Ensuring Capacity Adequacy in Liberalised Electricity Markets

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Abstract

This paper studies wholesale electricity markets where an exogenous price cap is enforced, compromising both short and long-term incentives. To guarantee capacity adequacy, policy-makers may provide support to generation through a capacity remuneration mechanism (CRM) and/or encourage demand response (DR). Such mechanisms are formalized within a common simple analytical framework, clarifying how these mechanisms relate to each other. We then divide them into two categories, depending on whether their implementation requires to make transactions based explicitly on spot prices higher than the price cap. While mechanisms that allow to keep implicit these high marginal costs are likely to be preferred from a political perspective, they also appear to be less efficient. If they are to be implemented nonetheless, we suggest that the price cap should be set higher than the marginal cost of the most expensive plant, and highlight that challenges for demand-response integration in CRMs remain.

Keywords: liberalised electricity markets, capacity adequacy, capacity remuneration mechanisms, demand response, electricity market design

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1 Introduction

Wholesale electricity markets have now been liberalised for many years in numerous countries. However many observers still raise doubts regarding the ability of decentralized market decisions to achieve the desired policy objectives. This concern has sometimes led policy-makers to impose different constraints on wholesale electricity markets. The most emblematic of such measures is probably the widespread use of a price cap, which sets an exogenous upper bound to the price at which power may be traded.

Price caps have been repeatedly criticized for creating a so-called "missing money" problem (Cramton and Stoft, 2006). Indeed producers' revenues are lower whenever the cap is binding, which decreases their incentives to invest in new power plants. As such, even in the absence of any market power issue, one may fear that in the long-run too little new capacity will be installed compared to what would be socially optimal. Additionally, when there is a shortage of capacity and prices are at the cap, they fail to elicit socially efficient demand reductions. As a consequence the System Operator (SO) has to take potentially suboptimal actions to balance the system and ensure the quality of service even at times of scarcity. For example, load is typically curtailed at the substation level, meaning consumers with a very high willingness-to-pay for power may be curtailed together with consumers with a much lower one. To tackle these issues, additional rules have been implemented in many markets in a move to restore short-term allocative efficiency and long-term investment incentives. Mechanisms interacting with wholesale electricity markets are nowadays mushrooming: explicit demand response (DR) mechanisms, interruptible contracts (similar in spirit to what is known as priority service (PS) in the economic literature), capacity remuneration mechanisms (CRMs), such as payments for capacity or strategic reserves (SR), etc.

Demand-side and supply-side mechanisms aimed at ensuring adequacy often coexist. It is therefore crucial to understand how they may compete and interact with one another and identify their limits. As an example, the EU state-aid guidelines (European Commission, 2014) state that the development of demand-side management should be an explicit target of any CRM scheme.[1]

This paper aims at improving our understanding of this interaction. In a first step, we show that both demand and supply-side adequacy mechanisms can be described within a common analytical framework, contributing to the literature by clarifying how these mechanisms relate to each other. Using this framework we observe that optimal investment signals can be restored by making the marginal costs during

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[1] 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).

peak states either explicit or implicit. The latter approach will often be preferred as it does not require to exhibit "socially unacceptable" prices. Unfortunately these mechanisms also appear to be more vulnerable to various inefficiencies, which we describe in more details than most of the existing literature.

In a second step we provide two simple policy recommendations if implicit mechanisms are to be used nonetheless. First, the price cap should be set higher than the highest marginal cost of conventional generation, so that the inefficiencies of the supply-side implicit mechanism are minimized. Second, a careful investigation of the limits of implicit mechanisms should precede the implementation of a demand-side mechanism.

The paper is organised as follows. Section 2 reviews the literature. Section 3 provides a simple common analytical framework for both DR and CRMs mechanisms, and proposes to divide these mechanisms into two families. Section 4 highlights a couple of policy recommendations for markets where transactions explicitly based on marginal costs higher than the price cap are unlikely to be allowed. Finally, section 5 concludes.

2 Literature review

This paper relates to two main streams of literature, one on demand-response mechanisms and another one on capacity remuneration mechanisms.

Demand-side mechanisms: PS and DR

Priority service (PS) has been studied in the economic literature well before the liberalisation of electricity markets and the subsequent debate about the missing money problem (Marchand, 1974; Tschirhart and Jen, 1979; Chao et al., 1988; Chao and Wilson, 1987; Wilson, 1989). This mechanism aims at ensuring efficient and incentive-compatible rationing of demand in situations of supply outages, when available generation is not sufficient to cover the whole demand. However, priority service may also be used to ration demand efficiently when consumers face exogenously-fixed prices such as price caps.

It is thus not surprising that a renewed interest in priority service emerged in recent years (e.g. Chao (2012)), as heated debates took place about what is labelled as "demand response" (DR) mechanisms (Chao, 2010; Hogan, 2010). Indeed, notably due to concerns about climate change, the issue of demand-side management is gaining more and more attention in many countries (see for example Zhang et al. (2017) for a case study of China).

Although there seems to exist more shades of DR mechanisms[2] than clearly formalized definitions, the basic idea is to make sure consumers face – and thus respond to – the wholesale price or the social marginal cost of electricity (or any signal that would reflect real-time market conditions better than their prevailing tariff). Yet, the details of the implementation matter a lot, as implicit subsidies to consumers may create significant distortions (Astier and Léautier, 2018), and consumers' attention may be hard to grab (Harding and Sexton, 2017; Gillan, 2018).

Supply-side mechanisms: CRMs

The literature on CRMs is more recent. Broadly speaking, it has developed alongside the liberalisation of electricity markets, as many authors expressed doubts regarding the ability of unregulated markets to sustain generation adequady on a smooth and continuous basis (see De Vries and Hakvoort (2004) for a detailed overview of such doubts). In particular, one of the main critics addressed to the energy-only market paradigm is its silence about the transient regime towards the equilibrium. Recent studies relying on system dynamics models have tried to fill this gap. For example Hary et al. (2016) illustrated the possible emergence of costly business cycles, and Petitet et al. (2017) compared the dynamic properties of different market designs.

There is a wide variety of mechanisms, ranging from direct payments for capacity to reliability option or strategic reserves (see e.g. Adib et al. (2008); Batlle and Rodilla (2010); Cramton and Stoft (2006); De Vries (2007); Lambin and Léautier (2018) for critical reviews of those mechanisms).[3] Those mechanisms may be technology-neutral or not, centralized or decentralized, volume- or price-based (see European Commission (2016), page 10 for a summary of those designs). In particular, the impact of CRMs, and/or the need for such mechanisms to allow plants to break even, may be different for different generation technologies (Levin and Botterud, 2015; De Maere d'Aertrycke et al., 2017). However CRM mechanisms all consist in giving additional payments to some generators in order to make sure there will be enough capacity available at times of high demand.[4]

So far CRMs have most often been justified by the "missing money" problem created by price caps (Joskow, 2013; Cramton et al., 2013). Price caps are indeed present in many markets. For example, the market coupling algorithm Euphemia and European market places use a price cap of $\bar{P} = 3000$

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[2] For example the terms implicit/explicit/active/passive DR, peak-time or critical-peak rebates/rewards/price/premium, demand-side management can all be found in the literature and/or industry reports.

[3] To some extent, this diversity may seem surprising given the numerous on-going debates regarding CRMs: "*Despite the lack of consensus whether there is a problem, several solutions have been developed, some of which have been implemented*" (De Vries and Hakvoort, 2004).

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

EUR/MWh for day-ahead transactions. In its inquiry on capacity mechanisms (European Commission, 2016), the European Commission has indicated that "*Where VOLL [Value Of Lost Load] has been estimated by MSs it ranges from* $11,000 EUR/MWh$ *to* $26,000 EUR/MWh$*, so significantly higher than existing European price caps*".[5] According to this study, the vast majority of countries having implemented some capacity mechanisms also have a price cap on day-ahead, intraday and/or balancing transations. At least two distinct reasons seem to underlie the implementation of a price cap. First, price caps may be a tool to mitigate market power abuses, which may otherwise occur in times of scarce supply. Second, high and volatile spot prices are often perceived as a political risk by decision-makers.[6] We assume in this paper that this second aspect is present, if not prevalent.

Some markets, such as the UK, or the Netherlands do not enforce a price cap. The present analysis does not intend to apply to such countries. These countries may nevertheless implement a CRM, as for example in the UK. A complementary justification given for CRMs is indeed a need to make up for a "missing market" for risk (Newbery, 2016), leading to an underinvestment in capacity. De Maere d'Aertrycke et al. (2017) illustrate this point by simulating how the limited availability of risk-hedging instruments and different liquidities for such products affect investment incentives. While the two families of mechanisms that we later highlight imply different risk profiles, the "missing money" problem is assumed to be the main motivation for implementing capacity adequacy mechanisms in this paper. The study of how risk-averse agents may react differently to both families of mechanisms is left for further research.

3 A common framework for capacity adequacy mechanisms in the presence of a price cap

3.1 Framework

Consider a wholesale electricity market in which the current structure and level of long-term assets is optimal – both on the supply-side (portfolio of power plants) and on the demand-side (portfolio of consumers' appliances). Further assume that all producers and consumers trade electricity at the wholesale price. In such an environment, textbook economics suggests that the (first-best) wholesale price in a given state-of-the-world t, which is denoted $p^*(t)$, should be determined by the intersection of the supply and demand curves.

Now suppose that, in order to prevent price spikes, a *price cap* $\bar{p}$ is set, so that the power price cannot

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[5] Price caps can be as low as $180 EUR/MWh$ in Spain and Portugal.

[6] "*[Price] caps and automatic mitigation protocols that constrain idealized free trading and market signals have been implemented in order to curb market power abuse and politically unacceptable price spikes*" (Oren, 2005).

exceed $\bar{p}$. If this price cap is of any use, it divides the set of states-of-the-world between two subsets. First, some states belong to the *off-peak* subset, defined as $OP(\bar{p}) \equiv \{t \,|\, p^*(t) \leq \bar{p}\}$. In such states, the market clears at the same price as when there is no price cap. Second, the other states will belong to the *peak* subset $P(\bar{p}) \equiv \{t \,|\, p^*(t) > \bar{p}\}$.

In such a context, capacity adequacy mechanisms face two issues. First, they need to restore short-term efficiency during peak states, that is to define rules such that demand and supply meet without inducing wasteful transactions. Second, they need to ensure long-term investment incentives, which will depend on the method used to share the surplus from trade during peak states between producers and consumers.

3.2 Low price cap : the need for both supply and demand-side mechanisms

Before presenting our canonical model, we first note that short-term efficiency may require an intervention both on the supply- and demand-side. Consider a situation where a low price cap $\bar{p}$ has been set, so that both demand and supply curves are elastic for prices in the neighborhood of the price cap. States t in which the price cap is binding correspond to the situation illustrated on Figure 1. Because the power price is constrained to be $\bar{p}$, the market will not clear unless a procedure to manage the imbalance between supply and demand is specified. Indeed, Figure 1 shows that when prices are at the cap the quantity supplied is smaller than demand: $Q_s(\bar{p}, t) < Q_d(\bar{p}, t)$.

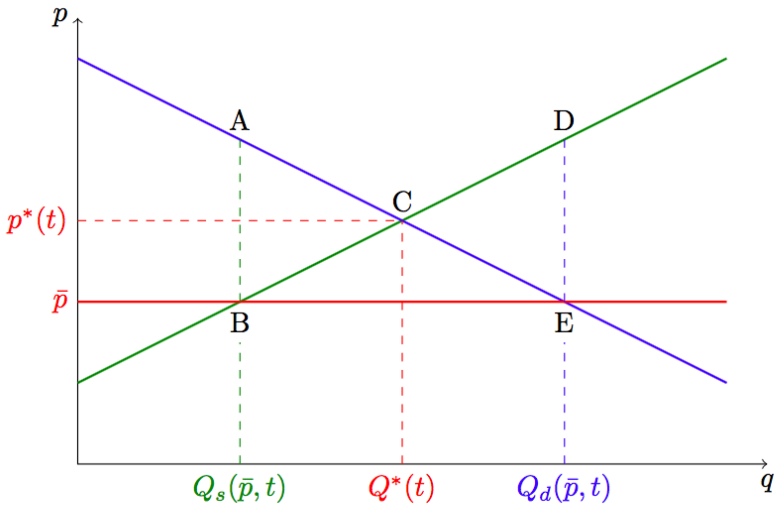

Figure 1: Supply and demand when the price cap is binding

One approach could be to ask producers to supply power at a loss (for example compensating them using public funds). A quantity $Q_d(\bar{p}, t)$ is then produced, creating a (short-term) deadweight loss represented by triangle CDE on Figure 1.

Another approach would be to shed load in order to decrease demand to the quantity $Q_s(\bar{p}, t)$ that producers are willing to supply at a price $\bar{p}$. Even assuming a perfectly efficient rationing rule (which is very hard to achieve in practice), this approach also creates a (short-term) deadweight loss represented by triangle ABC on Figure 1.

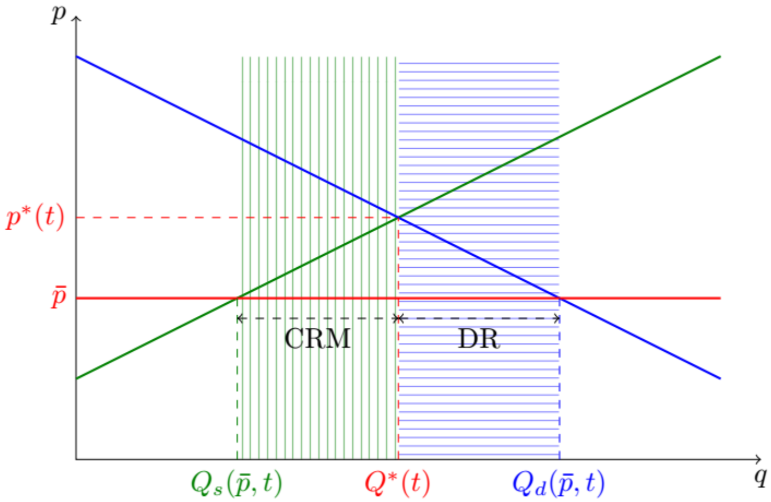

Figure 2: Complementarity of CRM and DR to restore short-term allocative efficiency

Restoring short-term allocative efficiency thus requires both a supply-side mechanism incentivizing generators in the green, vertically hatched region on Figure 2 to run their power plant, and a demand-side mechanism incentivizing consumers in the blue, horizontally hatched region to withdraw their demand.

3.3 Canonical models of capacity adequacy mechanisms

Theoretical models of capacity adequacy mechanisms usually focus on a single side of the market (see for example Chao and Wilson (1987) for demand-side mechanisms, and Joskow (2008); Cramton et al. (2013) for supply-side mechanisms). To preserve tractability, they assume that consumers (resp. producers) have a *state-independent* unit demand for power (resp. unit capacity of production).[7] For the sake of

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[7] This assumption may be reasonable for conventional power plants. See Chao and Wilson (1987) for an attempt to justify this (strong) assumption for consumers.

simplicity, the present section will also consider that either supply or demand is stochastic but not both at the same time. However, the model used allows to highlight the formal symmetry between both cases.

Let θ be the willingness-to-pay of a given agent for this unit (resp. her marginal cost to produce it) with cumulative distribution $F(.)$. Importantly, and consistently with most models underlying capacity adequacy mechanisms, agents are assumed to be risk-neutral. The distribution of θ is used to derive a state-independent price elastic curve $l(p)$ (demand curve for DR mechanisms and supply curve for CRM mechanisms). Note that $l(p)$ needs not be elastic for all price levels.[8]

The other side of the market is modelled as a random inelastic quantity Z which takes value $Z(t)$ in state t. Table 1 summarizes the notations used depending on whether the considered capacity adequacy mechanism focuses on demand-side or supply-side activation, while Figure 3 provides a graphical illustration (the various vertical lines represent different states t).

Ingredient	Demand-side mechanism	Supply-side mechanism
$Z(t)$	available supply	demand level
θ	willingness-to-pay	marginal cost
$l(p)$	$1 - F(p)$	$F(p)$
Examples	Chao and Wilson (1987)	Joskow (2008); Cramton et al. (2013)

Table 1: Ingredients of canonical capacity adequacy mechanisms

Let $p^*(Z) \equiv l^{-1}(Z)$ be the market clearing price that would prevail in the absence of the price cap constraint. From the distribution of $Z(t)$, one may derive a distribution $h(.)$ such that first-best market-clearing prices p^* are distributed according to $h(.)$ (that is, $h(p) \equiv \int_{t,\, p^*(Z(t))=p} d\mu(t)$, where μ measures the states-of-the-world).

As explained above, the price cap constraint creates a “missing money” problem, that is a missing transfer from consumers to producers which should be transfered back from consumers to producers in order to restore long-run investment incentives. For a producer who supplies a unit of energy in *all* peak states, this revenue shortfall induced by the price cap[9] is:

$$MM(\bar{p}) \equiv \mathbb{E}_t\left[(p^*(t) - \bar{p})^+\right] = \int_{\bar{p}}^{\infty} (p - \bar{p})^+ h(p)dp \tag{1}$$

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[8] In particular, demand may be inelastic for some levels of prices. A totally inelastic demand curve would however render DR mechanisms obsolete.

[9] Note that a symmetric situation may be envisioned in which a price floor is imposed in order to artificially protect producers’ revenues (in which case their would be a missing transfer from producers to consumers). While a price floor is set in many marketplaces (e.g. EpexSpot in Europe), the floor is rarely met. We therefore focus on price cap.

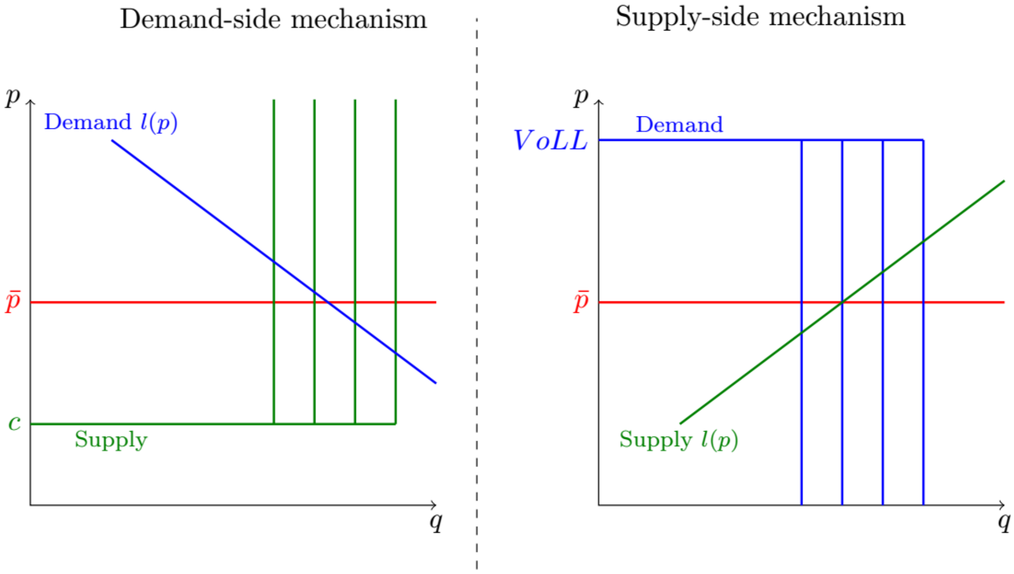

Figure 3: Graphical representation of canonical capacity adequacy mechanisms' assumptions

However, in order to restore allocative efficiency, a producer (resp. a consumer) should only supply (resp. consume) power during a peak state if his marginal cost is below (resp. her willingness-to-pay is above) the social marginal cost of power p. Consistently models of capacity adequacy mechanisms conclude that in order to be supplied in states such that $p > \bar{p}$, consumers with willingness-to-pay θ, willing to served at all times when cost of production is below their willingness-to-pay, should pay a missing money transfer:[10]

$$\pi_c(\theta) \equiv \int_{\bar{p}}^{\theta} (p - \bar{p})^+ h(p) dp \tag{2}$$

Symmetrically, producers with marginal cost θ, producing whenever the marginal value of energy is greater than θ should receive a compensating transfer:[11]

$$\pi_p(\theta) \equiv - \int_{\theta}^{\infty} (p - \bar{p})^+ h(p) dp \tag{3}$$

From (1), we see that:

$$\pi_c(\theta) \equiv MM(\bar{p}) + \pi_p(\theta) \tag{4}$$

Because $MM(\bar{p})$ does not depend on θ, equation (4) shows that there exists a formal analogy between DR and CRM payments. This will allow us to greatly simplify the exposition. Indeed, insights found in

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[10] Implementation details, and notably incentive compatibility, are discussed in the corresponding literature.

[11] Note that $\pi_p(\theta) < 0$, meaning that producers receive a payment.

a DR setting will carry over to CRMs and vice-versa.

3.4 Explicit and implicit mechanisms

In a first-best environment, agents with a type θ such that $\bar{p} \leq \theta < \max_t p^*(t)$ would not consume (resp. produce) power in every single peak state, since there exist states-of-the-world where their willingness-to-pay for power (resp. their marginal cost of production) is lower (resp. higher) than the first-best price of power. As such, these agents should not pay (resp. they should not receive) the full missing money transfer. The fact this missing money transfer is only partial allows to envision several mechanisms to recoup it.

Capacity adequacy mechanisms may then be schematically decomposed into two stages:

1. **A contracting stage (CoS)** where an initial transfer is made and parties agree upon rules that will prevail later on, notably when the price cap is binding.
2. **Trading stages (TrS)** where real-time (e.g. hourly) production and consumption occur, and the rules defined during the contracting stage apply.

Unconstrained wholesale markets correspond to a design without any contracting stage, except for classic and/or allowed financial contracts. The presence of a price cap, requires a contracting stage since one must specify what happens when the price cap is binding. Two main families of mechanisms may be envisioned – either implicit or explicit – as described in Table 2.

Type	Stage	Supply-side mechanisms	Demand-side mechanisms
Implicit Designs	CoS	Producers receive $\mathbb{E}_t\left[(p^*(t)-\bar{p})^+\,\mathbf{1}_{\theta<p^*(t)}\right]$	Consumers pay $\mathbb{E}_t\left[(p^*(t)-\bar{p})^+\,\mathbf{1}_{\theta>p^*(t)}\right]$
	TrS	Consumers/SO switch on the plant whenever $p^*(t)>\theta$	Producers/SO shed the load whenever $p^*(t)>\theta$
Explicit Designs	CoS	Producers receive $\mathbb{E}_t\left[(p^*(t)-\bar{p})^+\right]$	Consumers pay $\mathbb{E}_t\left[(p^*(t)-\bar{p})^+\right]$
	TrS	Producers pay $(p^*(t)-\bar{p})^+$ if they don't produce, and thus they pay in expectation: $\mathbb{E}_t\left[(p^*(t)-\bar{p})^+\,\mathbf{1}_{\theta>p^*(t)}\right]$	Consumers receive $(p^*(t)-\bar{p})^+$ if they don't consume, and thus they pay in expectation: $\mathbb{E}_t\left[(p^*(t)-\bar{p})^+\,\mathbf{1}_{\theta<p^*(t)}\right]$

Table 2: Taxonomy of capacity adequacy mechanisms (producers and consumers are assumed to have a unit demand/supply)

Schematically, the top left cell would correspond to strategic reserves (SR), the bottom left to a payment to operational capacity for example through reliability options (Vazquez et al., 2002; Chao and Wilson; Oren, 2005), the top right to priority service (PS) and finally the bottom right to DR.[12]

Importantly, the two families of designs differ by the implied necessity, or not, to compute *explicitly* what the first-best spot prices higher than the price cap would have been in the absence of a price cap.

Indeed, when the price cap is binding, explicit designs require to compute the would-be first-best prices $p^*(t) > \bar{p}$, which raises two challenges. First, computing such prices requires the implementation of a procedure to recover the would-be spot prices when the cap is binding (e.g. by requiring power exchanges to compute such prices). Second, and perhaps more importantly, explicit designs require to make transactions based on first-best prices $p^*(t) > \bar{p}$, making them observable and salient, while the actual market spot prices will be set at the cap. Such a design is thus likely to be hard to reconcile with the initial motivation(s) that led to the implementation of a price cap in the first place.

By contrast, although they do not remove the technical difficulty to build a credible counterfactual, implicit mechanisms allow to avoid using financial transfers based on high would-be first-best prices, replacing them with politically less sensitive activation periods. Indeed, one may implement an implicit mechanism by writing down contracts based on reliability, that is on a load-shedding or a generation-activation probability, which allows avoiding to explicitly compute the highest would-be spot prices. Indeed, integrating by parts the transfers of equation 2, one may rewrite:

$$\pi_c(\theta) = \int_{\bar{p}}^{\theta} \left(H(\theta) - H(p)\right) dp \tag{5}$$

$$(\text{and } \pi_p(\theta) = \pi_c(\theta) - MM(\bar{p}))$$

where $H(.)$ is the cdf of first-best spot prices (i.e. the cumulative sum of $h(.)$). Because H represents the fraction of the time during which first-best prices are lower than θ, $H(\theta)$ may be interpreted as a probability.

Consequently the above equation allows to frame implicit mechanisms in very simple terms for agents. For a demand-side mechanism, consumers may be asked to choose the reliability which they want to be supplied with and will self-select to choose $H(\theta)$ (Chao and Wilson, 1987). For a supply-side mechanism, producers may receive payments contingent on the number of days per year they want to be dispatched, in which case they will also self-select on $1 - H(\theta)$.

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[12] In which the baseline is previously contracted at its forward value.

Not surprisingly, implicit designs thus often emerge as the preferred paradigm of many current policies both on the supply and on the demand-side. Unfortunately, Section 4.1 shows that contrary to explicit designs, these mechanisms are not very robust to uncertainty, and incomplete and/or asymmetric information.

4 Implicit mechanisms and policy recommendations

4.1 Limits of implicit mechanisms

We assumed so far that consumers (resp. producers) had a fixed willingness-to-pay (resp. marginal cost) for a fixed unit demand (resp. supply) of power. In other words, their characteristics were *state-independent.* Uncertainty thus only affected the other side of the market, and/or non-relevant portions of the supply/demand curves (i.e. portions at price levels that never end up being at the margin). Unfortunately, this assumption is easily violated – i.e. the function $l(p)$ is very likely to be state-dependent.

On the demand-side, the assumption of a stable demand function over time and contingencies is clearly violated.[13] First, consumer may not know their willingness-to-pay at the contracting stage (e.g. last-minute changes in daily schedule). Because of this uncertainty, reliability of service should actually be an argument of consumers' preferences (Hartman et al., 1991). Second, customers usually consume electricity services, not capacity. This means the unit-demand assumption is often violated by non-convexities in demand (the willingness-to-pay for half the power needed to run a coffee maker is not half the willingness-to-pay for enough power to switch it on).

On the supply-side, although the assumption of a stable supply function sounds more robust, it also raises some difficulties. First, future marginal costs are contingent on future fuel prices. Second, the "unit supply" assumption is violated for non-dispatchable generators (e.g. wind, PV).

A better account of the uncertainty affecting the price-elastic side of the market is thus needed. First, the object of the uncertainty should be specified. For example, in the context of a demand-side mechanism, it may concern consumers' willingness-to-pay, the quantities requested, or both. Second one needs to characterize the nature of the uncertainty. Several information structures may be considered:

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[13] See for example Schweppe et al. (1988): "*Most customers (and generators) have time-varying and stochastic willingness to provide reserves, as well as stochastic time-varying overall demand [...] It is therefore inefficient to force them to precommit to a fixed level of interruption for a year as is the practice with many interruptible contracts*" ; or Woo (1990) (footnote 12): "*A consumer's valuation of each of his end-uses (e.g. air conditioning, cooking, etc....) often varies by time-of-use. Segmenting the total load over the available priority classes by time-of-use entails high information costs*".

- complete or incomplete information: changes in characteristics may be perfectly predictable or not;
- symmetric or asymmetric information: changes in characteristics may be publicly or privately known.

An exhaustive study of all the combinations offered by the above possibilities is beyond the scope of this paper. Instead the following sub-sections discuss a few representative examples to illustrate the problems that may arise, in the context of a demand-side mechanism.

4.1.1 Complete information with state-dependent volumes

Consider first a complete information environment where only the unit demand/supply assumption is violated.

Symmetric information

Consider an agent $(\theta, q(.))$ who is willing to pay $\$\theta$ per kWh up to a quantity $q(t)$ in state t (and zero for further consumption). This information is common knowledge at the contracting stage. For a demand-side capacity adequacy mechanism, restoring first-best transfers would require to ask this consumer to pay a reliability premium:

$$\pi_c(\theta, q(.)) = \mathbb{E}_t\left[(p^*(t) - \bar{p})^+ \, q(t)\mathbf{1}_{p^*(t)\leq\theta}\right] \tag{6}$$

which, by denoting $H(\theta) \equiv \#\left(\{t \,|\, p^*(t) \leq \theta\}\right)$ the measure of the subset of states in which the consumer would be served in a first-best environment, may be rewritten:

$$\begin{aligned} \pi_c(\theta, q(.)) \quad = \quad & \mathbb{E}_t\left[(p^*(t) - \bar{p})^+ \, \mathbf{1}_{p^*(t)\leq\theta}\right] \mathbb{E}_t\left[q(t)\right] \\ & + H(\theta)\mathrm{Cov}\left((p^*(t) - \bar{p})^+ \, , q(t) \,|\, p^*(t) \leq \theta\right) \end{aligned} \tag{7}$$

While the expression is slightly more complex, key is to note that a covariance term between the consumption level $q(t)$ and the capacity premium $(p^*(t) - \bar{p})^+$ appears. Because of this covariance term, consumer's additional payment can no more be expressed using only the reliability metric $H(.)$ unless the covariance term is public information (which may not be the case if the consumption profile $q(t)$ is not measured).

To understand the underlying intuition, note that the basic idea of an implicit mechanism is to elicit an absolute monetary value *ex ante* (WTP or marginal cost of supply) – which is a cardinal notion –, so as to be able to determine a ranking of activation *ex post* (curtailment or reserve) – which is an ordinal notion. For such a strategy to work, the function mapping the monetary value to the ranking must thus remain as stable as possible during the time elapsed between the signature of the contract and its execution. In particular (i) agents must indeed have unit demand/supply; and (ii) their willingness-to-pay (resp. marginal cost of production) must be time-consistent and known *ex ante*.

Asymmetric information

Under asymmetric information, two dimensions are unknown: 1) the type θ of agents and 2) their covariance term. As such, unless unrealistic conditions are met, a single instrument such as reliability is unlikely to allow to screen them both.

In addition, the issues raised by asymmetric information are exacerbated when the mechanism designer is biased against some market participants. The Appendix discusses this situation in the case of a demand-side mechanism in the canonical framework described in section 3.3.

Let us now turn to stylized situations where the unit-demand assumption is a good enough approximation, in order to focus on incomplete information at the contracting stage.

4.1.2 Unit demand under incomplete information

Consider an implicit mechanism where the agent has a state-independent type, but does not know it perfectly at the contracting stage. Instead, she has some expectations about her type characterized by a given distribution (whose support is assumed to span beyond $\bar{p}$). Assuming risk-neutrality, she will pick a contract $\hat{\theta}^*$ that maximizes her expected surplus:[14]

$$\max_{\hat{\theta}} H(\hat{\theta}) \left(\mathbb{E}\left[\theta\right] - \bar{p}\right) - \int_{\bar{p}}^{\hat{\theta}} (p - \bar{p})^+ h(p) dp \tag{8}$$

Not surprisingly, she will select $\hat{\theta}^* = \mathbb{E}\left[\theta\right]$ which will create some ex-post inefficiencies. For example, if it turns out that $\theta > \mathbb{E}\left[\theta\right]$, *ex post* welfare losses will be:

$$DWL = \int_{\mathbb{E}[\theta]}^{\theta} (\theta - p) h(p) dp \tag{9}$$

This inefficiency illustrates a fundamental weakness of implicit designs: *all the information learned after the contracting stage cannot be used to optimise the allocation.* It is therefore crucial to avail consumers with as much information as possible prior to contracting.

As a conclusion, in our attempt to clarify how the different types of capacity adequacy mechanisms relate to each other, we have highlighted that although implicit mechanisms are more likely to meet the political and/or acceptability constraints that led to the implementation of a price cap in the first place, such mechanisms are likely to be less efficient than explicit mechanims.

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[14] The equation refers to the situation where the agent is a consumer. The producer case is symmetric up to a constant and a sign change.

Policy-makers may thus face a trade-off between efficiency and acceptability, which might explain the widespread use of implicit mechanisms. Drawing on this observation, the next section formulates a couple of policy recommendations for the implementation of implicit mechanisms.

4.2 Double-sided uncertainty

Section 3.3 explained how the canonical models of capacity adequacy mechanisms reconcile the conflicting needs to have stable agent characteristics on the one hand (unit demand/supply, state-independent type), and state-dependent system conditions on the other hand (so that there exist times of scarcity). To do so, they essentially focus on the activation of a single side of the transaction (either supply or demand) – assumed to be roughly state-independent[15] – and assume that variations in system conditions are almost exclusively caused by shocks on the other side of the transaction. Formally, they rely on the strong assumption that the function $l(.)$ is state-independent in the relevant range of prices.

When a capacity adequacy mechanism must be implemented on both sides of the market, as illustrated on Figure 2, the robustness of the canonical model described in section 3.3 must be investigated.

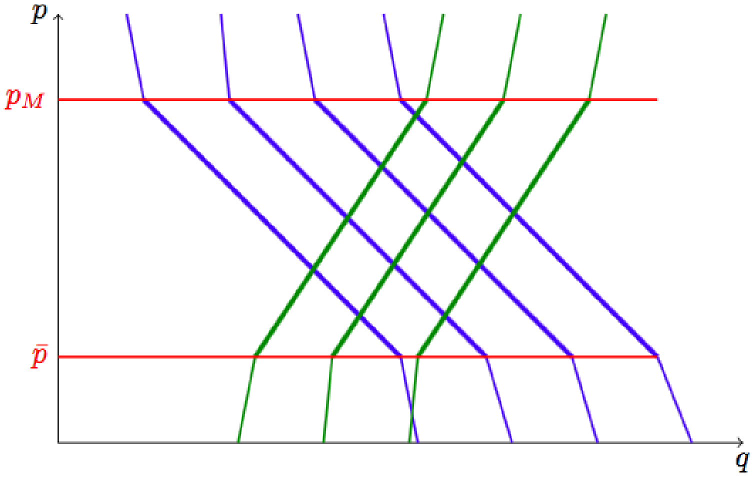

Figure 4: An extension of the canonical model robust to double-sided uncertainties

In this situation, the constraints to have stable agents' characteristics on both sides of the market on the one hand, and stochastic system conditions on the other hand, may seem irreconcilable. Indeed,

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[15] At least in the relevant price-range of the demand/supply function.

the only way out of this puzzle is to assume that the relevant portions of the demand and supply curves are state-independent, allowing the rest of the curves to be subject to random shocks: if one denotes $p_M = \max_t p^*(t)$, one may envision a situation where *in all states of the world*, the portion of the supply and demand functions between $\bar{p}$ and p_M (in bold on Figure 4) is composed of agents with a state-independent type θ and a unit demand/supply.

For electricity markets, this situation may for example be an approximation of a country whose generation park is composed of only renewables and thermal plants (so that shocks in renewables production act as a mere shift in the merit order), and where only a few industrial consumers are exposed to spot prices (so that shocks in inelastic residential consumers' demand above p_M act as horizontal shifts of the demand curve).

Because these conditions are however very unlikely to be met in practice, Section 4.3 draws on this observation to derive a couple of policy implications.

4.3 Policy implications and discussion

One may note that if the price cap is high enough, the supply curves on Figure 4 will become vertical above $\bar{p}$, meaning the missing money transfer from consumers to producers will not depend on the marginal cost of producers. Indeed Table 2 shows that if the marginal costs of a given producer is known to be below the price cap in all states of the world, implicit and explicit mechanisms do not differ (assuming implicit designs set penalties when the activation of a generator fails, as they usually do). Therefore, for such technologies no fundamental difference is observed between implicit and explicit mechanisms.

This is good news for policy-makers. Indeed, most price caps are already higher than the marginal costs of the most expensive conventional power plants. This means implicit mechanisms should not be subject to the limits exposed in section 4.1 if properly applied to conventional supply – which represented the bulk of adequacy resources in the latest capacity auctions.[16]

Unfortunately such an easy conclusion cannot be reached when it comes to adequacy schemes applied to demand-response. Indeed the underlying opportunity cost of demand response may range from 0 to extremely high values. Thus, explicit mechanims will inevitably entail state-dependent payments at the transaction stage, which implicit mechanisms are unlikely to be able to perfectly replicate. If implicit schemes are to be used nonetheless, it will be crucial to study carefully the limits underlined in section

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[16] As an example, DR represented 1.2GW out of 50.4 procured in National Grids T-4 auction to ensure capacity meets expected demand for the 2021/22 winter period: https://www.energy-storage.news/news/record-low-prices-in-uk-capacity-market-auction-trigger-concerns.

4.1 in the context of the considered market.

5 Conclusion

This paper studies wholesale electricity markets where an exogenous price cap is enforced, compromising both short-term allocative efficiency and long-term investment incentives. To guarantee capacity adequacy, policy- makers may provide support to generation through a capacity remuneration mechanism (CRM) and/or encourage demand response (DR).

First, this paper shows how such mechanisms may be formalized within a common simple analytical framework, contributing to the literature by clarifying how these mechanisms relate to each other. Capacity adequacy mechanisms are then divided between explicit and implicit designs, depending on whether their implementation requires to make transactions based explicitly on short-term marginal costs higher than the price cap.

A second contribution is to highlight that, while mechanisms which allow to keep implicit these high marginal costs are likely to be preferred from a political perspective (for the very same reasons that led to the implementation of a price cap in the first place), they also appear to be less efficient, notably because of uncertainty, and incomplete or asymmetric information.

To conclude, the paper formulates two policy recommendations if implicit mechanisms are to be implemented nonetheless. First, the price cap should be higher than the marginal cost of the most expensive plant in order to greatly simplify the supply-side capacity adequacy mechanism. Second, a careful investigation of the limits of canonical capacity adequacy mechanisms when applied to the demand side should preceed their implementation.

While this paper only considers the benefits of capacity and demand-response in terms of their participation to resource adequacy, other dimensions such as potential externalities may have to be considered if one is to compute an optimal full payment to these technologies. In addition, the model used assumed agents were risk-neutral. Extensions allowing to account for risk-aversion, either in generation investment decisions or in the contract arrangements between retailers and consumers, should deserve more attention. This is left for further research.

Biased mechanism designer

The mechanism designer of capacity adequacy mechanisms may be biased against certain types of agents for different reasons (e.g. he may want to favour final consumers over producers, protect small consumers unable to engage in profitable DR businesses) a situation explored in this Appendix. We focus on direct, implicit mechanisms and assume the social planner is biased against DR providers.

Assume consumers have unit demand, with constant willingness to pay θ which is private information of agents. θ is publicly known to be distributed with respect to cdf $F(.)$, and pdf $f(.)$. Consumers are assumed to have paid ex-ante the energy they would consume, absent load shedding. The timing is as follows:

1. Consumers report a type $\hat{\theta}$;
2. They receive an activation threshold $\tilde{\theta}(\hat{\theta})$, i.e. the would-be price above which consumers stop consuming (resp. producers start producing), and a transfer $t(\hat{\theta})$.

Consumer θ gains, if she participates to the mechanism are:

$$u(\theta,\hat{\theta}) = -(\theta-\bar{p})(1-H(\tilde{\theta}(\hat{\theta}))) + t(\hat{\theta}) \tag{10}$$

The first term corresponds to the utility loss due to the consumers giving up consuming when $p(t) > \tilde{\theta}(\hat{\theta})$. The second term is the payment made by the social planner for this service.

Assuming full participation (that is $\forall\theta \in [\underline{\theta},\bar{\theta}], u(\theta,\theta) \geq 0$), the problem of a mechanism designer biased against DR operators is:

$$\begin{gathered}\max_{\tilde{\theta}} \int_{\underline{\theta}}^{\bar{\theta}} \left(\int_{\tilde{\theta}(s)}^{+\infty} (p-\bar{p})h(p)dp - t(s) \right) f(s)ds \\ \text{s.t.} \\ \theta \in \arg\max_{\hat{\theta}} -(\theta-\bar{p})(1-H(\tilde{\theta}(\hat{\theta})) + t(\hat{\theta})\end{gathered} \tag{11}$$

Using standard mechanism design techniques, we derive:

$$\begin{cases} \tilde{\theta}(\theta) = \theta + \dfrac{F(\theta)}{f(\theta)} \\ t(\theta) = (\theta-\bar{p})(1-H(\tilde{\theta}(\theta))) + \displaystyle\int_{\theta}^{\bar{\theta}} (1-H(s))ds \end{cases} \tag{12}$$

Hence, to ensure truthful reporting, the social planner needs to distort the allocation of bad types (i.e.

those least useful to the system, i.e. those with high θ), while consumers with $\theta = \underline{\theta}$ are disconnected a the efficient threshold. It is easy to show that highest types ($\theta = \bar{\theta}$) get no rent, while better types do.[17]

In the demand response paradigm, this means some consumers will stop consuming later than what efficiency requires so the SO can limit the rents provided to DR operators.

In a CRM setting, it means a rent will be granted to low cost plants so that they don't report higher costs to get a higher compensation. In order to limit the rents given to low-cost producers, high cost plants will be dispatched later than in the optimal case (i.e. they will be assigned to a suboptimal activation schedule).

This type of schemes may be more robust when it comes to CRMs (as opposed to DR), for two reasons. First, there is less asymmetry of information on θ. Since θ, which corresponds roughly to fuel costs is verifiable, there is no incentives problem. Second, θ is usually much below $\bar{p}$. Assuming the generation market is sufficiently competitive no incentives to produce and sell on wholesale markets are required when the price is at the cap.

Note we considered $F(.)$ as fixed and given. However, a biased mechanism will also bias long-term investment incentives, that is how $F(.)$ evolves over time. For example, a mechanism biased against producers should lead to underinvestment in production in the long-term.

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[17] The principal may be only partially biased. Its objective would be to maximise $\alpha CS + (1-\alpha)PS$, where CS and PS are consumer and producer surplus, respectively. In that case the activation triggers would be $\hat{\theta}(\theta) = \theta + (2\alpha - 1)\dfrac{F(\theta)}{f(\theta)}$. That is, the triggers would get closer to optimal as α increases. If $\alpha = 1/2$, meaning the principal is unbiased, agents get assigned to the optimal schedule – and enjoy relatively high rents.

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