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CAN DEMAND RESPONSE MITIGATE THE IMPACT OF INTERMITTENT SUPPLY?

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INTRODUCTION

Traditional electricity systems have been designed to have the production side respond to changes on the demand side. The production has consisted of base load plants, generating electricity at a fixed level, and flexible power plants following demand fluctuations. However, increased electricity demand creates a need for more production and grid capacity. To avoid or defer such investments, it is possible to instead give customers incentives to reduce their demand during peak load hours. This concept is often called demand response (DR). DR, which deals with manipulating the demand curve, is part of a broader concept called demand side management (DSM) which encompasses all measures implemented on the demand side of the energy system.

As shown in Chapter 9 the introduction of renewable power could lead to new challenges for the electric grid, e.g. congestion and frequency instability. The need for flexible production or consumption may thus increase. Hence the importance of demand response may increase with increased production of intermittent renewable power. In Figure 10.1, the issues that can be addressed are encircled, it can be seen that demand response can help alleviate problems both on short timescales (milliseconds to minutes) and medium timescales (hours to days).

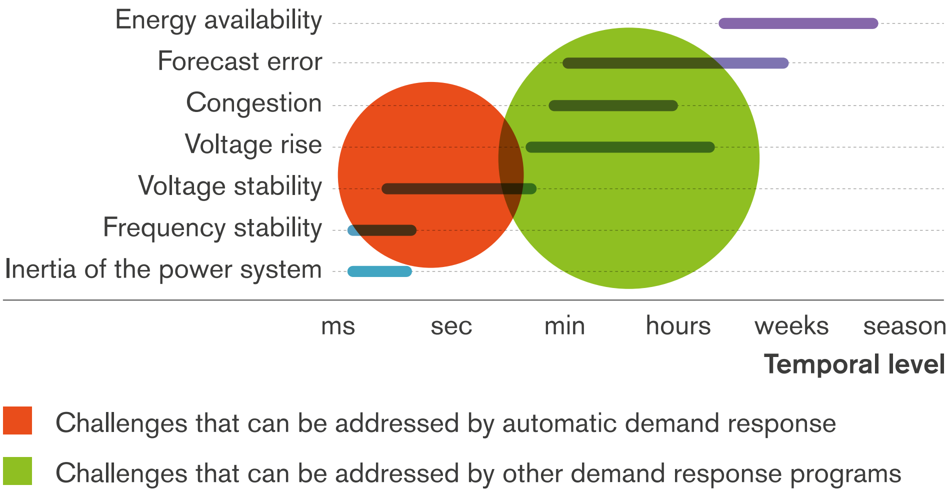

Figure 10.1 Grid related challenges where demand response could be effective; the red circle represents the challenges that can be addressed by automatic demand response; the green circle represent challenges that can be addressed by other demand response programs.

In this chapter some of these solutions are addressed together with a short summary of what demand response entails for different demand sectors. Two case studies are presented investigating how demand response could support integration of intermittent renewables to increase the maximum penetration level in the distribution system and to reduce congestions in the transmission system.

WHAT IS DEMAND RESPONSE?

Electricity demand is to a large degree seen as uncontrollable from a producer's point of view and varies with time of day and season, and consists of a large number of individual loads, from home appliances to industrial equipment. Conventionally, these loads and any changes in them are met by varying electricity generation up or down. However, some loads are not immediately required and could be shifted in time. Demand response implies that loads are dispatched or reduced to balance demand and supply. This dispatch occurs through implementing incentives or restrictions for the electricity consumer who is in control of the load. Demand response is thus a change made in the consumption pattern of an electricity consumer instigated by some driving force.[1] This change can be load curtailment, i.e. reducing the load, or a load shift, i.e. shifting the load in time. Thus, demand response can both result in a reduction of demand as well as a shift of demand in time. A reduction should not be equated with efficiency improvements as the reduction is due to a removal of load and not an improvement of its efficiency.

Traditionally, demand response has meant that the demand should be "flattened" to as large degree as possible.[2] The rationale for this is that less variation in demand reduces the need for reinforcements of weak grids (see Chapter 9),

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[1] Palensky, P and Dietrich, D. (2011) Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads, *IEEE Transactions on Industrial Informatics*, 7(3):381-388.

[2] See for example Doudna, J.H. (2001) Overview of California ISO summer 2000 demand response programs, *IEEE Power Engineering Society Winter Meeting,* 1:228-233.; Albadi, M.H. and El-Saadany, E.F. (2008) A summary of demand response in electricity markets, *Electric Power Systems Research*, 78(11):1989-1996.

reduce the losses, reduce investments in new peak power plants and reduce the use of expensive peak power plants, i.e. generation units with high running cost (Chapter 11). However, as more intermittent production is introduced, the goal is no longer to “flatten” the demand but instead make demand follow the intermittent patterns from the renewable production.

Figure 10.2 illustrates the difference in strategy, the left graph being the traditional way of demand response and the right presents demand response in a system with distributed intermittent generation. It can be seen that in the case of distributed intermittent electricity production a shift in demand could lead to increases in peak demand compared to the traditional case where the goal always is a reduction in peak demand. It should be noted that for distributed intermittent generation the increased peak demand may not affect the upstream grid since the electricity is produced locally while for systems with large centralised intermittent generation, e.g. large offshore wind power parks, the possible load shift may be limited by the transmission capacity of the grid.

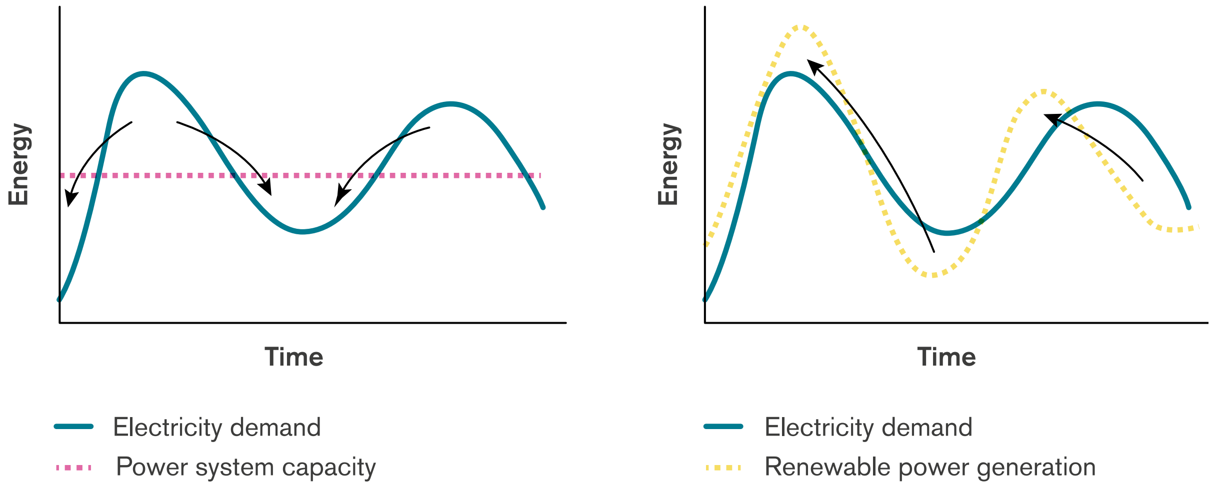

Figure 10.2 The difference between demand response strategy in a traditional electricity system (the left) and one with a considerable amount of intermittent generation (the right).

DEMAND RESPONSE IN DIFFERENT DEMAND SECTORS

Controllable loads are available in all sectors on the demand side, domestic, commercial and industrial. However, the sizes of the loads, how far in time they can be shifted, how inconvenient it is and the cost associated with shifting vary between different sectors.

For the domestic sector demand response could mean shifting of loads which services are not immediately required, e.g. starting the dishwasher an hour later. Other examples of similar loads are washing machines and dryers. Such loads are used to shift energy and can usually be shifted quite far in time (hours). However, once they have been started it is often inconvenient to stop them. There is also the possibility of using loads that can be shifted for short periods of time (up to minutes) but can be started and stopped without major implications, e.g. freezers and refrigerators. These loads can then be used for frequency control (see Figure 10.1). Electric space heating, water heating and air conditioning could also be used through storing hot water or allowing the indoor temperature to vary within a given temperature range. The size of space heating and cooling loads and the timeframe over which they can be shifted depend on building material and isolation as well as weather conditions. Available loads in Swedish households are provided in Table 10.1. The largest potential lies in shifting the heating demand. In warmer regions air conditioning is instead the major load.

All of these measures cause no or little inconvenience for the end user as the service of the appliance is still provided. However, there are limits to how far in time these loads can be shifted. These limits are set by the preferences of the consumers, i.e. the acceptable temperature range and acceptable time a load can be postponed or advanced. There is also the possibility for the consumer to avoid using a load altogether. However, this would imply that the service is not provided thus possibly reducing the comfort of the user.

Table 10.1 Important characteristics and corresponding average values for different DR loads in Swedish households with a distinction between single family dwellings (SFD) and multi-family dwellings (MFD).[1,2]

		Load size (Energy demand)		Cycle time	Displacement time	Prevalence
Load	**Household type**	**(kWh/year)**	**(kWh/cycle)**	**(hours)**	**(hours)**	**(appliance per household)**
Space heating[1]	SFD	6800-20000	n.a	n.a	n.a	n.a
	MFD	n.a				
Water heating[1]	SFD	1500-3000	n.a	n.a	n.a[2]	n.a
	MFD	n.a				
Fridge	SFD	200-230	n.a	n.a	0-1	0.62
	MFD	140-260				0.32
Fridge-Freezer	SFD	410-530	n.a	n.a	0-1	0.38
	MFD	450-500				0.58
Freeze	SFD	370-590	n.a	n.a	0-1	0.88
	MFD	330-440				0.45
Dishwasher	SFD	140-240	0.2-1	2	0-24	0.9
	MFD	70-210				0.51
Washing machine	SFD	110-210	0.3-1.2	1-2	0-24	1.01
	MFD	60-170				0.52
Dryer	SFD	100-130	0.4-2	1	0-24	0.59
	MFD	240-320				0.15

[1] Includes only direct electric heating. Source: Zimmermann, J. P. (2009)

[2] No values are given for space and water heating loads as these values highly depend on the storage capacity and the acceptance range for temperature fluctuations. Source: Timpe C. (2009)

In the commercial sector, which includes public buildings as well as offices and shopping malls, controllable loads are similar to those in the domestic sector. However, the possibility to shift appliances is limited, since most loads are used continuously, e.g. computers. Air conditioning and heating loads have, as in the domestic sector, the largest potential. There are other loads that could be used as well, for instance ventilation and regulation of the intensity of lighting.

For the industrial sector demand response could mean rescheduling of loads or shedding loads, i.e. stopping production or using duel fuel systems where other fuels can temporarily replace electricity. Industry demand response is already to some extent used today, through industries that take part in the electricity reserve, balancing and frequency markets. Here industries commit to shutting down loads in case the strain on the power system becomes too big. However, there might be possibilities for industries to reduce their costs further through a more active demand response.

Stopping production is associated with a loss in income, and to be attractive, savings from avoided electricity use have to be equal or greater than this loss. This means that electricity intensive industries, i.e. industries where electricity is a major part of production cost, are more likely to engage in demand response. Another limiting factor is the relatively low fluctuations in electricity prices making production planning based on electricity cost a low priority even if there where savings to be made. Rescheduling of loads requires that the load in question is flexible. Loads which operate at maximum capacity, i.e. are operated at all times, obviously cannot shift in time. Similarly, loads that are bounded to certain hours cannot be shifted either. In such cases, load shedding is the only possibility.

DEMAND RESPONSE PROGRAMS

There are several different ways to create incentives for electricity consumers to take part in demand response programs. Demand response programs could be designed in different ways depending on the aim. Figure 10.3 presents some of the DR programs that are in operation today. Most of these programs, e.g. critical peak pricing (CPP), locational marginal price (LMP) and direct load control (DLC), have been introduced to cope with issues related to power system stability and capacity problems in the power system. However, some could also be beneficial to use in systems with a high share of intermittent electricity generation. This section introduces some of the DR program that are employed today and that could be used to balance production from intermittent renewables.

As discussed above, demand response can mainly support renewable energy sources in the short to medium time range. On the short time range, e.g. for frequency stability, automatic demand response programs, such as direct load control (DLC), must likely be used to manage the fast response time needed. On the medium time range, other concept such as, real time pricing (RTP) can be an efficient measure to cope with intermittency in the production on a daily basis.

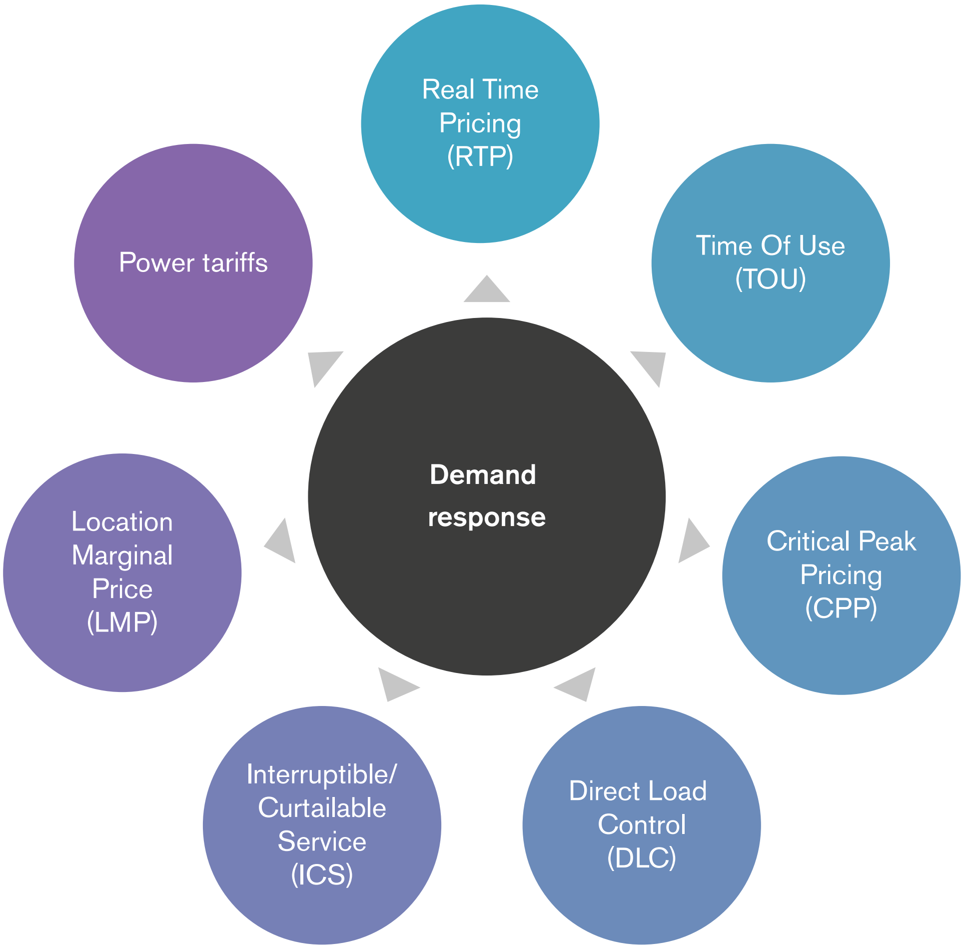

Figure 10.3 Different types of demand response programs.

DLC programs can be implemented both to cope with local congestions in the power system and for frequency control. These programs are most often automatically controlled and the customer appliances receives a signal from the transmission system operator (TSO) or distribution system operator (DSO) to reduce or turn off the power. Other ways are to use frequency measurement that automatically reacts on frequency deviations. Traditionally, customers could sign up for these programs and were then economically compensated for their reduction. However, other business opportunities arises, e.g. TSOs could subsidise thermostatically controlled equipment, such as refrigerators, heat pumps, air conditioners or water boilers equipped with a frequency control unit to give customers incentives to buy them. A study has shown that an aggregation of a large number of dynamically controlled loads has the potential to provide significant added frequency stability to power systems, both at times of sudden increase in demand (or loss of generation) and during times of fluctuating wind power.[3]

As discussed in Chapter 9 and 11, it is likely that the need for regulating power increases with increased levels of intermittent renewable generation. In the Nordic electricity market, the demand side can participate in both the regulating market, e.g. to maintain the balance and frequency within the system, and in the peak load

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[3] Short et al. (2007) Stabilization of Grid Frequency Through Dynamic Demand Control, *IEEE Transactions on Power Systems*, 22(3):1284-1293.

reserve, a reserve used to meet the demand when it is critically high. Today the majority of the reserve is provided by the generation side although the Swedish TSO is aiming at increasing the participation of the demand side.[4]

Although it is possible for electricity customers to participate, the requirements regarding response time and regulating capacity is high. These requirements leads to that the participating customer must either have a high demand, which is the case for industries or large commercial buildings, or be aggregated together with other customers. With evolving business models and increased incentives, the demand side participation may play an important role in the future regulating market.

The idea with real time pricing (RTP) is to let customers react on price fluctuations on the electricity markets by reducing or increasing their flexible demand. The electricity price depends both on the demand and the available generation. When there is a surplus of generation or low demand, the electricity prices are generally low while the opposite holds when there is a shortage of generation or high demand. For power systems with a high share of intermittent generation, situations with surplus or deficit will likely be more common and lead to a more volatile electricity price. RTP will create incentives for customers to reduce their demand during peak hours and increase it during off-peak hours, or during hours with excessive renewable production. This would both increase the power system reliability and help integrating intermittent renewable energy sources.

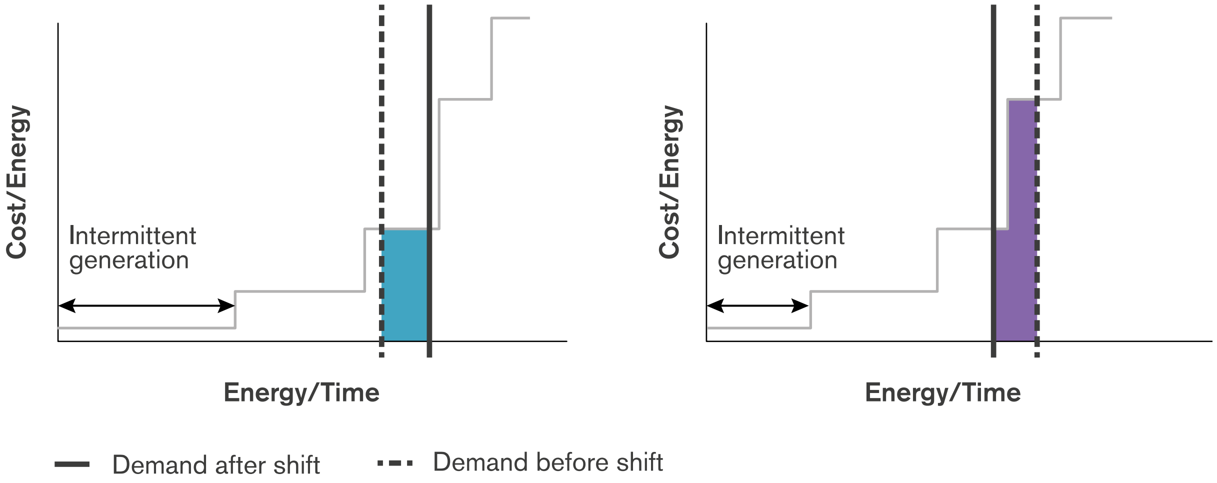

Figure 10.4 Supply curves for two different hours, one with a high amount of intermittent generation (the left) and one with a lower amount of intermittent generation (the right). The coloured areas are the reduction in system cost (purple) and increase in system cost (teal) after a shift of demand from the hour with low intermittent generation to the hour with high intermittent generation.

As an example, one can take two hours with the same amount of load. During one of the hours there is a lot of intermittent renewable electricity generation and in the other there is not. As the generation cost of intermittent renewable electricity is almost zero the marginal cost of production would be different in the two cases, see Figure 10.4. In the low intermittent renewable generation case (to the right in Figure 10.4), the marginal electricity cost is higher. If load could be moved from

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[4] Svenska Kraftnät. (2011) *Principer för hantering av effektreserven*. Press release. [accessed March 16 2011].

the hour with low intermittent renewable generation to the hour with high intermittent renewable generation the total cost of electricity for the two hours could be reduced. The area marked purple is the decrease in system cost for the low intermittent renewable generation hour and the area marked teal is the increase in cost for the high intermittent renewable generation hour. The purple area is larger than the teal resulting in a net reduction in system cost.

One important aspect regarding the design of an RTP scheme is the time difference between the announcement of the price to the customers and the actual consumption. A long time lag, e.g. using day-ahead price, would result in a price that less accurately reflects the demand and supply, which may result in increased need for balancing power. A shorter time lag would result in better reflection of the balance between demand and supply but with more difficulties for the customer to plan their electricity consumption, since they must forecast the electricity price for the coming day. Since the load profile could vary within different parts of a price area there is a risk of increasing the peak demand locally. The risk also increases with longer time lags and higher shares of flexible demand. This could be solved by implementing RTP together with some other demand response program such as power tariffs or locational marginal price.[5]

WHAT CAN DEMAND RESPONSE DO AT THE DISTRIBUTION SYSTEM LEVEL?

As shown in Chapter 9, the amount of intermittent electricity generation that could be integrated into the medium voltage distribution system investigated in the case study without any need for reinforcements of the system was limited to about 30% of annual demand. Reinforcing the system may be costly and other measures can be used to enable higher penetration levels at a lower cost. One of these measures could be to use DR.

A model aiming at investigating how DR can be used to increase the amount of PV that could be integrated into a residential distribution system without any reinforcements is currently under development at Chalmers. The model uses the same distribution system that is presented in Chapter 9. Up to now, only heat loads, e.g. space heating, are considered to be flexible although other loads, such as laundry machines, dishwashers and plug-in electric vehicles (PEV), can participate in the DR program and will be included as the model is further developed.

Preliminary results show that, by using DR, a higher share of PV can be integrated into the existing distribution system before reinforcements are required. Without DR the penetration level could reach 5.2 m^2 per building whereas with DR it could increase to about 7.8 m^2 per building. This means that, on a yearly basis, about 45% of the energy consumed can be generated from local PV systems, compared to 30% without any DR programs.[6]

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[5] Steen, D. et al. (2012) Price-based demand-side management for reducing peak demand in electrical distribution systems – with examples from Gothenburg, *NORDAC 2012*, Aalto, Finland, Sep. 10-11.

[6] This study focuses only on the static limitations such as line loading, voltage rise and transformer loadings, while other issues like protection system and short term harmonics are not treated. Further, the heat demand is assumed to be equal in all buildings and has been estimated based on the outdoor temperature and the average heat demand for a house in that region. The possibility to shift the heat supplied to a building in time is due to the thermal inertia of a building, i.e. some energy is stored in the building materials. For the study a relatively low thermal inertia has been assumed, to avoid overestimating the potential of DR. On the other hand, the thermal model of the building is simplified and the study assumes that there exist incentives to customers to participate in the DR and that all customers have the possibility to participate.

WHAT CAN DEMAND RESPONSE DO FOR CONGESTION IN THE TRANSMISSION NETWORK?

As presented earlier in the chapter, demand response can work on different timescales and help to address different problems that can arise when introducing intermittent renewable production in the power system. One of these issues is congestion in the transmission grid (see Chapter 9). Demand response can reduce congestion by adapting the demand in a region where import or export of electricity is limited by congestion. One can see demand response as a decentralised way of managing variations, i.e. the variation is managed in the region confined by congestion, which stands in contrast to the more centralised way of investing in new transmission lines in order to spread variations over a larger geographical area. These two strategies are thus two ways to increase the economical or environmental performance of systems with large amounts of intermittent generation.

Alleviating congestion by DR is illustrated here by the same model that is used in Chapter 9. Europe is divided into fifty different regions based on bottlenecks in the transmission system, i.e. areas between which congestion is likely to occur. In the example, describing Europe in 2020, 17% of the electricity generated comes from solar or wind and CO_2 emissions are reduced by 44% compared to 1990 (see Figure 9.3).[7]

Three scenarios are presented, a reference case with no demand response, a case where 10% of the load for a region during an hour can be delayed up to six hours and one with 20% and a delay time of up to 24 hours. The effect demand response has on congestion, i.e. on differences in marginal cost of electricity between regions, is investigated. The standard deviation of the marginal costs in the fifty regions is used as an indicator of the overall congestion in the system, here referred to as System Congestion. If the standard deviation is zero the marginal costs are the same in all regions and no congestion exists. It should be noted that the System Congestion parameter only says something about the relative marginal costs between regions, i.e. demand response could lower marginal costs in two regions, reducing total system cost, but the value of System Congestion could stay the same. System Congestion is thus only an indicator of reduced congestion and not of a change in total system cost.

In Figure 10.5, the System Congestion during three winter weeks is shown as well as the total European wind power output for the same period. As can be seen, the System Congestion is largest during peak load hours. This is mainly due to the fact that the desired power flow between areas is higher when the demand is high. Further it can be seen that the System Congestion generally increases for hours with high wind power production. As discussed in Chapter 9, the areas with high wind power production cannot export enough electricity to the neighbouring areas due to congestion resulting in large difference in the marginal electricity cost between areas. For the 10% and 6 hour DR case, System Congestion is somewhat reduced during peak load hours. However, the trend seen in the reference case is still there. With 20% and 24 hour DR, System Congestion is substantially

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[7] Göransson, L. et al. (2013) Linkages between demand-side management and congestion in the European electricity transmission system, *Energy*, 69:860-872.

reduced both for peak load hours and non-peak load hours, indicating that the delay time and DR volume plays an important role when DR are being used to reduce congestion in the power system. It can also be noted that even in the most optimistic DR case, System Congestion is still more prominent during periods with high wind power production.

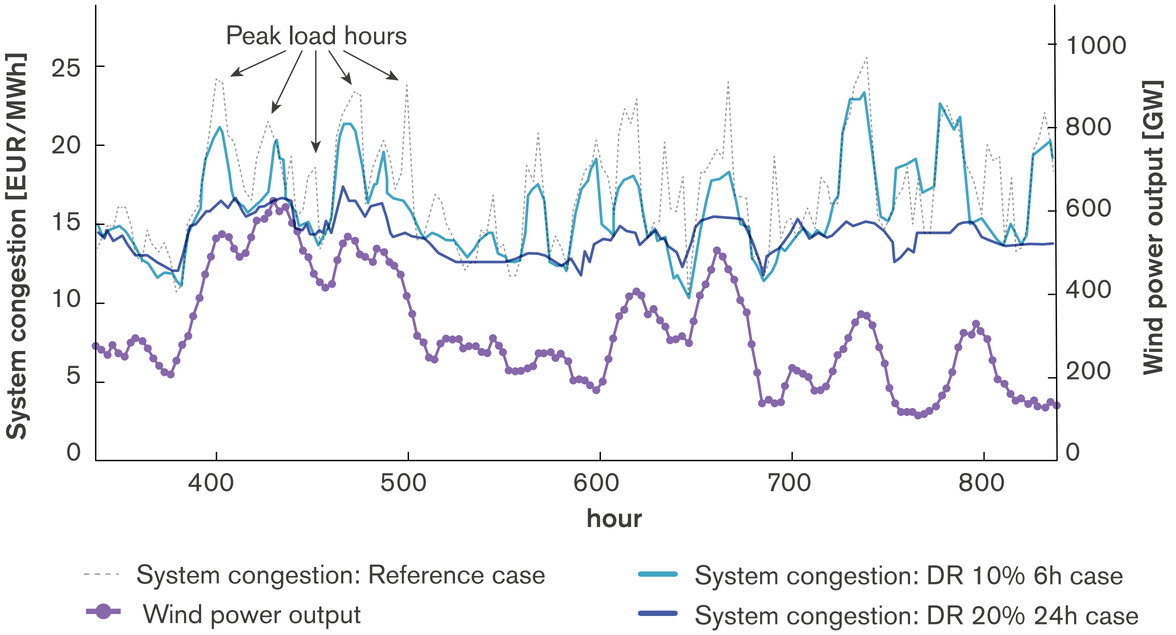

Figure 10.5 System Congestion and total wind power generation for three winter weeks. Three cases are shown one with no DR and two with DR, for both DR cases System Congestion is reduced.

Three types of congestion patterns are identified. In the following, we analyse the ability of demand response to alleviate each type.

The first type is peak hour congestion. Congestion between regions arises during peak load hours forcing the importing region to switch to a more expensive marginal generation technology. Such congestion occurs primarily between regions dominated by thermal generation. Demand response can shift load away from peak hours to off-peak hours, resulting in lower System Congestion during peak hours and higher utilisation of transmission lines during off-peak hours.

The second type is low load hour congestion. Congestion arises between regions where one region has a high share of intermittent generation relative to its load and the other region has a load that is large compared to export possibilities of the transmission line. During hours of low load and high wind power generation congestion arises between such regions. For these hours wind power is setting the marginal price in the region with a high share of wind production. However, limits in the transmission line prevent enough electricity to be exported to change the marginal generation technology in the importing region. Implementing demand response in such a case has a low impact on congestion as the controllable load is small compared to the generated wind power in the wind power region. This means that shifting load to hours with high wind power generation will not affect marginal production technology in the region during these hours and thus the congestion remains.

The third type of congestion is all hour congestion. In these cases congestion occurs at both peak and low load hours. This occurs between regions where the marginal cost in one region is always lower than in the other resulting in a constant flow of electricity from the low cost to the high cost region. This occurs if the two trading regions have fundamentally different supply structures, e.g. nuclear power dominating in France and natural gas dominating in Spain. Implementation of demand response in these cases can reduce marginal prices in each region individually, and shifting away load for some hours can reduce the difference in marginal cost between regions. However, as there are no hours without congestion the shift will typically result in an increased marginal cost difference in the hour to which demand was shifted. How this affects the average congestion between the regions depends on the individual supply structures of the regions, although typically the reduction is small.

In conclusion DR can have an effect on congestion, although its impact on congestion due to wind power appears to be low. However, DR needs to be considered in plans for investments in transmission lines aiming at integration of larger amounts of renewables.

CONCLUDING REMARKS

Generally, DR is about giving electricity consumers enough incentives to change the way they are using electricity. Traditionally, DR has been used to flatten the load profile to decrease the need for expensive peak power plants and avoid grid extensions but it could also be an effective way to facilitate the integration of intermittent renewables.

It has been shown that DR could be used to increase the maximal penetration level of renewables in distribution systems and to some extent reduce congestion in transmission systems with high shares of renewables. However, DR can mainly be effective to manage integration challenges on the short to medium time ranges, i.e. from milliseconds up to hours or days. For the short time range automatic demand response would likely be preferable while alternatives such as real time pricing can be used for the medium time range. On longer time scales other solutions such as energy storage or grid extension may be necessary (or more visionary DSM measures such as varying industrial production over seasons). In order to utilise the available DR potential the demand side needs to be integrated into a communications network, and hence, DR may co-evolve with smart grids and the internet of things.