The Integration of Demand Response in Capacity Mechanisms

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Abstract

Various market failures inherent to electricity markets have prompted regulators to ensure the power system can meet demand peaks. On the supply side, one can support capacity through a Capacity Remuneration Mechanism. On the demand side, Demand Response (DR) technologies can be rolled out. We find that if DR is not price-responsive but instead waits to be called upon by the transmission system operator, its social value is less than traditional generation: It participates to security of supply only if the system is tight and activation has been requested. We conclude that while all traditional generation should receive the same payment, the capacity payment to DR should be weakly decreasing in the operator's position in the load-shedding order. We observe that all schemes currently experimented fail to adequately account for this social value of DR: For stylized DR technologies, a menu of screening contracts implementing the first-best participation is provided.

Keywords- Demand response, Capacity remuneration mechanisms, Power market design, Priority service

1 Introduction

Liberalization of the energy sector and fast development of renewables have deeply modified the economic environment investors are navigating. Many European regulators are now implementing some form of capacity remuneration scheme (CRM), in order to increase demand coverage beyond what the energy market alone provides. What is an adequate remuneration structure and level for capacity remains actively debated in many European countries. An intuitive alternative to building more capacity, would be to encourage demand-response[1]. Indeed, in times of scarcity a transmission system operator (TSO) can identify consumers who need electricity the least, and get their load reduced in exchange for a financial compensation. This strategy may prove very effective: Gray Davis, governor of California during the California electricity crisis noted that he could have solved the crisis in 20 minutes

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[1]Throughout this paper we will stick to FERC's definition of DR as "changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized", see Federal Energy Regulatory Commission (2015)

had he been able to pass through the rising prices to consumers, a statement confirmed by numerous academic studies (Borenstein (2005), Faruqui et al. (2009)). ENTSO-E (2015) stresses that DR ”often has a high capacity value relative to its energy value in many countries. Participation in reserve capacity markets therefore opens significant opportunities for the development of DR and provides an additional revenue stream for DR capacities that can match technical requirements”. In turn, the EU state-aid guidelines state that Demand-side management development should be an explicit target of any CRM scheme[2]. Thus, the question of DR participation to adequacy and its integration in CRMs needs to be tackled. The subject has however been surprisingly under-studied in the academic literature. Much of the focus of previous research has been on assessing the technical potential of DR, but little has been done on market design. Regulators and TSOs are thus left with little theoretical guidance, leading to a patchwork of assorted designs. As an illustration, Smart Energy Demand Coalition (2015b) maps European Member States progresses in providing adequate conditions for DR development.

The originality of the present work is to link the concepts of DR and CRMs, in order to show how the former can be integrated in the latter. In our model, capacity remuneration is needed because of the presence of a price cap, which in turns makes prices and DR activation inefficient. The status-quo regulation is to say that DR is technically not capacity, and therefore should not receive any remuneration from the CRM –set aside implicit remuneration through energy market prices. Another extreme is to consider that DR is exactly like capacity, and should therefore receive a full payment. Most technology-specific CRMs (Spanish capacity payments to new combined-cycle gas turbines, German strategic reserve composed of ageing coal plants...) or generation-only schemes fall by default in the first category. Market-wide CRMs that allow explicit DR participation such as the British, French or PJM CRMs are in the second category[3]. However, our paper argues that the optimal solution lies between those two extremes, with an optimal payment that should depend on the ranking of the DR service in the activation order. If a DR operator commits to activating at least when prices are at the price cap, then this service is indeed equivalent to the one offered by thermal generation and the DR operator should receive a full payment for capacity. If DR activation is not prompted by market prices, but awaits a TSO order, then the payment should be smaller, as it is not activated as often as market-based DR is. The least it is activated, the least valuable the service, and the least the payment should be if the TSO wants to make sure there is optimal investment in DR.

2 Literature review

This paper relates mainly to three streams of literature.

[2]The Energy Efficiency Directive Article 15.8 states that ”Member States shall promote access to and participation of demand response in reserve markets”. The Guidelines on State aid for environmental protection and energy 2014-2020 art. 224 require the member states to provide an ”assessment of the impact of demand-side participation, including a description of measures to encourage demand side management” , http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX% 3A52014XC0628(01)

[3]Remuneration is derated to take account of particularities of DR such as availability, activation notice. However, no derating is applied to take account of the activation probability of each DR unit.

First, it contributes to the discussion on DR market design. Comprehensive overviews of the variety of potential market designs for DR can be found in Behrangrad (2015) or Warren (2015). DR yields many benefits beyond CRMs, including improving grid management and investments, helping integrate renewables, improve allocative efficiency of the power system, reduce power prices[4]. It has a huge potential, with estimates as high as 52 GW in Europe[5]. Optimal rewards for such services have been discussed (among others) in Bushnell et al. (2009), Astier and Léautier (2016), where authors stress that the incentives should be price-based, especially if baseline demand is unverifiable. Generally speaking, the benefits of price-responsive demand when prices are efficient have been described extensively, both in terms of short term benefits (allocative efficiency), and long term benefits through improved investment signals (Borenstein (2005), Borenstein and Holland (2003)). In this paper, we'll focus on the value of DR as a provider of capacity. DR's ability to participate to adequacy has been demonstrated with simulations (Albadi and El-Saadany (2008), Aalami et al. (2010)), experiments (Faruqui and George (2005), Faruqui and Sergici (2010)) and its technical and economic potential is estimated to be substantial (Borenstein and Holland (2003), Faruqui et al. (2007)). As an example Borenstein and Holland (2003) estimates that peak capacity in the U.S. could be decreased by 30 to 60 % if respectively one third or all consumers became price-responsive. For this potential to materialize, adequate market design needs to be implemented. The novelty of this work is to introduce inefficient pricing (by means of a price cap) in an analytical framework. We observe the price cap leads to inefficient activation and deployment of DR technologies, and propose a new market design that corrects this shortcoming. Even though our paper envisages the case of DR operators observing the prices in real-time, the model applies both to price-based and incentive-based demand-response[6]: only the states of the world when DR is activated matter, whether this activation is prompted by prices or by a grid operator request.

Second, this paper complements the literature on CRMs. There is a wide variety of mechanisms, ranging from direct payments for capacity to reliability option or strategic reserves (See e.g. the works Adib et al. (2008), Batlle and Rodilla (2010), Crampton and Stoft (2006), De Vries (2007) for critical reviews of those mechanisms). Those mechanisms may be technology-neutral or not, centralized or decentralized, volume- or price-based[7]. However they all essentially consist in giving additional payments to some generators in order to make sure they will be available capacity at times of high demand[8]. This is the only feature we need in our model, meaning the insights apply to all CRMs. So far CRMs have most often been supported based on the "missing money" problem created by price caps (see e.g. Joskow (2013), Cramton et al. (2013))[9]. To take advantage of its formal simplicity, we will keep

[4] Strbac (2008), Borenstein et al. (2002), Borenstein (2005) ; Borenstein (2002) ; Faruqui et al. (2007) ; Brophy Haney et al. (2009); Chao (2010); Hogan (2009), give thorough overviews of those benefits

[5] http://energy.sia-partners.com/20150205/demand-response-a-study-of-its-potential-in-europe

[6] Price-based DR refers to changes in usage by customers in response to changes in the prices they pay (e.g. real time pricing. Incentive-based DR refers to incentives separated from the retail electricity rate and can be offered by the grid operator or utilities. See US Department of Energy (2006) or Steen et al. (2012) for useful descriptions of those designs.

[7] see European Commission (2016), page 10 for a summary of those designs

[8] As such, there exists some scepticism over whether there is a real need for CRMs, and whether they constitute a state aid – see Léautier (2016), or the European Commission sector inquiry on electricity capacity mechanisms

[9] CRMs can also be defended on other grounds. For example, and importantly, there may be a need to compensate for a "missing

this motivation, leaving implementation details aside as they are not needed for our purpose. As a complement to current CRM designs, that apply de-rating factors to take account of imperfections such as notification requirements or availability probability (see e.g. National Grid (2016)), we will propose to de-rate DR payments according to a new dimension, namely the DR operators' rank in the load-shedding plan.

Finally, our conclusions and the model we'll use are reminiscent of the work on priority services (see e.g. Marchand (1974), Chao et al. (1986), Chao and Wilson (1987)): Assuming prices are capped below the value of lost load, one cannot rely only on the benefits of spot pricing (as exposed in Caramanis et al. (1982), Schweppe (1988)) since prices sometimes don't convey all necessary information. Thus, some form of activation order needs to be implemented. We suggest it could take the form of priority services. This idea of a complementarity of priority service and spot markets was explored in Chao (2012), albeit in a move to correct other market imperfections (namely, the lack of hedging instruments in presence of risk aversion) than the one studied in this paper (price caps). In our case when the principal is not biased against DR operators[10], this priority pricing replicates the efficient performance of a spot market, as in Wilson (1989)[11].

3 Framework and notations

A TSO strives to maximize social welfare in its balancing zone. It serves two types of consumers. The first type, cannot be made price-responsive. For example it is composed of residential areas, where implementing a DR technology (for instance a smart meter, enabling to reduce heating when market prices are high) in each house would be prohibitively costly. To set these ideas we name this category the "households". Even though this assumption is made essentially to keep the model simple while conveying intuition, I believe it is a reasonably realistic assumption. Léautier (2014) argues that rolling out smart meters in the residential sector may make little sense due to high installation costs and one should rather focus on big consumers[12], a doubt already cast in Borenstein (2005) who suggests the additional gains from putting smaller customers on real-time pricing may not justify the costs. Household demand is stochastic over time. For simplicity, their value of consumption is constant over time and same for all consumers, set at a common knowledge V_h (h standing for "household"). The TSO also serves a second type of consumers, the "industry". It is composed of a set I of individual consumers for whom implementing a DR technology may be worth considering (say, those are industrial clients with typically large consumption levels). For

market" for risk (see Newbery (2016), leading to underinvestment in capacity

[10]a good rationale for that is that DR operators are also consumers, and thus a principal may want to give an equal weight on DR and non-DR consumer surpluses

[11]When spot markets are capped, all conditions outlined in Wilson (1989) for priority services to be useful are met: service sometimes needs to be rationed, consumers have diverse preferences (i.e. there are efficiency gains from differentiation), spot prices don't operate freely. In our model, customer's preferences are perfectly consistent over time, meaning priority services can be efficient.

[12]Smart meter deployment costs have been estimated between \$ 95 and \$ 600 per consumer (see Faruqui et al. (2009)). In California, the regulator has authorised a 4 billion dollars expense to replace 10.5 million meters. Faruqui et al. (2009) estimated deployment costs to 51 billion euros for a Europe-wide deployment. Rious et al. (2012) estimates 30 million meters deployed in France will cost between 4 and 8 billion euros

simplicity each of those agents has unit demand, constant over time (absent DR activation). Borrowing from Doucet and Roland (1993), this unit demand will be referred to as "desired demand" (i.e. served demand if supply were unconstrained). As desired demand is fixed, the literature on self-rationing based on capping consumer demand at times of scarcity (Panzar and Sibley (1978), Woo (1990), Doucet and Roland (1993)) cannot be applied. Instead, we'll focus on the reduction of consumption below the desired load that prevails at all times. This reduction will be prompted either by prices or ex-ante contracting.

Each agent $i \in I$ has a given value of consumption V_i. If it wants to decrease consumption in some states of the world (for example when prices are high), it needs to install a DR technology at cost of installation r_i which we allow to be zero or even negative. We believe this framework is general enough to cover most DR technologies. V_i and r_i are per unit of power demand. They are unknown to the TSO, but it knows that industrial consumers have on average a higher value of consumption than the consumers. Thus, in case there is scarcity and all available DR is already activated, the TSO will choose to curtail households (V_h is in practice the value of lost load of the system), instead of industrial players[13]. However, the TSO also knows that some industrial consumers' characteristics can be such that $r_i + V_i < V_h$, meaning it will try to get those low opportunity cost potential DR operators to install the technology and activate at times of scarcity instead of curtailing households. The market has a price cap $\bar{P} < V_h$ – consistent with the the price cap being (much) lower than most Value of Lost Load estimates[14]. Hence there is a so-called "missing-money" problem, which motivates the implementation of a CRM – see e.g. Joskow (2013).

It is useful at this stage to note that the model does not take account of the (important) problems of asymmetry of information on volumes: industrial i's load without DR is fixed and known both by the TSO and operator i. Also, we don't address the problem of consumers' participation to CRMs: we consider that consumers have paid their due, and we then wonder what their remuneration for offering DR services should be, in order to have optimal investment and activation of DR technologies. In other words, we assume consumers have all paid their baseline demand. This eliminates the arbitrage opportunities highlighted in Astier and Léautier (2016), whereby consumers can inflate their desired consumption, and then re-sell an artificial load-shedding service. DR, and traditional generation are assumed to be 100% reliable. All agents are price-takers. This paper focuses on the opportunity cost of DR activation and its consequence on DR activation timing and optimal payment.

Figure 1 illustrates that while some DR behaves like generation (price-responsive DR, below the green part of the arrow), other DR services with values of consumption higher than the price cap but lower than V_h (orange part) will need to be tied with a contract if the TSO wants them to activate instead of curtailing households, as energy

[13]These assumptions reflect the spirit of most shedding plans implemented by European TSOs. Typically, small, non-strategic industry will be curtailed, and then residential areas will be affected. Hospitals, defence facilities but also important industrial sites like harbours are excluded from the load-shedding plan. As an illustration, the interested reader may refer to the Belgian load-shedding plan Economie.fgov.be (2015)

[14]The market coupling algorithm Euphemia and European market places use a price cap of $\bar{P} = 3000$ €$/MWh$. The European Commission (see European Commission (2016)) stresses that "Where VOLL has been estimated by MSs it ranges from €$11,000/MWh$ to €$26,000/MWh$, so significantly higher than existing European price caps"

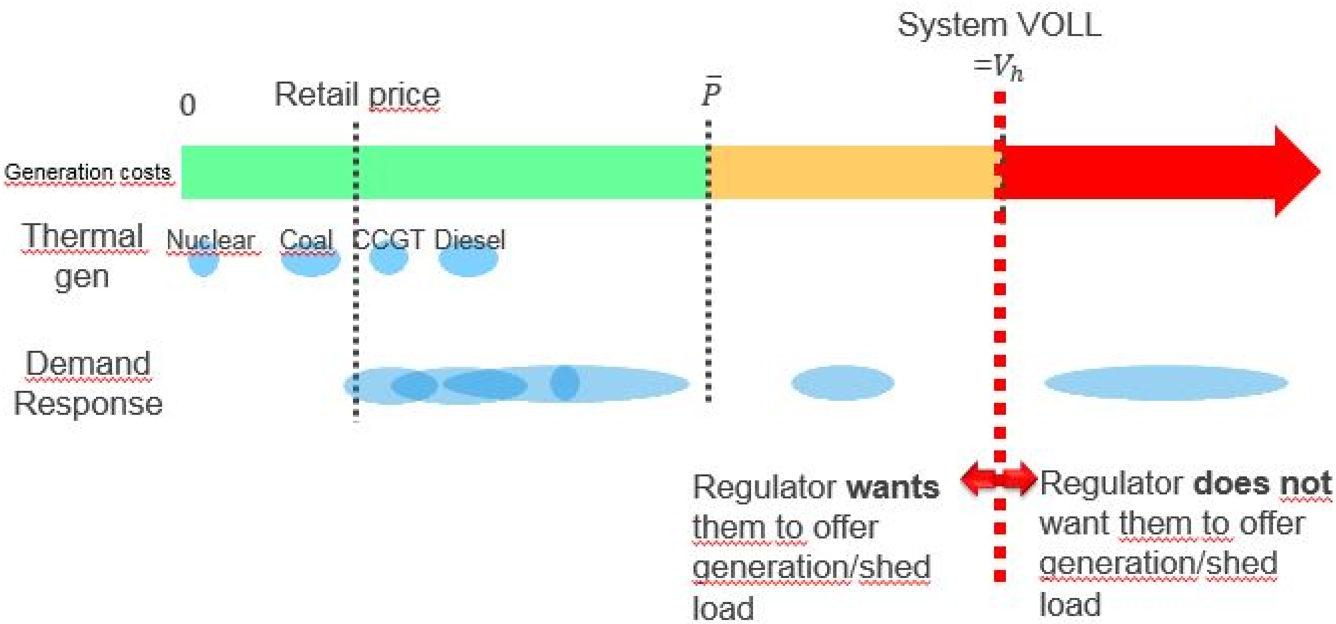

Figure 1: Illustrative short-run costs of generation and DR activation. Once installed, low value DR (green) does not need a contract to activate. Intermediate value DR (orange) needs one. TSO wants to make sure highest value DR (red) does not enroll in the DR scheme

prices won't send the adequate activation signal. This "orange" category, is not negligible. Figures reported in table 106 of London Economics (2013) show that around 20% of industrial demand in the UK has an opportunity cost lying between the price cap and the average value of lost load.

We'll exhibit a menu of complete contingent screening contracts that will ensure that all available welfare improving DR services will be implemented. Since baseline consumption for each operator i is common knowledge, DR_i can be considered as a generating unit with marginal costs equal to the gross value of consumption V_i. Following the revelation principle, we focus on direct mechanisms whereby the TSO asks potential DR operators to report their preference (i.e. their value of consumption V_i). We'll show that the resulting level of DR installation is optimal, and all contracts are incentive-compatible. The timing is as follows:

1. TSO presents a menu $MM(V)$ of payment to DR operators. In exchange, the TSO can request load reduction in some pre-defined, publicly known subset of the states of the world L_V.

2. Potential DR operator i can select a contract. If it does, it invests in the DR technology at cost r_i.

3. Desired demand l (without DR activation) realizes

4. DR may activate (i.e. operators agree to consume less than their desired, unconstrained unit demand), either prompted by high prices, or upon request from TSO if a contract was signed.

Denote:

- K: installed traditional generation – for simplicity, only one technology with marginal costs smaller than any value of consumption.
- l: Desired demand. We'll also refer to l as the "state of the world". l follows a probability density function $f(.)$. One can think of l as $l = l_h + l_I$ where:
  - l_h is (stochastic) demand from non-price responsive households. No DR potential.
  - l_I is (constant) industrial desired demand. There is some DR potential.
- $V_f(l)$: value of consumption of the first unserved consumer in state of the world l.
  - if there is excess capacity (all desired demand is fully covered: $K > l$): $V_f(l) = 0$
  - if TSO resorts to random curtailment: $V_f(l) = V_h$
  - otherwise, some but not all DR (either price-responsive or contracted) is activated: $V_f(l) = max\{V_i \,/\, DR_i\, is\, activated\}$

4 Optimal contract

Take a DR operator i, whose value of consumption is $V_i \in [0, \infty[$. V_i is the opportunity cost of DR activation, incurred by agent i. The overall social cost of activating such DR in states of the world L_V is $C(V) = \int_{L_V} V f(l) dl$. The gross social benefit $B(V_i)$ of activating this DR, is driven by the value of consumption of the first unserved consumer: $B(V_i) = \int_{L_{V_i}} V_f(l) f(l) dl$. Thus, the net social benefit is :

$$W(V_i) = B(V_i) - C(V_i) = \int_{L_{V_i}} (V_f(l) - V_i) f(l) dl \tag{1}$$

Hence, once the DR technology is installed it is optimal to activate DR i if and only if $V_i < V_f(l)$. We thus have that $L_{V_i} = \{l, V_f(l) > V_i\}$. It follows that if $V' > V$ then $L_{V'} \subset L_V$ and $W(V') < W(V)$. That is, the higher V is, the less frequent the activation is, and the smaller the net social benefit of such DR is. This intuition is the key driver of our main results.

To obtain optimal investment in DR in equilibrium, the TSO wants to make sure DR operator i receives $W(V_i) + C(V_i)$, such that there is entry if and only if

$$r_i + C(V_i) < B(V_i) = W(V_i) + C(V_i) \Leftrightarrow r_i < W(V_i)$$

This means there is investment if and only if the investment cost is smaller than the net social benefit. Note that DR operator i already gets some revenues through the re-sale of her foregone consumption on the energy market.

The TSO only needs to pay the difference between the gross value and those market revenues, henceforth denoted $MM(V_i)$:

$$MM(V_i) = W(V_i) + C(V_i) - EM(V_i) \tag{2}$$

where $EM(V_i)$ is the energy market revenues made by an operator i with underlying value of consumption V_i. An important assumption for the principal to offer first-best implementing contracts is that it knows the distribution of the characteristics (r_i, V_i) in the population of potential DR operators[15]. For ease of exposition, the next subsections study the cases with DR opportunity costs respectively below the price cap $\bar{P}$, between $\bar{P}$ and the system value of lost load V_h and above V_h.

4.1 Remuneration of DR: $V < \bar{P}$

To ease notations hereafter, the subscript i is omitted. Even though operators might pick up any contract, appendix 6 shows they report their opportunity cost truthfully. We slightly abuse notations in the integration domain by noting "$p < (=)\bar{P}$" the states of the world when the energy market price is below (at) the price cap. DR operators may be allowed to re-sell their load-reduction in the energy market:

- Sales on the energy market:

$$EM(V) = \int_{L_V \cap p < \bar{P}} V_f(l) f(l) dl + \int_{L_V \cap p = \bar{P}} \bar{P} f(l) dl \tag{3}$$

Where the first term represents revenues made when the price is set by the value of the first unserved consumer (meaning prices are efficient), and the second term is revenues when the price is at the cap.

- Opportunity cost of activation:

$$C(V) = \int_{L_V \cap p < \bar{P}} V f(l) dl + \int_{L_V \cap p = \bar{P}} V f(l) dl \tag{4}$$

- Recall that:

$$\begin{aligned} W(V) &= \int_{L_V} (V_f(l) - V) f(l) dl \\ &= \int_{L_V \cap p < \bar{P}} (V_f(l) - V) f(l) dl + \int_{L_V \cap p = \bar{P}} (V_f(l) - V) f(l) dl \end{aligned} \tag{5}$$

[15] As noted in Wilson (1989), this assumption may be reasonable if the distribution is stable over time, as consumers reveal their preferences through their past selection of contracts

As we saw earlier, the TSO needs to pay the "missing money" to DR operators:

$$\begin{aligned} MM(V) &= W(V) + C(V) - EM(V) \\ &= \int_{L_V \cap p = \bar{P}} (V_f(l) - \bar{P}) f(l) dl \equiv \overline{MM} \end{aligned} \tag{6}$$

Note that the capacity payment to DR is the same as for traditional generation, and does not depend on V : the set $\{L_V \cap p = \bar{P}\}$ is the same for all $V < \bar{P}$. Indeed, given that DR operators are price-takers, all existing DR is activated when $p = \bar{P}$, as long as the opportunity cost is lower than $\bar{P}$. Hence, the TSO payment should be independent of V when $V < \bar{P}$. The intuition is that indeed, the social value of a DR service based on a higher opportunity cost demand is less than that of a the service based on a smaller opportunity cost, since the service is called less often. However, this low social value service service also makes less profit in the energy markets. Those two effects cancel out and as long as $V < \bar{P}$, the missing money is the same for all services. Hence we recover the standard result that all types of capacity, should receive the same payment, irrespective of their position on the load-shedding order[16] (see eg. Cramton et al. [20]). Note that if $\bar{P} = V_h$, there is no need for a payment ($\overline{MM} = 0$). This case corresponds to an efficient pricing paradigm, and no CRM is needed at all.

4.2 Remuneration of DR: $\bar{P} \leq V < V_h$

If $V \geq \bar{P}$, the DR operator never activates, unless it signed a contract with the TSO. As discussed earlier on, optimality requires that the TSO activates DR only if $p = \bar{P}$ i.e. $\{L_V \cap p = \bar{P}\} = \{L_V\}$

- Sales on the energy market: $EM(V) = \int_{L_V} \bar{P} f(l) dl$
- Opportunity cost: $C(V) = \int_{L_V} V f(l) dl$
- TSO needs to give the missing money:

$$\begin{aligned} MM(V) &= W(V) + C(V) - EM(V) \\ &= \int_{L_V} (V_f(l) - \bar{P}) f(l) dl < \overline{MM} \end{aligned} \tag{7}$$

Note that the states of the world with activation is of smaller measure as V increases: $V' > V > \bar{P} \Rightarrow L_{V'} \subset L_V$. Hence the payment $MM(V)$ is decreasing in V on segment $[\bar{P}, V_h]$. The intuition is that a marginal increase in $V \in [\bar{P}, V_h]$ would result in a social welfare loss of $V f(V_f^{-1}(V))$, but in a loss in energy revenues of only $\bar{P} f(V_f^{-1}(V))$. Thus, the compensation of the TSO should be less as V increases.

[16]This is true for all services with equivalent availability at times of system stress, and same notice for activation

4.3 Remuneration of DR: $V_h \leq V$

Assume the TSO allows this DR to activate in states of the world L_V, just before resorting to random curtailment.

- Sales on the energy market: $EM(V) = \int_{L_V} \bar{P} f(l)dl$
- Opportunity cost: $C(V) = \int_{L_V} V f(l)dl$
- TSO needs to give the missing money:

$$
\begin{aligned}
MM(V) = W(V) + C(V) - EM(V) &= \int_{L_V} (V_f(l) - \bar{P}) f(l)dl \\
&= \int_{L_V} (V_h - \bar{P}) f(l)dl \equiv \underline{MM}
\end{aligned}
\tag{8}
$$

There will be entry if and only if

$$
\begin{aligned}
r_i(V) < W(V) &= \int_{L_V} (V_f(l) - V) f(l)dl \\
&\leq \int_{L_V} (V_h - V) f(l)dl < 0
\end{aligned}
\tag{9}
$$

Hence the TSO will not activate this technology (i.e. $\{L_V\} = \emptyset$) unless it *creates* some value, through other channels. Therefore, in equilibrium there is no entry in the in DR technologies with underlying opportunity cost higher than the system Value of Lost Load V_h, unless $r_i < 0$.

Figure 2 summarizes the main findings. $DR(v)$ denotes the amount of demand-response, having selected contract v or less. The main result is that payments to "upon-request" load-shedding must be lower than price-responsive DR. The intuition behind this is rather straightforward. Imagine a system where all consumers are non price responsive, set aside a substantial amount of industrial players whose opportunity costs lie between $\bar{P}$ and V_h. Assume there are enough industrial players so that random curtailment is never needed. The DR operator with highest opportunity cost is never activated, meaning she provides no welfare gain, and should therefore receive no payment even if the operator is technically available for load reduction. Conversely, traditional generation does suffer a missing money problem: when DR is activated, prices are stuck at $\bar{P}$, while the value of electricity is that of the fringe DR operator. An actual implementation of those payments would require a much finer modelling of power systems (esp. demand and DR implementation costs) and is left for future research. Figure 3 shows the optimal payment to DR as a function of the value of consumption V of the operators. The green line shows the opportunity costs of offering DR, once fixed costs r_i are paid and sunk. No DR with $V_i > V_h$ and positive fixed costs will sign a DR contract. Entry of DR with $V_i < V_h$ depends on r_i. Appendix 6 shows that those contracts are incentive-compatible, i.e. a potential operator with opportunity cost V_i asked to choose a contract $MM(\tilde{v})$ will

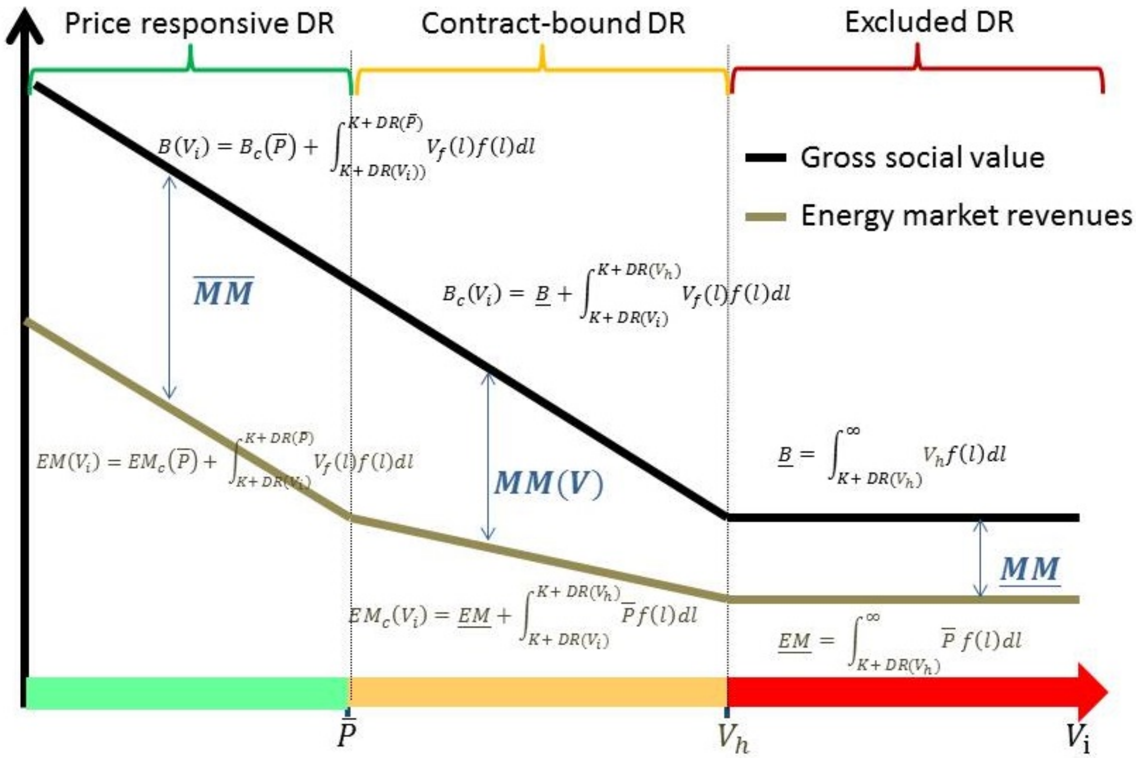

Figure 2: Illustrative gross social value, energy market revenues, and missing money as a function of DR operators' value of consumption. Assumes for illustration that $\forall i \in I$, $r_i > 0$ and $V_f(l)f(l) = cst$

indeed choose to report $\tilde{v} = V_i$.

Note again that this menu does not require DR operators to actually see and react to prices in real time. In the spirit of the priority service literature, one just needs them to know in which states of the world they will be required to shed load, given the opportunity cost they report.

5 Case studies

The intense debate on FERC's order 745 (see Chen and Kleit (2016)) has highlighted many misconceptions on DR value and what sort of incentives and monitoring it should receive. CRMs are still subject to active debates, starting from questioning whether it is state aid or not. This section sets itself the ambitious goal to clarify where we stand, when it comes to DR participation to CRMs. Indeed, while the previous section exposed an optimal capacity payment to DR, it would now be useful to compare it to designs currently in place. Smart Energy Demand Coalition (2015a) provides a very thorough overview of DR designs in place in various countries, highlighting their diversity. Warren (2015) provides insights on what features make them successful or not. Fortunately, in our simplified setting that focuses on the *capacity* value of DR, all of those designs can be reduced to either of two designs: i.e. no capacity payment at all, or full capacity payment ($\overline{MM}$ in the present model). This section

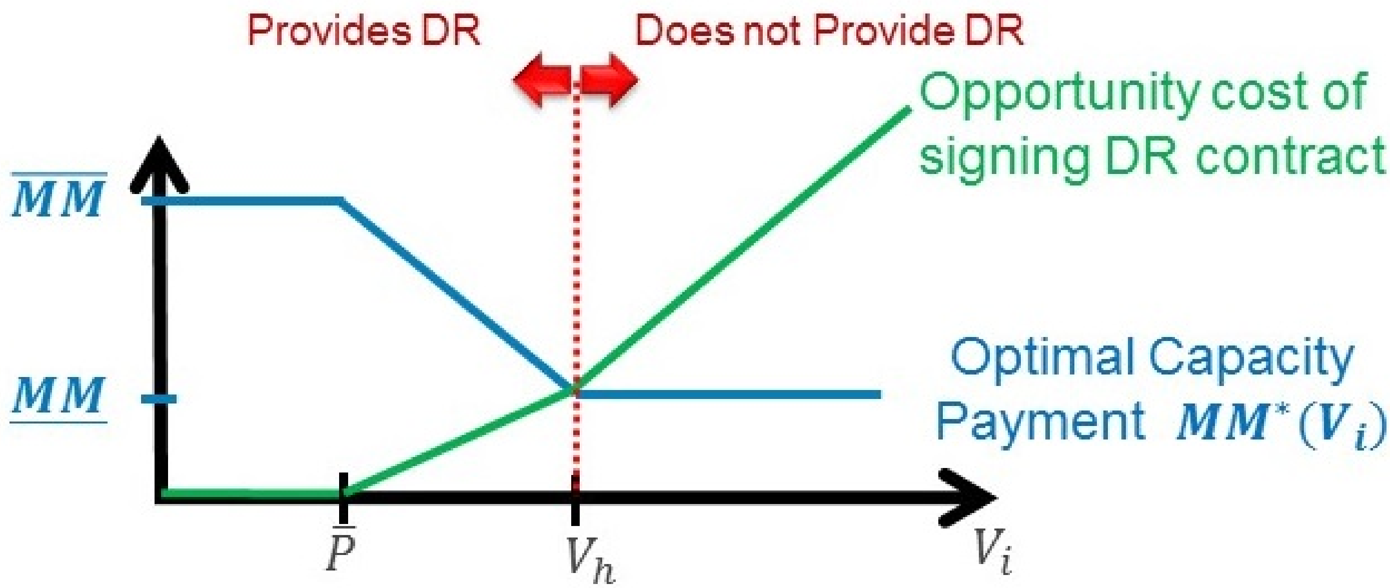

Figure 3: Optimal payment to DR and opportunity cost thereof, as a function of the value of consumption V

compares those payments with the optimal one.

Case 1: No capacity payment to DR

This corresponds to markets where there is no CRM (Netherlands, Denmark, Central Europe, ERCOT...), or where DR does not get remunerated for capacity. Even though there seem to be an agreement that DR should be remunerated as a participant to adequacy (see Cramton et al. (2013)), it remains often excluded. This exclusion can be *de jure* as in Italy or Spain (see Smart Energy Demand Coalition (2015a)) or *de facto* if eligibility criteria are too stringent –see European Commission (2016) for an interesting discussion on those criteria.

If there is no payment to DR at all, only those operators who can survive with energy market revenues offer DR – i.e. those with $V_i < \bar{P}$, and $r_i < W(V_i) - \underline{\mathbf{MM}}$. Figure 4 shows that the range for which the missing money payment exceeds the opportunity cost of providing DR narrows down compared to the optimal case studied above. No DR with underlying opportunity cost in $[\bar{P}, V_h]$ enrolls. DR with opportunity cost lower than the price cap but investment costs $r_i \in [W(V_i) - \overline{MM}, W(V_i)]$ don't enroll either despite their participation being optimal. Thus, there is not enough entry in the DR business.

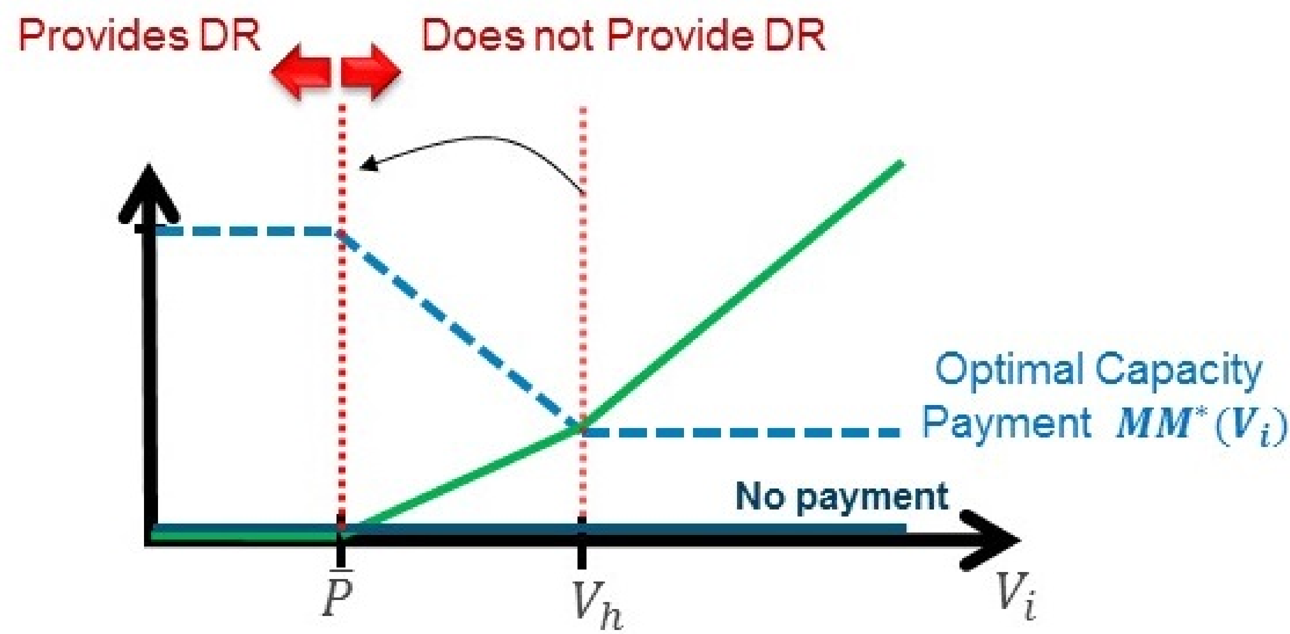

Figure 4: No payment to DR

Case 2 : Full capacity payment

This corresponds to markets where DR is allowed to participate in CRMs (PJM, France, UK...). Again, this requires that eligibility criteria make it possible to DR to qualify for the scheme.

Now, suppose that DR capacity is certified on the basis of **technical availability** at times of scarcity. DR with value higher than $\bar{P}$ is activated **upon request** from TSO. Figure 5 shows there is over-payment: even DR with $V_i > V_h$ sign a DR contract as long as $0 \leq r_i \leq \overline{MM} + \int_{L_{V_i}} (\bar{P} - V_i) f(l) dl$.

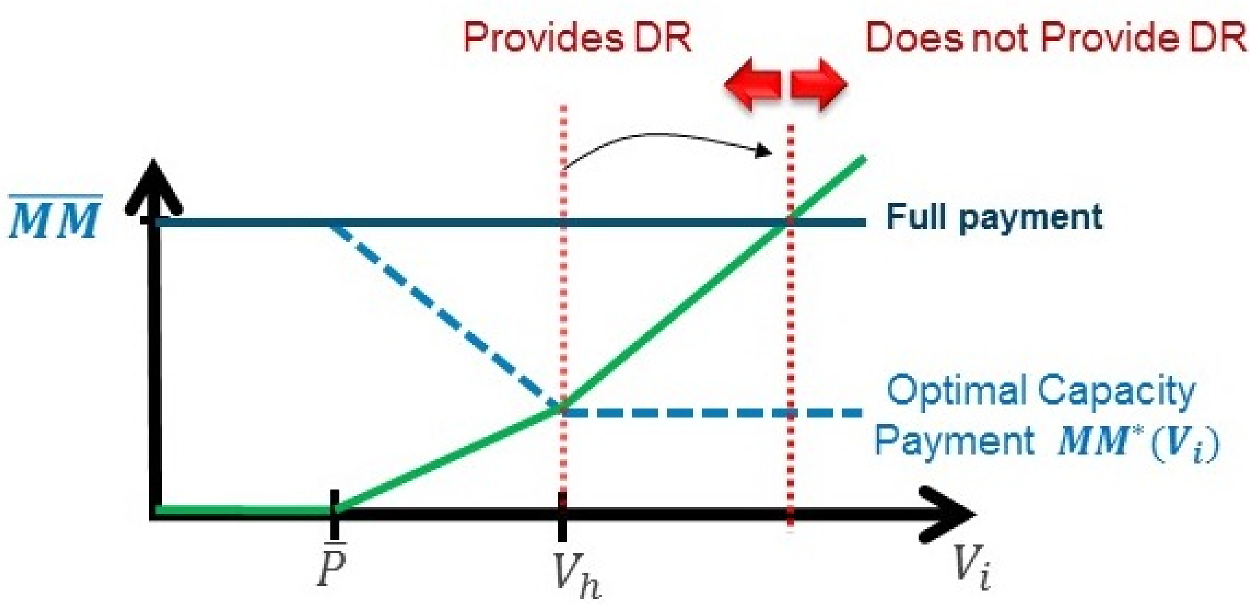

Figure 5: Full capacity payment to DR

With explicit participation of DR in CRM, the payment is excessive, and there is excess entry of high-opportunity cost DR. Similarly, an implicit participation (consumers offering this type of DR are exempt from CRM contribution) may constitute a hidden subsidy.

6 Conclusion

The integration of demand response in capacity mechanisms remains a key regulatory challenge. In this paper, we assumed that the presence of a price cap led regulators to provide additional remuneration for capacity. We observed that a side effect of this price cap is that prices sometimes failed to provide adequate information for DR activation. As a consequence, we showed analytically that even absent asymmetry of information on volumes (what would have been consumed by operator i absent a DR technology is public information), current designs fail to screen DR technologies and dispatch them optimally. In particular, we find that it is crucial to know whether DR will activate before the market hits the cap ($p < \bar{P}$) or when prices hit the cap ($p = \bar{P}$). In the former case, DR should receive the same capacity payment as traditional generation. However, if a DR operator does not commit to activating at a price $p < \bar{P}$ but instead awaits a request from the TSO, it should receive **only a portion** of the capacity payment. This portion should decrease in the priority level of the operator.

Potential extensions of this work include allowing for time-inconsistency of V_i and addressing the case when the regulator's objective function is biased against DR operators. In that case the TSO (i.e. the principal) needs to leave info rent to "good" type agents (in our case, low-opportunity cost operators), and distort activation periods.

Then, allowing for asymmetry of information on load-shedding volume availability would be very useful, albeit analytically much more complex.

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A Appendix: Proof of Incentive compatibility

Denote by $R(V_i, \tilde{v})$ the expected revenues a potential DR operator with opportunity cost V_i gets if it enrolls in a DR scheme and reports $\tilde{v}$.

A.1 case $V_i < \bar{P}$

We can assume away that $\tilde{v} > \bar{P}$. Indeed, the TSO payment is less, and DR is not activated during some profitable load-shedding events. An operator i will have to pay r_i and gets $\overline{MM}$, whatever the opportunity cost $\tilde{v} \in [0, \bar{P}]$ it announces. The revenues it gets are:

$$R(V_i, \tilde{v}) = \overline{MM} + \int_{L_{\tilde{v}} \cap p < \bar{P}} (V_f(l) - V_i) f(l) dl \\ + \int_{L_{\tilde{v}} \cap p = \bar{P}} (\bar{P} - V_i) f(l) dl \tag{10}$$

It is easy to see that the optimal choice is :

$$L_{\tilde{v}} = \{l / V_f(l) > V_i\} = L_{V_i} \tag{11}$$

Hence a potential DR operator reports her opportunity cost truthfully.

A.2 case $\bar{P} \leq V_i < V_h$

Assume that operator i reports $\tilde{v} \in [\bar{P}, V_h]$. It gets both a payment for capacity $MM(\tilde{v})$ and some energy market revenues:

$$\begin{aligned} R(V_i, \tilde{v}) =& MM(\tilde{v}) + \int_{L_{\tilde{v}} \cap p = \bar{P}} (\bar{P} - V_i) f(l) dl \\ =& \int_{L_{\tilde{v}} \cap p = \bar{P}} (V_f(l) - V_i) f(l) dl \end{aligned} \tag{12}$$

Again, it chooses optimally

$$L_{\tilde{v}} = \{l / V_f(l) > V_i\} = L_{V_i} \tag{13}$$

If it reports $\tilde{v} \in [0, \bar{P}]$, it gets:

$$\begin{aligned} R(V_i, \tilde{v}) =& \overline{MM} + \int_{L_{\tilde{v}} \cap p < \bar{P}} (V_f(l) - V_i) f(l) dl \\ &+ \int_{L_{\tilde{v}} \cap p = \bar{P}} (\bar{P} - V_i) f(l) dl \\ =& \int_{L_{\tilde{v}} \cap p < \bar{P}} (V_f(l) - V_i) f(l) dl \\ &+ \int_{L_{\tilde{v}} \cap p = \bar{P}} (V_f(l) - V_i) f(l) dl \end{aligned} \tag{14}$$

The second term is at best what it would get if it would report truthfully. The first term is negative as $\bar{P} \leq V$. Therefore reporting $\tilde{v} \in [0, \bar{P}]$ is not rational. If it reports $\tilde{v} \in [V_h, \infty[$, it gets:

$$\begin{aligned} R(V_i, \tilde{v}) =& \underline{MM} + \int_{L_{\tilde{v}} \cap p = \bar{P}} (\bar{P} - V_i) f(l) dl \\ =& \int_{L_{\tilde{v}} \cap p = \bar{P}} (V_h - V_i) f(l) dl \\ =& R(V_i, V_i) - \int_{L_{V_i} \cap p = \bar{P} \cap V_f(l) < V_h} (V_f(l) - V_i) f(l) dl \end{aligned} \tag{15}$$

$$< R(V_i, V_i) \tag{16}$$

Thus, operator i reports truthfully.

A.3 case $V_h \leq V_i$

Assume operator i reports $\tilde{v} \in [\bar{P}, V_h]$ to get higher payment for capacity. The revenues it makes is:

$$\begin{aligned} R(V_i, \tilde{v}) &= MM(\tilde{v}) + \int_{L_{\tilde{v}} \cap p = \bar{P}} (\bar{P} - V_i) f(l) dl \\ &= \int_{L_{\tilde{v}} \cap p = \bar{P}} (V_f - V_i) f(l) dl < 0 \end{aligned} \tag{17}$$

Hence, it makes negative profits: there is no entry, as is optimal. Similarly, if it reports $\tilde{v} \in [0, \bar{P}]$ it gets:

$$\begin{aligned} R(V_i, \tilde{v}) &= MM(\tilde{v}) + \int_{L_{\tilde{v}} \cap p = \bar{P}} (\bar{P} - V_i) f(l) dl \\ &= \int_{L_{\tilde{v}} \cap p = \bar{P}} (V_f - V_i) f(l) dl < 0 \end{aligned} \tag{18}$$

Thus, operator i reports truthfully.

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