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Electricity supply auctions: Understanding the consequences of the product definition

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ABSTRACT

We study the impact of product definition in electricity auctions. Recognizing the key role of the auction rules—pay as bid, uniform—the definition of the product itself emerges also as a critical step. Poorly designed products may impact both the market performance and the physical operation of the system. We investigate the impacts that the product definition can have on the market outcomes. A product definition implemented in some electricity markets is used to unveil critical aspects that must be considered when electricity products are defined. Our results provide guidelines for improving the product definition in electricity auctions.

1. Introduction

There is an ongoing worldwide trend towards the deployment of market structures in the electricity industry. The idea of implementing electricity markets started a few decades ago and it was sustained by several dimensions. The reasons to start this trend are multi-fold—technological, academical and historical—and can be summarized as follows. In the technological side, economically efficient generating units of small- and mid-size capacity became a reality [12]. Consequently, in the generation side emerged the possibility of having multiple suppliers of different sizes and the idea of implementing markets in electricity, at least in the generation side, started to take shape. The idea was taken in academia in which the framework of spot pricing for trading electricity emerged as a reality in the seminal work published by Schweppe et al. [23]. Last but not least, there was the historical context of the late seventies and early eighties in which the deployment of market structures at many levels of society became a popular trend [3,25,26]. These three dimensions paved the road to the deployment of market structures in electricity in Chile and UK in the early eighties [16] with the hope that the harnessing of the competitive forces would stimulate innovation, facilitating the achievement of a more efficient system which eventually would result in affordable prices. Although the restructuring process has brought some benefits, in particular in terms of increasing the efficiency and management of utilities [21], many authors have questioned and criticized the real accomplishment of the original market hopes and objectives [22,25,26]. Moreover, some authors still believe that the salient characteristics of electricity make vertical integration essential for an efficient planning and operation of electrical systems [15]. An historical overview about the development of electricity markets along with discussion of future challenges is provided in Chao et al. [5].

A key design element of electricity markets is treating electricity as a commodity. Accordingly, MW hs should not be treated differently to other commodities such as copper or oil. In addition, the MW h *commodity* can be provided without apparent distinction by any generating technology. As a result of this electricity-as-a-commodity viewpoint, several market structures from other commodity markets such as financial derivatives or forward contracts started to be adopted in electricity. Forward contracts are common instruments in commodity markets to hedge risk [14]. From the viewpoint of investments, a forward contract creates a long-term signal useful for investors whom do not want to rely on the volatility of the spot markets. In addition, a forward contract market could also improve market efficiency. Using standard economic theory, Allaz and Vila [1] show how the implementation of a forward market can make a duopoly market competitive.

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However, for the particular case of electricity, and once some of its complexities are considered, there is no clear agreement about the market benefits of forward contracts [2,17].

From a physical perspective, however, the use of forward contracts may facilitate the achievement of other objectives such as resource adequacy or appropriate technology mix. The auction processes held in Chile and Brazil are examples of the use of forward contracts for facilitating resource adequacy [16]. In addition, in the case of Brazil, the auction processes have facilitated the integration of new types of technologies. In terms of designing a market for electricity contracts, what and how to buy/sell are two natural questions that arise. Therefore, the essential issues are: (a) the product definition, the way in which the load is going to be categorized and what the basic unitary product is; and (b) the auction format, the way in which the sellers and the buyers are brought together and the method to clear the underlying product.

Several of the research efforts in electricity auctions have been focus primarily on the nature of the competitive bidding processes and on what auction formats and rules should be adopted, e.g., uniform or pay-as-bid formats [11], bypassing the discussion on the product definition. Those discussions are important especially given the experience in other instances such as US spectrum auctions, in which the results illustrate how the auction format and rules can impact the market outcomes [6].

In the literature we find little discussion about the characterization of the product in electricity markets. In the context of a public information game theory, Elmaghrabi and Oren [9] and Elmaghraby [10] make an analysis about the impact of the demand packaging in the outcome efficiency, showing how vertical-type packaging does not have efficient equilibria. Similarly, Barroso et al. [4] and Moreno et al. [16] present some notions about the importance of the product definition. This apparent lack of interest in the product definition might be also an aftermath of treating electricity as a standard commodity. However, this view fails to capture many of the complexities associated with electricity production such as ramping rates. For example, due to technical limitations, a coal power plant has a maximum load ramping that unable it to provide energy faster than an hydro power plant. In a similar way, nuclear units are usually used as base-load resource, due to their lack of ramping capabilities. Consequently, it is not only the energy that matters but also the instantaneous power and its trajectory. In addition, there are unique characteristics of electricity such as lack of massive storage capability, just-in-time manufacturing use and the several technical constraints of electricity generation that needs somehow to be considered in the specification about what is being traded in these markets. Recognizing in the definition of products the multiple capabilities and services that different technologies can provide seems critical for having a constructive relationship between the physical systems and the market structures.

There are real market designs that help to illustrate the impact of a poorly defined product. A clear example is the auction process performed in Illinois during 2006 [18]. The level of prices attained in the process was so high that the auction was canceled after one year of its realization and a new scheme for the procurement of power was defined [13,19]. The final auction prices for a subset of the auction products and the spot market prices in Illinois during 2007 are illustrated in Fig. 1. Note that the final auction prices of some products are above the market prices for about 90% of the time. In previous works the failure of the Illinois process has been attributed to the product definition based on the so-called *tranches* [18,7,8], definition that has been also used in auction process held in Maryland, Ohio, Pennsylvania and New Jersey. In addition to the Illinois experience, the aftermath of auctions using this type of products has been less than promising. For many years, electricity rates in New Jersey increased considerably after the implementation of auctions with these type of products. In Ohio the results of one auction realization were rejected by regulators. In Maryland, the implementation of the auction in 2007 resulted in a 72% increase of the electricity rates de Castro et al. [8].

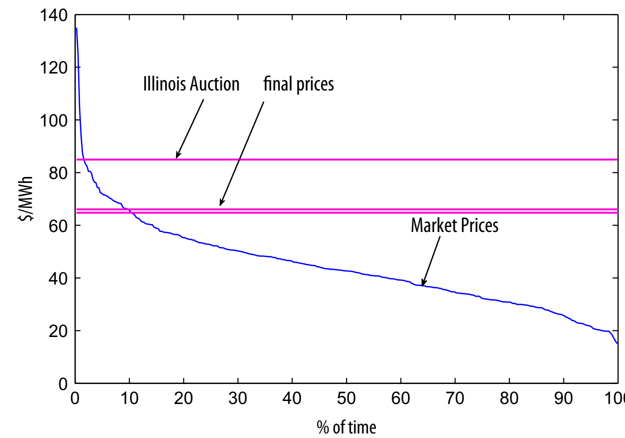

Fig. 1. Prices range of the illinois auction.

In this paper, we discuss the impacts of product definition in electricity auctions. Although the implications of a poorly defined product are noticed in both the market behavior and the physical operation of the electricity system, our focus is mainly on the market performance. Through some cases and examples, we identify critical market aspects that should be considered in the product design. Our results reinforce the importance of defining properly the product in electricity markets and provides guidelines for future research. The structure of this paper is as follows. Section 2 is devoted to provide economic reasons along with illustrative examples to show the impact that the product definition can have in the market outcomes. Analytical results about competitive prices for tranche-based products are presented in Section 3. Final remarks on product definition challenges are discussed in Section 4. Concluding remarks and future research directions are presented in Section 5.

2. Analyzing a product definition

When a market for contracts is implemented, a natural question arises: How do the terms of the contract impact the market outcomes? Such question has been overlooked in the electricity markets literature, mainly because in standard commodity markets the product definition is somehow natural—for Example 1 barrel of oil or 1 lb of copper. However, electricity is radically different to any other commodity due to the technology involved, its link to a physical network that is highly complex, and its importance for the well-functioning of society. Based on previous electricity auction processes, we claim that the product definition is a key element of any market for electricity contracts.

In this section, using a particular type of contract, we provide key elements that should be taken into account in the design of electricity contracts. Such elements are mainly related to economic and market performance. Although not discussed in this work, the definition of the contracts also impacts the achievement of other objectives beyond market and economic ones. In particular, the terms of the contracts will also play an important role in achieving objectives such as system reliability and environmental fulfillment. A non-interfering linkage between the market and the physical operation of the system can be only achieved by having products that capture the physical constraints and needs for achieving those objectives. Attributes such as location of the generating resources, volatility that different resources injects into the system, environmental impacts and flexibility should be also considered in the definition of appropriate products.

2.1. Tranche-based products

We use the product definition used in the 2006 Illinois auction to investigate the impacts of the product definition in market outcomes. We start defining the key terms of these type of contracts. Firstly, we introduce a load model. Assume that the load over a given period H is a random variable $\underset{\sim}{l}(h)$. Moreover, assume that the load can be further decomposed as

$$\underset{\sim}{l}(h) = l_f(h) + \underset{\sim}{\varepsilon}(h) \tag{1}$$

where $l_f(h)$ is a deterministic part and $\underset{\sim}{\varepsilon}(h)$ is a random one. The deterministic part is forecasted.

Consider an index set $\mathcal{I} = \{i : i = 1, \ldots, I\}$ of suppliers. The tranche-based contract $(\underset{\sim}{\gamma}_i)$ is defined to supply a fixed proportion (α_i) of the total load,

$$\underset{\sim}{\gamma}_i(h) = \alpha_i \underset{\sim}{l}(h) : 0 \leqslant \alpha_i \leqslant 1 \wedge \sum_{i \in \mathcal{I}} \alpha_i = 1 \tag{2}$$

$$\Rightarrow \sum_{i \in \mathcal{I}} \underset{\sim}{\gamma}_i(h) = \underset{\sim}{l}(h) \tag{3}$$

Note that the contracts themselves are random variables as their associated power depends on the not-yet-realized load. Consequently, the contracts are not only associated with energy but several other attributes such risk insurance and ancillary services. In forthcoming sections of the paper, we focus on specific attributes associated to the tranche-based contract.

2.2. Model for supplying contracts

In order to illustrate the economic issues emerging from the use of tranche-based products, a simple model for supplying contracts is presented. In this model, we focus only on the deterministic part of the load. Assume that the forecasted load (l_f) is decomposed in three components: base load (l^b), cycling load (l^c) and peak load (l^p), i.e., $l_f = l^b + l^c + l^p$. The load can be alternatively represented by the triplet $\boldsymbol{l} = \left(l^b, l^c, l^p\right)$. Assume an idealized set of generators $(\mathcal{I})$ to supply the load at the three load levels—base, cycling and peak levels. Considering a generator i, the total generated power is decomposed in base (s_i^b), cycling (s_i^c) and peak (s_i^p) power with their corresponding base (c_i^b), cycling (c_i^c) and peak (c_i^p) costs. The consideration of different costs for each load segment allows to capture some of the ramping capabilities of the resources. If a generator i cannot attend the peak demand then its cost is infinite, i.e., $c_i^p = \infty$. The generated power is subject to the maximum power $(P_{max,i})$, i.e., $s_i = s_i^b + s_i^c + s_i^p \leqslant P_{max,i}$. The generated power and cost can be alternatively represented by the triplet $\boldsymbol{s}_i = (s_i^b, s_i^c, s_i^p)$ and $\boldsymbol{c}_i = (c_i^b, c_i^c, c_i^p)$, respectively.

Let $(\boldsymbol{s}_i)_{i \in \mathcal{I}} = (s_i^b, s_i^c, s_i^p)_{i \in I}$ be the power allocation of all generators to supply the base, cycling and peak load segments. We say that the allocation $(\boldsymbol{s}_i)_{i \in \mathcal{I}}$ is feasible if:

$$\sum_{i \in I} s_i^b = l^b; \sum_{i \in \mathcal{I}} s_i^c = l^c; \sum_{i \in \mathcal{I}} s_i^p = l^p; \tag{4}$$

$$s_i^b + s_i^c + s_i^p \leqslant P_{max,i}, \forall i \in \mathcal{I} \tag{5}$$

The set of feasible allocations is denoted by $\mathcal{F}$. We say that a feasible allocation $(\boldsymbol{s}_i^*)_{i \in \mathcal{I}}$ is efficient if

$$(\boldsymbol{s}_i^*)_{i \in \mathcal{I}} \in \arg \min_{(\boldsymbol{s}_i)_{i \in I} \in \mathcal{F}} \sum_{i \in \mathcal{I}} \boldsymbol{s}_i \cdot \boldsymbol{c}_i \tag{6}$$

where $\boldsymbol{s}_i \cdot \boldsymbol{c}_i = s_i^b c_i^b + s_i^c c_i^c + s_i^p c_i^p$ is the standard inner product of vectors.

2.3. Market outcome analysis

By using several examples, we show that the use of tranche-based contracts create problems such as economic inefficiency, competition reduction, market concentration, information aggregation, insurance distortion and information asymmetry.

2.3.1. Inneficiency

If tranche products are used to determine allocation, inefficiency occurs providing there are different generators. Consider two generators with the following costs: $\boldsymbol{c}_1 = (c_1^b, c_1^c, c_1^p) = (5, 15, 50)$ and $\boldsymbol{c}_2 = (10, 12, 15)$ and total capacity $P_{max,1} = P_{max,2} = 10$. Assume that the demand is $\boldsymbol{l} = \left(l^b, l^c, l^p\right) = (4, 3, 3)$. By inspection, the efficient allocation is $\boldsymbol{s}_1 = (s_1^b, s_1^c, s_1^p) = (4, 0, 0)$ and $\boldsymbol{s}_2 = (s_2^b, s_2^c, s_2^p) = (0, 3, 3)$, with a total cost of $4 \cdot 5 + 3 \cdot 12 + 3 \cdot 15 = 101$. However, any tranche allocation of $\alpha \in [0, 1]$ for generator 1 and $(1 - \alpha)$ for generator 2 will produce a total cost of

$$\begin{aligned} &\alpha(4 \cdot 5 + 3 \cdot 15 + 3 \cdot 50) + (1 - \alpha)(4 \cdot 10 + 3 \cdot 12 + 3 \cdot 15) \\ &= 215\alpha + (1 - \alpha)121, \end{aligned}$$

which is more expensive than the efficient one □

2.3.2. Participant exclusion

Consider the same system than before but $\boldsymbol{c}_1 = (c_1^b, c_1^c, c_1^p) = (5, 15, +\infty)$. Being not able to provide power peak $(c_1^p = \infty)$, generator 1 cannot supply a fixed proportion of the load (α_1). The unique tranche allocation is to assign the load to generator 2. Generator 1 is ruled out of the market. The cost of this allocation is 121 □.

Note that in this scenario monopoly occurs and payments can be even higher than 121. In a general scenario with more generators, the tranche allocation may lead to the creation of bundling contracts—a third company could buy energy from different generators to meet the needs defined by the tranche. This bundling option works as a coordination device or as a mechanism of collusion. We examine it in the following example.

2.3.3. Market concentration

Consider now three generators with the following costs: $\boldsymbol{c}_1 = (5, 15, +\infty), \boldsymbol{c}_2 = (10, 11, 15)$ and $\boldsymbol{c}_3 = (12, 12, 13)$. Assume that the maximum capacities are $P_{max,1} = P_{max,2} = 10$ and $P_{max,3} = 15$. The load is defined by $\boldsymbol{l} = (10, 7, 5)$. The optimal allocation is $\boldsymbol{s}_1 = (10, 0, 0), \boldsymbol{s}_2 = (0, 7, 0)$ and $\boldsymbol{s}_3 = (0, 0, 5)$ with a total cost of 192. In the tranche allocation, generator 1 is excluded due to its inability to provide peak power. Thus, generators 2 and 3 have to supply a proportion of the load in its three levels subjected to their maximum powers, i.e., $\boldsymbol{s}_2 = \alpha \boldsymbol{l} \leqslant P_{max,2}$ and $\boldsymbol{s}_3 = (1 - \alpha)\boldsymbol{l} \leqslant P_{max,3}$. Therefore,

$$\begin{aligned} s_2 &= 10\alpha + 7\alpha + 5\alpha \\ &= 22\alpha \leqslant 10 \end{aligned} \tag{7}$$

$$\begin{aligned} s_3 &= 10(1 - \alpha) + 7(1 - \alpha) + 5(1 - \alpha) \\ &= 22(1 - \alpha) \leqslant 15 \end{aligned} \tag{8}$$

From Eqs. (7) and (8), the tranche allocation is restricted to $7/22 \leqslant \alpha \leqslant 10/22$. The corresponding generator costs and total cost (c_T) are

$$c_2 = c_2^b s_2^b + c_2^c s_2^c + c_2^p s_2^p = 252\alpha \tag{9}$$

$$c_3 = c_3^b s_3^b + c_3^c s_3^c + c_3^p s_3^p = 269(1 - \alpha) \tag{10}$$

$$\Rightarrow c_T = c_2 + c_3 = 269 - 17\alpha \tag{11}$$

Consequently, the minimal total cost is $c_T \approx 261.3$ and occurs when $\alpha = 10/22$. Now, assume that a company buys (or makes a financial arrangement with) the first two generators. Then, the company can provide the allocation $(10\alpha, 7\alpha, 5\alpha)$ with a cost of

$10\alpha \cdot 5 + 7\alpha \cdot 11 + 5\alpha \cdot 15 = 202\alpha < 252\alpha$. Depending on the auction's rule, the firm will pocket the difference. Of course, the company can do even better by combining all three generators. In that case, the total cost for the company will be the efficient one, but now there is a monopolistic firm in the market, which may charge even higher prices □

The example above makes clear that the tranche-based product might promote the concentration of companies. This can have undesirable impacts in the competition and, consequently, on the final price.

But there are another elements and issues related to the tranche-based product definition. Unlike the previous points, these additional elements are related to uncertainty issues. First, the tranches market cannot work properly because it does not transmit or convey useful information. Consider the following example.

INFORMATION AGGREGATION Suppose that two companies have similar costs, but different believes about the demand. One thinks that the demand will be 110 MW while the other thinks it will be 120 MW. Let us assume that the price of 1% tranche contract is 1 $/MW h. Consequently, the first company is expecting $1.1 for the contract while the second one $1.2. Note, however, that the price facing both companies is the same: 1 $/MW h. Hence, the same contract has different values for identical firms only because they expect different loads. Since the competition is in dollars per MW h, it is impossible to aggregate the generators beliefs in the electricity product. In contrast, a normal contract of 1 MW h during a period will pay exactly the same amount to both companies without being subjected to the demand uncertainty □.

This phenomena occurs because the tranche contract has an extra-dimension which is the load shape uncertainty. This additional dimension cannot be captured using a single dimensional price. This issue suggests that energy auctions with tranche-based contracts will reduce competition by favoring large generating companies that can take the risk of an uncertain product.

In terms of market considerations, there are two more elements that should also be taken into account in the design of contracts. First, understanding the type of insurance that the contract is providing. Second, how the contract terms can facilitate symmetry of information among the several parties involved. Those arguments were thoroughly explained in de Castro et al. [7]. For completeness, we summarize the main points here.

2.3.4. Uncertainty protection

How the contract impact the uncertainty faced by the players is another key considerations for contract design. In the case of the tranche-based products this was an important issue. The tranche definition shifts all the uncertainty into the sellers. Under a tranche-based product, the distribution companies are simply playing the role of delivering such product to the end-users. Any uncertainty associated with the capacity and volume along with other risks such fuel price escalation, which historically was faced by the utility companies, are completely removed from their realm. Hence, the tranche-based product is working as an insurance for the distribution companies.

An important matter of concern is how appropriate such insurance is and who, besides the distribution companies, benefit from it. In principle, given that having this type of insurance might certainly reduce price volatility, this insurance might seem legitimate even for consumers. However, in order to fully understand its legitimacy, it is necessary to understand that consumers and distribution companies are different players. In terms of risk faced, while consumers care only about the price that they will pay, distribution companies faces also the uncertainty on the total load that must be served. Also, while consumers are naturally assumed to be risk averse, willing to pay a premium for less volatile prices, economists, in general, tend to classify companies as risk neutral.

Since tranche-based products carry both the uncertainty of the load and the uncertainty of electricity prices, its actuarially fair value will be above an insurance just for the electricity price. Consequently, these type of products provide more protection than the end-users are interested in.

2.3.5. Asymmetric information

A last point to consider is related to information asymmetry issues that the product definition can bring. In the case of Illinois, the legislation allows any customer to shift its load to different providers. As discussed in de Castro et al. [7], this brought considerable uncertainties for the sellers related to the fact that the loads of large customers may change from the historical load shape.

The large consumers have the best information about their willingness to shift their loads from the distribution company. Given the direct contact between the distribution companies and the medium and large customers, the distribution companies are likely to be better informed than the sellers. As the seller of the contract is less informed than the buyer, it is possible that market problems leading to high prices or even the absence of trade may occur.

Tranche-based contracts also create moral hazard issues with respect to the large consumers and the distribution companies. A generator requires a price that pays for the impacts of the expected migration, thereby leading to higher prices to the large consumers. Such prices provide an additional incentive for medium and large customers to negotiate a direct deal with another generator for an explicit period not allowing any migration. The existence of this scenario adds further uncertainty to the contract for large customers products and, consequently, with higher prices large consumers are encouraged to leave the distribution companies.

3. Market clearing: a comparison

We study the market clearing prices considering tranche-based products. We assume, following the treatment of bilateral contracts in several markets [20], that contracts and bilateral-transactions are explicitly considered into the dispatch of the system. The comparison focuses on the energy attribute of the tranche-based product. Other attributes associated with the tranche-based contract such as transmission capabilities, capacity, load-following and other ancillary services are not included. A comparison of the whole set of services associated with the tranche-based product would require the consideration of all those associated markets and it is beyond the scope of this paper. However, as discussed in de Castro et al. [8], the aggregate of all those additional services corresponded to a minimum part of the contract final prices. Hence, in terms of the value of the contracts, the most important service was energy.

In order to focus the comparison on the energy attribute, the traditional economic dispatch problem is considered as a benchmark. We focus on the simplified case in which all the information is available, there is no uncertainty in the future load, and the only differences among suppliers are their costs and capacities.

3.1. Mathematical formulation

Consider an index set $\mathcal{I} = \{i : i = 1, \ldots, I\}$ of suppliers, and an index set $\mathcal{H} = \{h : h = 1, \ldots, H\}$ of time horizon. The supplier i provides a power $P_{i,h}$ at hour h subjected to a maximum of $P_{\max,i}$ and a minimum of zero; its cost function is given by $c_i(\cdot)$. The load for each hour is $l(h)$ and its maximum during the period is $l_{max} = \max\{l(1), \ldots, l(h), \ldots l(H)\}$. The centralized tranche allocation problem is defined by,

3.1.1. Centralized tranche dispatch

$$\min_{\alpha_i} \sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i(\alpha_i l(h))$$
$$s.t. \quad \sum_{i\in\mathcal{I}}\alpha_i = 1 \text{ and } 0 \leqslant \alpha_i \leqslant \min\left\{1, \frac{P_{\max,i}}{l_{max}}\right\} \ \forall i \in \mathcal{I} \tag{12}$$

In order to get insights about the optimal solution of the problem, consider its Lagrangian function

$$\mathcal{L}(\alpha_i,\lambda,\mu_i^+,\mu_i^-) = \sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i(\alpha_i l(h)) + \lambda\left(1-\sum_{i\in\mathcal{I}}\alpha_i\right) + \sum_{i\in\mathcal{I}}\mu_i^+\left(\alpha_i - \min\left\{1,\frac{P_{\max,i}}{l_{max}}\right\}\right) - \sum_{i\in\mathcal{I}}\mu_i^-\alpha_i \tag{13}$$

where the Lagrangian multipliers μ_i^+ and μ_i^- are nonnegative, and λ is unrestricted. The Karush–Kuhn–Tucker (KKT) optimality conditions $\forall i \in \mathcal{I}$ are,

$$\sum_{h\in\mathcal{H}} l(h)\frac{\partial c_i(\alpha_i l(h))}{\partial P_i} - \lambda + \mu_i^+ - \mu_i^- = 0, \tag{14}$$

$$\mu_i^+\left(\alpha_i - \min\left\{1,\frac{P_{\max,i}}{l_{max}}\right\}\right) = 0 \tag{15}$$

$$\mu_i^-\alpha_i = 0 \tag{16}$$

From the slackness conditions (15) and (16), if $0 < \alpha_i^* < \min\left\{1,\frac{P_{\max,i}}{l_{max}}\right\}$ then $\mu_i^{+*} = \mu_i^{-*} = 0$. From Eq. (14), the Lagrangian multiplier λ^* is equal to $\sum_{h\in\mathcal{H}} l(h)\frac{\partial c_i(\alpha_i^* l(h))}{\partial P_i}$. Given the convex structure of the problem, if the centralized dispatch has a solution it is possible to find a price that will support the efficient outcome. Let p^*_{tranche} be the competitive price associated with the tranche-based contract. Assuming price-taking behavior, supplier i faces the problem of maximizing his profits,

$$\max_{\alpha_i} \left[\sum_{i\in\mathcal{I},h\in\mathcal{H}} p^*_{\text{tranche}}\alpha_i l(h) - \sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i(\alpha_i l(h))\right]$$
$$s.t \quad 0 \leqslant \alpha_i \leqslant \min\left\{1,\frac{P_{\max,i}}{l_{max}}\right\} \tag{17}$$

The Lagrangian of this problem is given by,

$$\mathcal{L}(\alpha_i,\lambda,\mu_i^+,\mu_i^-) = \sum_{h\in\mathcal{H}} p^*_{\text{tranche}}\alpha_i l(h) - \sum_{h\in\mathcal{H}} c_i(l(h)\alpha_i) + \mu_i^+\left(\alpha_i - \min\left\{1,\frac{P_{\max,i}}{l_{max}}\right\}\right) - \mu_i^-\alpha_i \tag{18}$$

Writing the KKT conditions,

$$-\sum_{h\in\mathcal{H}} l(h)\frac{\partial c_i(\alpha_i l(h))}{\partial P_i} + p^*_{\text{tranche}}\sum_{h\in\mathcal{H}} l(h) + \mu_i^+ - \mu_i^- = 0 \tag{19}$$

$$\mu_i^+\left(\alpha_i - \min\left\{1,\frac{P_{\max,i}}{l_{max}}\right\}\right) = 0 \tag{20}$$

$$\mu_i^-\alpha_i = 0 \tag{21}$$

Using Eq. (19), the competitive equilibrium price is obtained and defined as

$$p^*_{\text{tranche}} = \frac{\sum_{h\in\mathcal{H}} l(h)\frac{\partial c_i(\alpha_i^* l(h))}{\partial P_i}}{\sum_{h\in\mathcal{H}} l(h)} \tag{22}$$

where i is any generator such that $0 < P_i^*(h) = \alpha_i^* l(h) < P_{max,i}\forall h$, i.e., $\mu_i^{+*} = \mu_i^{-*} = 0$ as the constraints are non-binding. In addition, comparing Eqs. (14) and (19), the following relation between λ^* and p^*_{tranche} is obtained

$$p^*_{\text{tranche}} = \frac{\lambda^*}{\sum_{h\in\mathcal{H}} l(h)} \tag{23}$$

Our interest is to compare the competitive equilibrium associated to the tranche-based market with the results of the economic dispatch problem. The economic dispatch and its associated prices are used as a proxy for the operation of a standard electricity market —as in the case of operating a spot-market dispatched at minimum cost. Given that the tranche-based market is assumed to operate independently, there is no consideration of any type of interactions between a market for tranche-based contracts and a spot market for electricity. A future research avenue certainly could be the consideration of the interaction between those markets and the study of related strategic issues. The comparison's main objective is to assess the effectiveness of tranche-based products to provide energy supply and how the allocation and prices of the tranche-based products are compared with a standard electricity market. As the results will show, just due to the key structural feature of the tranche-based products —providing a *fixed* percentage of the load— analytical bounds in terms of the competitive prices can be established.

In order to make a clear comparison, define $P^e_{i,h}$ as the supplier i delivered power at time h in the economic dispatch context, which may not be equal to $P_{i,h}$—supplier allocation in the tranche dispatch context. The centralized economic dispatch is defined by,

3.1.2. Centralized economic dispatch

$$\min_{P^e_{i,h}} \sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i(P^e_{i,h})$$
$$s.t. \quad \sum_{i\in\mathcal{I}} P^e_{i,h} = l(h), \quad \forall h \in \mathcal{H} \tag{24}$$
$$0 \leqslant P^e_{i,h} \leqslant P_{\max,i}, \quad \forall i \in \mathcal{I}, \forall h \in \mathcal{H}$$

In order to get insights about the optimal solution of the problem, consider its Lagrangian function

$$\mathcal{L}(P^e_{i,h},\lambda_h,\mu^+_{i,h},\mu^-_{i,h}) = \sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i(P^e_{i,h}) + \sum_{h\in\mathcal{H}}\lambda_h\left(l(h) - \sum_{i\in\mathcal{I}} P^e_{i,h}\right) + \sum_{i\in\mathcal{I},h\in\mathcal{H}}\mu^+_{i,h}\left(P^e_{i,h} - P_{\max,i}\right) - \sum_{i\in\mathcal{I},h\in\mathcal{H}}\mu^-_{i,h}P^e_{i,h} \tag{25}$$

where the multipliers $\mu^+_{i,h}$ and $\mu^-_{i,h}$ are nonnegative, and λ_h are unrestricted. The KKT optimality conditions $\forall i \in \mathcal{I}, \forall h \in \mathcal{H}$ are,

$$\frac{\partial c_i(P^e_{i,h})}{\partial P^e_{i,h}} - \lambda_h + \mu^+_{i,h} - \mu^-_{i,h} = 0, \tag{26}$$

$$\mu^+_{i,h}\left(P^e_{i,h} - P_{\max,i}\right) = 0 \tag{27}$$

$$\mu^-_{i,h}P^e_{i,h} = 0 \tag{28}$$

When the power limit constraints are non-binding, $\mu^{+*}_{i,h} = \mu^{-*}_{i,h} = 0 \forall i \in \mathcal{I}, \forall h \in \mathcal{H}$. Therefore, the Lagrangian multipliers λ^*_h are equal to $\frac{\partial c_i(P^e_{i,h})}{\partial P^e_{i,h}} \forall h \in \mathcal{H}$. The solution of this problem provides, for each hour h, the well-known marginal cost condition. The cheapest units will be loaded to their maximum power, while those units operating within their power limits will be loaded in such a way that they have the same marginal cost. The competitive price for each hour, p^*_h, is given by the marginal cost of the last dispatched unit,

$$p^*_h = \frac{\partial c_i(P^{e*}_{i,h})}{\partial P^e_{i,h}} \tag{29}$$

where i is any generator such that $0 < P^{e*}_{i,h} < P_{\max,i}$.

In order to understand how the tranche-based products prices, p^*_{tranche} are related to the benchmark prices p^*_h we focus on the structure of these problems. In particular, the economic-dispatch problem for the peak-hour has a very similar structure to the centralized tranche dispatch problem. The economic-dispatch problem for the peak-hour is given by,

$$\begin{aligned} \min_{P^e_{i,h_{peak}}} \quad & \sum_{i\in\mathcal{I}} c_i(P^e_{i,h_{peak}}) \\ s.t. \quad & \sum_{i\in\mathcal{I}} P^e_{i,h_{peak}} = l_{\max}, \\ & 0 \leqslant P^e_{i,h_{peak}} \leqslant P_{\max,i}, \quad \forall i \in \mathcal{I} \end{aligned} \tag{30}$$

by writing $P^e_{i,h_{peak}} = \kappa_i l_{\max}$, the problem for the peak-hour can be written as,

$$\begin{aligned} \min_{\kappa_i} \quad & \sum_{i\in\mathcal{I}} c_i(\kappa_i l_{\max}) \\ s.t. \quad & \sum_{i\in\mathcal{I}} \kappa_i = 1, \\ & 0 \leqslant \kappa_i \leqslant \frac{P_{\max,i}}{l_{\max}}, \quad \forall i \in \mathcal{I}. \end{aligned} \tag{31}$$

which reads similar to the centralized tranche problem, with the only difference that in the former problem the objective function spans over all the hours. When cost functions $c_i(\cdot)$ are monotonically increasing and its derivative are non-decreasing, it is straightforward to prove that (see the Appendix A):

a. Centralized tranche and economic dispatch optimal solutions are related by,

$$\alpha_i^* = \frac{P^{e*}_{i,h_{peak}}}{l_{\max}} \quad \forall i \in \mathcal{I} \tag{32}$$

b. Centralized tranche and economic dispatch total costs are bounded by,

$$\sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i(P^{e*}_{i,h}) \leqslant \sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i(\alpha_i^* l(h)) \tag{33}$$

c. Competitive prices for tranche and economic dispatch are bounded by,

$$\frac{\sum_{h\in\mathcal{H}} p_h^*}{H} \leqslant p^*_{\text{tranche}} \leqslant p^*_{h_{peak}} \tag{34}$$

Stricter bounds are going to depend on the specific form of the cost functions, e.g., linear or quadratic, and the level of similarity among suppliers.

3.2. Case A. Linear cost functions

In the particular case of linear cost functions given by $c_i(x) = \beta_i x$, a clear tranche-price bound can be found. In this case the solution of the centralized tranche problem is characterized by a marginal supplier, $i = m$, for which $\mu_m^+ = \mu_m^- = 0$, $\alpha_m \in [0, \min\{1, \frac{P_{\max,i}}{l_{\max}}\}]$. By the complementary slackness conditions we also know that,

$$\begin{aligned} \beta_i < \beta_m \ &\Rightarrow\ \alpha_i = \min\left\{1, \frac{P_{\max,i}}{l_{\max}}\right\}, \\ \beta_i > \beta_m \ &\Rightarrow\ \alpha_i = 0 \end{aligned} \tag{35}$$

In this case, the tranche equilibrium price is given by,

$$p^*_{\text{tranche}} = \beta_m \tag{36}$$

It is interesting to note that, in the linear case, the economic-dispatch problem of the 'peak-hour' has the same form, besides a scaling factor given by $\sum_{h\in\mathcal{H}} l(h)$, as the tranche-dispatch problem. Hence, it is clear that the competitive tranche-base price will be equal to the maximum hourly price of the economic dispatch problem,

$$p^*_{\text{tranche}} = \max\{p_h\} \tag{37}$$

In this simple linear case, the bound (37) is telling us that the tranche competitive price is *always* the maximum of the benchmark prices over the period. Under mild conditions, similar bounds are illustrated in the numerical exercise of the next section for a more general cost function structure. This is just a consequence of the structural feature of the tranche-based product of providing a fixed-percentage of the load.

Certainly, these high prices are even more natural to happen once uncertainty is considered and additional risk premiums are expected. For example, as Fig. 1 illustrates, in the Illinois process all the products were above market prices more than 85% of the time. However, the riskier products were 90% or 97% of the time above market prices.

Table 1
5-generator system data.

	Suppliers				
Parameters	G1	G2	G3	G4	G5
a_i (\$/MW h)	0.03	0.66	1.66	5	3.33
b_i (\$/(MW h)^2]	0.03	0.16	0.66	1.33	3.33
$P_{\max,i}$ (MW)	400	300	200	100	50
$P_{\min,i}$ (MW)	0	0	0	0	0

3.3. Case B. Quadratic cost functions

We illustrate the type of bounds that could emerge in tranche-based markets using a simple 5-generator test system. Consider a time horizon of 168 h. Cost functions have the quadratic form $c_i(x) = a_i x + b_i x^2$ and the system data is shown in Table 1. A typical load pattern is considered over the time horizon of study. Using a price duration curve, a comparison of the optimal tranche-contract price and prices associated with the economic dispatch is shown in Fig. 2.

In this particular case, it is interesting to note, that the benchmark prices are about 87% of the time below the tranche competitive price. These results show that tranche product prices, even in the most idealized situation, could be above benchmark market prices for long time periods. Certainly, these bounds depends on the technology mix of generators and the load patterns. In terms of technology mix, the more homogenous the mix is, the closer the tranche product prices are to the average

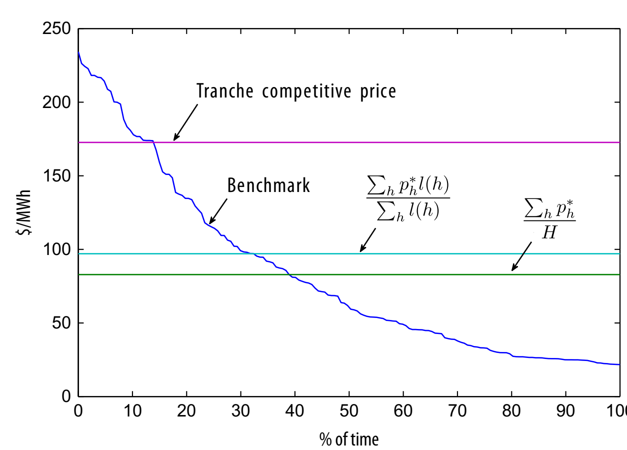

Fig. 2. Price duration curve.

benchmark prices. This is clearly visualized by thinking of the extreme case of having all suppliers with similar costs and a flat demand. With respect to the load pattern, higher tranche-based product prices are expected for more variable loads due to the structural flaw of providing a fixed percentage of the load. A product required to supply a fixed percentage of the load could result in situations in which the set of most expensive suppliers are required to provide energy even on the periods of extreme low load levels, e.g., base-load periods.

4. Final remarks

The results presented in this paper clearly illustrate the importance of defining appropriate products. We should highlight that this is just a starting point and our hope is that these results could increase the interest on this important topic. Finding a proper product is a highly challenging task by the many reasons explained in this paper. Moreover, the assessment of the ultimate level of appropriateness will be only possible once the market is implemented. However, it is clear that a careful analysis and research, aiming to make the market and the physical systems coexist by defining appropriate products, will increase the chances of positive outcomes—or at least will avoid potential bad outcomes.

The key conclusion of our results is that the definition of products must consider the attributes of the physical system and move beyond the notion of commoditized products. Moreover, for different jurisdictions the reality of the power system might also be taken into account. A system with high level of flexibility, resulting from large capacity of hydropower as in the Brazilian case, might behave in completely different way respect to a system with low flexibility. For example, usual products of electricity supply auctions based on blocks, as used in Brazil and Chile [16], must be appropriate for controllable technologies. In order to guide the appropriate technological mix, differentiate these blocks in terms of other attributes such as base, cycling or peaking units seems a proper element to consider in new designs. However, these products might not be proper to deal with generating units with volatile output. Appropriate products for those technologies must consider some uncertainty in their supply, hence interruptible contracts as defined by Tan and Varaiya [24] seems a good starting point to think about products for uncontrollable units. We are currently investigating these topics and our results will be presented to the academic community shortly.

5. Conclusions

In this paper, we study the impact of product definition in electricity markets. Using a product definition implemented in some US electricity markets, we reveal several consequences that an improper product definition can have in the market outcomes in terms of market efficiency, concentration, uncertainty allocation and clearing prices. We provide several economic reasons along with illustrative examples. Our findings provide guidelines about the desired attributes that an appropriate product should have. The key challenge is defining products that can effectively link the markets and their associated physical systems. Our results reinforce the importance of properly defining products in electricity markets and provide guidelines for future research.

Appendix A. Bounds of the centralized tranche problem

As shown in Section 3, the mathematical formulation of both the centralized tranche problem and the centralized economic dispatch for the peak hour are equivalent. This equivalency allows us establishing some relationships of both problems in terms of power allocation, total cost and competitive price. In this appendix, the proof of the main results are presented.

Proposition 1. *The optimal tranche-based allocation* α_i^* *are related to the dispatch of the peak hour* $\kappa_i^* = \frac{P_{i,h_{peak}}}{l_{\max}}$ *by,*

$$\alpha_i^* = \kappa_i^* = \frac{P^*_{i,h_{peak}}}{l_{\max}} \quad \forall i \tag{A.1}$$

Proof. It is straightforward to prove that the set of κ_i that solves (31) also is the optimal solution of the centralized tranche problem (12). Using the assumption that the cost functions $c_i(x)$ are monotonically increasing, we obtain

$$\begin{aligned}
&\sum_{i\in\mathcal{I}} c_i(\kappa_i^* l_{\max}) && \leqslant \sum_{i\in\mathcal{I}} c_i(\kappa_i l_{\max}) \quad \forall \kappa_i \\
\Rightarrow \quad & \sum_{i\in\mathcal{I}} \kappa_i^* l_{\max} && \leqslant \sum_{i\in\mathcal{I}} \kappa_i l_{\max} \quad \forall \kappa_i \\
\Rightarrow \quad & \kappa_i^* && \leqslant \kappa_i \quad \forall i,\ \kappa_i \\
\Rightarrow \quad & \kappa_i^* l(h) && \leqslant \kappa_i l(h) \quad \forall h, i, \kappa_i \\
\Rightarrow \quad & \sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i(\kappa_i^* l(h)) && \leqslant \sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i(\kappa_i l(h)); \quad \forall \kappa_i
\end{aligned} \tag{A.2}$$

consequently, κ_i^* is also a solution of (12). Hence, the centralized tranche allocation is just settled by the dispatch of the peak-hour. In other words,

$$\alpha_i^* = \kappa_i^* = \frac{P^*_{i,h_{peak}}}{l_{\max}} \quad \forall i \qquad \square \tag{A.3}$$

Proposition 2. *The total cost associated to the tranche-based products is lower bounded by the economic dispatch cost,*

$$\sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i({P^e_{i,h}}^*) \leqslant \sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i(\alpha_i^* l(h)) \tag{A.4}$$

Proof. Note that in the centralized tranche dispatch, the optimal power supplied by generator i at time h, $P^*_{i,h}$, is a fraction of its optimal power offered at the peak hour, $P^*_{i,h_{peak}}$. In other words,

$$P^*_{i,h} = \alpha_i^* l(h) = P^*_{i,hpeak} \frac{l(h)}{l_{max}} \tag{A.5}$$

Consider an inexpensive unit j which has to be used to its maximum power at any hour under an economic criterium. As shown before, the centralized tranche problem will assign $P^*_{j,hpeak} = P_{jmax}$ at the peak hour but it will also assign $P_{j,h} = P_{jmax}\frac{l(h)}{l_{max}}$ at any other hour. Therefore, as $P_{j,h} \neq P_{jmax}$ for the non-peak hours, we move away from the optimal solution of the dispatch problem. Therefore,

$$\sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i(\alpha_i^* l(h)) = \sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i\left(P^*_{i,h}\right) \geqslant \sum_{i\in\mathcal{I},h\in\mathcal{H}} c_i({P^e_{i,h}}^*) \qquad \square \tag{A.6}$$

Proposition 3. *The tranche price is upper bounded by the marginal price of the economic dispatch at the peak hour,*

$$p^*_{\text{tranche}} \leqslant p^*_{h_{peak}} \tag{A.7}$$

Proof. Consider that

$$\frac{\partial c_i(\alpha_i^* l(h))}{\partial P_i} \leqslant p^*_{h_{peak}}, \ \forall h \tag{A.8}$$

and therefore

$$\frac{\sum_{h\in\mathcal{H}} l(h)\frac{\partial c_i(\alpha_i l(h))}{\partial P_i}}{\sum_{h\in\mathcal{H}} l(h)} = p^*_{\text{tranche}} \leqslant \frac{\sum_{h\in\mathcal{H}} l(h)p^*_{h_{peak}}}{\sum_{h\in\mathcal{H}} l(h)} = p^*_{h_{peak}} \qquad \Box \tag{A.9}$$

Proposition 4. *The tranche price is lower bounded by the average of the hourly marginal price of the economic dispatch,*

$$\frac{\sum_{h\in\mathcal{H}} p^*_h}{H} < p^*_{\text{tranche}} \tag{A.10}$$

Proof. First of all, we establish a lower bound relating tranche prices with the economic dispatch ones,

$$\frac{\sum_{h\in\mathcal{H}} l(h)p^*_h}{\sum_{h\in\mathcal{H}} l(h)} < \frac{\sum_{h\in\mathcal{H}} l(h)\frac{\partial c_i(\alpha_i l(h))}{\partial P_i}}{\sum_{h\in\mathcal{H}} l(h)} \tag{A.11}$$

Consider that the marginal supplier of the tranche problem is the supplier i. For all h where $l(h) < l_{max}$ the supplier i will reduce its power by $\alpha_i[l_{max} - l(h)]$. Consequently, the power in hour h will be given, as expected, by

$$P^*_{i,h} = P^*_{i,h_{peak}} - \alpha^*_i[l_{max} - l(h)] = \alpha^*_i l(h) \tag{A.12}$$

In the economic dispatch context, the supplier i is the marginal supplier at the peak hour generating a power equal to $P^{e*}_{i,h_{peak}} = P^*_{i,h_{peak}} = \alpha^*_i l_{max}$. For any other hour h, two cases are possible:

- The supplier is still the marginal supplier. In this case, supplier i reduces its power by $l_{max} - l(h)$ at hour h and therefore $P^{e*}_{i,h} = P^*_{i,h_{peak}} - (l_{max} - l(h)) < P^*_{i,h_{peak}} - \alpha^*_i(l_{max} - l(h)) = P^*_{i,h} = \alpha^*_i l(h)$ $\forall h$. Considering that marginal cost functions are non-decreasing, then $p^*_h = \frac{\partial c_i(P^{e*}_{i,h})}{\partial P^e_i} < \frac{\partial c_i(\alpha^*_i l(h))}{\partial P_i}$ holds.
- The supplier is no longer providing power. In this case, as supplier i is ruled out, there must be a supplier j with a lower marginal cost than supplier i such that $p^*_h = \frac{\partial c_j(P^{e*}_{j,h})}{\partial P^e_j} < \frac{\partial c_i(\alpha^*_i l(h))}{\partial P_i}$ holds.

By using the previous result for all hours, it is clear that Eq. (A.11) is satisfied. In order to prove the original proposition, we focus on the following bound for the economic dispatch problem,

$$\frac{\sum_{h\in\mathcal{H}} p^*_h}{H} < \frac{\sum_{h\in\mathcal{H}} l(h)p^*_h}{\sum_{h\in\mathcal{H}} l(h)} \tag{A.13}$$

This relationship is easily proved by considering that marginal cost functions are non-decreasing with respect to the load levels. Both left and right side of expression (A.13) are of the form,

$$\sum_{h\in\mathcal{H}} \eta_h p^*_h \tag{A.14}$$

with $\sum_{h\in\mathcal{H}} \eta_h = 1$. In the left side the coefficients are given by $\kappa_h = \frac{1}{H}$, and in the right hand side by $\tau_h = \frac{l(h)}{\sum_{h\in\mathcal{H}} l(h)}$. If for a particular hour $h = i, \kappa_i \geqslant \tau_i$ then necessarily in order to respect the constraint $\sum_{h\in\mathcal{H}} \tau_h = 1, \kappa_j \leqslant \tau_j$ for any other hour $h = j \neq i$. Given that $\tau_j \geqslant \tau_i$, it is clear that $l(j) \geqslant l(i)$. By using the monotonicity of the marginal costs, it is obtained that $p^*_j \geqslant p^*_i$. Hence, hours with higher loads and higher prices are weighted more and then expression (A.13) follows. By combining (A.13) and (A.11) the original proposition is proved. $\Box$

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