

# Systems and Optimization Aspects of Smart Grid Challenges

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# Chapter 1

## The Role of Flexible Demands in Smart Energy Systems

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### 1.1 Requirements of Smart Energy Systems

Smart Energy Systems must be flexible in order to adapt to quickly changing system conditions. The largest challenge on the way towards smart energy systems is the integration of renewable and distributed energies due to various reasons. On the one hand most renewable generation, and first and foremost those with a high future potential, such as wind or for certain regions as well solar generation, are intermittent. This implies variability in electricity produced by these generators and uncertainty in forecasts. On the other hand renewable units are far smaller in size and more decentralised than conventional thermal power plants. Additionally and on the contrary to thermal power plants, renewable power plants are less controllable. In absence of storage technologies natural resources as wind or solar energy can only be used when wind is blowing or sun is shining. Moreover, at the moment in many countries, they savour priority in providing electricity when they are available. The rest of the generation mix has to adapt to it as they are little controllable. So, more flexibility is needed to integrate large quantities of renewable and distributed generation.

More flexibility can be achieved in a variety of ways. One way is to use more flexible thermal generation units. The conventional generation park may become more flexible by using more gas turbines, which can start-up quickly and are hardly constrained by their ramp rates. This potential is already being used and will go on to be exploited in the future. An upcoming problem is the high variable cost that gas turbines are subject to. Thus, they are situated at the end

of the merit order. Very high or quickly changing intermittent energy production may create complications from a system operations point of view when the time of their occurrence coincides with low demand hours, i.e. when generation units at the beginning of the merit order are on-line. These generation units are base and middle load thermal plants, which, depending on the energy system, may be nuclear or coal fired power plants. They comprise generally the least flexible generation units. So, gas turbines are a great deal to manage peak demands but may be less useful in handling intermittent generation peaks in low demand periods. An alternative to introduce more flexibility in the system could be the use of storage facilities. They could store energy when electricity production by renewable sources is high and produce during demand peaks. But potent storage technology is either not viable (e.g. batteries cannot be used at large scale), not (yet) available (e.g. hydrogen storage is still not commercially available) or already exploited to a large extent (pumped storage hydro plants). Looking at the counterpart of the generation side whose potential has barely been exploited until now might be a solution to the missing flexibility problem: the consumption side has been considered until recently as completely inflexible. This has to be examined with more detail as some electrical demands are not at all inflexible and it is not a question of existing technology, but rather of economics and good regulation to use the existing potential.

In the following chapter 1.2, we will give an insight into the objectives which Demand Side Management, and especially Demand Response, mechanisms pursue (section 1.2.1), estimate the potential of certain DR objectives (section 1.2.2) and classify and explain some Demand Response mechanisms in detail (section 1.2.3). We will then continue with a more precise view on specific types of flexible demands apt to be applied for the formerly mentioned mechanisms in chapter 1.3. International Experience is revised and an Outlook given in chapters 1.4 and the following.

## 1.2 Demand Response Mechanisms

To explain in detail the potential of Demand Response (DR) and the mechanisms applied to achieve it, first the concept of Demand Side Management (DSM) has to be discussed. Demand Side Management comprises all activities which have the aim to change the demand profile in time or size. In contrast to DR, the concept of Demand Side Management has a wider scope. DR mechanisms are those activities which are based on the reaction of demands to signals, especially price signals, while DSM includes as well information or education activities. We will focus on DR mechanisms as they include mechanisms which directly intend to change the demand profile and thus to provide higher flexibility to the system.

### 1.2.1 Objectives of Demand Response

While the objective of some DSM activities may be more general such as to sensibilise or to inform about the potential benefits of the reduction of energy

consumption, DR mechanisms aim to change the demand profile directly in a way that causes less costs by responding to economical signals. That may imply to reduce demand peaks or to flatten the overall demand curve via valley filling or demand shifting. Or as well to make demands to be more flexible in general.

Table 1.1: Overview DR objectives

|                            |                                                     |
|----------------------------|-----------------------------------------------------|
| Load Management Objectives | Peak shaving,<br>Valley filling,<br>Demand shifting |
| Further Objectives         | Flexible load shape                                 |

**Peak shaving** Shaving (or clipping) demand peaks implies reducing electricity consumption in high demand periods. This may be necessary in situations where demand exceeds available generation. This might happen in the case of a failure of one or more units during a demand peak. In this way peak shaving can avoid non-served energy. But in general, peak shaving may also be useful to flatten the demand curve in general to avoid serving peak demands, when costly generation plants are providing electricity.

**Valley filling** Valley filling means increasing consumption in off-peak periods. The objective is to handle more problematic situations in low demand periods. Electricity production by non-controllable generation could be higher than the instantaneous demand consumption. Valley filling could then relieve the overhang of generation without the need to spill valuable electricity. It is used as well to balance the daily demand curve during off-peak hours in contrast to peak shaving which act during peak hours.

**Demand shifting** Demand shifting refers to the movement of demand from one time instant to another. Normally the shift will be from high to low demand periods. So, the daily load curve is flattened both during peak hours by demand reduction and off-peak hours by demand increase. But as well the contrary is possible in the case that renewable energies produce a lot of electricity during peak-hours and demand has to be increased. Depending on the demands, consumption can be delayed or advanced in time only some minutes, some hours or even between night and day.

**Flexible load shape** Another objective of DSM and especially DR activities is referred to as flexible load shape. This objective is related to reliability, and it refers to the ability of demands to react to sudden demand or generation changes in real time operation as reserve provider. The occurrence of a sudden failure in thermal units, might make the reduction of loads necessary. Increases in load might be required in case of lack of wind production due to forecast errors.

These and other DSM objectives are described in [1] and [2] with more detail. The first mentioned objectives (peak shaving, valley filling and load shifting) are also known as load management objectives. Load is managed in such a way that complicated system situation are relieved. We will refer especially to peak shaving and demand shifting objectives in the following sections.

### 1.2.2 Demand Response Potential

The potential of demand to respond to system conditions has been fairly ignored until recently in Europe and until the end of the last century in the US electricity market. Flexibility came usually either from other, more flexible types of generation technology such as gas turbines, or from using some type of storage as for example pumped storage hydro plants.

So, the greatest part of the potential to use demand response is still to be exploited. In the literature this potential varies over a wide spectrum depending on the region, the type of consumption and the applied DR mechanism (see subsection 1.2.3). The DR potentials mostly cited in the literature can be differentiated into two. The first describes the maximum possible reduction of demand during peak hours, the peak shaving potential. The second potential refers to the maximum amount of energy, which can be balanced through the whole day by delaying or advancing certain loads, the demand shifting potential. A third potential commonly mentioned is the potential to decrease overall energy consumption by applying energy efficiency measures. But we will focus on the first two potentials as those are more important regarding the flexibility in the electricity system. The peak shaving potential ranges in the literature on average from 3% [3] to almost 25% [4] while the statements of the potential for demand shifting oscillate between 5% [5] and 20% [6]. More detail can be found in the sections 1.2.3 and 1.3.

The main driver of exploiting this latent flexibility resource is the benefit of employing it and thus the associated cost of implementation. One of the questions raised by many studies (e.g. [7, 8]) is exactly the profitability of applying Demand Response measures. Do costs outweigh benefits? This is the fundamental question as a wide acceptance among utilities and consumers is rather disputable if costs are not recovered. Results from three utilities in California (USA) analysed in the mentioned work of [7] come to very different conclusions about this issue. Authors in [8] conclude that costs of implementing DR mechanisms exceed by far the benefits in the case of Spain. However, the authors admit that further possible benefits should be evaluated in detail. Summarising the studies it seems that benefits are so far quite low or non-existent, but that benefits are most probable to get higher in the future. This future depends on the advances of DR technologies and consequently lower implementation costs, on higher opportunity costs of not applying DR (especially with the integration of renewable energies) and on using additional functionalities with the DR infrastructure.

Costs can be differentiated into investment and operation costs. Investment cost refer to enabling equipment that needs to be installed in the electric de-

vice, metering technology and possibly an energy management system grouping all individual devices for one point of consumption (common among residential consumers). Furthermore the term investment cost includes the whole communication and control infrastructure which serves to communicate with the electrical grid and thus the system operator. On the other hand operation cost include the fixed and variable costs of using DR technology. Fixed costs may refer to monthly internet rates (communication from domestic consumers might use the internet) or the cost of a control centre where price signal and their response are bundled to communicate with the system operator. Variable cost consider mainly the opportunity cost or the value of lost load in the case of peak shaving. In [9] the authors show that for industrial consumers investment as well as fixed costs are of minor importance as especially the metering and communication equipment might be already installed. In contrast the value of lost load can be very important if the demand cannot be recovered later which is the case of peak shaving. The cost distribution among residential consumers is completely the opposite: investment and fixed costs are major components of the total costs faced when applying DR mechanisms. Authors in [8] estimated costs and benefits for residential customers. They show that 56% of the total cost of implementation of a demand side management system is due to the installation of automatic control in existing appliances and smart plugs in homes. The control and communication infrastructure amounts to another 28%, smart meters to 15% and only 1% of total cost corresponds to the operation of the DR technology. In the work of [10] an extensive overview of international experiences about costs and benefits of smart metering is presented.

### 1.2.3 Types of Demand Response Mechanisms

Demand Response mechanisms are widely classified into two groups: price driven and incentive driven DR mechanisms [11, 12, 13].

Price driven mechanisms include those that are also known as dynamic pricing. Dynamic pricing implies that the price is not fixed but variable as it may be in Critical Peak Pricing, Time of Use Pricing or Real Time Pricing. More options are possible such as Extreme Day Critical Peak Pricing and Extreme Day Pricing.

Incentive driven DR mechanisms comprise direct load control and emergency demand programs, which are voluntary. Additionally, interruptible programs and capacity markets, which are usually mandatory and demand bidding programs are included in this category [14]. Consumers offering ancillary services can be accounted as well to this category. The last two mentioned mechanisms rely on a market structure.

The authors in [13] describe as well other measures. They mention on the one hand subsidies on bank credits for DR technologies, which have not shown the wished effects until now. On the other hand they argue that bill discounts are seen as doubtful regarding the effects caused and audits only reach a very limited number of customers.

We will focus only on the most common of the price and incentive driven DR mechanisms in the following part.

Table 1.2: Overview DR mechanisms

|                   |                                                             |
|-------------------|-------------------------------------------------------------|
| Price driven      | Critical Peak Pricing,<br>Time of Use,<br>Real Time Pricing |
| Incentive driven: |                                                             |
| voluntary         | Direct Load Control, Emergency demand programs              |
| mandatory         | Interruptible programs, Capacity markets                    |
| market structure  | Demand bidding programs, Ancillary services                 |

**Price driven DR mechanism** Critical Peak Pricing (CPP) assigns higher prices to specifically announced periods. This may occur on few occasions a year. Various implementation options exist: the critical peak period might be fixed or variable and consumers might be advised one day ahead or on the same day. In the work of [7] CPP implies that prices on critical days are five times higher than the standard price and six times higher than off-peak prices. The authors test two different options: first the critical peak period is fixed and consumers are advised one day ahead, second the critical peak period is variable and notification is on the same day. Consumers in the second option could choose to get the necessary equipment installed free of charge. For the first option critical peak reduction in energy was about 13% among residential consumers while the second option caused a 25% higher load reduction in peak periods. This was basically due to the free installation of enabling technologies (mostly smart thermostats).

Time of Use (TOU) pricing refers to a price structure where prices depend on the time of the day. This may include different prices for peak and off-peak hours or even more periods of the day. In [7] experiments are run with a TOU price during peak periods of 70% over the standard rate and 200% over the off-peak rates. TOU pricing caused an average peak reduction of almost 9% among commercial and small industrial consumers and about 6% among residential consumers. In the work of [15] TOU pricing is applied to commercial and industrial users and two to three periods each day are designated as high, medium or low pricing periods. The authors state as a main drawback the coarseness of TOU time periods which detained it from being really effective.

Real Time Pricing (RTP) implies that prices are adjusted close to real-time (hourly or half-hourly periods). Thus, RTP transfers prices and thus system information to customers almost without time loss. Effects of an introduction of real-time electricity pricing at household level are analysed by [16]. This work captures the habitual response to variations in mean hourly prices, the response to deviations from the mean price structure and the cross-hour parameter for substitution to another hour. In the study of [17] the response of commercial and industrial customer with respect to RTP is analysed. Great differences

in price responsiveness among customer groups and peak periods are found. Furthermore peak load reduction were observed to depend on the faced price differences (see as well section 1.3.2). The author of [18] applies RTP tariffs to smooth out daytime load pattern in order to increase the use of wind power as wind generation is often curtailed because of system restrictions. Under real-time pricing more wind is utilized in the system and a higher percentage of demand is served by wind. Benefits of applying tariffs such as Real-time-pricing and Time-of-use pricing in a system with high wind generation are shown as well in [19] for the domestic test case in Ireland.

More details and test studies on CPP, TOU and RTP can be found in [2, 3, 14, 20]

**Incentive driven DR mechanism** Direct load control uses an option to reduce, interrupt or even increase power consumption of electrical devices in remote control. Direct load control may be a means, which is used in other mechanisms such as interruptible programs or ancillary services [21]. Authors who analyse direct load control with an automated response find that specific loads are able to react to many short as well as to less frequent prolonged curtailments, (see [22, 23, 24] and [25]).

Emergency demand programs and interruptible services offer their participants some financial incentive to curtail load immediately in the case of a system contingency. This incentive may be a discount, bill credit or as well a penalty for not responding to the curtailment signal. Normally the number of hours as well as the power that can be curtailed are limited. In a capacity market program, consumers also have to curtail load upon request and will be penalised if they do not respond. In contrast to the interruptible service, capacity market programs are not offered by the load serving entity. The curtailment in Emergency demand programs is voluntary while it is mandatory in the other two mentioned mechanisms. Different experiences can be found in [2, 26] and [27].

In demand bidding programs consumers provide load reductions at a certain pre-specified price. This might be convenient for customers as they can normally rely on a fixed tariff but receive a pre-defined price for curtailments when prices in the wholesale market are high and load reductions are realized. Authors in [28] and [29] give an insight in different implementations.

Demands may offer positive as well as negative reserves by being disposed to suddenly decrease or increase consumption. Many small demands may offer ancillary reserves in a more reliable way than a large generation unit might do [30]. More details and studies on how demand may offer reserve can be found in [22, 31, 32].

**Comparison of DR mechanisms** In the work of [33] the effectiveness of some DR approaches (RTP, TOU, CPP, demand-reduction programs, and interruptible programs) is compared. TOU pricing in comparison to RTP pricing reflects the real wholesale electricity price only to a minor extent. The two drawbacks of CPP for the system, namely the limitation of price and hours that can

be curtailed, are at least for the consumer an advantage. Demand-reduction has the problem of finding a reliable baseline from which to pay the realised reduction. This leads to the adverse selection problem as first consumers will participate who have a consumption that is lower than the baseline. Customers whose consumption surmounts the baseline are not very likely to participate as they would pay more. If the baseline changes with the consumer behaviour, the consumer might be discouraged to reduce its consumption (moral hazard problem). Interruptible programs are mostly only a more coarse form of RTP or CPP. The authors conclude that demand reduction programs are worse alternatives than dynamic pricing such as RTP or CPP. On the other hand it has to be considered for the provision of reserves, that system operators do not have a guarantee that reserve is provided under RTP and CPP (response is probabilistic) while they have under interruptible or demand reduction programs. So, a sufficiently large number of independent customers is necessary to ensure a response induced by price changes.

### 1.3 Types of Flexible Demands

The following chapter will concentrate on the types of electrical devices which are apt to be used for DR mechanisms. We will consider first domestic consumers and then commercial and industrial ones. This distinction is important as households will act significantly different from commerce or industries due to the mere quantity of demand consumed and consequently the different financial incentives to be used to mobilize the existing DR potential.

Although households might be analysed as one type of consumer, demand levels, load curves and the penetration of certain electric devices depend not only on the region but as well on many other factors (e.g. ownership of air conditioning, number of bedrooms or annual income, see [7] for more information). Subsection 1.3.1 will give an overview on common domestic appliances which have a certain DR potential. For industrial consumers the possible types of demands not only depend on the region but on the particular industry and its underlying production processes. Hence, subsection 1.3.2 aims to point out the behaviour and possible use for DR mechanisms for some selected industry appliances.

A possible way of managing many small demands in an effective way is the concept of Virtual Power Plants (VPP). These VPPs aggregate and manage loads to participate in markets for example. On a domestic level, these VPPs would communicate with the residential energy management systems. In the case of industrial loads communication could be directly with the manager of the VPP. For further reading on that specific topic, we recommend [34] or [35].

#### 1.3.1 Domestic Demands

Domestic electricity consumption is making up 31% of total electricity consumption in Europe [36]. An important part of this consumption is due to thermal

Table 1.3: Overview electricity consumption per sector based on [36]

| Sector                        | TWh       | % of total consumption |
|-------------------------------|-----------|------------------------|
| Domestic                      | 839.111   | 30,7                   |
| Commercial                    | 769.947   | 28,3                   |
| Industrial                    | 980.994   | 36,1                   |
| Other                         | 128.870   | 4,9                    |
| Total electricity consumption | 2.718.922 |                        |

loads or those that are in some way controllable. We will focus on some of these appliances, study their penetration levels for the case of Europe and explain which DR potential can be used. We refer mainly to the studies undertaken by [5, 9] and [37]. Electricity consumption for household devices is primarily taken from [38] and [39].

In the considered studies the potential of participation of these household appliances have been analysed for various DR measures. These DR measures intend to achieve various DR objectives such as peak shaving and load shifting (see section 1.2.1). Peak shaving and energy efficiency potential have been considered via the application of total interruption of the working cycle, limitations in power consumption, the limitation to more efficient programs or the use of other decentralised electricity sources such as solar, CHP plants or district heating. Load shifting potential has been studied by delaying the start of the consumption process, prolonging some parts of the consumption process to delay later more energy intensive phases or the use of energy storage capacities.

Home appliances may be classified depending on their penetration level. Refrigerators and washing machines are present in more than 95% of the European households. Over 70% of the domestic consumers own ovens and heat pumps. Freezers, dish washers, tumble dryers and electric water heaters have a medium penetration level of 52%, 42%, 34% and 23%, respectively. To a lower extent air conditioning and electrical heating (both 8%) is common. These data rely on the study by [5]. Washing machines, dish washers, tumble dryers and heating pumps are non-thermal loads. In contrast to the other appliances, whose DR potential comes from controlling and reusing their thermal storage, their usage time can be altered completely. By shifting the consumption backwards or forwards as well as interrupting it completely, these appliances have great DR potential. All the mentioned home appliances amount to a significant part of the overall domestic electricity consumption, for the case of EU-27 of around 60% [39, 36]).

Further appliances such as induction cooktop and ironing robots, which are less common are analysed in the report by [37]. Appliances whose proper operation method makes them inapt to participate in DR mechanisms such as brown goods (e.g. TV, Audio), grey goods (e.g. PC, video-games), small household appliances and lighting are analysed in [37, 39].

Now, the more common household appliances will be described and their DR potential analysed in detail.

Table 1.4: Overview controllable domestic consumers

|                       | % of household<br>penetration | % of total dom.<br>consumption | DR objectives                                      |
|-----------------------|-------------------------------|--------------------------------|----------------------------------------------------|
| Refrigerator          | 106                           | 15                             | load shifting                                      |
| Washing machine       | 95                            | 6                              | load shifting,<br>load shedding,<br>valley filling |
| Oven and stove        | 77                            | 7                              | load shedding                                      |
| Heat pump             | 70                            | (a)                            | load shedding                                      |
| Freezer               | 52                            | (b)                            | load shifting                                      |
| Dish washer           | 42                            | 3                              | load shifting                                      |
| Tumble dryer          | 34                            | 2                              | load shifting (c),<br>load shedding                |
| Electric water heater | 23                            | 9                              | load shifting,<br>load shedding,<br>valley filling |
| Air conditioning      | 8                             | 2                              | load shifting                                      |
| Electric heating      | 8                             | 19                             | load shifting,<br>load shedding,<br>valley filling |

(a) incl. in Electric Heating

(b) incl. in Refrigerators

(c) load shifting to minor extent

**Refrigerator** The most distributed home appliance is the refrigerator with a penetration of 106% [5]. Refrigerators use an insulated box as containment at whose back a cooling device is situated. A cooling compressor is used to compress evaporated refrigerant vapour. Afterwards the vapour condenses releasing the heat and expanding back to the evaporator. So, main electricity consumption is used for the compressor. This compressor is active only 20 to 35% of the time connected to the electrical grid when no load is added. Refrigerators and freezers amount to 15% of total household electricity consumption. Refrigerators can bear a load shedding potential for very short time periods. But before an interruption of service is possible, temperatures have to be cooled down to lower temperatures to tolerate the disruption in the service without food quality degradation. So, load is shifted forward in time. The compressor starting time may be delayed or interrupted taking into account the temperature to maintain food quality. General efficiency has improved over the last years as more devices with a high efficiency (energy label "A" and upwards) have been bought. This improvement is expected to go on in the future.

**Washing machine** The second most common household appliance in Europe is the washing machine. It is made up of a drum which is filled up to a certain level with water and rotates. The washing process includes then immersing the clothes in the water, heating up of the water to a certain predefined temperature to start the washing phase followed by several rinsing phases and a final high speed rotation to dry the clothes to a maximal extent. The electricity is mainly used for heating up the water at the beginning and for driving the motor for the drum. Washing machines cause around 6,4% of residential electricity consumption in Europe. Already an 8% of the washing machines feature some kind of control option such as the start time delay [5]. The electricity consumption can be lowered in general if the hot water is either stored in an preceding cycle, the water intake is hot or the water is heated with other sources such as local solar or CHP plants. A limitation to energy efficient ("ECO") programs, the interruption of the washing cycle or a limitation of the power consumption (lowering of temperature) might be other measures. Washing machines can apply load shifting by using a start time delay which waits until a signal from an energy management system or directly from the electrical grid is received to start the corresponding washing program. Certain programs may also be interrupted ride through.

**Oven and Stove** Stoves and ovens contain a heating element which transfers heat via thermal conduction or radiation, respectively. 7,5% of total domestic electricity is consumed by electric ovens and stoves. Peak shaving potential lies in interrupting the cooking process for very short time periods but not directly after beginning in the heating-up phase.

**Freezer** Freezers work in the same way as refrigerators do. Normal temperatures range from  $-18^{\circ}\text{C}$  among normal conditions to  $-25^{\circ}\text{C}$ . The same load

shifting and energy reduction measures as for the refrigerator apply (see page 15).

**Dishwasher** Dish washer consist of a tub, which is filled with water to a certain extent. Water is then heated up and through rotating arms water is sprinkled over dishes to start the cleaning process. Several rinsing phases and a final drying phase are included in the dish washing process. Electricity is mainly needed for heating up the water and for the motor of the rotating arms. Each household with a dish-washer consumes around 241kWh per year making up 2,7% of total domestic electricity consumption (taking into account the penetration mentioned at the beginning of this chapter on page 13. As in other non-thermal loads the starting time of the dish-washing process may be delayed, interrupted or reduced to lower temperatures. The electrical heating of the water might be replaced in the same way as proposed for washing machines (see page 15).

**Tumble dryer** After a washing cycle in the washing machine, laundry may be tumbled dry. Therefore hot air is blown into the drum of the tumble dryer through the wet clothes. The wet air is either removed through venting to the environment or condensed by cooling down. Most electricity is used for heating up the air, rotating the drum and the fans. An annual consumption of 251kWh per household and a penetration of 34,3% cause around 2% of total domestic electricity consumption [5]. Load shifting is possible but is regarded to be used to less extent as washing the clothes is the directly preceding process. Furthermore the heating process may be interrupted to shift load but without interrupting the drum rotation. Limitation to energy efficient programs or reduction of the drying temperature is possible but would prolong the tumbling process. Efficiency gains can be achieved by heating up water, which then heats up the air, with alternative sources, the connection of heat pumps or the use of gas-fired heaters.

**Air conditioning** Air conditioning is used to adapt the room temperature to comfort levels. The underlying cooling process of the most common devices is the same as that in refrigerators and freezers. Although per household consumption is quite high, due to the quite low penetration level in the residential sector and to the limited time of use during the year, air conditioning is making up around 2% of total domestic electricity consumption. See subsection 1.3.2 for more information on the use in the commercial sector. The same DR measures as for refrigerators and freezers may be applied. Additionally, once passed a certain temperature threshold, cool outdoor air can be used to cool the room down.

**Electric water heating** Electric water heaters are used to warm up drinking water to be used in manifold household applications mostly in kitchens (e.g.

washing dishes) or bathrooms (e.g. showering). They can provide heat instantaneously or by using a storage. Electric water heatings may work in a centralised way distributing the heat to various devices (see heat pumps) or decentralised. An electric current flows through an electric resistance, which produces heat. Electric consumption of heaters is making up around 9% [5, 9] of total household consumption. A complete interruption of the power supply in charging (less than half an hour) as well as maintenance mode (for various hours) is possible. Load reduction is as well possible through lowering the desired temperature. The load shifting potential consists in delaying the beginning of the heating phase.

**Electric room heating** Electric heatings are working in a similar manner as electric water heaters do. The heat can either be transmitted to the environment directly or using a storage unit. Storage units have a core which is able to store the heat (in contrast to electric water heaters the storage element is not water). When room temperature goes below a given threshold room air is absorbed and warmed up while passing by the storage core before being distributed to the environment again. Especially night storage heating are considered nowadays as inefficient. Some countries are trying to minimise the use of this type of heaters in the future (see [5, 9]) as it may be responsible for about a third of the electricity consumption of the here considered home appliances. Room heatings with storage bear a load shifting potential as the heat charging process could be interrupted or even increased depending on outside and room temperature. An interruption, except during the warming up phase, or a limitation of power is possible for around half an hour [37].

**Heat pumps** Heat pumps are used to circulate the heat between different appliances (mostly between boiler and radiator). Its electricity consumption amounts to more than double the amount of that of tumble dryer and dish washer and are thus one of the largest consumers among the home appliances [5]. They can be turned off when outside temperatures are moderate until room temperature cool down to a given limit. In that way they are able to shed their load [9].

### 1.3.2 Commercial and Industrial Demands

Commercial and industrial demands make up a total of 64% of total electricity consumption in the EU-27 of which over half comes from industrial consumers [36]. This section will give some insight on specific examples of commercial and industrial appliances with DR potential.

**Commercial Demands** Largest electricity consumers in the commercial sector are office lighting, electric space and water heating, ventilation and commercial refrigeration with 21,6%, 19,7%, 12,6% and 8,7%, respectively. Circulators, pumps, cooking appliances cause from 6,8% to 5,3% of commercial electricity

consumption. Computers and air-conditioning are responsible for a minor share of the consumption [39].

In [7] small and medium commercial and industrial consumers and their response to different dynamic pricing tariffs (TOU, CPP and RTP) have been analysed. Central analysed devices with DR potential have been air conditioning and thermostats. On weekdays up to 9% peak reduction could be achieved applying a CPP tariff.

In [40] residential as well as small commercial consumers have been analysed and their consumption is classified into low, medium or high consumption and whether it has a rather flat consumption throughout the year or winter and/or summer peaks. This survey for the Spanish Mainland studied the behaviour of commercial consumers such as hotels as well as bars and restaurants whose main electrical devices with DR potential considered were air conditioning and room heating.

**Industrial Demands** Electricity consumption in industry process depends very much on the specific underlying process. The potential of either shifting, shedding or simply reducing the demand might be quite high. Highest DR potential include those processes which face both high electricity demands and high specific cost for electricity in the overall production process [9]. The authors of [9] found five processes, production of chloride, aluminium electrolysis, mechanical wood pulp production, steel production and cement milling, where the DR potential is significant and accounted for almost 20% of overall industrial electricity consumption for the case of Germany. Those processes use either electrolysis, mechanical refining, melting or milling. Only part of these processes could be used for load shedding (chloralkali and aluminium electrolysis, cement mills and electric arc furnace) while another part could be used for load shifting (chloralkali electrolysis and wood pulp production). The DR potential in three of the five analysed sectors is already exploited to a large extent.

Other authors do not go into detail on the specific underlying processes or appliances but give general recommendations based on the undertaken studies:

Authors in [41] divide the small industrialized and commercial consumers into various consumption classes. Those with flat load consumption curve should intend to shift load as far as possible. Those with a modulated peak and off-peak use should try to shift demand from the peak to the valley. Up to which extent this demand shifting is possible depends on the underlying process and has to be analysed for each load separately.

Authors in [17] study the reaction of over 50 commercial and industrial consumers to different dynamic pricing tariffs. They find huge differences in price responsiveness depending on the consumer group and peak periods. Most response was due to shifting demand from peak to off-peak periods rather than shedding it. As a consequence they recommend to use different tariff designs and expose consumers differently long periods to high prices depending on their load shedding capability. These authors found as well that the response of peak load reduction depends very much on the price difference from peak price to

the normal rate. Peak load reduction would be proportionally higher when the price difference was higher. This leads to the recommendation of applying CPP for industrial consumers.

**Electric Vehicles** Electric Vehicles (EV) are a consumption which is still not taken into account as the penetration of EVs is only starting. EVs might be a domestic consumption if owned by private persons or commercial or industrial consumption if belonging to a vehicle fleet of companies. Different types of EVs including pure battery EVs, extended-range EVs and plug-in hybrid are considered in the report [42]. The authors of this study estimate that in 2030 between 15% (sensible estimate of EV uptake) and 50% (most aggressive EV uptake scenario) will be electric most of which (88%) will be vehicles with four wheels and up to 8 seats apart from the driver's seat. The scenario which assumes a sensible estimate of EV uptake is considered to be the most likely one. Another interesting study can be found in [43]. Although EV penetration are estimated to be fairly low at least in the upcoming years, their DR potential might be important in the future as they are - within a certain range - very flexible demands. Taking into account the assumed specific consumption, the distance travelled each day and the forecasts taken into account for this study (including five EU-countries), they assume that EV will be responsible for 102TWh of additional yearly electricity consumption in 2030. This corresponds to a 1.8% (sensible EV uptake) to 7.3% (aggressive EV uptake) of total electricity consumption in these five countries assuming a 1% annual demand increase starting from consumption levels in [44]. Charging of EVs should be organised smartly taking into account the electric system conditions to not increase demand peaks even more [42, 43]. EVs could be used as a flexible load for valley filling during night. The use of EVs as flexible demand could even go further and be used as a storage device: the battery might be used as energy storage to shift load from peaks to valleys as described in [45].

## 1.4 International Experiences

In the following section DR mechanisms implementation and experiences of some selected countries are summarised. For further information we refer to an online database about the potential application and use of DSM in many countries, presented in [46].

**United Kingdom** The United Kingdom is leading in DR potential regarding the number of devices apt to support DR [47]. Not only smart meters but also old meters which are combined with a new unit or simply display units which are clipped on devices exist in the UK market. As in most European countries, DR programs for industrial and large commercial consumers have been in place for quite some time. This includes mainly interruptible programs which do not send economic signals but make use of some payment for the case of interruption. Apart, this type of customers may negotiate a TOU tariff with the supplier.

There are various TOU rates available for residential customers. One example is the Economy 7 tariff which offers during night hours a far cheaper rate than during the day. Especially for residential consumers with electrical heaters with storage (see subsection 1.3.1 on page 17) this is an interesting option. Loads are allowed to participate in markets for reserves (frequency and voltage, spinning reserves and others) in an aggregated form [48].

**France** In the Nineteen-nineties a very effective CPP program was introduced in France, the Tempo tariff. It distinguishes three types of tariffs indicated by colors: white, blue and red. While the white tariff is applied the majority of days of the year, the blue on around 12% of the days, the red one is applied on very few days. The red tariff is significantly more expensive than the normal rates. Consumers are informed of the type of tariff one day ahead [47].

**Italy** With the highest rate of smart meter roll-out in Europe, Italy may count to the European countries with the highest potential of DR use. Large industrial consumers are subject to interruptible energy programs which, depending on the program, shed load in real-time or with a 15-minutes notice margin [47]. TOU-rates are applied since some years with the aim of shifting load from peak to off-peak hours and will be extended consecutively to all consumers with smart meters.

**Spain** Although wind is considered to be the main driver of DR implementation in Spain by the authors [49], only few DR mechanisms are currently operating in Spain. These do not include domestic customers who simply pay a flat regulated tariff consisting of an energy charge and a peak demand charge. Commercial consumers with peak demands over 50kW are subject to Time-of-use tariffs. The author in [50] estimates that 20% of the total demand is subject to these tariffs. The System Operator is offering as well an interruptible load program. Currently 155 customers are taking part in this program with a total interruptible load of 2174MW [51], which amounts to almost 5% of the peak load.

**Nordic Region** The authors of [48] provide some insight into the Nordic Region and how demand is taking part in the markets of Denmark, Finland, Norway and Sweden. Loads can participate in the regional energy as well as the power market. Furthermore demands can provide reserves either through bilateral contracts or bids.

**United States** Demand Side Management and all type of DR mechanisms have a far longer history in the USA than in Europe. An overview of the initial experiences with DSM programs, especially in the USA, can be found in [2].

Some of the US markets will be mentioned in the following paragraph. In PJM there are currently seven DSM programs running [52]. An emergency DR program whose participation is voluntary and an interruptible service program

which is mandatory for up to 10 events each year, each lasting up to six hours. Furthermore there is a demand resource program which makes consumers eligible to receive capacity revenues. In a day ahead DR program consumers must submit bids in day ahead energy market and faces penalty for non-compliance. In the voluntary Real Time Demand Response Program customers need to notify PJM of the intention to curtail load one hours before load reduction is performed. Ancillary services can be provided by demands in a market. DR resources are required to bid into ancillary service markets, and to respond to any event similar to how a generator would. Additionally, an energy efficiency program is running, which allows consumers to receive a capacity credit for a certain time span. The minimum size for all programs is 100kW. It has been seen that the participation in Emergency programs is far higher than in economic programs [52].

In [48] the authors describe among others how demand is providing reserves in PJM and ERCOT markets. ERCOT, the ISO of the state of Texas, allows loads to provide various kinds of reserves. Furthermore, load is allowed to provide half of the energy needed during a contingency.

In NYISO five DR programs are currently in operation [52]. These include reliability based DR programs such as an emergency DR program, which is a voluntary program, an mandatory interruptible service and a Targeted Demand Response Program to respond to local reliability events within a particular zone to avoid the need to activate emergency events for the entire zone. Economic DR programs allow customers to offer curtailment bids in a day ahead market. Furthermore a Demand Side Ancillary Service Program was initiated in 2009 and allows demands to provide three ancillary services to NYISO markets. In NYISO some of these programs have minimum sizes: 100kW for emergency and 1MW for economic and ancillary services, respectively.

Although energy efficiency has not been the topic in this chapter because other DR objectives mechanisms are more related to the issue of smart grids, we refer to some literature for further reading: for a description of currently applied energy efficiency measures in Europe, Asia and Latin America, the work of [53] may be of interest. An evaluation of a multi-country study about energy efficiency in the new member countries as well as the EU-25 can be found in [54].

## 1.5 Outlook

Demand Response forecasts show a big potential for future DR use: from 174TWh implementing the adopted measures to 407TWh if implementing as well additional measures for EU-27 [38], or more than 13 GW for ten UCTE countries [47]. Load management programs which intend to shave peaks, fill valley or shift demands from peaks to valleys as well as the general higher flexibility of demand are of great interest when coming to the topic of smart grids. Smart grids are integrating not only a high number of distributed energies but also an increasing amount of intermittent renewable generation. More intelligence and

flexibility are needed in the electric system to face these challenges. DR mechanisms can help with both flattening the demand curve to avoid costly demand peaks and boosting the integration of renewables through more flexibility in the system.

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