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Demand response control structure in imperfectly competitive power markets: independent or integrated?

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Demand response is expected to be a key flexibility feature of increasingly renewable-based power systems in the next decade. Yet demand response requires investments and direct or indirect triggering actions from some actor of the power system, which has, therefore, some control over the realized demand response. This article interrogates the effects of different types of actors controlling demand response operations and the subsequent market impacts under Cournot competition. Analytical results linking demand response capacity and market equilibrium are obtained in a stylized setting for independently operated demand response by a regulated, price-taker, or price-maker actor and integrated generation and demand response. A real-world application for a 2035 French power system with a more bottom-up description of demand response constraints is also proposed. This paper has two main results. Firstly, power systems benefit from similarly smoothed and lowered prices with demand response, whatever the control structure of DR is at the initial deployment stages. Secondly, at larger installed DR capacity, we find a clear and non-negligible ordering of the studied structures in terms of market power exercise for the same flexibility provided. Sorting by increasing market power, regulated pure DR players, private pure players are close, then DR integrated to peak generation, DR integrated to mid-merit generation or uniformly spread across all generators, and finally integrated DR-base generation induces the most market power for little flexibility provided. In the latter case, market prices are virtually unmodified, but the integrated actor has gained market shares.

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KEYWORDS

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Executive summary

This article interrogates the effects of different types of actors controlling demand response operations and the subsequent market impacts when some agents act strategically in wholesale electricity markets. This links to the debate of contracting demand response with only independent actors or with already established retailers, which are generally a facet of utilities that possess generation capacities. The Clean Energy Package allows for both models. Here, by associating our results on generation-integrated demand response to retail-integrated demand response, we give insight into how this model choice may, in fact, matter in terms of market power exercise in the latter development stage of demand-side flexibility.

Several options of control over diffuse demand response capacities are explored, from a regulated pure demand response player to the integration of DR within large utilities to independent small demand response operators. We design models for the operation of each structure in an energy-only power market under imperfect competition in volume, i.e. with possible capacity withholding from the generation or demand response assets.
A stylized analysis yields quantitative relationships between demand response capacity and market prices for all considered control structures. This is a novelty of this work, as demand response analysis in an imperfectly competitive market relies essentially on numerical simulations in the literature. Then, in complement, a more realistically constrained model of demand response under Cournot competition in different control scenarios is calibrated and simulated for 2035 France.

Policy-wise, the main results of the paper are twofold. Firstly, power systems benefit from similarly smoothed and lowered prices with demand response whatever the control structure of demand response is at initial deployment stages. In other words, depending on the intensity of the need for more flexibility in the considered system, control allocation does not have to be a primary focus of the regulator at early/current stages. Secondly, at larger installed DR capacity, these control's market effects are stronger, in descending order, with pure demand response players (with a slight advantage for regulated pure players), then with demand response integrated to peak generation, then with integration to mid-merit generation or uniformly spread across all generators, and finally with integrated demand response and base generation. This control structure effect is sizable. In the latter case, market prices are virtually unmodified, but the integrated actor has gained market shares. For the pure demand response players (resp. integrated with base generation) control structure, demand response implies a reduction of up to 16% (resp. 0.8%) of the winter average day-ahead price and a decrease of up to 26% (resp. 1%) of the winter volatility of day-ahead prices.

1 Introduction

In the next few decades, power systems are bound to accommodate increased demand and massive integration of variable renewables simultaneously. They face therefore a growing need for clean flexibility resources, i.e., other than polluting fast thermal units. Among these flexibilities, demand response (DR) - the possibility for a part of the demand side to react out of its ordinary pattern in response to a signal from the system - is expected to be critical, especially in the next decade in Europe (IEA (2022),RTE (2023),Commission (2023)). Yet, demand response, and above all diffuse,[1] demand response remains largely an unrealized potential, its large-scale deployment expected in the upcoming years. Several actors are currently taking positions on DR, and notably on diffuse DR potentials, meaning large generators, small pure players, or even energy communities (ThinkSmartgrids (2024),SEDC (2017)) invest in or seek to operate DR assets. Such diversity makes all models of demand response control structure[2] still plausible.

The present study focuses on the impact on markets and power systems of the control structure of demand response assets under imperfect competition. At the dawn of an expected, even called for, mass deployment of demand response, with the diversity of existing business models, this paper contributes to decision-makers' information as the regulatory framework is still consolidating.

The effect of different control structures on investment and operations has had to be analyzed for all power system assets with public interest and opportunities to exert market power, such as transmission networks, hydropower assets, or storage. Willems (2002) addresses the status to be given to transmission networks during the unbundling process of the early 2000s. Johnsen (2001) examines how ownership concentration on the supply side with hydropower and storage induces market power. In terms of methodology and concerns, those studies echo what is tackled in the present paper. Demand response is indeed projected to soon become pivotal in the supply-demand balance (IEA (2022),RTE (2018)), thus providing flexibility services necessary for the system to hold. Moreover, it has been underlined that demand response players behave strategically in an intertemporal fashion (Nouicer et al. (2023),Roos et al. (2014)).

More theoretically, supply-born market power in power markets is justified by high capital expenditures being a barrier to the entry of new competitors. Such costs hardly exist for demand response, apart from smart-meter rollout, which is increasingly achieved (more than 95% of end consumers are equipped in France, for example). However, different types of barriers for demand response are identified by practitioners (ACER (2023)). Among them, we can highlight the qualification process allowing an incumbent to trade demand-side flexibility in the wholesale market as a legal or security-related barrier for DR actors themselves. But a barrier also exists from the end-consumer side as contract-switching rates are low in the retail market (e.g., around 3% per quarter for low-capacity consumers

[1]Residential and from tertiary sector appliances.

[2]In this paper, a control structure designates the wholesale market actor offering demand-side flexibility and either directly commanding load-shedding actions at an aggregated scale or crafting and diffusing incentives for such actions towards end-consumers. Some authors such as Sioshansi (2010) or Megy and Massol (2023) have used the term 'ownership structure' to name such actors for other assets. We prefer the term 'control structure' as ownership relates more, in the context of demand response, to the questions of compensation mechanisms and of the property rights of yet-to-be-realized variations of consumptions from a given 'normal' pattern. The fact that different compensation mechanisms between pure DR players and suppliers are allowed by the Electricity Directive (Article 17-4) in the EU is a motivation to consider such different control structures.

in France), so that actual participation into a DR program is still limited and not so many actors acting as intermediaries between consumers and the wholesale market can develop. Thus, opportunities of market power exercise may exist in the context of DR.

Hence, demand response presents this mix of market power opportunities and common interest that was at the heart of the market power control during power markets deregulation. A discussion of the interaction of market power and demand response seems, therefore, justified.

Yet, two crucial differences have to be underlined and justify a specific discussion regarding market power and demand-side flexibility. On the one hand, the past unbundling process dealt primarily with the supply side, while DR is obviously demand-side with possible control by supply-side firms. On the other hand, unbundled assets were already present, while DR has yet to be deployed to the scale of interest. Thus, even though methods to analyze the links between market power and control structure can be drawn from the deregulation studies, demand response has also to be looked at as (battery) storage, that is, in a prospective fashion, balancing control/ownership possibilities, deployment rates, system services, and induced market power. This newer approach is taken in this paper, following the spirit of Sioshansi (2010) or Jiang and Sioshansi (2023) for storage. As these authors point out, there is an interest in evaluating whether an asset should be independently operated or can be added to the pool of utility assets. Such studies, notably that of Jiang and Sioshansi (2023) or previous work by the authors regarding demand response, call "independent operator" a welfare-maximizing centralized agent / an infinity of profit-maximizing atomistic price-taker agents behaving in a perfectly competitive energy market. These studies conclude that, except for some odd cases, this independent agent operates and invests in the asset in a socially optimal way. Applied to demand response, this implies that private atomistic operators of load shifting capacities in such a competitive market act socially optimally, except for some cases[3]. However, other control structures are not considered. Moreover, results for storage can not be directly translated for demand response as storage assets do not face exactly similar constraints. Namely, the main differences between DR and storage assets come from load-recovery in a maximum time after a load-shedding event (think of having to provide cold again for a tertiary sector cold storage) and from time availability (you can not shed a load that was not to be consumed in the first place, think of space heating during the summer).

There is a literature gap: the question of demand response capacities control and its impact on market equilibria remain scarcely explored, and due to DR specificity, the current body of literature dealing with the effects of different control of assets of common interest for power systems does also not tackle this question entirely.

Demand response studies focus indeed primarily either on the technical feasibility of demand response (e.g., Chapman et al. (2016) for the design of the DR signal), the preparedness of consumers and their rationale for entering a DR program (Richter and Pollitt (2018),Broberg and Persson (2016)), or the economic relevance of DR at the system level (Müller and Möst (2018), Bradley et al. (2013)). Analysis sometimes account for the strategic behavior of flexible consumers (Roos et al. (2014),Campaigne and Oren (2016)) or the

[3]These cases arise when a bad forecast of demand levels and marginal costs of generations is made at investment time. More realistically, if information is not exactly perfect, a centralized independent agent may have more information than each of the decentralized atomistic agents so that the resulting decisions of the independent agent may be closer to the above theoretical point and thus avoid falling into these odd cases because of wrong forecasts.

integration of DR as assets of strategic market players (Vuelvas and Ruiz (2019)[4]Nouicer et al. (2023)). Following this branch, another body of studies is dedicated to relevant market designs for both allowing demand response in and mitigating strategic actions of flexible consumers (Astier and Léautier (2021)). Investment in DR capacities and their subsequent operations are generally analyzed under perfect competition (Joskow and Tirole (2006) for implicit DR through retail contracts under different metering paradigms,Asensio et al. (2017)Marañón-Ledesma and Tomasgard (2019) for expansion plannings accounting for DR). Each of these papers formulates its own hypotheses over the control of DR and its decision-making framework but do not test the sensitivity to this framework of their results on DR properties. Hence, the literature does not interrogate the control structure of demand response assets and its effects on power markets. Moreover, demand response effects on non-competitive power markets are only explored numerically but not analytically (Vuelvas and Ruiz (2019)). The present paper contributes to bridging those literature gaps by analyzing a set of equilibrium models in a general setting and then with a numerical application based on French system data.

The general modeling framework of this paper draws from mainstream non-competitive energy-only market models. It enriches them by representing demand response as an energy-constrained generation with total load-related capacity inspired by the technical literature on demand response.

Since the liberalization of power markets, it has been common to model them as under Cournot competition (Borenstein and Bushnell (1999),Willems (2002),Hobbs et al. (2005),Armstrong and Galli (2010)) even when considering new flexibility assets (Schill and Kemfert (2011)). This is due to the presence of historically big utilities, the concentration of which is fostered by the high investment costs of generation plants. Moreover, power market behavior has frequently been monitored to align with imperfect competition in volume partially at least (Lundin and Tangerås (2020)). That is why such a competitive framework is chosen in this study.

From a market perspective, demand response capacities are either modeled through elasticities (Lima et al. (2017),Muratori and Rizzoni (2016),Auray et al. (2020),Vuelvas and Ruiz (2019)) or as a specifically, energy-constrained generation with an analogy with storage or hydropower (Fatouros et al. (2017),Bruninx et al. (2018),Nouicer et al. (2023),Okur et al. (2019)). The former approach represents fixed preferences of the consumer, which is in turn active but not strategic. Since strategic behavior of demand response capacities is to be modeled here - as motivated by, e.g., Nouicer et al. (2023) or by a possible unique state-wide ownership over pivotal DR -, such a framework is unsuitable for the present study. Moreover, using elasticities implicitly implies that an infinite number of small players decide on load-shifting actions. In the French wholesale market, only 14 actors are qualified to directly trade aggregated demand-side flexibility. Retailers, usually linked to traditional utilities, are also contracting for demand response of their end-consumers, but are also a small number of actors from the wholesale market perspective (in France, the sole historical retailer accounts for more than 60% of the end consumers). Thus, the hypothesis that an infinite number of actors are deciding on load-shifting and playing in the wholesale market does not seem valid for the present study.

The latter approach is more promising, as DR actors are modeled as market players,

[4]These authors propose a numerical simulation describing demand response operations in a power market under Cournot competition. Their modeling framework is the closest to that of the present paper but is only exploited through simulations for one type of DR allocation in their study.

the specifics of DR being detailed in the constraints limiting the actions of these players. Furthermore, this representation is flexible enough to be directly integrated into the model of traditional generators, which is paramount for studying independent and integrated DR in the same framework. Demand response differs in this approach from traditional generation by its energy constraint (here, as in e.g., Okur et al. (2019) or Nouicer et al. (2023), a one-to-one energy recovery after a given duration since only load shifting will be considered) and its capacity constraint (here proportionally to the total available load following Verrier (2018) and the idea that demand response is a variation from an 'ordinary' consumption pattern). More details on how DR is modeled, and notably how they are analogous but still different from storages, are given in Section 2.2.

Several options of control over diffuse DR capacities are explored, from a regulated pure DR player to the integration of DR within large utilities to independent atomistic DR operators. We design models for the operation of each structure in an energy-only power market under Cournot competition. A stylized analysis yields quantitative relationships between DR capacity and market prices for all considered control structures. This is a novelty of this work, as demand response analysis in an imperfectly competitive market relies solely on numerical simulations in the literature (see below). Then, in complement, a more realistically constrained model of DR under Cournot competition in different control scenarios is calibrated and simulated in 2035 France.

Policy-wise, the main results of the paper are twofold. Firstly, power systems benefit from similarly smoothed and lowered prices with demand response whatever the control structure of DR is at initial deployment stages. In other words, depending on the intensity of the need for more flexibility in the considered system, control allocation does not have to be a crucial focus of the regulator. Secondly, at larger installed DR capacity, these control market effects are stronger, in descending order, with pure DR players (with a slight advantage for regulated pure players), then with DR integrated to peak generation, then with DR integrated to mid-merit generation or uniformly spread across all generators, and finally with integrated DR - base generation. In the latter case, market prices are virtually unmodified, but the integrated actor has gained market shares.

This links to the debate of contracting DR with only independent actors or with retailers, which is generally a facet of utilities that possess generation capacities. The Clean Energy Package allows for both models. Here, by associating our results on generation-integrated DR to retail-integrated DR, we give insight into how this model choice may, in fact, matter in terms of market power exercise in the latter development stage of demand-side flexibility.

The remainder of the paper is organized as follows. Different control structures over demand response are reviewed and modeled in Section 2. Section 2.2 presents the complete and more complex models to introduce notations and the modeling spirit of the paper sketched above. In Section 3, analytical insights on the market equilibrium reached with each control structure over DR capacities are shown in a simplified setting. Specifically, closed-form solutions of equilibrium prices and activation conditions as a function of DR capacity in each control scenario are obtained, extracting comparative insights on price smoothing and market power exercise. These insights are then tested in Section 4 on a numerical prospective application of the complete model based on the 2035 French case. Concluding remarks are given in Section 5.

2 Modeling control structures of demand response in imperfectly competitive power markets

To evaluate the outcomes of giving an independent operator control over all load-shifting capacities, this section models imperfect power markets (in the form of Cournot competition) and seeks to compare different structures of control over load shifting. Namely, operations and market prices are to be compared depending 1) on the integration or not of the load-shifting capacities to generators' pools and 2) on the perspective of the load-shifting operator (welfare- or profit-maximizing, price-taker or price-maker). For each case, a market model based on mixed complementarity problems is adapted to fit the assessed control structure of DR. These structures are presented in the next section.

2.1 control structures of explicit demand response in power markets

The variety of representations of demand response in an imperfect energy market echoes the various stages of its deployment and associated energy levels engaged and tests options on the type of actor (private/regulated, small/concentrated) supporting it.

Affecting load shifting to an independent operator without market power while traditional generation firms exerting market power reflects two types of DR development. On the one hand, it could represent an early stage of demand response deployment. In such cases, even though load shifting is centralized, it is not a price maker because of its low level relative to base, fixed demand, or that generation is already highly concentrated (which is the case in numerous European countries) while being imperfectly regulated. On the other hand, it could model a different nature of demand response deployment, which would be massive yet diffused among atomized actors such as energy communities. The current discussion in the EU considers such an option, and actors are assessing barriers it may face (see, for example, section 3.2 of ACER (2023)).

An independent and strategic operator of load shifting would model a regulated actor, such as a TSO, activating demand response to smooth prices and system balance while being aware of other actors' generations.

The case of oligopolistic producers with load shifting capacities (i.e., no independent operator and load shifting is a supplementary tool in the volume war of producers) considers a private utility-born demand response deployment. Several options of demand response control among producers are considered, where load shifting capacities are either uniformly spread among all producers or affected depending on their size or nature (peak, mid-peak, or base-load generation). The operation incentives may be different for demand response whether it is coupled with fast-ramping peak generation or with slow-ramping base generation. In the first case, shaving peaks at lesser costs could drive out of the market peak generations but increasing demand could create new opportunities for such generation. In the second case, the production volume of slow-ramping units is not threatened by DR but whose infra-marginal rents would be. Base-load generation with demand response would probably better manage its slow-ramping characteristic during low-demand periods. Therefore, for all integrated control structures, the operation incentives are not obvious a priori, yet seem crucial information for regulators or market designers.

In the following, the considered market structures will be denoted by stating the control of DR (integrated or independent with the label IDRO for independent demand response operator) and either the distribution of DR among producers (uniform, all to base, all to

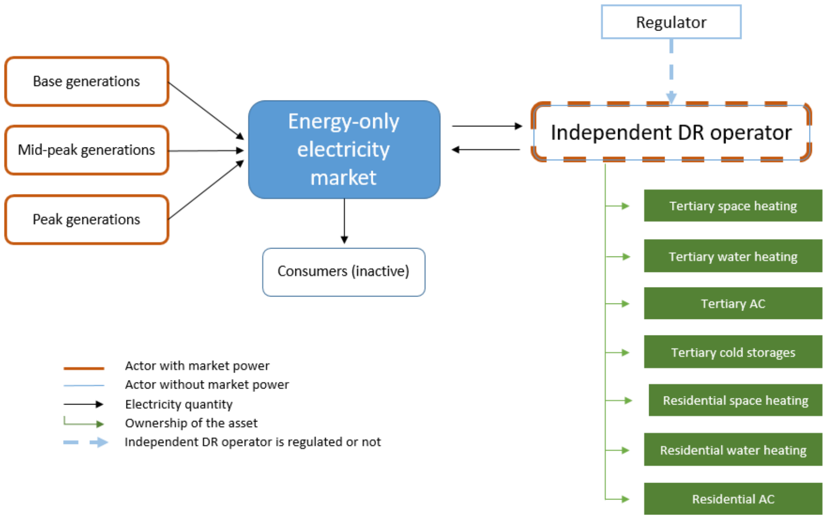

Figure 2.1: Representations of an independent load-shifting operator in an imperfectly competitive power market

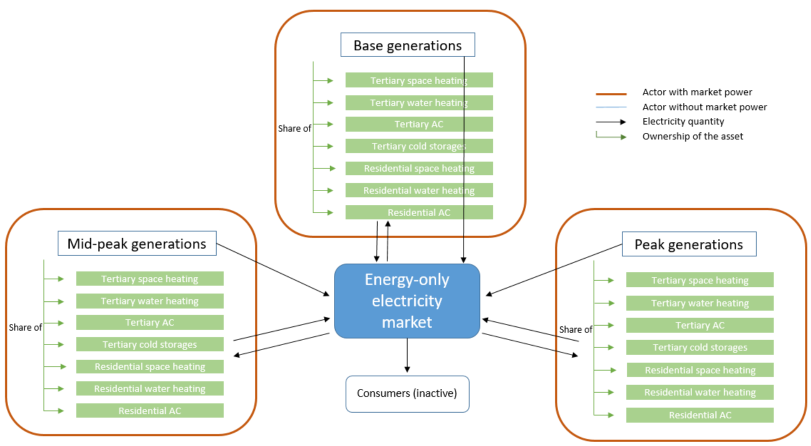

Figure 2.2: Representation of integrated load-shifting operation within strategic generators

peak...) or the objective and market power of the IDRO (profit-maximizing with or without Cournot market power, or welfare-maximizing).

2.2 Models

This section provides the mathematical models of each control structure presented previously. Good properties regarding the existence and uniqueness of a Nash equilibrium for this class of open-loop single-level equilibrium models are recalled here. The reader only interested in the effect of DR capacity and control on the said equilibria should head to the reduced and analytically tractable version of these models of Section 3.

Common setting. Classically, the energy-only market is characterized by an inverse demand function, chosen affine $P_t(L) = B_t - A_t L$ with $B_t, A_t > 0$ for tractability and following classical representations (e.g., Hobbs and Helman (2004)). A representative consumer chooses its consumption level L_t in order to maximize its benefit of consumption $BE_t(L_t)$ (such that $BE_t\prime(L_t) = P_t(L_t)$) minus its payment for such consumption at the exogenous market price λ_t. This representative consumer aggregates the "normal" behavior of all consumers in the sense that demand response capacities will be modeled as the flexible part of a specific appliance's consumption, which is isolated as an exogenous share of the total load. The consumers' problem entails the following KKT condition at each date t:

$$0 \geq -L_t \perp P_t(L_t) - \lambda_t \leq 0.$$

G profit-maximizing generators are considered, competing à la Cournot, which is both a standard modeling paradigm for day-ahead electricity markets because of the high concentration of utilities and a choice supported by observation (Lundin and Tangerås (2020)). Generators are constrained regarding production capacity and ramping rates. The latter constraint should not be overlooked as we model flexibility asset allocation and operations.

Demand response is modeled as J load-shifting potentials, which are either affected by generators or by an independent demand response operator. The operation of each potential is constrained by its time-limited recovery of shed load and capacity limits for load reduction and increase. The time limit on load recovery is the main difference between demand response and storage as modeled in, e.g., Jiang and Sioshansi (2023). In a bottom-up fashion, it encompasses the notions of electricity consumption benefits, comfort, and demand response as a short-term peak-shifting asset. Load reduction is limited by a time availability factor, which is particular to each potential and describes the ordinary pattern of this load by an installed share of flexible load (in $[0, 1]$), and by a share of the total generation at each date. Load increase is similarly limited in capacity but is not constrained by an availability factor to depict the out-of-pattern nature of a load-shifting event. Hence, load reduction has a time-dependent capacity, and capacity investment in load shifting is intended to unlock a share of this load.

Independent load shifting operator description. Load-shifting operations are independent of generators in that the latter can not decide on load shifting while the independent operator can not affect generations, even though it may be aware of these generations if it is a price-maker. Moreover, the independent operator may be either system-minded or of private interest, which means that it maximizes the system welfare, in the form of consumers' benefits from total supply minus consumers and suppliers' costs and its load-shifting costs, or its profits.

A profit-maximizing independent demand response operator (IDRO) solves in turn

$$\max_{d,u\geq 0} \mu \left[\sum_t \sum_j \left(B_t - A_t(\sum_g x_{g,t} + \sum_{j\prime} d_{j\prime,t} - u_{j\prime,t}\right)(d_{j,t} - u_{j,t}) - AC_j d_{j,t}\right] \tag{2.1}$$

$$+ (1-\mu)\left[\sum_t \sum_j P_t(d_{j,t} - u_{j,t}) - AC_j d_{j,t}\right] \tag{2.2}$$

$$\text{s.t. } d_{j,t} \leq A_{j,t} s_j \delta_j \left(\mu \sum_g x_{g,t} + \sum_{j\prime \neq j} d_{j\prime,t} - u_{j\prime,t} + (1-\mu)L_t\right) \tag{2.3}$$

$$u_{j,t} \leq s_j \delta_j \left(\mu \sum_g x_{g,t} + \sum_{j\prime \neq j} d_{j\prime,t} - u_{j\prime,t} + (1-\mu)L_t\right) \tag{2.4}$$

$$d_{j,t} \leq \sum_{k=1}^{\Delta_j - 1} u_{j,t+k} \tag{2.5}$$

The parameter μ takes value 1 for an IDRO with market power and value 0 when the IDRO is a price-taker. In both cases, the IDRO maximizes profit and generates profits by selling load reduction from the J flexible loads it controls while paying for a DR variable cost AC_j and for load recovery at market price. These marginal costs of activation AC_j are chosen to be positive based on empirical studies finding a negative willingness to pay for direct load control (Richter and Pollitt (2018)), or demand-side response in general (Broberg and Persson (2016)). Constraint 2.3 limits load reduction to a currently available capacity. This capacity is specific to each DR potential and each date. It is a part of the normal load of this particular appliance modeled by the ordinary share of the total load of this appliance at this date ($A_{j,t} * s_j$ with s_j the maximum share of this appliance and $A_{j,t}$ an availability factor which takes value 1 when the maximum share is hit at t). The capacity is given by this normal load weighted by the flexible share of this appliance $\delta_j \in [0, 1]$. The latter exogenous parameter reflects the investment effort that has been realized in demand response. Contrarily to classical generation, demand response capacity is bounded by ordinary consumption patterns, and thus, a demand response capacity should be understood as the available share for load reduction of the normal load profile, hence the proposed representation. If the IDRO can exercise market power, it is aware of the generation decisions of other actors, and this total quantity is explicitly stated instead of the total load L_t. Constraint 2.4 affects similarly load increase but is no longer affected by the availability parameter. After a load reduction is activated, the consumer leaves indeed its ordinary consumption pattern and has to recover this load in the future. This extra-ordinary recovery should therefore not be limited by the ordinary load profile of the appliance. Finally, Constraint 2.5 provides a time limit for load recovery after a load reduction event, parameterized by a DR potential-specific maximum time for recovery Δ_j. It encompasses comfort, physical, legal, or economic stringencies on load shifting for the considered potential, the allowed time for recovery being for example shorter for residential appliances than their tertiary sector counterparts.

A regulated hence welfare-maximizing price-maker IDRO is represented by the following problem

$$\max_{d,u\geq 0}\sum_t BE_t\left(\sum_g x_{g,t}+\sum_{j\prime} d_{j\prime,t}-u_{j\prime,t}\right)+\sum_j P_t\left(\sum_g x_{g,t}+\sum_{j\prime} d_{j\prime,t}-u_{j\prime,t}\right)(d_{j,t}-u_{j,t})-AC_j d_{j,t} \tag{2.6}$$

$$\text{s.t. } d_{j,t}\leq A_{j,t}s_j\delta_j\sum_g x_{g,t}+\sum_{j\prime\neq j} d_{j\prime,t}-u_{j\prime,t}$$

$$u_{j,t}\leq s_j\delta_j\sum_g x_{g,t}+\sum_{j\prime\neq j} d_{j\prime,t}-u_{j\prime,t}$$

$$d_{j,t}\leq\sum_{k=1}^{\Delta_j-1}u_{j,t+k}$$

which is similarly constrained to the previous IDRO model but differs profoundly in its objective. The IDRO maximizes the benefits of load consumption and the profits realized from load-shifting operations. This corresponds to a welfare-maximizing agent (see another example in Hobbs and Helman (2004)) and modifies the optimal solution. The latter will indeed be marked by a supplementary weight on the price level, which can be seen with the factor 2 appearing in the KKT condition associated with $d_{j,t}$ and $u_{j,t}$ in Appendix B.2.

Regardless of the objective of the IDRO, the supply side is modeled by price-maker producers with a homogeneous generation technology representative of a real generation asset (e.g., nuclear, CCGT, OCGT...). Each generator g then solves

$$\max_{x\geq 0}\sum_t\left(B_t-A_t(\sum_{g\prime} x_{g\prime,t}+\sum_{j\prime} d_{j\prime,t}-u_{j\prime,t})-c_g\right)x_{g,t} \tag{2.7}$$

$$\text{s.t. } x_{g,t}\leq K_g \tag{2.8}$$

$$\forall t>1, x_{g,t}-x_{g,t-1}\leq R_gK_g \tag{2.9}$$

$$\forall t>1, x_{g,t-1}-x_{g,t}\leq R_gK_g \tag{2.10}$$

where Constraint 2.8 is a capacity constraint, and Constraints 2.9 and 2.10 limit upward and downward ramping of generation to an exogenous portion of the capacity.

Integration of load shifting and generation In the case of integrated load shifting and generation, d and u are supposedly spread across generators so that the new problem of generator g writes

$$\max_{x\geq 0}\sum_t\left(B_t - A_t\sum_{g\prime}(x_{g\prime,t}+\sum_{j\prime}d_{g\prime,j\prime,t}-u_{g\prime,j\prime,t})\right)(x_{g,t}+\sum_j d_{g,j,t}-u_{g,j,t})-c_g x_{g,t}-\sum_j AC_j d_{g,j,t} \tag{2.11}$$

$$\text{s.t. } x_{g,t}\leq K_g \tag{2.12}$$

$$\forall t>1, x_{g,t}-x_{g,t-1}\leq R_g K_g \tag{2.13}$$

$$\forall t>1, x_{g,t-1}-x_{g,t}\leq R_g K_g \tag{2.14}$$

$$d_{g,j,t}\leq A_{j,t}s_j\delta_{g,j}\sum_{g\prime}x_{g\prime,t}+\sum_{j\prime\neq j}d_{g\prime,j\prime,t}-u_{g\prime,j\prime,t} \tag{2.15}$$

$$u_{g,j,t}\leq s_j\delta_{g,j}\sum_{g\prime}x_{g\prime,t}+\sum_{j\prime\neq j}d_{g\prime,j\prime,t}-u_{g\prime,j\prime,t} \tag{2.16}$$

$$d_{g,j,t}\leq\sum_{k=1}^{\Delta_j-1}u_{g,j,t+k} \tag{2.17}$$

This integrated problem concatenates the previous generation problem of generator g and that of the DR operation under its control. Producer g has here access to the share $\delta_{g,j}$ of the DR potential j ($\sum_g \delta_{g,j} = \delta_j \in [0,1]$) so that asymmetries of demand response control can be considered generator-wise (the main focus of this paper) or potential-wise (specialization of DR aggregators by sector -industrial, tertiary, residential- or by type - water heaters, space heaters, AC...). Constraints 2.15 and 2.16 are capacity limits on DR operations rewritten to account for the integration of DR to all of the other generators.

The above optimization problems have concave objective and linear (so convex) constraints. Thus, associated Karush-Kuhn-Tucker conditions are both necessary and sufficient. Searching for Nash-Cournot equilibrium of the modeled market reduces to solving the mixed complementarity problem formed by the KKT conditions of each actor (generators, DR operators and passive consumer) and the market clearing condition. KKT conditions associated with each optimization problem of this section are displayed in Appendix B.1 to B.2. As such, the Nash-Cournot equilibrium remains analytically intractable. Before numerically solving these KKT conditions in a realistic setting inspired by the French power system in recent years, we seek to gain analytical insights from a simplified problem in the next section.

3 Insights from a stylized setting

This section provides a cruder but analytically tractable model of demand response in different control structures. For each structure, insights are given on the changes in market prices as the installed capacity δ of load shifting evolves. The main results are 1) that even in this simplistic setting, equilibria differ profoundly from one structure to the other and 2) that the evolution of market prices with δ takes different directions for the same system parameters in different DR control structures.

3.1 Description and reduced problems

We focus on a single cycle of load reduction - load increase and a single DR potential the installed capacity (i.e., the share of the available demand from this appliance that has been made flexible) of which is $\delta \in [0,1]$. The two dates are denoted $t = 0, 1$ and correspond to a high-demand hour and a low-demand hour respectively. Peak and off-peak hours are characterized by different origins of the inverse demand function B_0 and B_1 but are similar regarding the effect of total production on prices, i.e. $A_t = A$ is constant. The demand response operator(s) can reduce the load by d during the high demand hour $t = 0$ with linear variable cost AC and recover this exact load d during the low demand date $t = 1$. Finally, only two price-maker generators indexed by $g \in \{b, p\}$ with linear variable costs and *no capacity constraints* are considered. Note that in such a setting, without demand response, there is no equilibrium where both generators produce if their marginal costs differ. We also suppose that $B_0 > c_p + c_b$ so that there is room for both generators during the peak hour and $B_0 > B_1 + 3AC$ so that the margin between peak and off-peak hours suffices for our DR potential to be activated. Generator g without control over demand response capacities maximizes its profit on the two stages period and solves

$$\max_{x_{g0}, x_{g1} \geq 0} (P_0(x_{b0} + x_{p0} + d) - c_g)x_{g0} + (P_1(x_{b1} + x_{p1} - d) - c_g)x_{g1}$$

which translates into the following necessary and sufficient KKT conditions

$$\begin{aligned} 0 \geq x_{bt} \perp B_t - 2Ax_{bt} - Ax_{pt} + (\mathbb{1}_{t=0} - \mathbb{1}_{t=1})Ad - c_b \leq 0 \\ 0 \geq x_{pt} \perp B_t - Ax_{bt} - 2Ax_{pt} + (\mathbb{1}_{t=0} - \mathbb{1}_{t=1})Ad - c_p \leq 0. \end{aligned}$$

3.2 Equilibrium prices

3.2.1 Symmetric solution without DR

Without demand response, a duopoly solution where $x_{b,t}, x_{p,t} > 0$ exists if and only if the constant marginal costs of our two producers are equal. In such case, the problem is separable in time and optimal generation decision and market prices write from the above KKT conditions,

$$P_t = \frac{B_t + c_b + c_p}{3}. \tag{3.1}$$

3.2.2 Price-taker profit maximizing independent DR

The market is now completed with an independent DR operator, which solves the following reduced version of Problem 2.2

$$\begin{aligned} &\max_{d \geq 0} \pi(d) = (P_0 - P_1 - AC)d \\ &d \leq \delta L_0 (= x_{b0} + x_{p0}) \qquad [\gamma] \end{aligned}$$

which reduces to the KKT conditions

$$\begin{aligned} &0 \geq \gamma \perp d - \delta L_0 \leq 0 \\ &0 \leq d \perp B_0 - B_1 - AC + \gamma - Ax_{b0} - Ax_{p0} + Ax_{b1} + Ax_{p1} - 2Ad \leq 0. \end{aligned}$$

A solution with all means activated is given by the solution of the square invertible linear system

$$A\begin{bmatrix}2 & 1 & 0 & 0 & 1\\ 1 & 2 & 0 & 0 & 1\\ 0 & 0 & 2 & 1 & -1\\ 0 & 0 & 1 & 2 & -1\\ 1 & 1 & -1 & -1 & 2\end{bmatrix}\begin{bmatrix}x_{b0}\\ x_{p0}\\ x_{b1}\\ x_{p1}\\ d\end{bmatrix} = \begin{bmatrix}B_0 - c_b\\ B_0 - c_p\\ B_1 - c_b\\ B_1 - c_p\\ B_0 - B_1 - AC + \gamma\end{bmatrix}. \quad (3.2)$$

Depending on the saturation of the capacity constraint on DR, i.e. the nullity of γ, and therefore on system parameters, two candidate equilibrium emerge. Solving system 3.2, the objective of the IDRO problem rewrites $\pi(\gamma) = \frac{\gamma}{2A}(B_1 + 3AC - B_0 - 3\gamma)$. So, if the optimal d does not saturate the capacity constraint, $\gamma = 0$ and the optimal profits of the IDRO are null. If the optimal d is at maximum capacity, $\gamma = \frac{2\delta}{9+6\delta}(B_0 + B_1 - c_b - c_p + 3AC) + \frac{B_1 - B_0 + 3AC}{3+2\delta}$. This is possible only for δ such that $\gamma < 0$, if it is not verified then no equilibrium exists that saturates DR capacity. Moreover, $\gamma < 0$ is equivalent to $2\delta(B_0 + B_1 + 3AC - c_b - c_p) < 3(B_0 - B_1 - 3AC)$ and, replacing γ by its value in the objective of the IDRO we have that $\pi(\gamma) > 0$ is also equivalent to $2\delta(B_0 + B_1 + 3AC - c_b - c_p) < 3(B_0 - B_1 - 3AC)$. Thus, for such δ, there exists a unique equilibrium which is to saturate the DR capacity and which yields market prices

$$P_0^{\text{sat}} = \frac{B_0 + c_b + c_p}{3 + 2\delta} + \frac{\delta}{3 + 2\delta}(c_b + c_p) \quad (3.3)$$

$$P_1^{\text{sat}} = \frac{B_1 + c_b + c_p}{3 + 2\delta} + \frac{\delta}{3 + 2\delta}(2B_0 + 2B_1 + c_b + c_p) \quad (3.4)$$

Reciprocally, for δ that do not verify the previous condition, there exists a unique (we supposed $B_0 > B_1 + 3AC$) equilibrium which is to activate $d = (B_0 - B_1 - 3AC)/2A$ and which yields market prices

$$P_0^{\text{unsat}} = \frac{B_0 + c_b + c_p}{3} + \frac{AC}{2} + \frac{B_1 - B_0}{6} \quad (3.5)$$

$$P_1^{\text{unsat}} = \frac{B_1 + c_b + c_p}{3} - \frac{AC}{2} - \frac{B_1 - B_0}{6}. \quad (3.6)$$

In both cases, note that the no DR result is retrieved when δ vanishes to zero. With saturation, demand response reduces market price during the peak hour and increases it by the same amount during the off-peak hour (because $B_0 - B_1 - 3AC > 0$), without a direct link between market prices and δ. With saturation this link is direct: P_0^{sat} is strictly decreasing as δ grows while P_1^{sat} is strictly increasing. The increase of P_1^{sat} is quicker than the decrease of the peak hour price as $P_1^{\text{sat}\prime}(\delta)/|P_0^{\text{sat}\prime}(\delta)| = (6B_0 + 4B_1 + c_b + c_p)/(2B_0 + c_b + c_p) > 1$. Hence, for small installed capacity and if demand response has no market power, each increment of DR capacity increases the off-peak hour price more than it decreases the peak hour price. Moreover, a threshold, which may be smaller than 1, exists for δ after which supplementary DR capacity does not change market prices. At this point, the increase of off-peak price and decrease of peak price are equal.

For clarity, a dummy illustration of equilibrium prices as functions of DR capacity δ is presented in Figure 3.1. It appears clearly that the optimal non-saturation condition directly derives from the sell high-buy low incentive for the IDRO not to decrease peak prices too much. Figure 3.1 also displays that off-peak price increases are of higher magnitude than peak price decreases, even to the point that off-peak prices exceed peak prices due to DR energy recovery when DR is saturated. This latter effect disappears in the non-saturated case since $P_1^{\text{unsat}} \simeq 55.8 < P_0^{\text{unsat}} \simeq 60.8$ in the example.

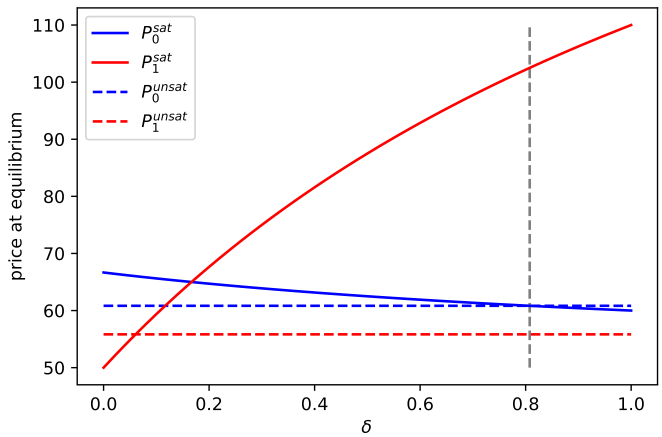

Figure 3.1: Equilibrium prices with a price-taker IDRO as functions of DR capacity δ. System parameters are chosen such that DR activation condition ($B_0 > B_1 + 3AC$) is verified and that the optimal non-saturation condition appears for a $\delta < 1$ (vertical dashed line). $[B_0 = 100, B_1 = 50, c_b = 10, c_p = 90, AC = 5]$

3.2.3 Price-maker profit maximizing independent DR

Now we conduct the same analysis in the case of independently operated DR with market power. Thus the problem of generators remains similar to that of the previous section but the IDRO now solves a reduced version of Problem 2.1:

$$\max_{d\geq 0} \pi(d) = (B_0 - A(x_{b0} + x_{p0} + d) - B_1 + A(x_{b1} + x_{p1} - d) - AC)d$$
$$d \leq \delta(x_{b0} + x_{p0}) \qquad [\gamma]$$

which reduces to the KKT conditions

$$0 \geq \gamma \perp d - \delta(x_{b0} + x_{p0}) \leq 0$$
$$0 \leq d \perp B_0 - B_1 - AC + \gamma - Ax_{b0} - Ax_{p0} + Ax_{b1} + Ax_{p1} - \mathbf{4}Ad \leq 0.$$

The factor 4 before d changes the equilibrium and the condition of saturation of the DR capacity compared to the previous case without market power. Solving for an equilibrium where all decisions are positive reduces to the same linear system as 3.2 but with a coefficient 4 in the bottom right of the matrix. This new system remains invertible, which means that there exists vectors of decisions parameterized by γ that are candidate to be a Nash-Cournot equilibrium of our problem.

In this setting, the objective of the IDRO rewrites as a function of γ, $\pi(\gamma) = (B_0 - B_1 - 3AC - \gamma)(B_0 - B_1 - 3AC + 3\gamma)/32A$. A non saturated optimal solution would be such that $\gamma = 0$ so would yield positive profits $\pi^{\text{unsat}} = (B_0 - B_1 - 3AC)^2/32A$. This is coherent with a DR operator with market power that limits its output in order to extract positive profits from its operations. In comparison, if DR capacity is saturated, $(3+2\delta)\gamma^{\text{sat}} = [\frac{14}{3}B_0 + \frac{2}{3}B_1 + 2AC - \frac{8}{3}(c_b + c_p)]\delta - (B_0 - B_1 - 3AC)$. This situation is a candidate equilibrium if $\gamma^{\text{sat}} < 0$ that is $[14B_0 + 2B_1 + 6AC - 8(c_b + c_p)]\delta < 3(B_0 - B_1 - 3AC)$ which is a more stringent condition than its counterpart in the price-taker case. Moreover, the saturated solution has also to verify $\pi(\gamma) \geq \pi^{\text{unsat}}$ to be an equilibrium of the initial problem which happens to never be verified. Indeed, $\pi\prime(\gamma) = (B_0 - B_1 - 3AC - 3\gamma)/16A$ is positive for all $\gamma \leq 0$ and the objective of the IDRO is thus a strictly increasing function of γ in $\mathbb{R}_-$, so that in particular $\pi^{\text{unsat}} > \pi(\gamma^{\text{sat}})$. Due to market power, it is never optimal for the IDRO to saturate its capacity as the IDRO is incentivized to produce less in order to keep higher market prices and extract more profits. Note that, had saturation been optimal, replacing γ^{sat} by its expression, market prices write exactly as they did in the previous section for a price taker IDRO:

$$\text{(Non-optimal) } P_0^{\text{sat}} = \frac{B_0 + c_b + c_p}{3 + 2\delta} + \frac{\delta}{3 + 2\delta}(c_b + c_p)$$
$$\text{(Non-optimal) } P_1^{\text{sat}} = \frac{B_1 + c_b + c_p}{3 + 2\delta} + \frac{\delta}{3 + 2\delta}(2B_0 + 2B_1 + c_b + c_p)$$

This similarity translates the fact that for small δ, where $\gamma^{\text{sat}} < 0$ is valid, price-maker and price-taker independent demand response behave closely, which is to be expected as a small DR actor may not possess much market power.

At equilibrium, notably for bigger installed capacityδ, it is typically no longer optimal to saturate demand response, and market equilibrium is:

$$P_0^{\text{unsat}} = \frac{B_0 + c_b + c_p}{3} + \frac{AC}{8} + \frac{B_1 - B_0}{24} \tag{3.7}$$
$$P_1^{\text{unsat}} = \frac{B_1 + c_b + c_p}{3} - \frac{AC}{8} - \frac{B_1 - B_0}{24}. \tag{3.8}$$

Market prices reflect a transfer between peak and off-peak hours but with a quarter of the value of the transfer in the price-taker IDRO case. Hence, with a price-maker independent DR operator, market prices are less affected than with price-taker DR, in the direction of decrease during peak hours but also in the direction of increase during off-peak hours. In other words, for the same large installed capacity, price-maker independent DR operator provides four times less arbitrage between peak and off-peak hours.

However, operational constraints materialized here uniquely by capacity may prove stringent enough to make the impact of DR on market prices closer in the cases of price-maker and price-taker DR. Indeed, the ratio of the absolute price reduction during peak hours due to DR in the price-taker saturated case (gap between 3.1 and 3.3) over that in the price-maker case (gap between 3.1 and 3.7) writes

$$|P_0^{\text{noDR}} - P_0^{\text{sat}}|/|P_0^{\text{noDR}} - P_0^{\text{unsat}}| = \frac{8\delta}{3 + 2\delta}\frac{2B_0 - c_b - c_p}{B_0 - B_1 - 3AC} \tag{3.9}$$

The condition on δ for this ratio to be strictly lower than 4 (the value of the ratio when the optimal decision in the price-taker case is *not* to saturate DR capacity - see 3.5) is $2\delta(B_0 + B_1 + 3AC - c_b - c_p) < 3(B_0 - B_1 - 3AC)$. This condition is exactly the condition on δ for which saturation is optimal in the price-taker case. Hence, for all small δ such that saturation would have been optimal in the price-taker IDRO case and these δ only, a price-maker IDRO provides a peak price reduction which is strictly closer than four times that provided in the price-taker case. This gap due to market power exercise strictly increases with δ before jumping and ceiling to 4 as δ reaches the optimal non-saturation condition in the price-taker case. The initial gap for $\delta \simeq 0$ is approximately $4/3\frac{B_0-(c_b+c_p)/2}{B_0-B_1-3AC}$ which is positive and guided by the ratio of the "size" of the peak compared to average generation cost and the size of the "step" between peak and off-peak accounting for the necessary activation of DR for taking this step.

Finally, the market power of the independent demand response operator deploys its full effect of hindering the system effects of DR (peak shaving, price time arbitraging) only after a sufficiently large DR capacity is available. This threshold is the same as that over which price-taker DR would also not saturate its capacity. So, in terms of capacity investment in DR from a system planner perspective, it seems, whatever the control structure of profit-maximizing independent DR is, on the one hand that there exists a common (across control structures) capacity threshold over which investment is a loss for the system as supplementary capacity would never be activated. On the other hand, for initial capacity levels the potential market power of an independent DR operator has a non-null but small outcome on the magnitude of the peak shaving provided, making this market power concern rather marginal in the early stages of development of DR.

3.2.4 Welfare-maximizing independent DR

We end the investigation on independent DR with the case of a perfectly regulated, system/public-minded DR operator whose objective becomes to maximize welfare. Reducing to the stylized setting Problem 2.6, the IDRO now has to solve

$$\max_{d\geq 0} \pi(d) = BE_0(x_{b0}+x_{p0}+d) + BE_1(x_{b1}+x_{p1}-d) + (B_0 - A(x_{b0}+x_{p0}+d) - B_1 + A(x_{b1}+x_{p1}-d) - AC)\, d$$

$$d \leq \delta(x_{b0}+x_{p0}) \qquad [\gamma]$$

which boils down to the following KKT conditions with different weights on each decision variables

$$\begin{aligned} &0 \geq \gamma \perp d - \delta(x_{b0}+x_{p0}) \leq 0 \\ &0 \leq d \perp 2(B_0 - B_1) - AC + \gamma - 2Ax_{b0} - 2Ax_{p0} + 2Ax_{b1} + 2Ax_{p1} - 6Ad \leq 0. \end{aligned}$$

The linear system obtained from KKT conditions by choosing the case where all decisions are positive is still invertible even though the rows associated with d in both the system's matrix and its constant vector. Once again, candidate solutions for being a Nash-Cournot equilibrium of the initial problem are parameterized by $\gamma \leq 0$ and thus separate into two distinct cases depending on the saturation of DR capacity at the solution. Moreover, the objective rewrites as a function of γ such that $50A\pi\prime(\gamma) = 2(A-1)(B_1-B_0)+(3-13A)AC-(3+2A)\gamma$. As power demand is generally very inelastic, A can be taken sufficiently small ($3 > 13A$, $A < 1$) so that $\pi\prime(\gamma)$ is equal to 0 for a positive γ. Thus, $\pi(\gamma)$ is in particular strictly increasing on $\mathbb{R}_-$ and at optimality $\gamma = 0$ and $d = B_0/5 - B_1/5 - 3AC/10$. Note that the condition on the step between peak and off-peak hours for the latter candidate decision to be optimal, that is $B_0 > B_1 + \mathbf{3/2}AC$, is larger than that which prevailed for the profit-maximizing IDRO ($B_0 > B_1 + 3AC$). This means that a welfare-maximizing IDRO tends to activate its DR potential on more common occasions than a profit-maximizing one, the latter specifically targeting occurrences of higher demand gradients than the former.

Moreover, provided $B_0 > B_1 + \mathbf{3/2}AC$ and because the welfare-maximizing IDRO has been given market power in Problem 2.6 as it models a regulator-controlled actor, we find again that it is optimal never to saturate DR capacity. Market prices in this case are

$$P_0^{\mathrm{W,unsat}} = \frac{B_0 + c_b + c_p}{3} + \frac{AC}{10} + \frac{B_1 - B_0}{15} \tag{3.10}$$

$$P_1^{\mathrm{W,unsat}} = \frac{B_1 + c_b + c_p}{3} - \frac{AC}{10} - \frac{B_1 - B_0}{15}. \tag{3.11}$$

So, if activated, the welfare IDRO provides a peak price reduction/off-peak price increase/shifted energy volume that is 2/5 of the amount provided by a private price-taker IDRO with large enough installed capacity of DR (compare the gaps 3.1-3.3 and 3.1-3.10, as in 3.9). This score is higher than the private price-maker IDRO which would provide 1/4 of the amount. This means that the system-related objective (i.e., regulation) of the present case counterbalances partially the market power incentive to reduce DR outputs, even though the present IDRO still has the information of a price-maker actor.

Moreover, the same hypothetical analysis as was performed in the previous section where the $\gamma < 0$ of the saturated case is computed and injected into market prices yields again equilibrium prices that take the forms P_0^{sat} and P_1^{sat} obtained for the price-taker profit-maximizing IDRO. Hence, similarly to the price-maker private IDRO, a private price-taker IDRO and a welfare-maximizing IDRO behave closely for small installed capacity. The gap of peak price reduction between the price-taker and welfare-maximizing case increases with the installed capacity but peaks at $\frac{5}{2}\frac{1}{1+3/2AC/(B_0-B_1-3AC)} < 5/2$ instead of the 4 of the previous section.

3.2.5 Integrated DR

To conclude this section, a last type of control structure is analyzed in the stylized setting: integrated DR and generation in a price-maker producer. Now, integrated generators b and p solve the following reduced version of Problem 2.11:

$$\begin{aligned}
\max_{d_g, x_g \geq 0} & (P_0(x_{b0} + x_{p0} + d_b + d_p) - c_g)x_{g0} + (P_1(x_{b1} + x_{p1} - d_b - d_p) - c_g)x_{g1} \\
& + (P_0(x_{b0} + x_{p0} + d_b + d_p) - P_1(x_{b1} + x_{p1} - d_b - d_p) - AC)d_g \\
d_g \leq & \ \delta_g(x_{b0} + x_{p0} + d_{g^-}) \qquad [\gamma_g]
\end{aligned}$$

which reduces to necessary and sufficient KKT conditions

$$\begin{aligned}
& 0 \geq \gamma_g \perp d_g - \delta_g(x_{b0} + x_{p0} + d_{g^-}) \leq 0 \\
& 0 \leq x_{g0} \perp B_0 - c_g - \delta_g\gamma_g - 2Ax_{g0} - Ax_{g^-0} - 2Ad_g - Ad_{g^-} \leq 0 \\
& 0 \leq x_{g1} \perp B_1 - c_g - 2Ax_{g1} - Ax_{g^-1} + 2Ad_g + Ad_{g^-} \leq 0 \\
& 0 \leq d_g \perp B_0 - B_1 - AC + \gamma_g - 2Ax_{g0} - Ax_{g^-0} + 2Ax_{g1} + Ax_{g^-1} - 4Ad_g - 2Ad_{g^-} \leq 0.
\end{aligned}$$

These conditions differ from that of the previous structures above all because of two new features. The first is the capacity constraint on demand response of a producer is affected by the generation decision of this same producer thus adding a term in γ_g in the KKT condition associated with x_{g0}. The second is, of course, the dimension of the space of DR activations in the system increased. This makes in fact the system degenerate as if we look for an equilibrium where all decision variables are positive then the resulting linear system is

$$A \begin{bmatrix} 2 & 1 & 0 & 0 & 2 & 1 \\ 1 & 2 & 0 & 0 & 1 & 2 \\ 0 & 0 & 2 & 1 & -2 & -1 \\ 0 & 0 & 1 & 2 & -1 & -2 \\ 2 & 1 & -2 & -1 & 4 & 2 \\ 1 & 2 & -1 & -2 & 2 & 4 \end{bmatrix} \begin{bmatrix} x_{b0} \\ x_{p0} \\ x_{b1} \\ x_{p1} \\ d_b \\ d_p \end{bmatrix} = \begin{bmatrix} B_0 - c_b - \delta_b \gamma_b \\ B_0 - c_p - \delta_p \gamma_p \\ B_1 - c_b \\ B_1 - c_p \\ B_0 - B_1 - AC + \gamma_b \\ B_0 - B_1 - AC + \gamma_p \end{bmatrix}$$

which is not invertible. Hence, there exists either no equilibrium or infinitely-many equilibria such that all demand response and generation variables are positive for all actors. In order to decide between the two, let's parameterize the previous system by d_b and d_p:

$$A \begin{bmatrix} 2 & 1 & 0 & 0 \\ 1 & 2 & 0 & 0 \\ 0 & 0 & 2 & 1 \\ 0 & 0 & 1 & 2 \end{bmatrix} \begin{bmatrix} x_{b0} \\ x_{p0} \\ x_{b1} \\ x_{p1} \end{bmatrix} = \begin{bmatrix} B_0 - c_b - \delta_b \gamma_b \\ B_0 - c_p - \delta_p \gamma_p \\ B_1 - c_b \\ B_1 - c_p \end{bmatrix} - Ad_b \begin{bmatrix} 2 \\ 1 \\ -2 \\ -1 \end{bmatrix} - Ad_p \begin{bmatrix} 1 \\ 2 \\ -1 \\ -2 \end{bmatrix}$$

so that

$$3A \begin{bmatrix} x_{b0} \\ x_{p0} \\ x_{b1} \\ x_{p1} \end{bmatrix} = \begin{bmatrix} B_0 - 2c_b + c_p - 2\delta_b \gamma_b + \delta_p \gamma_p \\ B_0 + c_b - 2c_p + \delta_b \gamma_b - 2\delta_p \gamma_p \\ B_1 - 2c_b + c_p \\ B_1 + c_b - 2c_p \end{bmatrix} - 3Ad_b \begin{bmatrix} 1 \\ 0 \\ -1 \\ 0 \end{bmatrix} - 3Ad_p \begin{bmatrix} 0 \\ 1 \\ 0 \\ -1 \end{bmatrix}.$$

For the initial system to allow infinitely-many equilibria when all decision variables are positive, the latter solution has to be compatible with the KKT equations resulting from the choice $d_b > 0$ and $d_p > 0$. Suppose $d_b > 0$, then the following equation must stand

$$\begin{aligned} 0 =& B_0 - B_1 - AC + \gamma_b - 2\left[\frac{B_0 - 2c_b + c_p - 2\delta_b\gamma_b + \delta_p\gamma_p}{3} - Ad_b\right] - \left[\frac{B_0 + c_b - 2c_p + \delta_b\gamma_b - 2\delta_p\gamma_p}{3} - Ad_p\right] \\ &+ 2\left[\frac{B_1 - 2c_b + c_p}{3} + Ad_b\right] + \left[\frac{B_1 + c_b - 2c_p}{3} + Ad_p\right] - 4Ad_b + 2Ad_p \end{aligned}$$

which after some algebra is equivalent to $\gamma_b = AC/(1 + \delta_b/3)$. This final equation is never true because $\gamma_b \leq 0$ and $AC, \delta_b > 0$. Hence, by contradiction, d_b is null. The same can be done for d_p. Furthermore, a similar reasoning applies to the case where only one producer is endowed with DR capacity (e.g., $\delta_b = 0$ or $\delta_p = 0$). Thus, in this simplistic setting, there is no equilibrium where a price-maker producer endowed with both DR and generation capacities activates both. In other words, depending on its marginal generation cost, the marginal cost of DR and decisions of its rivals, an integrated producer behaves alternatively like a pure DR player or like a pure generator. So that for one couple of dates bridged by a DR activation, the integrated producer should impact the system similarly than a price-maker independent demand response operator.

If we look at the solution where $\delta_b = 0$, $d_p, x_{p1}, x_{b0}, x_{b1} > 0$ and $x_{p0} = 0$, which appears to be uniquely determined by the dual variable γ_p and system parameters, we have

$$3A \begin{bmatrix} x_{b0} \\ x_{p0} \\ x_{b1} \\ x_{p1} \\ d_p \end{bmatrix} = \begin{bmatrix} B_0 + AC + c_p - 2c_b - \gamma_p \\ 0 \\ B_1 + c_p - 2c_b \\ B_0 + B_1 - 2AC + 2c_b - 4c_p + 2\gamma_p \\ B_0 - 2AC + c_b - 2c_p + 2\gamma_p \end{bmatrix}.$$

Reasoning as in the previous sections, we notice that the derivative of the objective of producer p in this case writes $9A\pi_p\prime(\gamma_p) = -2\gamma_p + 3c_b - 5c_p$ so that $\pi_p(\gamma_p)$ admits a maximum which may be reached for a negative γ_p if $3c_b < 5c_p$, that is saturation of DR capacity and non-saturation may be optimal depending on the values of the system parameters. Saturation imposes $0 > (2+\delta_p)\gamma_p = (\delta_p - 1)B_0 - (2\delta_p + 1)c_b + (2+\delta_p)(AC + c_p)$ that is the condition on DR capacity $0 < \delta_p[B_0 + AC + c_p - 2c_p] < B_0 + c_b - 2(AC + c_p)$ which differs from that of the IDRO cases. Market prices are in the two regimes

$$P_0^{\text{Int p, unsat}} = \frac{B_0 + c_b + c_p}{3} + \frac{AC}{3} \qquad P_0^{\text{Int p, sat}} = \frac{B_0 + c_b(\delta_p + 1)}{\delta_p + 2} \tag{3.12}$$

$$P_1^{\text{Int p, unsat}} = \frac{B_1 + c_b + c_p}{3} \qquad P_1^{\text{Int p, sat}} = \frac{B_1 + c_b + c_p}{3} \tag{3.13}$$

Here, DR activation does not modify the market price during the off-peak hour in both cases and surprisingly increases the peak price if DR capacity is saturated at the equilibrium. Moreover, in the saturated case, which is optimal for small installed capacity, the peak price is strictly increasing with δ_p. System-wise, it seems, therefore, detrimental in terms of market prices and energy transfer from peak to off-peak time to endow DR to a price-maker horizontally integrated producer.

3.2.6 Summary results from the reduced models

Table 3.1 summarizes the main analytical results drawn from the two-stage stylized model. Derived insights are that a regulated independent DR operator tends to activate more of its capacities but also provides better price smoothing than a price-maker private operator. Yet it provides only 40% at best of what atomistic operators would, should they coordinate. Moreover, we have shown that, even in the most favorable price-taker case, off-peak prices increase more than peak prices decrease by the action of load-shifting capacities in a power market with Cournot generators. Finally, integrated DR can't be activated along with generation in this framework: it is expected that peak integrated players would behave in general as pure DR players while insights regarding base integrated players are less clear.

control structure	**Peak hour price (P_0)**	**Peak hour price reduction gap ratio** $\lvert P_0^{noDR} - P_0^{price-taker}\rvert / \lvert P_0^{noDR} - p^{tested}\rvert$
No DR	$\frac{B_0+c_b+c_p}{3}$	-
IDRO price-taker		
—— (DR saturated)	$\frac{B_0+c_b+c_p}{3+2\delta} + \frac{\delta}{3+2\delta}(c_b + c_p)$	1
—— (DR non-saturated)	$\frac{B_0+c_b+c_p}{3} + \frac{AC}{2} + \frac{B_1-B_0}{6}$	1
IDRO price-maker	$\frac{B_0+c_b+c_p}{3} + \frac{AC}{8} + \frac{B_1-B_0}{24}$	≤ 4 with threshold effect
IDRO welfare-maximizing	$\frac{B_0+c_b+c_p}{3} + \frac{AC}{10} + \frac{B_1-B_0}{15}$	$\frac{5}{2}\frac{1}{1+\frac{3AC}{2(B_0-B_1-3AC)}} < \frac{5}{2}$ with threshold effect
Integrated DR-generation (both active)	no equilibrium	-

Table 3.1: Equilibrium prices depending on the control structure in the two stages model. The threshold effect relates to the saturation condition in the price-taker IDRO case: the ratios marked with this effect strictly increase with DR capacity as long as it verifies the saturation condition, then the ratios jump upward to the reported values and remain constant.

Note that the crude model from which these conclusions are drawn may be too stylized to apply in a real-world application, especially regarding horizontally integrated demand response. Notably, this stylized model does not consider the crucial case where a price-maker generator with DR is limited by its generation capacity. This limited generator could no longer price out of the market more expensive rivals and use DR to break from this barrier, increase its rents during peak hours, and recover easily during an off-peak hour because of its low generation cost. Unfortunately, including generation capacity in the reduced model makes it analytically intractable. That is why we move back to the more general models of Section 2.2 and solve them numerically based on French data from recent years in the next section.

Taking the particular example of the French system does not hinder the fact that all stylized insights obtained in Section 3 rely on the relative place in the merit order of the two generators present in this reduced system. This means that the conclusions drawn on the relative performances of the different control structures considered are not affected by the nature or the absolute cost-level of the base generation, and to a lesser extent the cost-gap between generators.

4 Application: independence of explicit demand response potentials in 2035 France

To complement the analytical study of the effect of DR control structure of wholesale energy-only market prices, the present Section proposes a calibration of the general models of Section 2.2 on a policy-inspired 2035 French power system.

4.1 Data and calibration

This case study seems adapted to the present study for several reasons. Firstly, France's and, more generally, Europe's power systems are characterized by the presence of historic and big generators, thus detaining a possible market power in volumes (Lundin and Tangerås (2020)). Since the liberalization of these markets, it therefore has been common to model them as under Cournot competition (Hobbs et al. (2005),Armstrong and Galli (2010)) even when considering new flexibility assets (Schill and Kemfert (2011)). Secondly, France, as with Europe as a whole with the Green Deal, seeks to increase massively the share of its electricity produced by variable renewable energies (VREs). However, even if the 2050 horizon power mix is still debated (RTE (2021)), the 2035 power mix is largely fixed either because of the continuation of existing generators or because of the existence of legally binding texts or firm industrial commitment. Notably, a massive entry of VREs is expected (e.g., around +17.5 GW of offshore wind, +19 GW of onshore wind and +45 GW in PV). Similarly, in conjunction with long-term economic planning, the 2035 total demand becomes increasingly foreseeable (RTE (2023)). Therefore, 2035 France can be calibrated without many bets on the future. Finally, the strong increase of VRE capacity in the mix within the next decade creates a need for more flexibility in the system without much time to deploy it, making demand response, and especially diffuse residential and tertiary demand response, one of the main closing variables of the supply-demand balance during the decade (RTE (2023)). Hence, France and Europe are preparing for a crucial deployment of demand response capacities in the next decade (Bureau et al. (2023),Commission (2023)), notably in the large and untapped diffuse sectors. Several options of DR control are still possible to develop in this context as both large generators and small pure players or even energy communities (ThinkSmartgrids (2024)) are currently taking positions on DR, notably on diffuse DR potentials.

The case study is constituted by running the models of Section 2.2 during a representative winter week and a representative summer week of a stylized 2035 French power system. Generation is materialized by representative technologies that are supposed to act as Cournot competitors, which is not so far from reality considering EDF's monopoly on the massive nuclear French fleet. Building on capacity planning and costs and ramping rates from the literature (Pahle et al. (2022)), six representative generators are chosen and calibrated as in Table 4.1.

Technology	Capacity K_g (MW)	Marginal cost c_g (€/MWh)	1 hour ramping rate R_g (%)
Hydro	8000	10	100
Nuclear	61000	30	30
CCGT	9669	76	55
CCGT 2	3200	104	60
OCGT	2015	128	70
Oil	2566	142	80

Table 4.1: Representative generation technologies, installed capacity and marginal costs.

Inverse residual demand function parameters B_t and A_t are calibrated from:

- day-ahead prices and hourly demand extrapolated from an average of 2018, 2019, 2021 and 2022 data for France from SMARD of the German Bundesnetzagentur,
- planned VRE capacities for France stated above and associated load factors from renewables.ninja (Pfenninger and Staffell (2016),Staffell and Pfenninger (2016)) for wind and PV, and from ENTSO-E historical 2018, 2019, 2021 and 2022 data for run-of-river hydropower,
- a -0.8 electricity demand elasticity ϵ found for France in a recent study (Auray et al. (2020))

For a given date t, residual demand D_t^0 and market price P_t^0, the following calibration can be made $A_t = -P_t^0/(\epsilon D_t^0)$ and $B_t = (1 - 1/\epsilon)P_t^0$.

Demand response is materialized by seven potentials from the residential and tertiary sectors the calibration of which is given in Table 4.2 building on data from the literature (Gils (2014), Marañón-Ledesma and Tomasgard (2019)). Notably, the maximum share of an available potential over total demand s_j is reconstructed from projections of equivalent capacities of each considered appliance adapted from Gils (2014), Müller and Möst (2018) and Marañón-Ledesma and Tomasgard (2019). The crucial hourly availability factor $A_{j,t}$ follows calibration of Gils (2014) adapted to reflect economic activities of tertiary and residential sectors depending on the week day. All considered appliances have also thermal-sensitive availability: average day temperature is taken from the projections of renewables.ninja (Pfenninger and Staffell (2016),Staffell and Pfenninger (2016)) and the translation of temperature into power demand is taken from Gils (2014). Resulting availability profiles for the representative winter and summer weeks are displayed in Figure C.1.

In order to explore various control structures of demand response, several scenarios are considered. A first set of scenarios relies on an independent demand response operator, which

Technology	Δ_j (h)	s_j (%)	AC_j (€/MWh)
Residential space heating	1	10	10
Residential water heating	12	45	7
Residential AC	1	1	10
Tertiary space heating	2	6	5
Tertiary water heating	12	8	5
Tertiary AC	1	1	5
Tertiary cold storage	1	8	20

Table 4.2: DR potentials for the French case study

is either private and price-taker (labeled "IDRO pt profit"), private and price-maker ("IDRO Cournot profit"), or welfare maximizer ("IDRO welfare"). The IDRO has control over all DR potentials and on DR potentials only. A second set of scenarios explores integrated generation-DR operations with either all G generators controlling $1/G$ of each DR potential (labeled "Integrated uniform"), or all R affected to a particular generator where DR is entirely endowed either to the major base load generator ("Integrated nuclear"), or to a mid merit order generator ("Integrated ccgt"), or to the most costly generator ("Integrated peak"). Finally, a run is made without demand response for comparison.

All scenarios are run for the two representative weeks and for 50 δ ranging from 0, where there is no demand response, to 1, where all flexible demand of each DR appliance is available, thus modeling greater integration of diffuse DR in the mix. Note that the level of flexible demand is similar for all potential, with our notations, $\delta = \delta_j$ for all j in the IDRO scenarios and $\delta = \sum_g \delta_{g,j}$ for all j in integrated DR scenarios. Implemented in GAMS and solved using Path, the set of 50 cases runs in less than 15 minutes for all scenarios, except the larger Integrated uniform scenario where it takes around 1.5 hours, on a PC using a 2.80 GHz Intel(R) Core(TM) i7-1165G7 CPU and 16 Go of RAM.

4.2 Results

Results from the simulations are displayed in Figure 4.1 in terms of market prices average over time and market prices standard deviation over time during the simulated week. From a regulator perspective, these are two variables of the main interest as consumers are primarily sensitive to average prices, which permeate from wholesale through the retail market and long term contracts while flexibility assets from supply or demand-side are remunerated on price deviations and other generators, large consumers or retailers are quite averse to these. Simulation results tend to confirm some of the analytical insights of Section 3. First, all control structures but primarily all different types of IDRO have similar impact on market prices for low DR installed capacities. The differentiation between IDRO scenarios both in terms of price average and deviation appears, in fact, only for very large DR capacities, above 60% of the maximum potential. At the extreme case of full DR deployment, a welfare-maximizing IDRO yields slightly better performance in terms of market prices average, but the main result both from here and Section 3 seems to be the relatively unchanged results as soon as DR is independently operated whatever the type of pure player.

Moreover, the impact for all scenarios except "Integrated nuclear" is to reduce average market prices and their deviation, that is to exert an arbitrage between peak and off-peak hours. As expected, the magnitude of this effect is higher during the winter week than

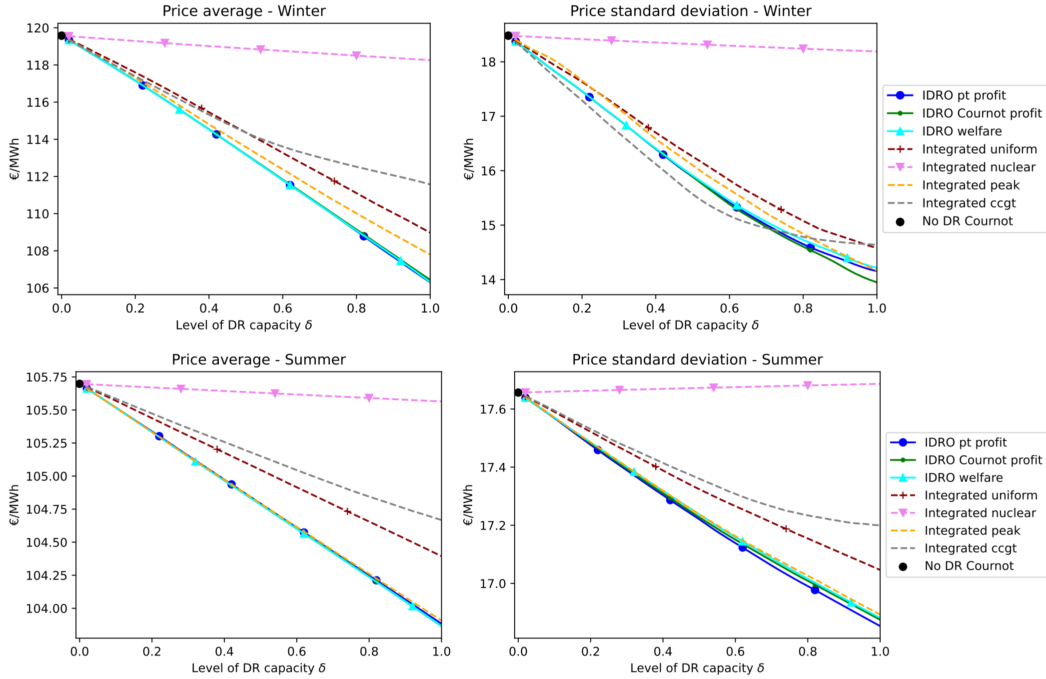

Figure 4.1: Average (left) and standard deviation (right) of market prices during a typical winter (top) and typical summer (bottom) weeks for different control structures of DR.

during the summer week when the system is less tight and residual demand lower so that peak/off-peak ramps are less steep.

Regarding integrated DR, "Integrated peak" yields close results from the IDRO cases. This echoes with the analytical insight of Section 3 where a non-capacity constrained generator activates only separately either its generation capacity or its DR capacity, becoming *de facto* an IDRO in the latter case. With all DR integrated to the most expensive generation, this result may apply as the last mean of the generation merit order virtually never reaches its full capacity - because we do not account for lost load here through a change in the inverse demand function. Hence, peak generation is often out of the market, and the integrated peak generation - DR operator acts, in fact, as an independent DR operator most of the time. This hypothesis is also supported by the fact that "Integrated peak" and IDROs curves coincide almost entirely during the summer week (when peak is never called) and that there is a slight difference between the "Integrated peak" scenario and IDRO ones during the winter week (when peak can be sometimes called at full capacity and the insights from Section 3 no longer holds).

On the other side of the merit order, integrating base-load generation and all demand response potentials results in only a slight decrease in market prices and even an increase in price deviation during summer. This is in line with the computation of $P^{\mathrm{Int,unsat}}$ in Section 3 where the integration of DR to generation would tend to maintain high peak prices and not affect off-peak prices. These higher price averages and deviations in the "Integrated nuclear" case could be related to the interaction of generation capacity constraints and own dr operations depicted in Section 3. A price-maker generator with DR is limited by its generation capacity to price out of the market more expensive rivals and uses DR to replace them thus maintaining a similar price profile than in the no DR case, which is the result observed in the simulations. However, a more detailed analysis of this mechanism seems needed.

Finally, as expected from Section 3, and confirming the role of the merit order of the controlled generation in DR operations for integrated DR-generation, "Integrated ccgt" acts as an intermediate of base and peak integrated DR. During winter, when more expensive generators can be called, CCGT makes use of its cheaper DR capacity to price out these upper merit order rivals thus lowering price volatility because CCGT becomes more often the last called generation but lowering price averages with DR only until the point where CCGT would drive itself out of the market. Hence, the more "Integrated nuclear" looking end of the curve of "Integrated ccgt." During summer, CCGT is, by default, the marginal generation most of the time and, therefore, acts like the integrated nuclear for smaller installed DR capacities. Uniformly spreading DR capacities among generators mitigates most, but not all, adversarial effects on price averages and deviations and makes integrated DR perform closer to independent DR.

Computing Lerner indexes for each hour, at each DR capacity level, and for each control structure confirms the trends drawn from the evolution of price averages and price deviations. Results for the winter week are displayed in Figures D.1 and D.2[5]. Figure D.1 shows that tightness of the system seems to be the primary driver of market power exercise but also that increased capacity opens new windows for exercising market power, this effect being stronger for integrated DR and especially integrated DR-base generation. Figure D.1[6] corroborates this difference in market power exercise depending on the control structure but displays more clearly the above similarity between independent DR and integrated DR-peak generation. Moreover, increasing DR capacity is shown to reduce the Lerner index for most control structures, with different intensities that fit with our previous results, the reduction being similar and bigger for independently operated DR. Yet, independent, centralized and regulated DR seems to bring about the same market power mitigation for slightly lower DR capacity than other independent control structure.

5 Conclusion

Perceived as an essential flexibility resource for power systems in the next decade, demand response is yet to be deployed and integrated into power markets on a massive scale. Diffuse load-shifting from the residential and tertiary sectors is increasingly prospected by regulators, network operators, private utilities, or smaller energy communities as new assets to invest in and operate. However, it is still unclear whether the type of demand response operator affects DR operations and, more generally, power markets.

To investigate the relationship between demand response control structure and its market effects, this paper proposes different scenarios of control over demand response assets. It models their operations in imperfectly competitive power markets. From these models, analytical insights and numerical simulation results are drawn, which intend to inform

[5] Lerner indexes are computed as $(p_t - mc_t)/p_t$ where p_t is the observed (here simulated for the considered control structure) market price and mc_t the marginal cost of the system at the same date (here the market prices obtained if all actors, generators and DR, are price-taker).

[6] Even if this figure is specific to one hour of the winter week, similar behaviors are found for all 168 hours of the week and also in the summer week, but not included here for brevity.

decision-makers at the dawn of demand response deployment. Such combined insights on demand response and market power are the main contributions of the present paper.

The independence of demand response operation appears more crucial than the type (regulated, atomistic, or with market power) of an independent operator in both our analytical and numerical results regarding price levels and volatility. In all cases, the direction of the impact of independently operated DR is similar (reduced peak prices, reduced volatility). Our analytical model highlights a difference in magnitude occurring for large installed DR capacity, with private price-taker DR yielding the most significant impact on prices, followed by regulated DR, which provides 2/5 of the previous effect, and then by private price-maker DR with only 1/4 of the first effect. The three types of DR operators have the same impact on markets for low DR capacity. In coherence, our real-world simulations display differences only after 60 to 75% of DR potentials have been installed.

Moreover, these differences appear smaller than those between independent DR and integrated DR-generation operations. The latter depends strongly on what part of the generation merit order is endowed with demand response capacities. Peak generation with control over DR tends to act similarly to independent DR since, for most hours, such generation is priced out of the market. On the contrary, base generation with control over DR tends to use it to gain market shares while maintaining price levels and volatility, pushing out of the market a more expansive generation.

Policy-wise, our results suggest the following insights. On the one hand, power systems benefit from similarly smoothed and lowered prices with demand response, regardless of the control structure of DR at the initial deployment stages. Hence, the main conclusion for the near future in terms of DR development is that concerns regarding market power and control structure are of secondary importance compared to the benefits of DR for the system. On the other hand, at larger installed DR capacity, the consequences of control choices are more substantial, in ascending order, with pure DR players (whatever their status), then with DR integrated to peak generation, then with DR integrated to mid-merit generation or uniformly spread across all generators, and finally with integrated DR - base generation. In the latter case, market prices are virtually unmodified, but the integrated actor has gained market shares. This could, however, be interesting in terms of greenhouse gas emissions of the power system if base generation is less carbon-intensive than peak means since DR is inherently non-emissive.

Finally, the present paper relies on stylized models to extract analytical insights into market operations. Future research could use the same approach to address DR investment incentives, with the idea of investigating which type of structure is the most suited to bear the investment. Another research line could be to add stochasticity in the models of the present paper in order to account for renewables variability and to depart from our perfect foresight setting to link DR capacity, optimal generation policies, and expected prices or emissions.

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A Notations

Parameters	
J	Number of shiftable loads/DR potential
AC_j	Variable cost of activation for shiftable load j (in €/MWh)
δ_j	Share of appliance j that is flexibilized (independent DR)
$\delta_{g,j}$	Share of appliance j that is controlled by generator g and flexibilized (integrated DR)
s_j	Maximal share of total demand that flexible appliance j represents without DR
$A_{j,t}$	Availability factor of load j at time t
Δ_j	Maximum time to recover reduced load for appliance j
G	Number of generators
c_g	Variable cost of generation g (in €/MWh)
K_g	Capacity of generation g (in MW)
R_g	Maximal variation of generation of generator g between t and $t+1$, in share of installed capacity
μ	Takes value 1 for independently operated DR with market power and 0 for the case without.

Variables	
$x_{g,t}$	Generation decision of generator g at time t
$d_{j,t}$	Load reduction decision for DR potential j at time t (DR independent)
$d_{g,j,t}$	Load reduction decision for DR potential j controlled by generator g at time t (DR integrated)
$u_{j,t}$	Load increase decision for DR potential j at time t (DR independent)
$u_{g,j,t}$	Load increase decision for DR potential j controlled by generator g at time t (DR integrated)

B KKT conditions of the general models of Section 2.2

Negative dual variables are associated with generators' capacity constraints 2.8 ($\alpha_{g,t}$), upward ramping rates 2.9 ($\chi^+_{g,t}$) and downward ramping rates 2.10 ($\chi^-_{g,t}$) and with demand response operations' reduction capacity constraints 2.3 ($\gamma^+_{j,t}$), increase capacity constraints 2.4 ($\gamma^-_{j,t}$) and recovery time limit 2.5 ($\zeta_{j,t}$) . Notations are extended to integrated demand response operations by adding an index g on the latter series of dual variables.

The following sections provides the necessary *and sufficient* KKT conditions of the problems solved by each market actors.

B.1 Independent and profit-maximizer DR operator

$$0 \geq \zeta_{j,t} \perp d_{j,t} - \sum_{k=1}^{\Delta_j - 1} u_{j,t+k} \leq 0$$

$$0 \geq \gamma^+_{j,t} \perp d_{j,t} - A_{j,t} s_j \delta_j \left(\mu \sum_g x_{g,t} + \sum_{j\prime \neq j} d_{j\prime,t} - u_{j\prime,t} + (1-\mu) L_t \right) \leq 0$$

$$0 \geq \gamma^-_{j,t} \perp u_{j,t} - s_j \delta_j \left(\mu \sum_g x_{g,t} + \sum_{j\prime \neq j} d_{j\prime,t} - u_{j\prime,t} + (1-\mu) L_t \right) \leq 0$$

$$0 \leq d_{j,t} \perp (1-\mu) P_t + \gamma^+_{j,t} + \zeta_{j,t} - AC_j +$$
$$\mu \left[B_t - A_t (\sum_g x_{g,t} + \sum_{j\prime} d_{j\prime,t} - u_{j\prime,t}) - A_t d_{j,t} - \sum_{j\prime \neq j} \delta_{j\prime} s_{j\prime} (A_{j\prime,t} \gamma^+_{j\prime,t} + \gamma^-_{j\prime,t}) \right] \leq 0$$

$$0 \leq u_{j,t} \perp -(1-\mu) P_t + \gamma^-_{j,t} - \sum_{k=1}^{\Delta_j - 1} \zeta_{j,t-k} +$$
$$\mu \left[-B_t + A_t (\sum_g x_{g,t} + \sum_{j\prime} d_{j\prime,t} - u_{j\prime,t}) - A_t u_{j,t} + \sum_{j\prime \neq j} \delta_{j\prime} s_{j\prime} (A_{j\prime,t} \gamma^+_{j\prime,t} + \gamma^-_{j\prime,t}) \right] \leq 0$$

B.2 Independent and welfare-maximizer DR operator

$$0 \geq \zeta_{j,t} \perp d_{j,t} - \sum_{k=1}^{\Delta_j - 1} u_{j,t+k} \leq 0$$

$$0 \geq \gamma^+_{j,t} \perp d_{j,t} - A_{j,t} s_j \delta_j \sum_g x_{g,t} + \sum_{j\prime \neq j} d_{j\prime,t} - u_{j\prime,t} \leq 0$$

$$0 \geq \gamma^-_{j,t} \perp u_{j,t} - s_j \delta_j \sum_g x_{g,t} + \sum_{j\prime \neq j} d_{j\prime,t} - u_{j\prime,t} \leq 0$$

$$0 \leq d_{j,t} \perp \gamma^+_{j,t} + \zeta_{j,t} - AC_j + 2 \left[B_t - A_t (\sum_g x_{g,t} + \sum_{j\prime} d_{j\prime,t} - u_{j\prime,t}) \right] - A_t d_{j,t} - \sum_{j\prime \neq j} \delta_{j\prime} s_{j\prime} (A_{j\prime,t} \gamma^+_{j\prime,t} + \gamma^-_{j\prime,t}) \leq 0$$

$$0 \leq u_{j,t} \perp \gamma^-_{j,t} - \sum_{k=1}^{\Delta_j - 1} \zeta_{j,t-k} - 2 \left[B_t - A_t (\sum_g x_{g,t} + \sum_{j\prime} d_{j\prime,t} - u_{j\prime,t}) \right] - A_t u_{j,t} + \sum_{j\prime \neq j} \delta_{j\prime} s_{j\prime} (A_{j\prime,t} \gamma^+_{j\prime,t} + \gamma^-_{j\prime,t}) \leq 0$$

B.3 Generators without demand response capacity

$$0 \le x_{g,t} \perp B_t - A_t \left(\sum_{g'} x_{g',t} + \sum_j d_{j,t} - u_{j,t} \right) - A_t x_{g,t} - c_g + \alpha_{g,t} + \chi^+_{g,t} - \chi^-_{g,t} - \chi^+_{g,t+1} + \chi^-_{g,t+1} \le 0$$

$$0 \ge \alpha_{g,t} \perp x_{g,t} - K_g \le 0$$

$$0 \ge \chi^+_{g,t} \perp x_{g,t} - x_{g,t-1} - R_g K_g \le 0$$

$$0 \ge \chi^-_{g,t} \perp x_{g,t-1} - x_{g,t} - R_g K_g \le 0$$

B.4 Integrated DR/generation operator

$$0 \ge \alpha_{g,t} \perp x_{g,t} - K_g \le 0$$

$$0 \ge \chi^+_{g,t} \perp x_{g,t} - x_{g,t-1} - R_g K_g \le 0$$

$$0 \ge \chi^-_{g,t} \perp x_{g,t-1} - x_{g,t} - R_g K_g \le 0$$

$$0 \ge \zeta_{g,j,t} \perp d_{g,j,t} - \sum_{k=1}^{\Delta_j - 1} u_{g,j,t+k} \le 0$$

$$0 \ge \gamma^+_{g,j,t} \perp d_{g,j,t} - A_{j,t} s_j \delta_{g,j} \sum_{g'} x_{g',t} + \sum_{j' \neq j} d_{g',j',t} - u_{g',j',t} \le 0$$

$$0 \ge \gamma^-_{g,j,t} \perp u_{g,j,t} - s_j \delta_{g,j} \sum_{g'} x_{g',t} + \sum_{j' \neq j} d_{g',j',t} - u_{g',j',t} \le 0$$

$$\begin{aligned} 0 \le x_{g,t} \perp -c_g + \alpha_{g,t} + \chi^+_{g,t} - \chi^-_{g,t} - \chi^+_{g,t+1} + \chi^-_{g,t+1} - \sum_{j'} \delta_{g,j'} s_{j'} (A_{j',t} \gamma^+_{g,j',t} + \gamma^-_{g,j',t}) \\ + B_t - A_t \left(\sum_{g'} x_{g',t} + \sum_{j'} d_{g',j',t} - u_{g',j',t} \right) - A_t \left(x_{g,t} + \sum_j d_{g,j,t} - u_{g,j,t} \right) \le 0 \end{aligned}$$

$$\begin{aligned} 0 \le d_{g,j,t} \perp \gamma^+_{g,j,t} + \zeta_{g,j,t} - AC_j - \sum_{(g',j') \neq (g,j)} \delta_{g',j'} s_{j'} (A_{j',t} \gamma^+_{g',j',t} + \gamma^-_{g',j',t}) \\ + B_t - A_t \left(\sum_{g'} x_{g',t} + \sum_{j'} d_{g',j',t} - u_{g',j',t} \right) - A_t \left(x_{g,t} + \sum_j d_{g,j,t} - u_{g,j,t} \right) \le 0 \end{aligned}$$

$$\begin{aligned} 0 \le u_{g,j,t} \perp \gamma^-_{g,j,t} - \sum_{k=1}^{\Delta_j - 1} \zeta_{g,j,t-k} + \sum_{(g',j') \neq (g,j)} \delta_{g',j'} s_{j'} (A_{j',t} \gamma^+_{g',j',t} + \gamma^-_{g',j',t}) \\ - B_t + A_t \left(\sum_{g'} x_{g',t} + \sum_{j'} d_{g',j',t} - u_{g',j',t} \right) - A_t \left(x_{g,t} + \sum_j d_{g,j,t} - u_{g,j,t} \right) \le 0 \end{aligned}$$

C Calibration of the availability factor of DR potentials

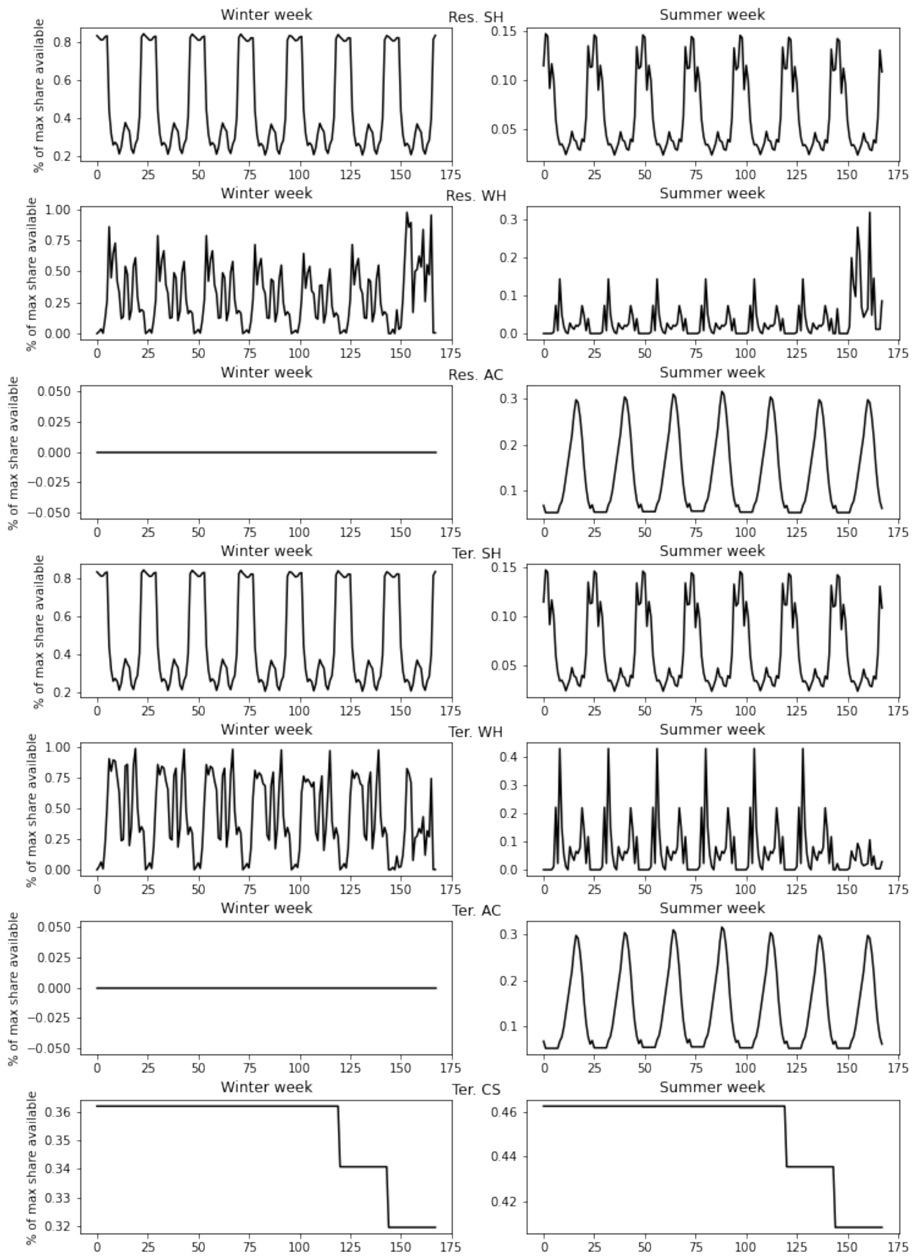

Figure C.1: Availability factor of considered load-shifting potentials during a typical winter week (left) and typical summer week (right).

D Lerner indexes from numerical simulation results

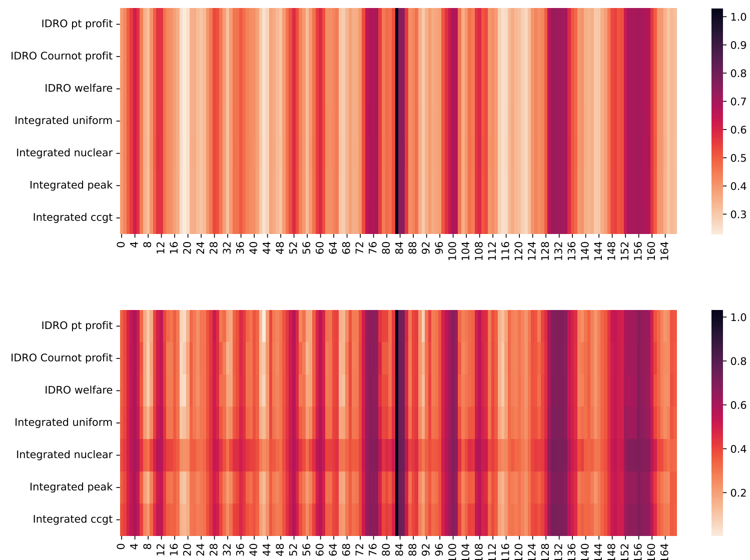

Figure D.1: Lerner index for each DR control structure depending on the hour of the simulated winter week. Top: no load shifting capacity ($\delta = 0$). Bottom: Maximal load shifting capacity ($\delta = 1$).

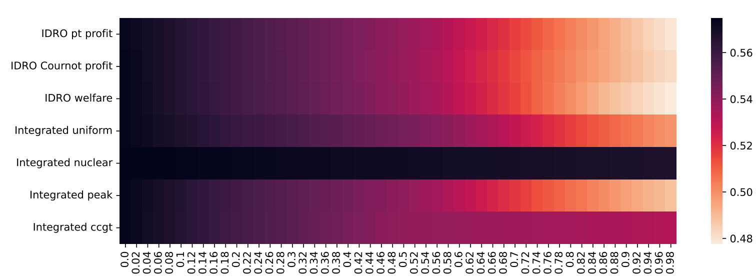

Figure D.2: Lerner index at hour 59 of the winter week for each control structure depending on the installed DR capacity δ.

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