Demand Response Mechanism Design and the Impact of Crucial Parameters on its Effectiveness

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***Abstract*—Electric loads offer a great flexibility resource for electric systems. The exploitation of this resource may be necessary not only to reduce system variable costs but also to integrate high amounts of renewable energies. Demand Response (DR) mechanisms, in which demands reduce, increase or shift consumption, must be implemented to use this inherent flexibility.**

We use a two-part model consisting of a day-ahead unit commitment and a real-time simulation to represent a centralized approach of Direct Load control for residential and commercial consumption. Two parameters of the DR mechanism are especially interesting for its performance and will be analyzed in detail. First, DR potential, which indicates the share of total hourly consumption that can be modified. Second, the cost which incur consumers to change their electricity consumption.

We find a lower impact of using various devices at once than summing up individual impacts of each device. Thus, concentrating on few devices with high DR potential coinciding with hours adjacent to peak or off-peak hours may increase the effectiveness of DR. Furthermore, we come up with positive net benefits to consumers when considering DR costs, but in practice these may result too low to persuade consumers to participate in DR programs.

***Index Terms*—Demand Response, Load management, Power system modeling**

I. Overview

Demand Side Management (DSM) has come into the focus of energy planners and governments as demands hold a flexibility potential which has been almost completely unused in the past. Flexibility is crucial to integrate a high amount of renewable energies into the electricity systems. This is due to the intermittent nature of a large part of these energies, which refers to their variable and difficult to forecast outcome.

The authors of [1] present DSM as a way to achieve different load shape objectives. Among others there are three load management objectives, including peak clipping, valley filling and load shifting. While peak shaving implies the reduction of peak loads mainly with the intention to reduce peaking capacity, valley filling intents to build up new demands to increase electricity consumption in off-peak hours. Load shifting considers the combination of the former two objectives. Demand shifting has been selected for the analysis in this paper as the integration of renewables into the system may be one of the main forces to foster the implementation of DSM, see [2] and [3]. Thus, demand shifting may be considered as the main approach to adapt existing loads (in contrast to valley filling for new loads) to changed system conditions regarding the availability of generation. This should help maximize the use made of renewable generation. Furthermore, the adaptation of demand to system conditions may not only lower cost by reducing peak demands but also increase the reliability as demand is able to function as system reserve, too.

DSM objectives can be implemented in manifold types of mechanisms: A common way to classify DSM mechanisms can be found in [4] distinguishing between incentive-based and price-based mechanisms. Incentive-based programs comprise direct load control [5], interruptible demands [6] or demand bidding [7]. Price-based mechanisms include real-time pricing, see [8] and [9], or time-of-use pricing [10] among others. We opt for analyzing the direct load control as in this mechanism automatic control may be provided to the system operator. Thus, it may be representing the most optimistic case to determine where the limits of the impact of DSM mechanisms are. Nonetheless, the other mentioned DSM mechanisms should come up with similar results if they have been implemented effectively from the point of view of the electric system.

Many DSM mechanisms are considered in the literature and as different as their implementations is their impact on system outcome and their effectiveness. Demand Response (DR) mechanisms, which imply the response of demands to price signals, are the main focus of today's DSM programs. But the devil is in the details and the impact of many parameters of these DR designs is unknown. Which effect an increase of the demand potential on the reduction of system variable costs, emissions and the dispatch of other generation technologies has is not sufficiently known. The costs which should be considered as acceptable for consumers for participating in Demand Response mechanisms is not well studied in the literature neither. The application of DR should be focused on those consumption types that have the highest impact on system outcome. But the quantification of individual impacts has not been carried out so far. These are only some of the open questions, which we want to analyze in detail in this article.

II. Applied Methods

We use ROM, a unit commitment model in which costs are minimized to determine the dispatch of generating units and responsive demands in the day-ahead planning [11]. Furthermore, a subsequent real-time simulation takes into account wind and demand forecast errors and possible unit failures. ROM is implemented as a mixed integer programming problem in GAMS using CPLEX.

The unit commitment model considers equation 1 as the objective function. Total cost ct takes into account variable

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cost CV_t, fixed costs CF_t and startup costs CS_t for each thermal generator t as well as the cost of non-served energy CN. The variable cost CV_t is multiplied with generation $g_{p,t}$ for each time period p and thermal generator t. Fixed costs CF_t are multiplied with the unit commitment decision $uc_{p,t}$, startup costs CS_t with the startup decision $on_{p,t}$ and the cost of non served energy with the non-served energy nse_p.

$$ct = \sum_{p,t} \quad [CV_t g_{p,t} + CF_t uc_{p,t} + CS_t on_{p,t} + CN nse_p] \tag{1}$$

In this article we will refer several times to ct as the total system cost. Constraints include the energy balance (equ. 2), hydro storage balance (equ. 3), up and down reserve restrictions RU_p and RD_p (equ. 4 and 5), maximum generation limits $PMax$ (equ. 6), ramping limits RU_t and RD_t (equ. 7 and 8) as well as the logic sequence of unit commitment decisions (equ. 9).

$$d_p - W_p - nse_p = g_{p,t} + g_{p,h} - c_{p,b} \tag{2}$$

$$e_{p,b} = e_{p-1,b} - (g_{p,h} - Eff_b c_{p,b}) + I_{p,h} \tag{3}$$

$$\sum_t (PMax_t - g_{p,t}) + \sum_h (PMax_h - g_{p,h}) - \sum_b c_{p,b} \geq RU_p \tag{4}$$

$$\sum_t g_{p,t} + \sum_h g_{p,h} - \sum_b (PMax_b - g_{p,b}) \geq RD_p \tag{5}$$

$$g_{p,t} \leq PMax_t uc_{p,t} \tag{6}$$

$$g_{p,t} - g_{p-1,t} \leq RU_t \tag{7}$$

$$g_{p-1,t} - g_{p,t} \leq RD_t \tag{8}$$

$$uc_{p,t} - uc_{p-1,t} = on_{p,t} - off_{p,t} \tag{9}$$

Equation 2 equals variable demand d_p, wind production W_p and non-served energy nse_p with thermal $g_{p,t}$ and hydro generation $g_{p,h}$ and resting the consumption by pumping units $c_{p,b}$. The hydro storage balance is determined by the difference of energy stored in the reservoirs in two consecutive hours, $e_{p,b}$ and $e_{p-1,b}$, which has to equal the production $g_{p,h}$ in that hour, the consumption $c_{p,b}$ taking into account the efficiency Eff_b and natural inflows $I_{p,h}$.

We will implement demand response representing the view of a central planner who is able to modify demands depending on the systems needs as presented in [11]. The variable demand d_p is determined by the original demand D_p and demand variations (increasing $dv_{p,up}$ and decreasing $dv_{p,do}$ demands), see equ.10. Demands can be shifted within a certain time p' forwards and backwards. The variable $dvh_{p,pp,up,do}$ connects the origin and destination of the shifted demand. Hour pp is used as an alias for p and used to indicate the destination hour of a demand variation in the origin hour p. Then, $dvh_{p,pp,up,do}$ indicates the demand which has been increased in hour p and decreased in hour pp. Accordingly, $dvh_{pp,p,up,do}$ is the demand that has been decreased in hour p and increased in hour pp. The sum over all hours pp is then the total increased demand $dv_{p,up}$ and the total decreased demand $dv_{p,do}$ in hour p, see equation 11 and 12, respectively. For each origin hour p the sum of increased demands $dvh_{p,pp,up,do}$ has to equal the sum of all decreased demands $dvh_{pp,p,do,up}$ in destination hours pp, see equation 13. DSM potential is determined in equations 15 and 14, providing an upper and lower Limit L_{up} and L_{do}, which is a percentage of the original demand.

$$d_p = D_p + dv_{p,up} - dv_{p,do} \tag{10}$$

$$dv_{p,up} = \sum_{pp=p-p'}^{p+p'} dvh_{p,pp,up,do} \tag{11}$$

$$dv_{p,do} = \sum_{pp=p-p'}^{p+p'} dvh_{p,pp,do,up} \tag{12}$$

$$\sum_{pp=p-p'}^{p+p'} dvh_{p,pp,up,do} = \sum_{pp=p-p'}^{p+p'} dvh_{pp,p,do,up} \tag{13}$$

$$L_{up} D_p \geq dv_{p,up} \geq 0 \tag{14}$$

$$L_{do} D_p \geq dv_{p,do} \geq 0 \tag{15}$$

The cost, which consumers incur when participating in Demand Response programs is often ignored in the literature. Neglecting the existence of this type of costs lets us consider the most optimistic case first and set an upper limit for possible impacts on the electric system operation which is later enhanced by including different levels of DR costs. Accordingly, we will include electric devices individually to analyse the impact on demand response, system costs and the use of other generation technologies.

First, we will change the parameter of demand response potential by analysing the potential of different consumption types (households and commerces) and typically used devices in detail. Each considered device has a different DR potential depending on its underlying consumption pattern, the penetration in households and the share in total household consumption. Thus, we represent the penetration of intelligent devices that can adapt to system signals and shift the electricity consumption in these consumer types. We can analyse the effect which a variation of these devices, and herewith of the behaviour of each consumer type, has on the overall system operation. This work will be presented in section IV.

Second, the amount of the DR cost will be analysed. This DR cost can be understood as an intrinsic cost to the consumer. If the cost is too high consumers will barely take part in DR mechanisms. We vary this DR cost considering values found in the literature and own estimations to evaluate the sensitivity of consumer behaviour and system outcome to this costs.

This work is based on [12]. It will focus exclusively on the centralized demand response mechanism and provide more detail considering the modelling of consumption types and specific electric devices. The analysis of DR costs has not been part of the work in [12].

III. Data for Case Study Spain

We will apply the model to the case of Mainland Spain. Spain has ambitious Renewable Energy targets for 2020. Over 33% of the demand shall be produced by renewable energies in 2020. Almost half of this production shall come from wind and another fifth from solar energy [13], both intermittent energy sources. Furthermore, Spain's interconnection capacities are quite limited. So, Spain has to cope with variable and uncertain energy sources to a major part on its own. Increasing peak demands are another challenge for the operation of the electric system in Spain in the future. Thus, flexibility in the form of Demand Response mechanisms is a possible solution to upcoming problems, which has to be studied in detail.

Installed capacities for renewable and conventional generation are taken from [13] and [14], respectively. Time series for wind, solar and other renewable energy have been obtained from [15] and scaled to the installed capacity of 2020. We will focus on domestic and commercial demands leaving apart the industrial consumption mainly for two reasons. First, the consumption pattern of industries is not as homogeneous as for the other two segments and depends very much on the underlying industrial process. So, a generalization is far more difficult. Second, many industrial consumers especially those which have a high DSM potential because of the proper industrial process and whose share of electricity costs within the total production costs is high already take part in DSM mechanisms [16]. In Spain, 151 large industrial consumers, corresponding to over 2 GW take part in an interruptible demand program [17].

A. Domestic demands

We will use historic time series of residential and commercial demands derived from [15]. Then, we select electric devices which are apt to participate in demand response mechanisms and determine the Demand Response potential taking into account forecasts on penetrations in households and commerces of these devices. Table I shows a summary of the most important domestic electric devices in Spain based on [18].

TABLE I
OVERVIEW OF CONTROLLABLE DOMESTIC CONSUMERS

	% of household penetration	% of total dom. consumption	DR objectives
Refrigerator	100	19	load shifting
Washing machine	93	7	load shifting, load shedding, valley filling
Oven and stove	77	5	load shedding
Freezer	23	4	load shifting
Dish washer	53	4	load shifting
Tumble dryer	7	2	load shifting (a), load shedding
Electric water heater	22	7	load shifting, load shedding, valley filling
Air conditioning	49	2	load shifting
Electric heating	41	7	load shifting, load shedding, valley filling

(a) load shifting to minor extent

Penetration in households depends on various factors such as weather, practices or income. Other international studies considering the part of total household consumption which each appliance is responsible for and the electricity consumption per household can be found in [19], [20], [21], [22]. The authors of [19] and [21] refer to EU-27, but specify as well details about specific regions. The region EU-15 is analysed in [22]. In [19], Spain is part of the Southern Region (together with Italy) and different scenarios (2010 and 2025) are considered. The works of [20] and [23] have been elaborated in the same project as [19] (Smart-A-project).

Data for domestic and commercial flexible demands can be obtained as well from the INDEL project [24], which has been elaborated during more than 10 years in collaboration with the Spanish System Operator.

Comparing the mentioned international studies to table I (based on [18]), in Spain there is a far higher penetration of electric heating and air conditioning than in other countries.

Deriving from the former tables the devices with both a high consumption and a high penetration in households, we select the devices in table II to evaluate the domestic DSM potential. Annual consumption per household as well as total consumption of each device is derived from [18]. The number of households in 2020 has been calculated scaling up the assumed data (17,7 million households in Spain). We assume household penetrations to be constant until 2020.

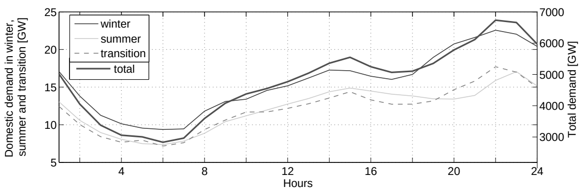
TABLE II
SELECTED DEVICES TO BE ANALYSED

	kWh/HH and day	GWh/ day	TWh/ year	penetration households
Electric heating	1567/ 784 (a)	30.6	4.4	41
El. water heater	1183	12.2	4.5	22
Refrigerator	658	31.0	11.3	100
Washing machine	274	12.0	4.4	93
Air conditioning	646 (b)	15.2	1.4	49

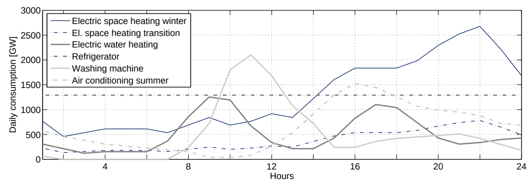
(a) Electric heating is used at full potential from December to February and at half potential half of October, November, March and April.
(b) Air conditioning is used only from June to August.

We assumed that proportions of these five domestic household devices among the total domestic electricity consumption are equal in the year 2020. They have been selected, first due to their high penetration in households (see table I) and to the thermal inertia (electric space heating, electric water heating, air conditioning and refrigerator) or to the flexibility in time (washing machine) of their underlying process which makes them ideal DSM devices. Electrical water (EWH) and space heating (ESH) and refrigerators (REF) will be considered in detail due to their high share of total domestic electricity consumption. Furthermore washing machines (WM) and air conditioning (AC) will be analysed due to the high flexibility of shifting the demand. We will assume that demand can be shifted one hour forwards or backwards. Later, a possible shift of up to four hours is considered for the case of the washing machine. The authors in [19] analyse the shifting potential of various appliances (including all of the selected devices in this study). The value of one hour, that demand can be shifted, has been chosen as an average for the reported values. For example [19] determine the shifting potential of some devices as the washing machine or the electric heating to be higher than one hour but some other devices such as the electric water heater or refrigerator to be a bit lower (half an hour). The direction of shifting is cited for all devices but the electric water heater to be possible in both directions in the cited reference. This flexibility of moving demand is confirmed by various other studies. In the work of [25] direct load control on residential customers is applied. Results in this pilot study show that loads (such as electric heating, cooling or washing machines) have been moved from peak to off-peak hours independently of whether forwards or backwards in time. Similar results are shown in [26], where, depending on the objective function, different operation schedules are determined. The author in [27] applies DSM to commercial and industrial customers and, depending on the loads, shifting to certain hours before or after the original consumption is possible.

We then use the average consumption pattern from [24], see figure 1(b), the penetration of the considered devices in households and the share in the total domestic electricity consumption of each of these devices to define an hourly demand shifting potential which can be modified to analyse the impact on operation as described in section II. This potential indicates the hourly share of total consumption which can be shifted forwards or backwards in time.



(a) Domestic demand



(b) Daily Consumption of domestic DSM devices

Fig. 1. Electricity consumption of households in (a) and domestic DSM devices in (b)

The typical demand curve of domestic demands can be seen in figure 1(a). It can be observed that electric space heating is only used in winter. On the contrary, air conditioning is only used in summer. The energy consumption of these two devices is highest during late evening with a peak at 22 o'clock for electric space heating and in the early evening for air conditioning (peak at 16 o'clock). The use of these devices is basically linked to the weather. The refrigerator electricity consumption is leveled through the whole day. Washing machines have a peak in their use during the morning and electric water heating is used during the whole day having two consumption peaks at 10 and 17 o'clock. In relative numbers the electric water heating is going up to more than 5% in its consumption peak. The refrigerator, whose electricity consumption is constant throughout the day, is responsible for up to 4% of total domestic electricity consumption during night time but less than 3% during the day. Air conditioning is responsible for 3% in its consumption peak.

B. Commercial demands

DSM potential in the commercial sector is far harder to estimate. Many of the data sources coincide with those of the domestic consumption already cited in section III-A. Authors in [21] describe the devices with the highest electricity consumption in the tertiary sector in EU-27. Selected devices are summarized below in table III.

TABLE III
CONSUMPTION OF FLEXIBLE DEMANDS IN THE TERTIARY SECTOR

	TWh	% of total consumption in tertiary sector
Space and water heating	150	19.7
Ventilation	96	12.6
Commercial refrigeration	66	8.7
Pumps	45	5.9
Air conditioning	22	2.9

In the INDEL project [24] the commercial sectors with the highest electricity consumption in Spain are summarized. The two biggest consumers are the restauration sector (29%) and food (20%). Of less importance are fuel and lubricants, textile and shoe shops and other types of small commerces. Penetration rates of flexible demands in these two electricity consumers are summarised below.

1) Restaurant (Restaurants, Bars)
   a) Space heating 33% penetration
   b) Air conditioning 54% penetration
   c) Refrigeration 99% penetration
2) Food (Supermarkets)
   a) Space heating 7% penetration
   b) Air conditioning 33% penetration
   c) Refrigeration 96% penetration

From [24] average demand curves can be obtained for restaurants and supermarkets. Furthermore, hourly utilization for the mentioned devices (space heating and air conditioning) are taken from the same reference. Refrigeration is assumed to be constant through the whole day.

Analogously to domestic loads, the DR potential can be derived from the penetration of the considered devices in commerces, the share in the total commercial electricity consumption and the daily load pattern.

IV. ANALYZING THE IMPACT OF INDIVIDUAL DEVICES IN DEMAND SHIFTING

A. DR potential scenarios

With the intent to determine the impact of the modification of certain parameters in DR mechanism design, we will analyse a series of important electric system operation results. We will detect whether a decrease in the parameter DR potential leads to a proportionally higher system cost. So, we will analyze the impact on system costs of different levels of DR potential represented by different devices. The impact of specific devices for the different consumer types will be observed and quantified. In this way we can relate the impact on costs, demand response and other outcomes to the consumer type and device. We can thus determine whether the typical consumption pattern of this device, the DR potential or other influences have caused this change in system outcome.

Knowing the individual impact can give ideas on which devices to concentrate on for DR mechanisms. Furthermore, especially favourable or unfavourable consumption patterns can be encouraged or penalised with price signals.

We ran 12 scenarios as shown in table IV. Next to a base scenario without DR, seven scenarios correspond to the domestic consumption and three to the commercial consumption, another one includes both consumption types. The ”Dom” scenario includes all five selected electric household devices. All of them can be shifted one hour forward or backward. Scenarios ESH, EWH, WM and REF and AC represent cases in which only one electric device is flexible and can be shifted. Scenario ”Com” includes the whole commercial demand potential and Res and Alim, represent the scenarios for the Restaurant and Food sector, respectively. Scenario ”Dom+Com” includes both domestic and commercial potential. Additionally another scenario has been calculated to estimate the DR potential of moving washing machine consumption up to four hours in time (WM4). As mentioned earlier, the DR potential takes into account the actual consumption pattern, the share among total consumption and the penetration of each device. If the time which demand can be shifted is p', then the DR potential for hour p is the maximum of the consumption in the hours $p-p'$ to $p+p'$. In our case shifting is possible one hour in any direction. Hence p' is 1 and the the DR potential of a certain hour p is determined by the maximum consumption among these three hours: the last hour $p-1$, the current hour p and the next hour $p+1$.

TABLE IV
SCENARIOS OF DEMAND RESPONSE POTENTIAL ANALYSIS

Scenario name	Type of demand	Considered devices/sectors	Shift in time
Base	domestic	no DR	-
ESH	domestic	Electric space heating	up to 1h
EW	domestic	Electric water heating	up to 1h
REF	domestic	Refrigerator	up to 1h
WM	domestic	Washing machine	up to 1h
AC	domestic	Air conditioning	up to 1h
Dom	domestic	ESH,EW,Ref,WM,AC	up to 1h
Res	commercial	Restaurants	up to 1h
Alim	commercial	Food stores	up to 1h
Com	commercial	Restaurants, food stores	up to 1h
Dom&Com	domestic, commercial	ESH,EW,Ref,WM,AC, Restaurants, Food stores	up to 1h
WM4	domestic	Washing machine	up to 4h

B. DR potential results

Figure 2 shows how much demand has been shifted from one hour to another during the whole year in each scenario. Domestic demand variations (scenario Dom) correspond to 1.5% (5,600 GW) of total demand, while commercial demand (scenario Com) makes up 3% (11,000 GW). If domestic and commercial devices (Dom+Com) are applied for shifting demand, 3.5% of demand (12,900 GW) are shifted. The variations of the single domestic households devices are rather low varying from 0.1% (300 GW for air conditioning) up to 0.8% (3,100 GW for refrigerator). The restaurants and food sector come up with a very similar quantity of demand which has been moved. It is remarkable that the sum of demand variations of the single device scenarios (ESH, ESH, WM, REF and AC) is higher than the domestic scenarios (Dom) in which the sum of the individual potential has been input data. The same happens to the sum of annual demand variation from restaurants and food stores in comparison to the commercial potential (Com) scenario. While the commercial annual demand variations is double as much as the domestic ones, a scenario combining these two potentials (Dom+Com) shows only a slightly higher use of that potential (12.900 GW). In the scenarios which consider more than only one device, different consumptions are summed up and the aggregated DR potential is derived when consumption patterns of various devices overlap. Normally demand increases occur during off-peak hours and demand decreases happen to be during peak hours. The aggregated DR potential may be so high that at times hours when demand is normally maintained at the same level (i.e. it is not shifted, because it is neither peak nor off-peak hour) coincide with hours of high DR potential. In these hours it may not make sense to exploit the DR potential and as a consequence demand variations and cost savings do not rise at the same pace as DR potential. The reason of not using the full DR potential in aggregated scenarios is the following: Demand shifting is used to flatten the cost curve. Decreasing demands in peak hours reduce costs in these hours. The marginal technology which marks the marginal cost in these hours may change. On the other hand demand increases in off-peak hours increase the cost and the marginal cost may rise as well when the marginal technology is changing. Once the cost curve is completely flat, that means the same marginal technology is producing in all hours, there is no reason to shift more demand in a cost minimizing approach. Demands will not be shifted although the DR potential is not used. This happens to the aggregated scenarios: the DR potential is not fully exploited because there is no economic reasoning of doing so. This leads us to the conclusion that it is of utmost importance first to focus on DR devices which have a sufficiently high DR potential to be fully exploited and second to care about the timely coincidence of adjacent hours to peak and off-peak hours with hours of high DR potential. This assumption has to be adapted when electric consumption can be shifted more than one hour.

Although we considered in the calculations an hourly Demand Response potential derived from the household penetration and specific hourly consumption as input data, we will comment shortly on the averaged potential, i.e. the average of the whole year. The highest average potential hold refrigerators with 3.1% of total demand that can be shifted, the lowest potential have air conditioning devices (0.35%), the other household devices lie in between (WM and ESH 1.1%, EWH 1.2%). Results in figure 2 show this trend. Refrigerators have the highest, air conditioning the lowest demand variations.

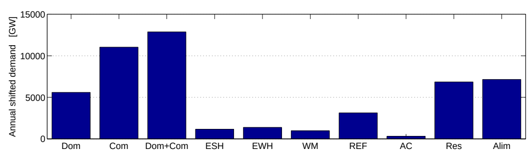


Fig. 2. Annual Shifted Demand

The same is true for the cost savings, some of them represented in figure 3. We refer here to thermal variable cost. The savings are determined with respect to the Base scenario without DR. Cost savings up to 1.2% (187 million €) can be achieved when using the potential of both domestic and commercial demands. Using only the commercial DR potential, brings up almost double the cost savings (149 million €) of using only the domestic households devices for demand shifting (79 million€). Again the use of the refrigerator shows the highest (0.3%) of cost savings among the single device scenarios (ESH, EWH, WM, REF and AC). This scenario represents the case where only the domestic refrigerators were able to shift demand. The low cost saving in the case of ESH may be explained with the consumption pattern (see figures 1(a) and 1(b)). The highest consumption of ESH coincides with the domestic and as well the total consumption peak. Moving ESH consumption one hour forward or backward lets the consumption still fall in the general demand peak of the evening. So, not only the DR potential is an indicator of how system results may change but also the consumption pattern and time coincidence of device's DR potential with the adjacent hours of general system peak is affecting results.

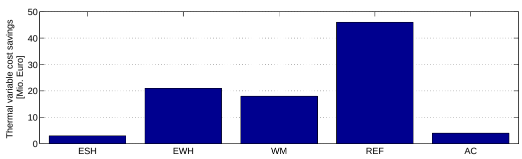


Fig. 3. Operational Thermal Variable Cost Savings

Changes in production technologies with respect to a base case without DR shows that pumped storage generation is reduced in all scenarios. That is caused by the fact that DR devices are used to decrement demand instead of using pumped storage generation during peak hours. That may also be the reason for the decrease of coal generation: Pumping consumption is done during night times when base load plants such as nuclear or coal units are running. Other peaking technologies such as gas turbines produce less energy due to the same reason, the reduction of the demand peaks. Combined cycles produce more energy in comparison to a scenario without DR. With a decrease in the use of mainly pumping, coal units and gas turbines, a reduction of emissions is achieved. If both, domestic and commercial devices are used, more than 2% of total emissions can be reduced per year, see figure 4. Especially the commercial sector shows high emission reduction results, mainly due to the fact that we focus on three specific devices, Electric Space heating in winter, Air conditioning in summer and refrigeration, which represent a high share among the total commercial electricity consumption.

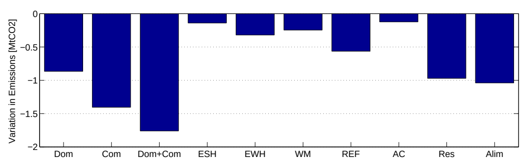
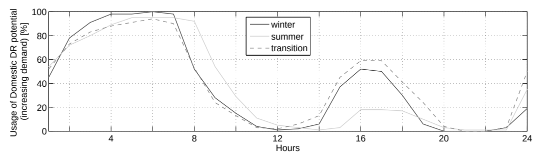


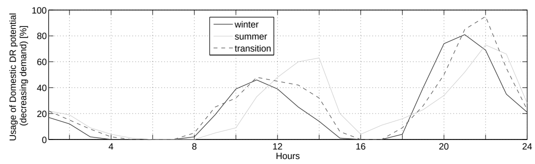
Fig. 4. Emissions Savings

The figures 5(a) and 5(b) show the rate of the DR potential which has been actually used on an average day in winter, summer and the transition period between both seasons. The DR potential is derived from the actual consumption of the five household devices which are included in this analysis. This consumption can be shifted one hour forward or backwards minimizing the thermal operation cost of the energy system. Figure 5(a) shows the usage of the DR potential of demand variations upwards, and figure 5(b) presents the variations in downward direction. ESH is only consuming in winter, while AC only in summer. The other three devices consume electricity during the whole year.

DR potential usage of the total of all domestic demands (scenarios Dom) for upwards demand variations is high (over 50%) during night time from 2 to 8 o'clock in the morning and as well in the early evening between 15 to 18 o'clock. In winter months the whole DR potential is exploited. In summer months the second peak during the early evening is far lower, reaching only 20%. For demand decreases DSM potential usage is lower. Most potential is used in early morning hours from 13 to 14 o'clock and in the evening from 21 to 23 o'clock. In summer more demand is reduced during the day peak, while in the transition period most of the DR potential is used in the evening hours (up to 90%). These figures show how in general demand shifting is used to move demand from demand peaks to demand valleys.



(a) Increasing



(b) Decreasing

Fig. 5. Usage of domestic DR Potential for increasing demands (a) and decreasing demands (b)

An additional analysis has been carried out letting washing machine electricity consumption be able to be shifted up to four hours forwards or backwards (WM4). Annual shifted demand increases from 966 GWh (0.4% of total demand) to 2085 GWh (0.8% of total demand) represent an increase of 215%. Nonetheless operational costs are reduced by only 0.06% and emissions by 0.04%. This is mainly due to the low DS potential of washing machines. Although washing machine consumption is now mainly shifted to the night, the overall amount is very low, so that a minor positive effect on system outcome is hardly noticeable.

V. Demand Response Cost and Their Impact on System Outcome

A. *Literature survey on DR costs*

When consumers take part in Demand Response programs where the system operator may interrupt consumption, costs are caused to the consumer. The cost of re-organizing the underlying industrial process in case of industrial loads or the inconvenience in case of domestic consumption should be taken into account.

The DR cost to the consumer has to be distinguished from the cost of investing in DR technology. Investing in DR technology may include the installation of the communication and control infrastructure. This cost is not taken into account in this article. Neither do we consider price signals sent in DR mechanisms which apply dynamic pricing. Dynamic pricing mechanisms send financial incentives implicitly with the price, which reflects the electricity system condition.

We will consider the intrinsic cost to consumer which occurs when the consumer has to shift demand to other hours in the analysis carried out in section V-C. In the literature overview of this section we will include as well other concepts such as incentives in the form of extra payment to be paid by the consumers, bill discounts for the participation in a DR program or a penalty in case of non-compliance of demand reductions. The literature survey will serve as an orientation to modify the level of this DR cost to consumers in the model.

An overview over incentive-based Demand Response programs and how incentives are set in each program is provided in [28]. In contrast to incentive-based DSM progams, price-based (or market-based) DR programs use the implicit incentives of price signals as mentioned above. One example of implicit incentives is provided by [29]. The authors analyze natural market incentives and emphasize that market-based incentives are preferable to arbitrarily or administratively set payments.

The main difficulty in administratively set incentive payments is explained with two underlying problems in [30]. The authors argue that the real problem is the asymmetric treatment of demand and generation in the wholesale market.

Another complaint comes from the authors in [31], who argue that current levels of compensation may be insufficient to cover DR costs. The authors distinguish fixed DR costs like a DR action plan for a company from variable costs which may include the deference of production. Furthermore, the actual problem is that DR benefits for the customer are quite low (around 1-2%), so that the perceived cost of the customer may be well above the benefits (although the perceived cost may not correspond to the true cost). That is one of the reasons authors in [32] want to focus on the other DR benefits apart from the cost reduction due to the reduction of consumption, such as a higher reliability, lower peak period costs for all consumers or less incentive for peaking units to bid above marginal costs. These benefits are normally not taken into account, when determining the level of payments to be assigned to the consumer.

Whether DR costs outweigh DR benefits is examined in various studies [10], [33], [34], [35]. Different conclusions are drawn from three utilities in California (USA) [10]. In [33] DR cost is related to the implementation of a control and communication infrastructure, the adaption of households to intelligent devices, the development of new business cases and the operation and maintenance of this system. From the considered cost only 1% is due to the operation of the system and a vast majority due to the infrastructure. The authors find higher costs than benefits for the case of Spain. But they consider that including future benefits (which were not considered in the study), benefits are most likely to exceed costs. An important aspect is considered by the authors of [34]: DR programs may cause important benefits during specific events, but they incur building and maintenance cost, which may be higher in some years than the perceived benefits. Authors in [35] come to a far more positive result: they observe that mandatory utility DSM programs show double the benefit than the incurred cost. In conclusion, the evaluation of DR costs depends very much on the specific program and especially in regions where DR programs are only beginning and the whole infrastructure has still to be built (e.g. Europe), costs are considered high in comparison to the created benefits.

Various numerical examples exist in the literature. Some of them apply an extra cost for consumers, some a payment for reducing loads in high peak times, others use bill discounts or penalties if consumers don't reduce to the pre-specified levels. We will present some of the costs and other financial incentives here to demonstrate the range found in the literature. The authors of [29] state that the quantity of an incentive payment is usually related to the value of the interrupted load, as a substitute the cost of peaking capacity is often used. In the work of [28] a numerical example of a demand bidding program includes an incentive payment of 0.006 €/kWh, which is only paid in the event of an outage. In [36] incentive payments and penalties between 0.006 €/kWh and 0.025 €/kWh are applied to different numerical examples of various DR programs. The incentive is paid for each load reduction while penalties are applied to those loads which do not curtail electricity consumption to the predefined level. Both studies apply the numerical example to Iran. Authors in [37] describe DSM programs in New England. In these programs a guaranteed minimum of 0.39 €/kWh for a 30-minute response or a 0.27 €/kWh for a two-hour response is paid. Next to this energy payment a capacity payment is paid. The author in [38] implements numerical example for load reduction offering the consumer a 0.19 €/kWh payment. This payment can be understood as an opportunity cost for holding backup generation, for materials and inconvenience caused by any load reduction. In [39] a payment of 0.37 €/kWh is paid for energy reduction by demands. The authors understand this payment as an indicator for the inconvenience in the case of domestic customers and the reduction and/or rescheduling of the production in case of industrial customers. Authors in [25] study a system in Norway and apply an energy peak payment of 0.08 €/kWh which is applied only in peak periods to encourage load reductions. In a demand side bidding case for a Spanish university consumer demand bids are within the range of 0.5 €/kWh for the reduction of the electricity consumption of air conditioning devices to 3 €/kWh for the reduction of essential ilumination and other loads [40]. In none of the mentioned studies the origin of the DR cost and incentive payment or the data basis for its estimation is sufficiently explained. The values found in the works of [38] and [39] can be interpreted as intrinsic cost to the consumers.

This short numerical overview demonstrates that the range of the numerical values on DR cost and incentive payments is wide. In the upcoming scenario section V-B we will select a range of values to determine the impact on thermal costs, demand variations and consumer benefits.

B. DR cost scenarios

In the former subsection V-A we analysed not only the intrinsic cost for consumers to move demand to other hours but also other financial incentives. Now, we want to focus on the specific DR cost. In detail, we will concentrate on those costs which consumers have to face with the participation in DR programs. As already mentioned above, this cost can be understood as the inconvenience caused by shifting load to other hours, as the cost for rescheduling industrial processes or the cost for holding backup generation. We will use the ROM model with a cost minimizing objective function as explained in section II in which the decision is taken by a central system operator. This may represent the situation in a direct load control DR mechanism. DR costs are modeled as an additional cost to the system as implemented in [11]. We applied the DR cost to increasing demands as we suppose that inconvenience for consumers is greater in off-peak hours when demand is increased than in peak hours, when demand is decreased. Thus, in the dispatch where the system pretends to minimize total operation costs this DR cost is taken into account.

We will assume perfect competition in our model. This implies among other things that no single generator or consumer is able to influence the electricity price and information is available for everybody. Under the assumption of perfect competition the results of a cost minimization are the same as those of a benefit maximization by consumers [41]. So, we can conclude from the results on the response of the consumers.

For this analysis we will evaluate results concerning variations in Demand Response, system costs and benefits to users. The results should indicate a range in which DR costs affect system outcome and consumer benefits. These results will give hints on the range of DR costs that are acceptible for consumers. If these DR costs are too high, consumers won't participate in the DR programs as they perceive no or very little benefit by taking part in these programs.

As there are many factors influencing the cost of shifting demand a spectrum of costs is considered. We select values for DR costs close to the lowest and the highest value found in the literature review in section V-A. We are aware that the values found apply to other electric systems and thus our results can't be compared directly to these other systems. This analysis aims to compute a range of possible impacts. The lowest value, 0.005 €/kWh in scenario 1, is close to that found in [36]. The highest value, 0.5 €/kWh, is close to that in the work of [39]. We consider three other scenarios in between. The second scenario represents an intermediate cost of 0.02 €/kWh, which corresponds to the variable cost of the cheapest thermal unit in Spain. The third scenario represents as well a fixed cost of 0.08 €/kWh, which coincides with the variable cost of peaking units in the Spanish system. A fourth scenario is defined considering the DR cost equal to the hourly marginal cost in the base case, which coincides with the dual variable of the energy balance constraint in a case without demand response. The reference case can be understood as the scenario where consumers do not face DR costs. See table V-B for an overview of the considered scenarios.

TABLE V
SCENARIO DESCRIPTION FOR DIFFERENT DR COST TO CONSUMERS

Scenario name	Cost applied to increasing demands in €/kWh	Description
Reference	-	Without extra payment
1	0.005	Close to lowest value found in literature
2	0.02	Lowest variable generation for Spain
3	0.079	Highest variable generation cost for Spain
4	$0.039 - 1$	Hourly marginal cost (dual variable of energy balance)[1]
5	0.5	Close to highest value found in literature

C. DR cost results

We will first analyse the results from the point of view of the system operator. In a next step we will comment on the results from the point of view of the consumers.

In figure 6 annual demand variations are compared to the reference case without any DR cost. Introducing small DR costs such as in scenario 1 already reduce these demand variations by more than 26% with respect to original demand changes in the reference scenario. If a higher cost is assumed almost all demand variations are close to zero such as in the last scenarios (94% in scenario 4 and 98% in scenario 5).

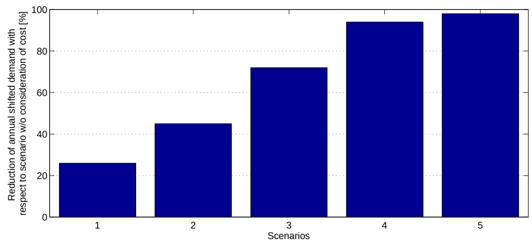
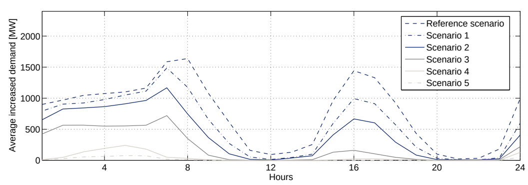
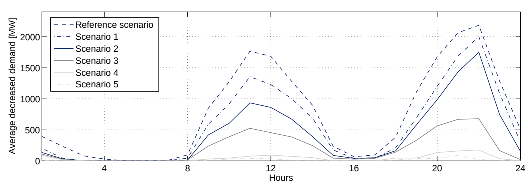


Fig. 6. Annual Demand Variations considering various DR cost scenarios



(a) Upwards



(b) Downwards

Fig. 7. Average increasing (a) and decreasing (b) demands

In demand shifting as we apply it demand increases and reductions are levelled out throughout the day. Hence, a rise in demand increases in off-peak demand hours, leads to more demand decreases in peak hours, see figures 7(a) and 7(b). This may alter the marginal generation technology and may have effects on costs. Demand reductions in peak hours may change the marginal technology. The same applies to demand increases in off peak hours.

DR costs affect the thermal variable cost to a minor extent. For the low DR cost values there is a 0.09% cost increase for scenario 1 with respect to the reference scenario. Thermal variable costs increase by 2.14% for the highest value for scenario 5.

With regard to the consumer benefit we find two effects. First, the mere existence of a DR cost to consumers demotivates the participation in DR programs as we have seen in figure 6. Already the existence of a very low cost (scenario 1) changes the reaction of demand notably (26% less demand variations). Nonetheless we find that the change in demand variations are not proportional to DR costs. The relation is rather inversely under-proportional, meaning that doubling the cost of DR to consumers implies demand variations of more than 50% than those in the original scenario.

The second effect we find is that lower participation in demand response programs results in lower specific benefits. This will be explained in continuation. We analyse the benefits from selling and buying the demand increases and decreases, respectively, at marginal price. Total benefits range from 19.65€ per household and year for scenario 1 to 4.62€ per household and year in scenario 5 (see table VI for an overview of numerical results). If we consider that electricity consumption has to be bought at marginal price, this benefit makes up between 1.14% (scenario 1) and 0.26% (scenario 5) of the total electricity bill for domestic consumers. If we deduce DR cost from this benefit, we find a 0.71% benefit reduction in scenario 1 and up to almost 83% reduction of benefits in scenario 5. The resulting "net benefit", that means the benefit of selling and buying demand variations at marginal price and after taking into account the DR cost, is somewhat lower for consumers in scenario 1 (1.13%) and practically inexistent for the highest scenario 5 (0.04% of the electricity bill or 0.8€ per household and year). More details as well on the outcome of the other three scenarios can be found in table VI.

If we compare the view of the system operator and that of the consumer we find a contrary trend. When we compare the scenarios to the reference scenarios without DR cost, there is a slight increase when including higher DR costs due to the fact that less demand is shifted from peak to off-peak hours. Cost increases up to 1.79% for the considered scenario 5 (see table VII) were found. Nonetheless cost will always be lower or equal to the case when no DR is applied. For scenario 5 costs decrease only 0.4% with respect to the no-DR-scenario. The higher DR costs the more Demand Response (i.e. shifted demand) will tend to zero. On the other hand, as well benefits tend to decrease to zero the higher DR costs and the lower demand variation are. For the highest DR cost considered in scenario 5 benefits are around 76.57% lower than without considering the DR costs and the impact on consumer behaviour is accordingly.

TABLE VI
ANALYSIS OF BENEFIT TO CONSUMER

	Reference	Scenario 1	2	3	4	5
Benefit of DR in €/HH and year	19.72	19.65	18.93	17.90	7.30	4,62
Share of total electricty bill in %	1.14	1.14	1.10	1.03	0.42	0.26
Net benefit in €/HH and year	19.72	19.51	14.77	9.61	3.32	0.80
Share of total electricty bill in %	1.14	1.13	0.86	0.56	0.19	0.04
Decrease of benefit in %	0	0.71	21.98	46.33	54.56	82.78
Net benefit in Mio. €/year	350	349	336	317	130	82
Decrease of benefit w/r to Reference in %	-	0,35	4,02	9,23	62,97	76,57

TABLE VII
ANALYSIS OF CHANGE IN TOTAL COST TO CONSUMER

	no DR	Reference	Scenario 1	2	3	4	5
System cost in Mio. €	20.99	20.55	20.56	20.56	20.61	20.84	20.91
Cost increase w/r to Reference in %	-	-	0.08	0.04	0.29	1.41	1.79
Cost decrease w/r to no DR in %	-	2.1	2.0	2.1	1.8	0.7	0.4

In conclusion, we see that despite high DR cost to consumers DR cost savings exist from the point of view of the system operator. Nonetheless we argue that consumer benefits should be carefully evaluated as net benefits are small even for the case when no cost is considered (1.14% for Reference scenario). The real value of these costs reductions must be determined to evaluate whether a DR mechanism provides the expected outcome in terms of total shifted demand. We doubt that net benefits well under 1% of the total electricity cost for domestic consumers, which is the case for scenarios 2 - 5 with relative cost savings from 0.86% to 0.04% of the electricity cost, respectively, will have an impact in their behaviour.

With these results none of the tested DR costs should be considered as the cost over which the implementation of DR mechanisms does not make sense from the point of view of both, the consumer and the system operator, as the decision boundary is fluid. Here, we want to emphasize the importance of taking into account the DR cost which consumers face when implementing DR .

As the authors of [10] state it is fundamental to know the consumers, their price responsiveness and load patterns to design an effective DR mechanism. DR costs should reflect true cost. Which components should be included in this cost, is open to debate. Whether the sunk cost of the communication and control infrastructure should be allocated only to consumers, depends very much on the amount. If real and perceived benefits are small, consumers might not take part in the DR program and thus cost savings are not possible.

VI. Conclusions

In this paper a detailed analysis of crucial parameters for Demand Response programs and their impact in the system is presented. First, the impact of the Demand Response potential of single household devices and their joint domestic consumption as well as two specific commercial sectors and their joint commercial consumption have been computed. We found that the implementation of DR in several appliances does not lead to the sum of the impacts for these single devices considered separately. Instead we found an under-proportional trend in the increase of demand variations, cost savings and emissions reductions the more devices were included in the DR program. Focussing on few but well selected devices has a higher impact than DR programs which include all types of devices. Furthermore, two factors are critical concerning the impact of DR: A high DR potential of considered devices and the timely overlapping with adjacent hours to peak and off-peak hours of electricity consumption. Results are limited to the assumption of a possible demand shift of up to one hour. An enlargement of the shifting window from one up to four hours in the case of the washing machine has shown no significant impact as its overall consumption is low. Future work should include testing the sensitivity of results to the number of hours demand can be shifted in any direction.

Second, we have analysed the effect of DR costs to consumers. We performed a literature review and found a wide spectrum of DR cost evaluations and incentive payments. We find that, although from a system operator's point of view, the implementation of DR may be economically reasonable and net benefits for consumers are positive, these net benefits may be so low that consumers might not be interested in taking part in DR programs. A range of DR cost values derived from the literature has shown that in four out of five scenarios considered these benefits are far below 1% of the total electricity costs for domestic consumers. Thus, the DR cost borne by, or assigned to, the consumer should be carefully evaluated when designing DR programs. Too high DR cost will leave DR programs idle with hardly any impact on system outcome. Some financial incentives might be necessary to convince consumers to take part in DR mechanisms.

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