

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Demand response and distributed solar generation in the Swedish residential sector

- A techno-economic evaluation

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Abstract

There is an urgent need to transform the electricity system so as to reduce greenhouse gas emissions. Among the possible pathways for such a transformation, the demand side of the electricity system is likely to take a more active role than it has historically. As part of this, consumers will take on the role of electricity producers, through distributed generation, as well as being more active in the management of their loads through demand-side management measures. Therefore, there is a need to investigate what this more active consumer might entail. The overall aim of the work of this thesis is to investigate the potential for demand response (DR), i.e., the shifting of loads in time, and the interplay between DR and distributed solar photovoltaic electricity (PV) generation in a Swedish context.

To assess the potential for DR in Swedish single-family dwellings (SFDs), a building-stock model that employs an hourly energy balance is used to calculate the net energy heating demand for a set of sample buildings, which are taken as representative of all Swedish SFDs with electrical heating. Actual measured load profiles are used for the analysis of the interplay between DR and solar PV. For the modeling of solar technologies, a modeling framework based on empirical models is used.

There is a considerable technical potential for the DR of electric space heating in Swedish SFDs, with 7.3 GW of load. Shifting limits of up to 12 hours are observed during summer, although the maximum number of consecutive hours with a considerable reduction in load during winter is approximately 3 hours. Given the current Swedish electricity prices, up to 5.5 GW of decreased load and 4.4 GW of increased load are observed. The modeling shows that DR shifts up to 1.46 TWh of electric heating, corresponding to 1% of the total Swedish electricity demand.

The synergic effects of DR and solar PV are significant for the DR of hydronic loads, showing an ability to reduce yearly electricity cost by up to 5% depending on the size of the installation. However, due to the seasonal mismatch between the hydronic load and PV electricity generation, the impact is diminished as PV installations increase capacity to more than 4.2 kW_p for the average household. The DR of appliance loads shows weak potential for improving the value of a PV investment, despite generous shifting time-frames.

Overall, it can be said that the economic incentives for DR are low given current electricity prices. However, DR might be valuable in a future electricity system in which more flexibility is required. The largest share of the potential of DR lies in managing the hot water and space heating loads, which may entail the least burdensome behavioral changes for consumers.

List of publications

This thesis is based on the following papers:

- I.** Nyholm, E., Puranik, S., Mata, E., Odenberger, M. and Johnsson, F. "Demand response potential of electrical space heating in Swedish single family dwellings" Submitted for publication
- II.** Nyholm, E., Odenberger, M. and Johnsson, F. "An economic assessment of distributed solar photovoltaics in Sweden - the impact of demand response" Submitted for publication
- III.** Norwood, Z., Nyholm, E., Otanicar, T. and Johnsson, F. "A Geospatial Comparison of Distributed Solar Heat and Power in Europe and the US." *PLoS One* 2014; 9(12): e112442.

Emil Nyholm is the principal author of Papers I and II. Zack Norwood and Emil Nyholm are the principal co-authors of Paper III. Professor Filip Johnsson, who is the main academic supervisor, contributed with discussions and editing of all three papers. Mikael Odenberger contributed with discussions and editing of Papers I and II. Érika Mata contributed with discussions and editing of Paper I. Sanket Puranik contributed with method development, discussions, and editing of Paper II. Todd Otanicar contributed with method development, discussions, and editing of Paper III.

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1. Introduction

The use of energy has enabled us to create the complex society in which we live. Since the 19th century, a key supplier of this energy has been and still is fossil fuels. Since fossil fuels are abundant and cheap, they drive technological progress at an increasingly rapid pace. However, the burning of fossil fuels has brought with it environmental costs, in that it constitutes the largest source of anthropogenic greenhouse gas emissions and, consequently, the main cause of climate change.

The 2°C target set out in the Copenhagen accord aims at limiting the global long-term average temperature increase to no more than 2°C relative to pre-industrial levels. To reach this goal with a *likely* degree of certainty, greenhouse gas emissions will need to be reduced by 40%-70% by 2050, as compared to the 2010 levels (IPCC 2014). As the global energy system is currently dominated by fossil fuels, achieving these reductions requires transformation of the energy system. A major part of this transformation needs to be concerned with the electricity system.

In all the scenarios conceivable for this transformation, the demand side, which is the main focus of this thesis, plays an important role: through decreased energy use, efficiency improvements, and helping to balance supply and demand in the system. Figure 1 gives an overview of the impacts of demand-side management (DSM). Since demand can be used both to optimize the use of the existing infrastructure and to avoid the need for new investments, DSM can play roles in the different pathways proposed for a more sustainable energy system. In scenarios with high levels of intermittent renewable electricity generation, for instance, those proposed by Delucchi and Jacobson (2011) and Lund and Mathiesen (2009), DSM could help to avoid curtailment of generated electricity through shifting demand or reducing the amount of needed generation by introducing efficiency measures. Furthermore, DSM could play similar roles in scenarios that propose massive expansion of the electricity grid in order to harvest remote renewable energy sources, a scenario discussed by Chatzivasileiadis, Ernst et al. (2013), or in the development of the Smart grid (Farhangi 2010). Scenarios with extensive deployment of carbon capture and storage technologies, as proposed by Odenberger and Johnsson (2010), could benefit from DSM through more efficient operation of power plants.

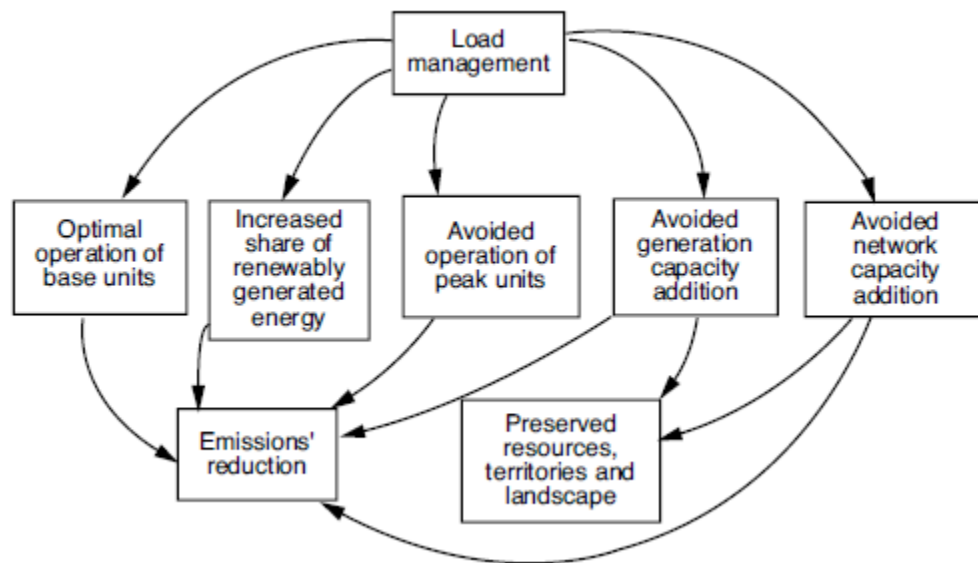


Figure 1. Different ways in which demand-side management can help in managing the energy system. Figure taken from (Abaravicius and Pyrko 2006).

Given the multiple benefits to be derived from DSM, it is highly likely that the demand sector of the energy system will play an important role in a future, more-sustainable energy system. Therefore, it is important to investigate the actual potentials of DSM.

1.1 Aim and Scope

The aim of this thesis and the appended papers is to investigate demand response (DR), which is a part of the DSM concept, and distributed generation (DG) in the Swedish residential sector. Thus, the focus is on:

- Identifying the technical potential and short-term economic potential of DR of electric space heating in Swedish single-family dwellings (SFD), and investigating the behavior the building stock as a means of energy storage in terms of using time-shifting times and capacities; and
- Investigating and quantifying the potential synergetic effects of solar photovoltaic electricity generation and demand response for Swedish households, as well as examining the impacts of different electricity pricing schemes on these synergetic effects.

The focus here is exclusively on the demand side and distributed generation; the remaining supply side is not modeled. However, possible impacts on the supply side are discussed.

1.2 Overview

Chapter 2 gives a general description of DSM/DR and distributed generation, as well as a review of issues related to the power system that could be handled using DR. It also gives an overview of strategies to incentivize DR, as well as DG. Furthermore, DR and DG in the context of the residential sector are described. The methodology section is divided into two parts. Chapter 3 gives an overview of ways to model energy demand in the residential sector and the different methods applicability in modeling DR. Chapter 4 gives the rationale behind the choice of demand modeling approaches used in Papers I and II, as well as short descriptions of the approaches that were applied. Furthermore, the solar energy modeling used in Papers II and III is briefly covered. Chapter 5 summarizes and discusses

the main findings from the three papers. Chapter 6 contains concluding remarks, as well as some ideas for future studies.

2. Demand response and distributed generation

In Papers I and II, the demand response among Swedish residential consumers is investigated. The concept of DR is part of a broader concept, known as demand-side management (DSM).

DSM encompasses a broad set of measures that can be applied to the demand side of the energy system. The objective is to diminish, increase or reshape the electricity/energy demand according to a specific goal. Included in the concept are: 1) energy efficiency measures, i.e., decreasing total load/demand either through technical or behavioral changes, and fuel-switching, e.g., replacing oil boilers with heat pumps; and 2) demand response measures, which aim at reshaping the demand without necessarily changing the total demand (Gellings 1985). While the idea of influencing demand has been around since the 1970s, it is only recently, due to increases in intermittent renewable energy sources and the emergence of an information communication technology infrastructure, that the interest in DSM has grown. Traditionally, DSM, and particularly DR, have had the goal of increasing the efficiency of the existing generation capacity, through increasing its load factor, as well as increasing the utilization of grid infrastructure, thereby decreasing the need for extra investments in peak generation facilities and grid reinforcements (Strbac 2008). This has been achieved through reducing the load during peak hours, known as ‘peak clipping’, which decreases the need for peaking capacity and building load during off-peak hours, known as ‘valley filling’, thereby increasing the load factor of base-load generation. Therefore, the main aim of DR has been to reduce peak demand (Fig. 2a). However, as more intermittent generation is introduced into the power system, it is not necessarily given that a reduction in peak demand is the desired outcome of DR. Depending on the generation profile of the intermittent source, a buildup of larger peak demand might be desirable (Fig. 2b).

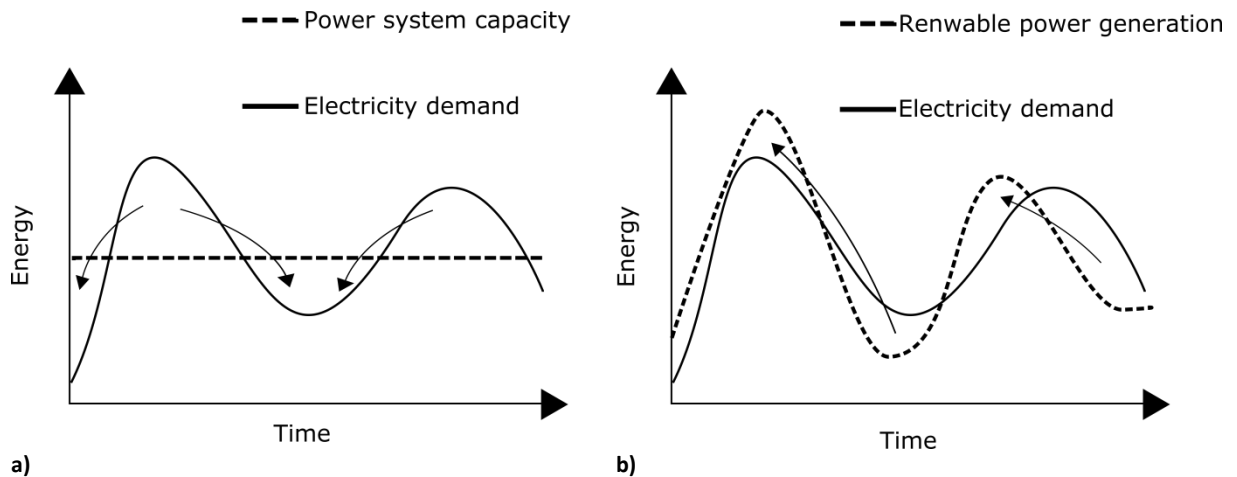


Figure 2. Difference between demand response strategies in a traditional electricity system (a) and one with a considerable level of intermittent generation (b) (Nyholm and Steen 2014).

The concept of distributed generation is generally not included in definitions of the DSM concept, as it is not a consumer load. Distributed generation is defined by Ackermann, Andersson et al. (2001) as:

“Distributed generation is an electric power source connected directly to the distribution network or on the customer side of the meter.”

Thus, it is not given that distributed generation is owned and operated by consumers. The distributed solar generation investigated in Paper II should thus be more accurately defined as consumer-based distributed generation.

2.1 The use of demand response coupled with intermittent generation

As mentioned in the *Introduction* section, DR can contribute to the handling of several issues within the power system. In both Papers I and II, the DR of energy on an hourly basis is investigated. Paper II investigates DR from the consumer perspective in terms of increased value of self-generated electricity, which means that system aspects are not investigated. In Paper I, the system implications of DR, as well as the benefits to consumers of individual consumers acting in their own best interests are investigated. Additional issues that can be handled using DR, as described found in the literature, are described below.

On a time-scale of milliseconds to minutes, stability issues concerning frequency and voltage can occur. The possibility for using DR to modulate such instabilities is outside the scope of this thesis, although it has been investigated by others, e.g., Short, Infield et al. (2007) concerning frequency control. Short, Infield et al. (2007) have concluded that allowing refrigerators to react to frequency fluctuations has the potential to confer frequency stability in cases involving sudden increases/decrease of demand or generation and during fluctuations related to wind power generation.

On longer time-scales, i.e., extending from minutes to days, the problem is that scheduled/predicted generation must meet the predicted demand. Increased intermittent generation introduces two issues concerning this requirement: uncertainty and shortage or surplus of available generation capacity. Uncertainty arises from the need to predict scheduled generation from intermittent sources with the use of forecasts. Any errors in the forecast will result in a discrepancy between scheduled generation and actual generation. This will increase the need for generation that is traded on intra-day and intra-hour markets. In such situations, DR could be used to handle the issue instead of activating additional generation. The possibility of using DR for managing forecast errors is also beyond the scope of this thesis, although it has been investigated by Madaeni and Sioshansi (2013) among others. Madaeni and Sioshansi (2013) concluded that DR in the form of real-time pricing could reduce the cost of wind uncertainty in the Texas electricity system (wind power making up 18% of installed capacity) by \$0.20–2.27/MWh of wind power generation depending on the level of uncertainty and the responsiveness of the demand.

There is also the issue of low or high levels of predicted generation. As the scheduling of generation from the intermittent sources is dependent upon uncontrollable weather patterns, it cannot be based on predicted demand. As a consequence of this, and assuming that there is sufficient intermittent generation in the system, the level of generated electricity can be higher than the demand for electricity. By the same token, when generation from intermittent sources is low there is a substantial need for dispatchable generation. The difference between demand and intermittent generation, i.e., the demand for electricity minus intermittent electricity generation, is often referred to as the ‘net

load'. The load and net load for the Danish system during 2014 (40% of electricity supply coming from wind power) are shown in Figure 3. It is clear that the net demand becomes negative during parts of the year, indicating that generation is greater than demand, which necessitates curtailment of that excess generation. In the case of Denmark, although excess generation can sometimes be exported to neighboring countries, there are still hours of curtailed generation.

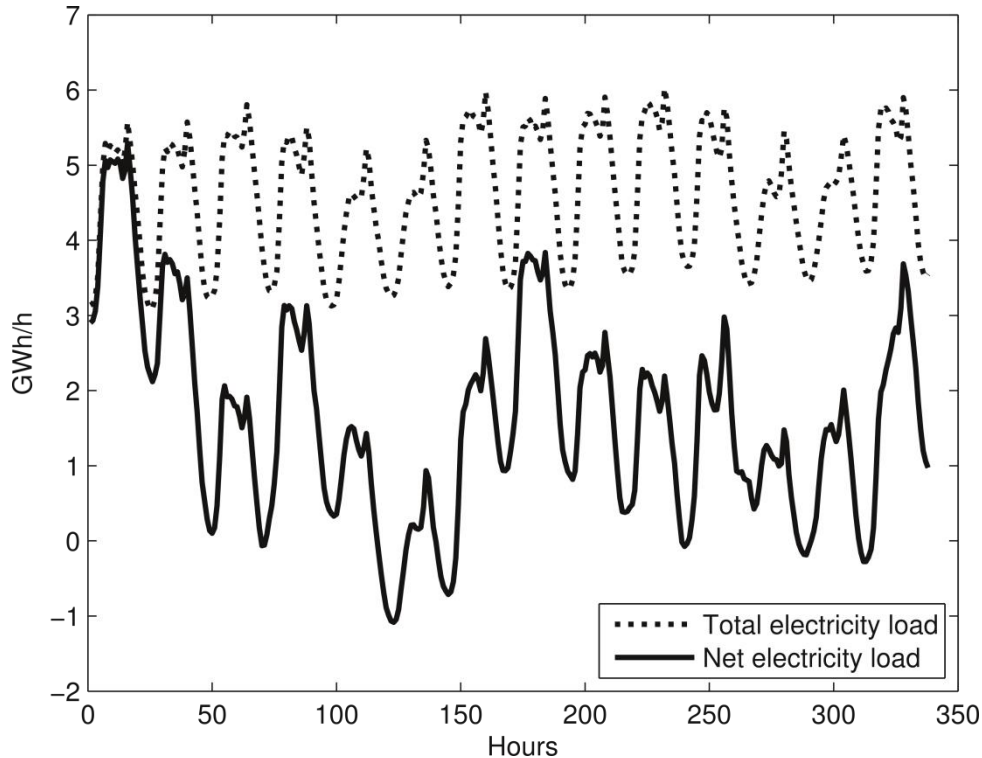


Figure 3. The total and net electricity loads in Denmark for two winter weeks in 2014.

Similarly, there are periods during which the net load is almost the same as the total demand. In these situations, DR can be used to shift load to hours with curtailment and away from hours with lack of generation, yielding a higher utilization/capacity factor for the intermittent generation and reducing the need for back-up generation. The impact on utilization times has been investigated by Hedegaard, Mathiesen et al. (2012). Hedegaard, Mathiesen et al. (2012) concluded that DR can help to reduce fuel costs and CO₂ emissions in the Danish energy system, which contains 50% wind power (on energy basis), through increasing the utilization of wind power and thereby, decreasing the need for fossil fuel plant operation.

2.2 Demand response programs

DR can be implemented through several different methods/programs, depending on the intended purpose and time-frame. In Papers I and II, DR through *real-time pricing* is applied. This tool was chosen because it is commonly regarded as the primary way to activate DR in residential demand, as the “instantaneous” cost of generating electricity is passed on to the consumer (Borenstein 2005, Borenstein 2005, Faruqi and Hledik 2009, Faruqi, Harris et al. 2010). Furthermore, following the installation of smart meters in Swedish households, it is possible for consumers to partake in real-time pricing.

On a broad scale, DR can be classified into *price-based* programs and *incentive-based* programs (Albadi and El-Saadany 2008, Palensky and Dietrich 2011). The difference between these two programs is the way in which consumers are guided into shifting or reducing load. In price-based programs, the instantaneous underlying cost of generating electricity is to varying degrees passed on to the end-consumer. The end-consumer is then free to react to the price by shifting or reducing load. However, as acting on the price signal is entirely voluntary, consumer involvement is not guaranteed, i.e., consumers can choose to pay the higher price instead of reducing/shifting load. Thus, the precise magnitude of the load reduction is not known when using price-based programs. In contrast, incentive-based programs are based on contractual arrangements between consumers and other actors in the electricity market (e.g., grid operators and utilities), and can thus be regarded as dispatchable. Consumers who are enrolled in an incentive-based program are paid for either pre-contracted or measured load reductions. Although participation in an incentive-based program is voluntary, if pre-contracted consumers fail to respond when asked they usually are penalized. An additional difference between the two DR types is that price-based programs can be applied either to affect demand continuously or only during critical periods for the power system, whereas incentive-based programs are only used during critical periods. The two programs also diverge with regard to the time-scale and electricity market segment in which they operate (see below).

The United States Department of Energy (2006) defines the following DR programs:
A. *Incentive-based* DR programs

- *Direct load control (DLC)*, whereby the utility or DSO can control remotely customer loads and use them as it sees fit. In return for making their load available, customers receive a fixed payment or electricity rate discounts, regardless of whether or not the load is used. The load is primarily used on short time-scales (>15 min).
- *Interruptible/Curtailable(IC) programs* are related to DLC, with the difference being that the utility or DSO does not have direct control over the consumers' load. Instead, the customers are asked to reduce their load to an agreed-upon level. If the customers fail to comply they face penalties. These programs operate on an hourly time-scale.
- *Capacity programs* work in the same way as IC programs, i.e., customers offer load curtailments as system capacity to replace conventional generation or delivery resources. However, the customers only receive payment for load that is actually curtailed. Customers typically receive day-of notice of events.
- *Ancillary services programs* are similar to capacity programs, although the load is used on the reserve market and customers must thus be ready to reduce load on short notices.
- In *Demand bidding/buyback programs*, end-users can offer their load curtailment at a desired price on the day-ahead market, which is analogous to bidding on generation capacity.

B. *Price-based* programs

- For *Time-of-use (TOU) pricing*, electricity prices are set at different levels during a given time period, reflecting diurnal variations, off-peak and peak hours, and even seasonal variations. These prices are generally fixed months in advance to reflect the average generation cost during the specified period.

- *Critical peak pricing* applies the same pricing structure as TOU pricing, with the added possibility to change prices during extreme peak hours at short notice.
- *Real-time pricing* is where the customers are charged an hourly fluctuating electricity price. The final electricity price can be set on a day-ahead basis or on a real-time (hour-ahead) basis, and it is supposed to reflect the actual hourly cost of electricity generation.

2.3 Distributed generation in the residential sector

Distributed generation in the residential sector has existed since the dawn of electricity generation, with one of the first hydroelectric power stations being built in the country house of Craggside in England in 1870 (Irlam 1989). However, residential electricity generation is nowadays dominated by solar power in terms of installed capacity. The value of distributed generation can be higher for consumers in the residential sector, as compared to other actors in the electricity system. The reason for this is that in addition to the wholesale price of electricity, residential consumers pay fees and taxes on the electricity that they purchase. In the case of DG in Sweden, which is considered in Paper II, an energy tax, a value added tax, and a markup are all added to the wholesale price. Furthermore, a grid fee per unit of bought electricity has to be paid to the grid owner. Thus, electricity that is generated “behind the meter” can side-step the need to buy electricity, and thus, it has a higher value than if the generated electricity was sold on the spot market. This difference also increases the residential consumers’ incentive to engage in DR, as increasing the self-consumption of generated electricity can be more lucrative than simply shifting between high-price and low-price hours.

There are several different pricing schemes for compensating residential solar PV owners for the electricity that they feed into the grid.

- An hourly RTP scheme: in similarity to the RTP scheme described in Chapter 2.2, electricity is sold and bought by the hour.
- Monthly electricity price: electricity is still sold and bought by the hour albeit at a fixed monthly electricity price.
- Net metering scheme, whereby a bill/payment is received for the monthly net consumption/generation.
- Tax reduction: as currently available in Sweden, for each kWh fed into the grid a fixed amount is added to the price.
- Feed-in tariffs, whereby consumers receive a guaranteed price for their generated electricity.
- Net billing, which is similar to net metering, except that instead of paying for the net consumption a discount is received on the following electricity bill. In this scheme, the consumer still has to pay taxes and fees on all the electricity drawn from the grid.

In Paper II, the first four schemes are investigated. Feed-in tariffs are not included, as they are only dependent upon electricity generated from PV panels, which means that there is no interplay with demand.

2.4 Demand response in the residential sector

The residential sector is made up of numerous loads of various magnitudes, both in terms of specific load size and overall level of energy used. In relation to these loads, different potentials can be specified. In Papers I and II, the *technical potential* is identified and the *economic potential* for DR is investigated. The technical potential constitutes the actual physical potential that is present, e.g., the

load of space heating and the maximum time-frame within which it can be shifted. The economic potential is the share of the technical potential that can be utilized in an economically optimal way. This potential can be viewed from a system perspective, i.e., minimizing total system costs. However, in Papers I and II, the economic potential is investigated only in part, as the supply side of the electricity system is considered to be static. Since economic potentials are seldom reached, a third type of potential needs to be introduced: *achievable potential*. This potential constitutes the share of the economic potential that is actually utilized. The size of this potential is dependent upon several factors. For the residential sector, the factors may include whether the consumer is informed of the possibility of economic savings through DR or if they feel that the eventual inconvenience outweighs the savings. Defining the achievable potential for DR is outside the scope of this thesis, as any investigation of this potential would require a behavioral analysis. Such an analysis has not been performed. Nevertheless, identifying the achievable potential is useful for identifying the gap between the achievable and economic potentials, as well as the measures that must be taken to close this gap. However, the achievable potential should not be regarded as an upper limit as to what can be attained by implementing DR (Kramer 2012).

As previously stated, the residential sector consists of a myriad of different loads, ranging from home entertainment systems to heat pumps. Theoretically, almost all of these loads are flexible if the electricity price is sufficiently high, thus making the total technical potential for DR substantial (residential electricity demand constitutes 23% of the total Swedish electricity demand). However, it is difficult to distinguish which residential loads are actually suitable for DR and to what extent these loads are available for DR. As residential consumers, in contrast to industrial or commercial consumers, are not rational cost-minimizing entities, do not necessarily follow financial logic. Furthermore, the utility that one consumer extracts from a certain load might be totally different than that obtained by another consumer, i.e., one person may be happy to postpone starting the dishwasher for 12 hours, whilst another individual is always in dire need of clean cups and runs the dishwasher as soon as it is full. The selection of loads used for the DR in Papers I and II is based on an evaluation of the literature regarding the DR potential of residential loads, in terms of energy and power, but also in terms of acceptance among consumers.

Mert, Suschek-Berger et al. (2008) investigated consumer attitudes concerning smart appliances, i.e., appliances that have the possibility to communicate and can thus be used for DR, in five different EU countries (Austria, Germany, Italy, Slovenia and the United Kingdom). They found that consumer acceptance for smart appliances was high, i.e., consumers were willing to adopt smart appliances as long as they had control over the finishing time of the appliance. The study only investigated loads that could be shifted without having a strong impact on the service that they provided; thus, loads (such as cooking appliances and televisions) that require more extensive behavioral changes were omitted. Paetz, Dütschke et al. (2012) conducted a study of consumer acceptance of smart meters, variable tariffs, and smart appliances, which included all residential loads. Similar to the findings of Mert, Suschek-Berger et al. (2008), consumers in the study were generally positively inclined to adopt smart technologies, stating that their main motivations in doing so were monetary savings and environmental benefits. However, having to change one's routine and experiencing decreasing personal flexibility limited the willingness of the subjects to engage with smart technologies. Thus, loads that must be serviced instantly, such as lighting, cooking, and entertainment, were often seen as non-shiftable by consumers. Several other studies that investigated consumer acceptance, such as Hargreaves, Nye et al. (2010), Stragier, Hauttekeete et al. (2013), and Fell, Shipworth et al. (2014), have

reached the same general conclusion that consumers are not willing to make major behavioral changes. Other obstacles/fears perceived by consumers included misuse of the measured data. Assessing the impacts of such concerns is not within the scope of the present work but obviously needs to be addressed if the potential for DR is to be realized.

Based on the work of Mert, Suschek-Berger et al. (2008), Seebach, Timpe et al. (2009) assigned residential appliance loads to four qualitative classifications with respect to their suitability for DR: 1) specific load during operation; 2) availability; 3) shifting flexibility; and 4) convenience for consumers. Where *the specific load during operation* relates to the size of the shiftable appliance load, a larger load is obviously better for DR. *Availability* relates to how often the load can be accessed for DR. *Shifting flexibility* relates to how far ahead in time the load can be shifted, where the possibility to shift the load for a long period obviously is beneficial. *Convenience for consumers* reflects the degree to which the DR operation of the appliance is likely to avoid causing inconvenience to the costumer. Table 1 shows the resulting indicators for nine different appliances. The indicators range from low (red color), indicating that the specific load performs poorly in relation to the classification, to very high (dark green), indicating that the load performs well in relation to the classification. One further classification that is important but not explicitly shown is the total shiftable energy, although it can be extrapolated by combining *specific load during operation* and *availability*. Electric heating (EH) (investigated in Papers I and II) and water heating (WH; investigated in Paper II) are the most promising candidates. The remaining loads studied in Paper II have both pros and cons, with dishwashers (DW), washing machines (WM), and driers (TD) allowing for a high load to be shifted, although they have low availability. For refrigerators/freezers the opposite is true.

Table 1. Classification of nine different residential loads in four different aspects that are important for DR potential. The colors correspond to how well the different loads perform in relation to the different classifications, ranging from red (poorly) to dark green (very well). Adopted from Seebach, Timpe et al. (2009).

	WM	TD	DW	RF	FR	AC	WH	EH	CP
Specific load during operation	high	high	high	low	low	mod.	high	very high	low
Availability	low	low	low	high	high	low	mod.	mod.	mod.
Shifting flexibility	mod.	mod.	high	low	low	low	mod.	high	mod.
Convenience for consumers	low	low	mod.	high	high	low	mod.	high	mod.
Abbreviations: WM, Washing machine; TD, tumble dryer; DW, dishwasher; RF, refrigerator; FR, freezer; AC, air conditioner; WH: water heating; EH, electric heating; CP, circulation pump; mod., moderate.									

It is clear from these studies that washing machines, dryers, dishwashers, refrigerators, freezers, tap water heating, and space heating are the loads that are most accepted by consumers for use in DR, as well as being among the largest loads in the residential sector. Therefore, the initial modeling and analysis of DR in the residential sector was focused on these loads, as in Paper II (all of the above) and Paper I (space heating).

The demand side of the energy system could be used as a tool to address several different issues that can arise as the energy system is transformed, ranging from frequency regulation on the millisecond scale to the shifting of energy demand over days. As shown, there are several ways to incentivize both DR and distributed generation in the residential sector. The combination of these two factors could also generate additional benefits for consumers through increasing the value of the distributed generation. The possible economic benefits of such a combination in the Swedish context have not

been investigated previously. Papers II and III shed light on the possibilities for this combination. Furthermore, it is shown that electric heating (space heating and hot tap-water heating) has the largest potential for DR in terms of energy, load, convenience, and flexibility. Thus, it is of interest to investigate the potential for DR of electric space heating and how it can be used (Paper I).

3. Literature review of residential electricity demand models

Traditionally, modeling of residential electricity demand has been used to generate demand forecasts that can be used for planning expansions of the power system. When modeling electricity demand for DR purposes, some requirements that are not essential for traditional demand modeling have to be met. First, a time resolution that is sufficiently high to address the intended purpose of the DR, i.e., if the purpose is to model frequency response a resolution of milliseconds is needed, whereas for energy balances an hourly resolution is adequate. Second, it is desirable that the method is able to generate specific load profiles for different end-uses. However, it is not required to know these profiles in order to model DR. Third, if the storage of energy is to be included, e.g., through thermal inertia of buildings or hydronic heating systems, a description of the characteristics of that storage needs to be represented. Fourth, if a country/region-wide potential is desired the model needs to be scalable. This chapter gives a brief overview of residential electricity demand models and their suitabilities for DR modeling with respect to these requirements. Furthermore, the rationale behind the approaches used for DR in the different papers is given. These approaches are the actual measured load profiles on an appliance level (in Paper II) and a model describing the thermal behavior of the Swedish single family dwellings (SFD) building stock (in Paper I). A short description of the methodology used for solar energy modeling (Papers II and III) is also given.

3.1 Overview of methodologies for modeling residential electricity demand

Electricity demand models have been reviewed extensively (Swan and Ugursal 2009, Kavgić, Mavrogianni et al. 2010, Grandjean, Adnot et al. 2012, Torriti 2014). However, the usefulness of these different models in terms of DR modeling has not been studied. Below, the most common approaches to demand modeling and their applicability to DR will be presented briefly.

There are two overarching types of modeling frameworks used in demand modeling: top-down and bottom-up. Top-down approaches make use of macroscopic data, such as GDP, appliance prevalence, floor area, and other factors that can influence electricity demand, and thereby create econometric models. Such models are not suitable for modeling DR as they do not allow for a sufficiently high temporal resolution, so they are not covered in this overview.

Bottom-up models can be broadly divided into statistical models and engineering models. These models have in common that they, in contrast to top-down models, model the electricity demand and profile based on individual houses/households and thereafter scale up/extrapolate to represent the entire building stock or a targeted type of consumer. For statistical models, such house/household load profiles are created through regression analysis, more specifically *conditional demand analysis (CDA)* (Parti and Parti 1980) in the case of individual loads, or through evolutionary or supervised learning algorithms. Such algorithms can be *artificial neural network models (ANNs)* (Park, El-Sharkawi et al. 1991) and *support vector machines* for supervised learning or *genetic algorithms* in the case of evolutionary algorithms. Other types of algorithms in conjunction with those mentioned above have also been used. As ANNs are the most commonly used, they are the only models covered here. Engineering models work by modeling each end-use separately using data that describe the end-use. The behaviors of occupants can also be included. The different approaches in engineering models include *probabilistic* models (Capasso, Grattieri et al. 1994) and *archetype* models (Mata, Sasic Kalagasidis et al. 2013).

The CDA method was first developed by Parti and Parti (1980). In contrast to other regression model approaches used for demand prediction, CDA breaks down the contributions of the individual loads to the total household load. Here, selected appliances are used as some of the independent variables to explain the total demand, which is set as the dependent variable. The minimum required in terms of data is the total electricity demand curve for individual households and the existence or non-existence of appliances. A disadvantage of CDA is that appliances with a high penetration rate cannot be distinguished from the remaining load due to multicollinearity. This is a drawback because these appliances include a large share of appliances thought suitable for DR. The time resolution that can be achieved is dependent upon the available data. New loads cannot be introduced, as the profiles are extracted from existing data. Furthermore, there is no possibility to represent energy storage possibilities.

An ANN employs statistics to learn the relationship between the input values and desired output values, without relying on an actual physical description of the loads. The name ANN is inspired by the neural networks in the brains of animals. Park, El-Sharkawi et al. (1991) were the first to use this method to describe electricity demand. The method uses several layers of what are called neurons, where the layers can be classified as the input layer, hidden layers, and output layer (Fig. 4). The signal/information, e.g., time of day, flows from the input layer that continue through the hidden layers and arrive at the output layer, e.g., electricity consumption for dishwashers. The output from each neuron, with the exception of the input neurons, is generated by passing through a function the weighted output values from all the neurons in the previous layer. The values of the weights in each layer are determined by a learning/training algorithm, which adapts the weights using an input set and a target output set. The weights are changed until the error between the output and the target output becomes sufficiently small. The target/training output set would comprise the actual measured load curves, and the input could be the temperature or time of day. With this method, a sufficiently high time resolution is possible given that consumption data are available. Similar to CDA, new loads cannot be introduced because the profiles are extracted from existing data. Furthermore, to represent the storage input, data that describe the storage, e.g., indoor temperature or water storage temperature, need to be collected.

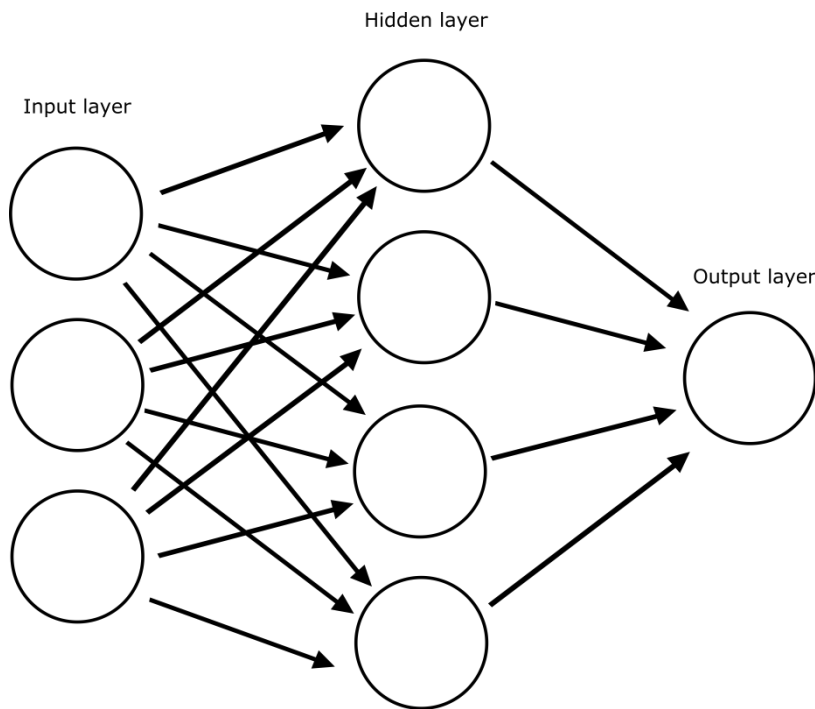


Figure 4. The concept of an artificial neural network.

In engineering modeling approaches, synthetic load profiles are created based on appliance and/or building data, e.g., cycle times and power demand appliances or the thermal behaviors of buildings. These models can also be coupled with functions that describe the behaviors of the household inhabitants. Models that incorporate inhabitant behavior on an individual household level can be classified as *probabilistic models*. These probabilistic models aim to mimic the behaviors of household inhabitants, e.g., what time they leave the house or what time they use the dishwasher, and thereby construct load curves for different end-uses. This is done through assigning probabilities to occupancy and occupant behavior. The level of detail used to describe the behaviors varies between models. Paatero and Lund (2006) used a random factor to determine occupancy level. Others have based their behavior analyses on so-called ‘use of time’ surveys where participants are asked to keep a diary of their daily activities, together with information on where the activities were performed and with whom (Capasso, Grattieri et al. 1994, Richardson, Thomson et al. 2010, Widén, Molin et al. 2012). These data are then used to create a model for occupancy behavior. To create descriptions for a specific region, all the households in the region are modeled and then aggregated into a single load curve. The models allow for very detailed DR modeling, as the actions of individual occupants are considered and given that the data for appliance behaviors are available, a high time resolution is possible. New loads can be introduced to the model if the technical data for them are available. The occupant behavior for the new specific load can obviously not be modeled, but must instead be based on assumptions. In a similar way, storage can be added. However, if the DR in an electricity system on a country scale is to be investigated, individual occupant resolution is not feasible.

Models that use archetypes or samples include a limited number of households, supposedly representative of the diversity within the region being modeled. These parameters are then weighted so that the total load for the region is calculated. In the case of archetypes, this is achieved through creating a set of typical representations for the load that is to be modeled. Paper III is based on this concept and uses a physical building model together with the 571 archetypes developed by Mata, Sasic

Kalagasidis et al. (2013) to describe the space heating demand of the Swedish SFD stock. Occupancy behavior in the form of probabilistic models for archetype households can be incorporated into archetype models. Shimoda, Fujii et al. (2004) applied a *use of time* study to specify 460 archetypes composed of 23 household types and 20 dwelling types. The model was used to describe the load profiles of end-uses and the total load for the city of Osaka. Time resolution can be high given that appliance data are available. However, if weather-dependent loads, such as space heating, are modeled the resolution of the available weather data would also limit the time resolution. Storage can also be included. Scaling up the results is easy, as the archetypes are selected to represent the region being modeled.

Table 2 summarizes the presented modeling approaches, as well as their suitabilities for DR modeling. All these approaches, with the exception of the top-down macroeconomic approach, can be used in DR modeling. However, if some form of energy storage or new load is to be introduced engineering approaches are the only suitable choice. Furthermore, the use of CDA or learning algorithms requires extensive measured data in order to be useful for modeling in a larger context. Therefore, an archetype engineering approach seems to be the most suitable for modeling large systems.

Table 2. Overview of the suitabilities of different electricity demand modeling approaches for DR modeling.

Modeling approach	Time resolution	Load resolution	Storage representation	Scalability	Suitability for DR
Top-down macroeconomic	Low	High	No	Yes	Not suitable
CDA/regression (Parti and Parti 1980)	High	Medium	No	Yes, given that data are representative	Suitable, requires extensive data
Learning/genetic algorithms (Park, El-Sharkawi et al. 1991)	High	High	Yes	Yes, given that data are representative	Suitable, requires extensive data
Engineering probabilistic (Capasso, Grattieri et al. 1994)	High	High	Yes	Low/High if coupled with archetypes	Small-scale or in combination with archetypes
Engineering archetype (Mata, Sasic Kalagasidis et al. 2013)	High	High	Yes	High	Suitable

3.2 Usage of the different methodologies for demand response modeling

The choice of demand representation is dictated by the chosen way of modeling the DR. Depending on which potential is to be investigated, the approach to DR modeling can vary. Listed below are some examples of how the different demand modeling approaches are used for DR.

The use of CDA in combination with DR has not been described in the literature. However, CDA has been performed on an hourly time-scale by Aigner, Sorooshian et al. (1984). The use of neural network demand modeling to estimate the technical potential for DR has not been reported previously,

whereas ANN is widely used for load profile forecasting. The absence of these two modeling approaches for DR is likely due to the fact that if hourly loads for individual end-uses are to be modeled extensive data regarding the load data for each end-use have to be available. Currently, such measured data are not readily available.

Archetype models have been used by Hedegaard and Balyk (2013) to model the DR of space heating/HP and investing in accumulation tanks in Denmark. By investigating the economic potential for DR by incorporating it into an energy system dispatch model, they have concluded that DR can reduce the need for peak and reserve capacity investments. Papaefthymiou, Hasche et al. (2012) investigated the economic potential for DR of heat pumps in two future German electricity systems with RES penetrations of 36% and 47%. This was achieved through incorporating heat pumps into a mixed-integer stochastic optimization model, which dispatches electricity generation and includes uncertainty related to the wind forecast. They did not include the investment cost for the heat pumps, but instead evaluated their value in terms of their ability to reduce the system cost.

Probabilistic models have been used to investigate DR. Paatero and Lund (2006) used load curves created from their probabilistic model (based on a random factor for occupancy) to investigate the possibility to cut peak load. This was achieved by generating 10,000 household load curves and then applying predefined shifting schemes. Gottwalt, Ketter et al. (2011) used hourly variable electricity prices together with a probabilistic model to apply DR to household loads. Widén, Molin et al. (2012) introduced a different DR modeling approach, in which the probability of a load being activated was to a certain extent governed by the electricity price, resulting in more loads being initiated during low-price periods and *vice versa*. This enables the model to capture the actual potential, as not all the loads are moved and the behavior is not deterministic.

To model DR, it is not necessary to know the specific end-use load profiles. Sioshansi and Short (2009) used short-term price elasticities for electricity demand to model real-time pricing for DR in the region served by the Electric Reliability Council of Texas. They investigated the impacts of DRs on the curtailment of wind, and concluded that it could increase utilization by 7% given an elasticity of -0.3, and thereby increase the value of wind generation. Bruninx, Patteeuw et al. (2013) used cross-elasticities, thereby capturing demand changes due to price changes in other hours. The cross-elasticities are needed, since once the load is shifted a decrease in one hour will lead to an increase in another hour. They concluded that cross-elasticities are not suitable because they give rise to erratic unexplainable behavior.

Gils (2014) performed an extensive evaluation of technical potential of DR in Europe, which included all the demand sectors and suitable loads within each sector. Each load was assigned a characteristic load profile based on meter data or characteristic load profiles taken from other sources. Gils concluded that there was a minimum load reduction potential of 61 GW and a maximum load increase potential of 68 GW in the European electricity system for every hour of the year.

In summary, engineering methodologies represent the dominant approach when modeling electricity demand for DR purposes. This is probably due to the need for extensive measured data with a high temporal resolution in CDM or ANN if the potentials on a system scale are to be investigated. In Papers I and II, engineering approaches are used to model demand. One major benefit of the engineering modeling approach is that it allows for the inclusion of the modeling of energy storage. As storage of

energy is both modeled in Paper I, through storing heat in the building structure, and in Paper II, through the storage of energy in water tanks, an engineering approach was required.

4. Modeling in this work

As shown in Chapter 3, a modeling framework for describing the electricity demand is needed in order to model DR. As Papers I and II aim to investigate the DR of all SFD electric space heating in Sweden and household loads in combination with PV, respectively, a description of the loads is required. Paper III creates a modeling framework for several different solar energy technologies, enabling a comparison. Furthermore, the results from Paper III serves as an input to the description of PV generation used in Paper II.

4.1 Demand response modeling

This work applies two types of DR modeling. In Paper I, an archetype engineering modeling approach is used that describes the Swedish SFD stock. This is because the overall DR potential of electric space heating in Swedish SFDs is investigated, so an approach that describes all of Swedish SFDs is required. Paper II applies an engineering modeling approach using actual measured demand profiles of Swedish households. This is the case as only the consumer perspective is investigated, and there was no need to scale up to a system level. However, the sample used should represent a cross-section of households. The use of actual measured data also allows for the inclusion of all possible loads, which would otherwise only be possible through a detailed probabilistic engineering modeling approach.

In Paper I, the technical potential of utilizing the Swedish SFD stock as energy storage via the introduction of changes to the indoor temperature is examined. Furthermore, the impact on demand of DR caused by the current hourly real-time pricing scheme available to end-consumers is investigated. To capture the thermal inertia of the building stock and temperature-dependent heat losses, both of which are important factors in characterizing the DR potential, a bottom-up engineering modeling approach is used. An energy balance involving 571 archetype households/SFDs/houses is modeled and then scaled up to represent the complete Swedish building stock. The energy balance is described by Mata, Sasic Kalagasidis et al. (2013). Changes that were made to the original input data of Mata et al. (2013) include the inclusion of hourly variations in internal heat gains, as well as power ratings for the electric heating systems (further details can be found in Paper I). Using an archetype model is necessary as modeling every single household is unfeasible, both from the model run time and data handling perspectives.

In Paper II, the impacts on consumer investment of DR coupled with solar PV for different electricity pricing schemes are investigated. The measurements used represent 21 different Swedish SFD households taken from a previous study by Zimmermann (2009) for evaluating energy efficiency measures. The loads investigated concerning DR are: dishwashers; washing machines; dryers; refrigerators; freezers; hot tap-water heating; and hydronic heating. The shifting period applied in the case of appliances is 24 hours, and in the case of cold appliances 1 hour either to a preceding or a succeeding hour. For the hydronic space heating and hot-water demands, there is the possibility to store heat, which means that the shifting time variable is only limited by the size of the storage. The sizing of the storage is based on a detailed description of the modeling approach, which can be found in Paper II.

In both modeling approaches, the generation side of the electricity system is assumed to be constant and unaffected by changes on the consumption side.

4.2 Solar energy modeling

In Paper III, an extensive modeling framework is presented that incorporates the following different solar energy systems: non-tracking photovoltaics (four different PV technologies are included: poly-Si, mono-Si, CdTe, and CIGS); 2D-tracking photovoltaics; high-concentration photovoltaics; flat-plate thermal; evacuated tube thermal; concentrating trough thermal; concentrating solar combined heat and power; and hybrid concentrating photovoltaic/thermal. In the modeling empirically verified models are used for thermal and PV collectors. However, a physical model was applied for the hybrid concentrated photovoltaic/thermal collector because no empirical verified model was found. To investigate the synergetic effects of solar PV generation and electricity demand, which is the goal of Paper II, it is essential to describe the PV electricity generation with a temporal resolution similar to the investigated demand, as well as accurately describing the electrical output from the technology. This requires a modeling framework similar to the one presented above, which makes it possible to accurately determine hourly electricity outputs given that data for that resolution are available. For a more detailed description of the modeling procedure, see Paper III.

5. Results and Discussion

The results presented here are an overview of the results concerning DR in the Swedish residential sector from Paper I and Paper II. The results cover the technical and economic potentials of DR for SFDs, as well as the possible economic gains for households from the DRs of space heating, tap water heating, and appliances. The possible synergies between solar PV generation and DR are then presented, and the application of DR in the Swedish system is discussed. The results from Paper III are used in part in the discussion, but are also fundamental components of the results presented in Paper II.

5.1 Demand response potentials in the Swedish residential sector

Technical and short-term economic potentials of DR

In Paper I, the technical and short-term (the production side is considered fixed) economic potentials for DR of space heating in Swedish SFDs is investigated. Figure 5 shows the total electric space heating demand and the level of electric space heating demand shifted for each month of Year 2010, as obtained from the modeling in Paper I. With approximately 1.46 TWh out of 17.5 TWh of total electric heating demand shifted, it is clear that only a fraction of the available demand is utilized under the current price structure, and that the majority of the demand is shifted during the winter months. It is not certain that the total electricity demand is available for shifting, as it is dependent upon the extent to which households are willing to change their indoor temperature. In Paper II, it is shown that the upper boundary of an allowed temperature increase of 2.8°C (from 21.2°C to 24°C) only limits the amount of load shifted to a certain hour during a few hours with shifting. Overall, it can be said that given the current electricity price structure the price of electricity is limiting the potential of DR.

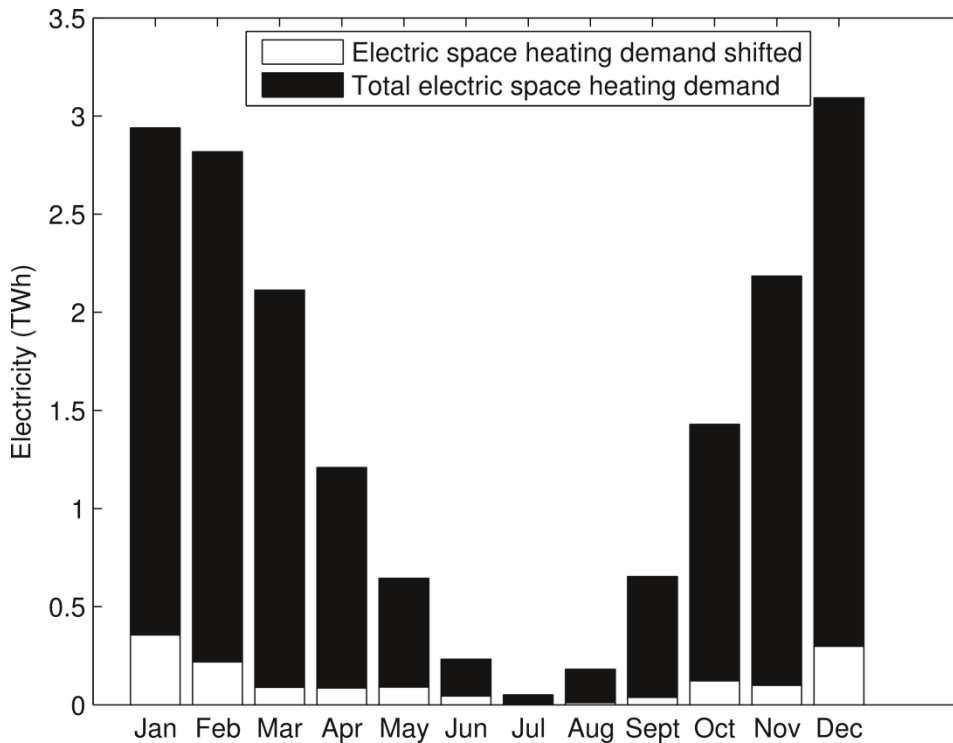


Figure 5. The total electric space heating demand for each month for Swedish SFDs during Year 2010, and the level of demand that is shifted, as obtained from the modeling. Compiled from the results in Paper I.

All parameters that have an impact on the energy flux in and out of a building, as well as its volumetric heating capacity will influence the time-frame for possible shifting. Thus, the pattern of shifting varies with the actual season and time of day. The maximum amount of time observed between an increase and decrease in space heating load is 12 hours during the summer. During winter months, shifting periods become shorter, as energy is lost to the surroundings at a higher rate, with the longest observed shifting times being 10 hours. However, the maximum number of consecutive hours with a considerable reduction in load during winter is approximately 3.

Regarding the technical potential identified, the installed heating capacity is 7.3 GW (assuming a fixed COP for heat pumps) and the building stock has the ability to retain 6.9 GWh/°C (with a high level of uncertainty due to the rough estimates of the effective heat capacities of the buildings). In the modeling, an increase in load of up to 4.4 GWh/h and a decrease in local of 5.5 GWh/h are observed.

In both Paper I and Paper II, the shifting of load through storing energy in the form of thermal energy results in an increase in electricity demand. This loss is considerably smaller for households with hydronic heating (Paper II), as compared with other heating sources, due to the possibility to store the energy in a water tank instead of within the building structure itself. The DR values presented in Figure 5 result in an overall electric heating demand increase of 0.9% (152 GWh).

Economic gains from DR

In Paper I, the economic gains from shifting electric space heating is investigated, while Paper II shows the economic gains associated with shifting hydronic space heating and hot tap-water heating, as well as appliance loads for a sample of Swedish SFDs. In both cases, it is clear that for the prevailing electricity prices and price structure the economic incentive for an individual consumer is low. Modeling the results from Papers I and II shows that taking into account the electricity price in Sweden during Year 2010, the investigated year with the highest electricity prices (64% above the 14-year average annual price for electricity and exceeding the average diurnal price fluctuations), the economic incentive for space heating in Swedish SFDs is in the range of 0.3%–12% (average, 3%) of the yearly electricity cost. The corresponding monetary value range is 0.9–330 €/year (corresponding to 0%–1.3% of the median disposable income of persons living in Swedish SFDs). Similar values are reported for the DR of hydronic loads in Paper II. The values for appliance DR are considerably lower, with savings of 0.3% on the annual electricity cost.

Synergies of demand response and distributed solar generation

As mentioned in Chapter 2, additional value can be derived through combining DR and consumer-based solar generation, and this is investigated in Paper II. Figure 6a shows the improvement in annual electricity cost from combining DR of hydronic loads and solar PV (with the size of installation here represented as the array-to-load ratio, ALR) for the households investigated in Paper II. The improvements are in comparison to having an hourly electricity price without DR. The maximum, minimum, 25th and 75th percentiles, as well as the mean value for the investigated households are shown. Figure 6b shows the corresponding data for the DR of appliances. As shown in Figure 6a, as the ALR increases the DR exhibits an s-curve with regard to its ability to improve the yearly electricity costs. The impact of combining PV and DR is negligible up to an ALR value of 0.5, owing to the absence of excess electricity generation from the PV panels. As all the electricity is already being used in-house, there is no extra gain to be derived from shifting loads. For all the households, diminishing returns for the benefit of DR are apparent at an ALR of 3. This happens even though the available shiftable load is considerably larger than the total PV electricity generation at this ALR value, with an average of 8100

kWh/year of available hydronic DR compared to on average of approximately 4000 kWh/year of electricity generated. Thus, the observed s-curve indicates that most of the new solar electricity generation with an ALR >3 occurs during hours in which there is no possibility to utilize the additional available DR loads.

There is a noticeable spread in values among the investigated households, which increases with increasing ALR. However, they all show the same s-curve.

For the appliance loads shown in Figure 6b, an s-shaped curve is also observed, showing the same properties as for the hydronic DR. In addition, the improvements in annual electricity cost essentially plateau for ALR values ≥ 3 . This leveling out of the improvements shows that the technical limitation of the synergetic effects of appliance DR and solar generation is reached even with a generous shifting time of 24 hours applied. However, it should be noted that the largest appliance loads, for refrigeration and freezers, are not as flexible (± 1 hour), which reduces their usefulness. Furthermore, the synergetic effects of appliance DR and solar PV are less pronounced than those of the DR of hydronic loads, with improvements in electricity cost of <1% compared to 4.5% points for the hydronic loads. However, the maximum value shows a considerably higher increase with increasing ALR. This is attributed to one single household and explained by the fact that the appliance load constitutes a relatively large part of the total load of that household. Thus, it exhibits a lower ratio for generated electricity to shiftable load, as compared to the other households.

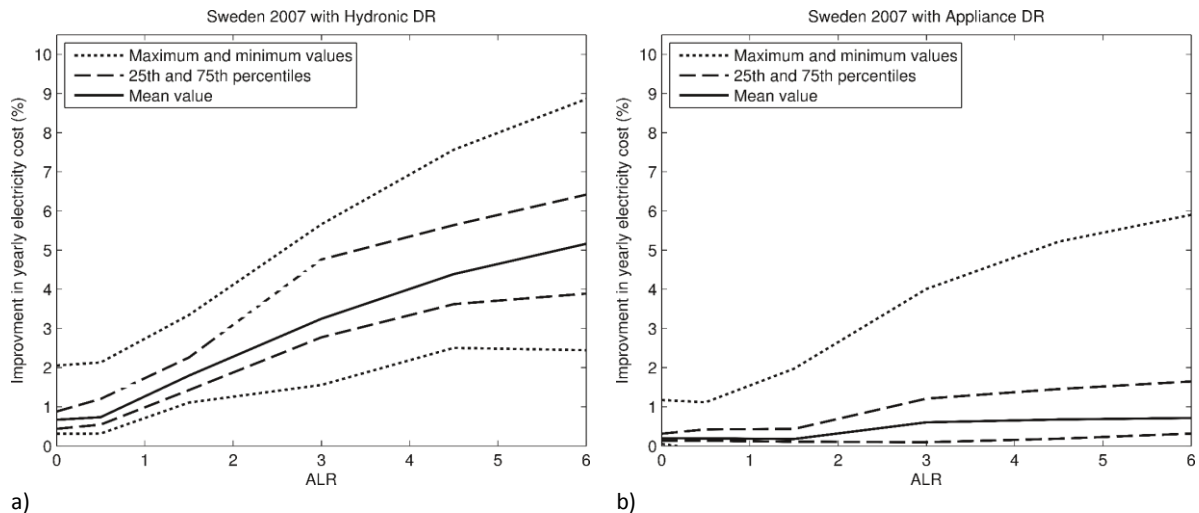
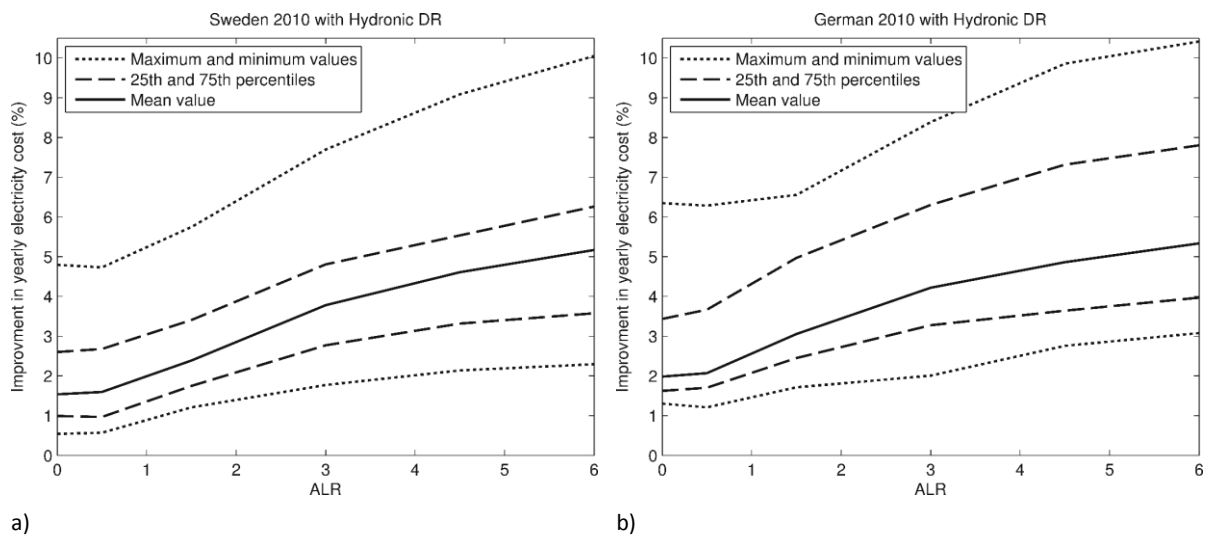


Figure 6. Improvements in annual electricity costs compared to an hourly pricing scheme for different ALRs for: a) DR of hydronic loads; and b) DR of appliance loads. Adopted from the results in Paper II.

In Figure 7a and b, a pattern similar to that in Figure 6 is shown, albeit for the electricity prices in Year 2010 for Sweden (a) and Germany (b). As shown in Paper II, the higher electricity prices in these years (64% and 25% higher than the 14-year average annual electricity prices for Sweden and Germany, respectively) generate an incentive to invest in larger PV panels. However, despite larger diurnal price variations (which is the most relevant time-frame for DR coupled with solar power) over the 2 years (on average: 30% for Sweden in Year 2010 and 60% for Germany in Year 2010, as compared with 10% for Sweden in Year 2007), the synergetic effects of combining DR and solar PV are actually smaller compared to those identified for Year 2007. This is due to the fact that the improvement in yearly electricity cost is smaller between ALR 0 and ALR 6 for these 2 years, with mean increases of 3.5% and 2.5% for Sweden and German, respectively, as compared to 4.5% for Sweden in Year 2007. This is the case because in both of these years, solar electricity generation coincides with the higher daytime electricity prices, thereby reducing the marginal value of shifting electricity to these hours. Thus, as long as dispatchable generation predominates and demand is the main price setter, higher price variations will dampen the synergetic effects of DR and solar PV. The overall value of DR for the 2 years is nonetheless larger, as shown in Papers I and II and discussed above, due to the benefit achieved through shifting load from high-price hours to low-price hours.



a) b)
Figure 7. Improvements in annual electricity cost compared to an hourly pricing scheme for different ALRs for DR of hydronic loads for: a) the Swedish electricity price in Year 2010; and b) the German electricity price in Year 2010. Adopted from the results in Paper II.

Figure 8 shows the improvements in yearly electricity cost from combining the DR of hydronic loads and solar PV for the tax reduction pricing scheme (hourly electricity price with an increase in value of €0.069/kWh for electricity sold to the grid). It is evident that with increasing ALR the value of DR is considerably reduced. An s-shaped curve can still be discerned, as the underlying shifting limitations described above are still there. However, as the price difference between selling the electricity and using it in-house is smaller, the incentive to shift hydronic loads is reduced (this is the case since the storage of heat results in an increased demand due to losses; see Paper II). Although the increase in impact of DR with increasing ALR is small, implementing the tax reduction scheme preserved the incentive for DR between hours with high and low electricity prices. For years with larger fluctuations

in electricity price, retaining the DR possibilities can result in savings of up to 6% of the yearly electricity cost, as can be seen in Figure 7b.

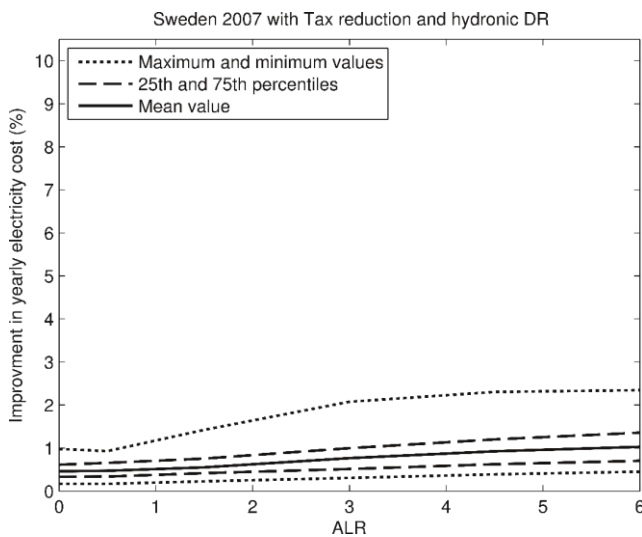


Figure 8. Improvements in annual electricity cost compared to an hourly pricing scheme for different ALRs for a tax reduction pricing scheme coupled with the DR of hydronic loads. Adopted from the results in Paper II.

5.2 The potential uses of DR in Sweden

Solar power

As shown in Paper II, the use of a net metering pricing scheme results in an economically optimal investment in solar PV for a household. Thus, if maximal installation of PV capacity is desired, applying such a pricing scheme would be beneficial. However, doing so would remove all the incentives for DR. The implementation of the tax reduction scheme discussed above (which is in currently in use in Sweden) would result in practically the same installation sizes as net metering whilst retaining the incentive for DR. Even though there are no large gains to be made from combining DR and PV generation given the tax reduction scheme (see Figure 8), it is important that the incentive for DR between hours without PV electricity generation is retained. As is also shown in Paper II, DR has a considerably smaller impact on increasing the value of the consumer's PV investment compared to the discount rate that they apply. Similarly, the value of the DR of hydronic loads is comparable to the reduction in PV investment cost seen over the last couple of years (it should be noted that a continuous price reduction of the same magnitude is unlikely). Therefore, future investment cost reductions are more likely to spur investment in PV than is an incentive to implement DR. Furthermore, it should be noted that at current (2014) electricity prices, investments in PV are not profitable in their own right.

Depending on how electricity prices develop in the future, the economic benefits to be derived from the combination of DR and solar PV will vary. If the price of PV installations continues to fall and installations become more prevalent they could start to influence electricity prices. This is already happening in Germany, which is experiencing lower electricity prices during hours with high solar generation, with a solar PV penetration of 6.5% (on an energy basis). Such a price structure would reduce the overall profit associated with investing in a solar panel. However, it would increase the value of DR in combination with PV. Although, as described above for ALRs >3, the physical restrictions imposed on the DR start to reduce its impact; a different electricity price structure would not alter this.

Furthermore, the restrictions linked with using the hydronic space heating load in combination with PV obviously translate to the electric space heating load investigated in Paper I. In fact, the potential is even lower because tap water heating is not included. The restriction is also evident when the monthly DR potentials (Fig. 5) are compared with the seasonal electricity generation output from solar PV for Sweden (Fig. 9) (results from Paper III). It is clear that the level of electricity generation is considerably higher during summer than during winter, with the monthly DR potentials showing the opposite pattern (Fig. 5).

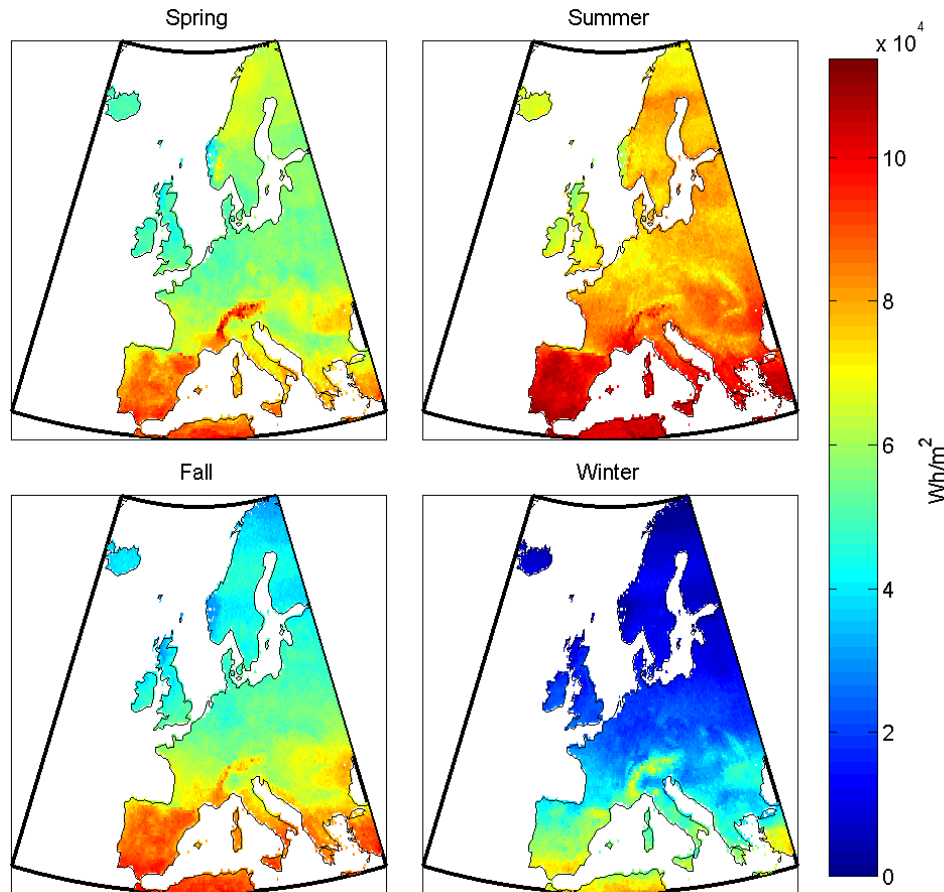


Figure 9. Seasonal electricity generation from one square meter of collector for a non-tracking mono-Si PV system. Figure taken from Paper III.

Other benefits and drawbacks

As discussed above, the skewed generation profile of PV's, i.e., considerably higher output during summer than during the other seasons, limits the usefulness of DR as high levels of solar PV enter the system. The other major intermittent energy source is wind power. The usefulness of DR in conjunction with wind power is not the focus of this work. However, the values obtained for the technical potential and economic potential in Paper I can be compared to those for the installed wind power capacity in Sweden (4.4 GW) and the amount of energy generated from that capacity (11 TWh). This power capacity is of the same magnitude as the installed heating capacity. Holttinen (2005) has shown that the longest time periods with low (<5% of installed generation capacity) generation can be up to 50 hours in the Nordic electricity system. Given the current installed wind capacity in Sweden and an assumed average capacity factor of 0.2, 33 GWh of storage would be needed to increase the capacity

factor from 0.05 to 0.2 during the 50-hour period. Such an increase would correspond to an indoor temperature increase of at least 4.8°C in all Swedish SFDs (ignoring the increase in demand due to increased heat transfer). However, as shown in Paper I, the maximum shifting time for an allowed temperature change of 2.8°C is 12 hours. Thus, although there is a fair amount of energy available for shifting, the time-frame during which this energy can be shifted is too short compared to the observed time-frame for variations in wind output.

Furthermore, it should be noted that the capacity available to increase and decrease space heating load is not constant. During the cold winter months, the potential to decrease load is generally greater than the potential to increase load, whereas the opposite is true for the summer months. This phenomenon does not apply to appliance loads.

The considerable power capacity noted for the electric space heating demand could also be used to address several of the issues presented in Chapter 2.1, e.g., to forecast errors and to enable frequency stabilization. As the change in load is instantaneous, it could help to reduce the need for spinning and non-spinning reserves used during contingency events. A possible 3–4 hours of reduced load, as described in Paper I, would be sufficient for power from the tertiary reserve market to be activated. However, as the need for contingency services in the case of a failing power generator or transmission line cannot be planned, consumers would have to accept a reduction in indoor temperature to below the desired level if electric space heating was to be used. As the indoor temperature would have to be restored, any tertiary reserve activated would need to handle this increase in demand. The seasonal variations in heating load (Fig. 5) obviously hamper the ability of heating loads to replace contingency services.

Obviously, other factors will have impacts on the usefulness of DR, e.g., the correlation between generation and demand and the surrounding generation system. For instance, the Swedish electricity system contains a sizeable amount of regulatable hydropower, which obviously can execute the same functions as increased use of DR. This could limit the usefulness/need for DR in the system. However, as transmission connectivity with continental Europe increases, restricting the system to Sweden would be wrong.

The use of DR through day-ahead pricing for controlling the shifting electric space heating load results in new overall system peaks. This behavior indicates that automation of the DR could require a more centralized control system, i.e., some form of dispatch of the DR loads.

6. Conclusions and future work

Demand response and distributed generation are two tools that could be used to restructure the energy system in a way that is less CO₂-intensive. The work within this thesis is concerned with the technical potential and short-term economic potential of DR of electric space heating in Swedish SFDs, as well as the synergetic effects between DR and distributed solar generation.

Under the current conditions in Sweden, the amount of electric heating demand that is shifted is low, with only 8% of demand being used. As this shifting is primarily limited by economic incentives, it will be possible to utilize the electric heating demand to a greater extent if desired. The shifting times observed indicate that management of solar power variability may be the optimal strategy. However, there is a poor correlation between heating demand and solar generation. The technical potential for DR of electric space heating is 7.3 GW and 6.9 GWh/°C in terms of power and energy, respectively. However, given the current Swedish electricity prices, up to 5.5 GW and 4.4 GW of this potential are used for decreasing load and increasing load, respectively.

No synergetic effects are seen between distributed solar generation and DR up to an ALR of 0.5, as all the generated electricity is already used in-house. Up to an ALR of 3, increasing returns from DR appear for both hydronic loads and appliance loads. However, the skewed generation profile of solar generation of electricity limits the synergetic effects of DR and solar PV. This limitation results in diminishing returns for DR as the ALR increases above 3, as excess electricity generation will primarily occur during hours in which the possibility for DR has been exhausted. This effect is prominent for the DR of appliance loads, where essentially no increase is seen from combining DR and PV for ALR values >3.

Furthermore, the tax reduction obtained for excess electricity that is sold to the grid preserves the connection between the price and the time period during which the electricity is generated. Thus, as market penetration of PV panels increase and starts to influence electricity prices, the tax reduction could be retained without distorting the reimbursement scheme for generated electricity. This would also preserve some of the incentive for consumer DR.

It can be concluded that the economic incentive for DR is low given current electricity prices. This is true both in relation to DR that is coupled to residential PV generation and DR without PV generation. Moreover, in the case of DR of electric space heating, the economic gains represent the main limitation to DR, which means that considerably more of the identified technical potential could be utilized. It is also debatable whether day-ahead pricing should be used as the driver for automated DR.

Overall, it is clear that heating loads have the strongest potential as DR loads. These loads, in particular hydronic heating loads, would also be a good initial stepping-stone for the implementation of DR, not least because the impact on everyday life would be minimal.

To evaluate the full energy system potential of DR in the residential sector, the impacts of DR on the generation side of the energy system need to be evaluated, especially considering that system values that are not reflected in the price paid by consumers could become available. This can be achieved through incorporating the DR into a wider system context in which modeling of the dispatch of the supply side is included. This would also allow assessment of the benefits of DR used in combination with wind power.

The combination of consumer-based, distributed solar PV and energy storage in the form of batteries, with the goal of increasing self-consumption, also warrants investigation.

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