programmes. Therefore, these two hypotheses form one barrier. In total, this has led to the identification and confirmation of 10 different barriers to the introduction of demand response. An overview of the final results is given in Table VI.

Table VI. Overview of final barriers.

Type	Barriers	Label	Organiser
Price-based demand response	The uncertain benefit to consumers forms a barrier to price-based demand response for households in the Netherlands.	Customer	Market player
	The need for new billing systems forms a barrier to price-based demand response for households.	Technical	Distribution system operator
	The current allocation and reconciliation process forms a barrier to price-based demand response for households.	Regulatory	Market player
	Privacy concerns about data sharing form a barrier to price-based demand response for households.	Customer	Distribution system operator
	The creation of new demand peaks forms a barrier to price-based demand response for households.	Technical	Distribution system operator
	Dutch law forms a barrier to dynamic network tariffs for households.	Regulatory	Distribution system operator
	The lack of interest of consumers forms a barrier to dynamic electricity prices for households.	Customer	Market player
Direct load control	The uncertainty of the benefit to the distribution system operator forms a barrier to direct load control in the Netherlands.	Institutional	Distribution system operator
	Regulation forbidding Dutch distribution system operators to offer direct load control only to some consumers forms a barrier to direct load control in the Netherlands.	Regulatory	Distribution system operator
	The low prices on market form a barrier to direct load control programmes of market players in the Netherlands.	Institutional	Market player
	Technology to control appliance	Technical	Market player, distribution system operator

5. DISCUSSION

5.1. Implications and recommendations

By identifying the barriers to the introduction of demand response, in particular to Dutch households, this research contributes to both theory and practice. It fills a gap in the literature about demand response by shedding light on the specific situation of Dutch households and by giving a clear and extensive overview of what obstructs the introduction of residential demand response in this particular case. Furthermore, the identification of barriers has value to society for two reasons. First of all, the identification of barriers can give direction to which steps have to be taken in order to overcome these barriers and introduce demand response at households. This way, it can contribute to the introduction of new products or services for consumers and ultimately to more renewable electricity in the Netherlands. Second, because four demand response options were examined (based on two possible categories and two possible organising parties), it gives information on which of these options is the most viable to introduce.

Based on the results, some recommendations regarding the best demand response option can be made. The results have revealed there are many barriers to demand response programmes by a DSO, both to price-based demand response and to DLC. This includes doubt about the advantages, for example, the financial benefit and the effect on reducing peaks in the network, as well as difficulties in implementation, due to regulation, costs and technical issues. There are fewer barriers to demand response programmes organised by market players, and these are most likely easier to overcome than barriers to programmes organised by a DSO. This suggests that to successfully introduce demand response to Dutch households, the focus should first be on demand response organised by market players.

5.2. Limitations

The chosen research methods do have some limitations, which could impact the outcomes of this research. First of all, the literature study, which constituted the first part of the methodology, has been extensive but may not have been exhaustive, which might have had a negative effect on the reliability of the research. Nevertheless, collecting an extensive amount of articles as well as adding a second step to the research, that is, the interviewing of experts, has reduced the potential negative effect of this limitation on the reliability of this research.

The second part of the methodology, the interviews, has a similar limitation. The selection of experts can be considered to be somewhat arbitrary. The selection approach was unstructured: some experts were selected because in their field, they were the easiest to get in contact with. Also, some experts declined to be interviewed. This could mean some experts with a different view or more expertise have been missed, influencing the reliability of the process in which the hypotheses were either rejected or accepted. The potential consequences of this limitation have been reduced by interviewing a broad spectrum of experts, both in function and in organisation. Still, the research might have benefited from a more structured approach to the selection of experts for interviews.

Third, the research design, in which first a literature study was carried out to identify barriers and second experts were interviewed to examine the earlier found barriers, might have been too narrow. Some barriers might not yet have been described in the literature and thereby missed. A more open design, in which first unstructured, open interviews were conducted to let the experts freely identify barriers, which would later be checked by a study of literature, could have led to the identification of new barriers. The potential consequences have been limited by conducting a broad literature study, leading to a relatively large number of barriers. Furthermore, interviewees were asked if they believed other barriers existed besides the ones identified in the literature in this research. In fact, only one new barrier was identified in this way.

Even when these limitations to the research are taken into account, possible other explanations of why the introduction of residential demand response in the Netherlands is obstructed can be rejected. The structured approach of the research leads to high internal validity, because possible other explanations, that is, other barriers, have been taken into account but have been rejected after discussion with the experts in interviews.

5.3. Recommendation for further research

Based on the outcomes of this research, three interesting directions for further research can be identified. First of all, further research could focus on how the identified barriers could be overcome. Overcoming the barriers and introducing demand response in the Netherlands could reduce the fluctuation and high prices on the electricity market. By mitigating these negative consequences of renewable energy, further research could contribute to more renewable energy in the Netherlands.

Second, this research has focused on the Dutch situation. Further research could focus on different countries, to identify if similar barriers apply. Identifying barriers in other countries could give valuable information about which country would be the most suitable to introduce residential demand response first.

Third, this research has limited its focus on demand response categories in which consumers are rewarded financially for their participation. Some interviewees referred to possible changes in consumer's behaviour, that is, changes in electricity demand, for other than financial motives. However, not much is known about the effectiveness of these methods and little information is available in literature. Further research could examine if these methods face different barriers and maybe barriers that are easier to overcome. This way, further research could examine an underdeveloped field of research and contribute to the introduction of demand response.

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Table VII. Barriers to demand response for each category and organiser.

	Market player	Distribution system operator
Price-based demand response	Allocation and reconciliation process Uncertain benefit to consumers Lack of interest of consumers	Need for new billing systems Privacy concerns about data sharing The creation of new demand peaks Regulation
Direct load control	Low prices on market Technology to control appliance	Uncertainty of the benefit to the distribution system operator Regulation Technology to control appliance

6. CONCLUSION

Based on the results from the literature study and the interviewing of experts, the barriers that may obstruct the introduction of residential demand response programmes in the Netherlands have been identified. They are summarised in Table VII. Barriers depend on who introduces the programme, which can be either a DSO or a market player such as an electricity supplier. It also depends on which demand response programme is introduced: the two most likely options for households are price-based demand response and DLC. With price-based demand response, the electricity price per kilowatt-hour is not fixed anymore but changes in time. With DLC, consumers receive a fixed reward in exchange for giving a DSO or market player the ability to remotely control appliances at home.

A DSO can introduce price-based demand response by changing its fixed network tariff into a tariff per kilowatt-hour, which changes in time: a dynamic network tariff. The literature study and expert interviews revealed four barriers to a dynamic network tariff. The first barrier is the need to change the current billing system, as a new system is needed to bill all consumers. The second barrier is formed by privacy concerns, which make it impossible to make dynamic network tariffs mandatory for every Dutch household. Third, even though price-based demand response can reduce peaks in the demand, it can also create new demand peaks, which limits the effectiveness of the programme. Finally, regulation, especially the requirement to work in a non-discriminatory way (while grid problems are a local issue), forms a barrier. So the need for a new billing system, privacy concerns, new demand peaks and regulation form barriers to price-based demand response organised by a DSO.

An electricity supplier can introduce price-based demand response by changing its fixed electricity price per kilowatt-hour into a price that changes in time. When this dynamic electricity price is introduced, three different issues form a barrier. The first is the current allocation and reconciliation process, in which electricity suppliers have to pay for the assumed electricity demand by their residential customers instead of the real electricity demand and thereby limits their ability to reward customers for shifting demand. Second, the financial benefit to a household depends on their ability to shift demand, which is uncertain and can be limited. Third, consumers are not really interested in electricity and therefore most likely also not really interested in a dynamic electricity price. So the three barriers to price-based demand response organised by an electricity supplier are the current allocation and reconciliation process, the uncertain benefit to consumers and the lack of interest from consumers.

Direct load control faces different barriers than that faced by price-based demand response. Three barriers obstruct a DLC programme introduced by a DSO. First of all, it is uncertain if a DSO will benefit financially from using DLC instead of using the current solution, which is to enlarge the capacity of the grid. Second, similar to the price-based demand response by a DSO, regulation obstructs the DSO, especially the requirement to work in a non-discriminatory way and the limited role behind the meter. Finally, at the moment, the hardware and software needed to control appliances is unsatisfactory. So the three barriers are the uncertainty of the benefit to a DSO, regulation and the hardware to control appliances.

The last barrier to DLC organised by a DSO, the hardware to control appliances, also applies to the situation in which the programme is organised by a market player. Second, the financial reward for flexibility is too low to compensate for the costs of installing and running a residential demand response programme and it is uncertain if these prices will increase. So the hardware and software as well as the limited financial benefit form a barrier to DLC organised by a market player.

In conclusion, in total, 10 different barriers have been identified that potentially obstruct the introduction of demand response programmes for households in the Netherlands. Further research is necessary on how to overcome these barriers.

NOMENCLATURE

BRP: = balance responsible party
CPP: = critical peak pricing
DLC: = direct load control
DSO: = distribution system operator
EU: = European Union
EV: = electric vehicle
IGCC: = International Grid Control Cooperation
PTU: = programme time unit
PV: = photovoltaic
RTP: = real-time pricing
TSO: = transmission system operator
TOU: = time of use

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