Average incremental cost pricing in electricity auctions

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ABSTRACT

Wholesale electricity markets are typically organized as uniform-price auctions with non-convex bids. The main implication of these non-convexities is that they impede the existence of "market-clearing" prices. Stevens et al. (2024) analyse several pricing mechanisms that deal with this issue. Our paper extends these analyses to average incremental cost (AIC) pricing. The underlying idea of AIC pricing is to price at the "average incremental cost" in order to eliminate the need for discriminatory make-whole payments. We formalize this notion and study its consequences for market participants. We show that AIC pricing eliminates make-whole payments for suppliers with the possibility of inaction in a one-sided auction. Regarding the network, we show that AIC prices guarantee that there is no price arbitrage opportunity in the network. Inflating the price to eliminate make-whole payments can however worsen the incentives of market participants, thus creating the risk of exacerbating self-scheduling behaviour. Our analysis also provides a comparison of AIC pricing with marginal pricing, convex hull pricing and another approach that eliminates make-whole payments. Such a comparison is critical for correctly appreciating the relative merits and drawbacks of AIC pricing.

1. Introduction

Although marginal pricing has often been contemplated as the Holy Grail of economic theory, it is also very well known that there can be *optimal* departures from marginal cost pricing (Baumol and Bradford, 1970). A classic example is the case of public utility regulation. This situation involves a regulated firm, or the State, which sells a set of products while bearing some fixed costs that should be recovered from its revenues. Pricing at marginal cost, in this case, leads to a shortfall of revenue: the price must be *inflated* above marginal cost in order for the fixed cost to be recovered (leading to so-called Ramsey-Boiteux pricing). A related problem is analysed by Ronald Coase in *The marginal cost controversy* which studies a situation of increasing return to scale (Coase, 1946). The solution proposed by Coase relies on multi-part pricing: the marginal price is *complemented* with additional payments. Indivisible fixed costs as well as increasing returns to scale are typical examples of non-convexities in production processes. The two paramount solutions that we have just described to deal with these non-convexities involve either inflating the commodity price above marginal cost or complementing this uniform price with side payments.

Since the restructuring policies that led to the liberalization of power systems and to the existence of a market for power, wholesale electricity markets have typically been organised in a highly centralized fashion, relying on sealed-bid uniform-price auctions. Most of these auctions, in particular the one held in the day ahead in the US as well as in Europe, include non-convex bids. These bids enable market participants to express the fixed (non-convex) costs encountered in the operation of a power plant, such as start-up costs[1]. However, the main implication of these non-convexities is that they impede the existence of a uniform "market-clearing" price. As in the case of the aforementioned economic literature, marginal pricing in these auctions fails to support the efficient allocation of resources as the fixed costs are omitted from the price signal.

This issue has led to various heterogeneous practices implemented by electricity auctioneers, as well as to a number of possible solutions advocated in the scientific literature. The practical solutions that have been implemented in these auctions often involve a combination of both inflating the uniform price of energy above marginal cost, as well as complementing this price with discriminatory side payments. Stevens et al. (2024) recently covered a wide range of alternative electricity market pricing mechanisms in the presence of non-convexities. The main objective of this paper is to extend the analysis of Stevens et al. (2024) to Average Incremental Cost (AIC) pricing, which has been introduced in several recent articles (O'Neill et al., 2023; O'Neill and Chen, 2023; Chen et al., 2024).

AIC pricing aims at inflating the price to the "average incremental cost" in order to fully eliminate the need for side "make-whole" payments. Make-whole payments are often considered undesirable for they are discriminatory, non-transparent and they do not have spatial nor temporal resolution. Our paper aims at formalizing the AIC approach as well

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[1] By "fixed costs", we'll always mean the *avoidable* fixed costs, i.e. costs that can be avoided in the short-term operation of a power plant, as opposed to *sunk* fixed costs such as investment costs.

as understanding its economic consequences on the incentives of market participants. More specifically, the material of the paper is organised as follows. Section 2 introduces the auction model as well as the two useful concepts of "revenue shortfall" and "lost opportunity costs". For the most part, this repeats the model introduced by Stevens et al. (2024), although the section adds some novel discussions. Section 3 then introduces the average incremental cost pricing approach. We provide its formal definition and we derive its main property, namely that it eliminates the need for make-whole payments, which we briefly place in the perspective of alternative pricing approaches. In section 4, we then derive a set of theoretical properties of AIC pricing, which characterise how these prices affect suppliers, consumers and the network operator. One important result that we establish is that AIC prices guarantee locational price consistency: it ensures there are no arbitrage opportunities on the network. These properties are further illustrated by stylized examples and by simulations on realistic auction datasets, which also enables a comparison with alternative pricing schemes. Mixing both theory and numerical simulations enables us to understand what problems could or could not be encountered with AIC pricing, as well as getting a sense of the expected magnitudes of these problems in practical applications. An important observation is that inflating the uniform price so as to fully eliminate make-whole payments can also worsen the incentives of market participants to follow the cleared allocation, thereby creating the risk of exacerbating self-scheduling behaviour. Sections 3 and 4 constitute the core of the paper. Section 5 adds certain discussions about possible variants of AIC pricing and its sensitivity to modelling choices and implementation choices. Section 6 discusses the main findings and concludes.

2. The model

Let us consider the following electricity auction model:

$$z^* = \min_{c,q,x,f} \sum_{g \in \mathcal{G}} c_g \tag{1a}$$

$$\sum_{g \in \mathcal{G}_i} q_{g,t} - D_t^i = \sum_{\substack{l \in \\ from(i)}} f_{l,t} - \sum_{\substack{l \in \\ to(i)}} f_{l,t} \; \forall i \in \mathcal{N}, t \in \mathcal{T} \tag{1b}$$

$$(c, q, x)_g \in \mathcal{X}_g \;\; \forall g \in \mathcal{G} \tag{1c}$$

$$f \in \mathcal{F} \tag{1d}$$

The network constraints are represented with the convex set $\mathcal{F}$ with f standing for flow variables. The topology of the network is assumed to be fixed. There is an inelastic demand D_t^i in each node i of the network and each period t. Suppliers are modelled with decision variables (c, q, x) belonging to a production set $\mathcal{X}_g$. There could be both *convex suppliers* and *non-convex suppliers*: a convex supplier has a convex production set $\mathcal{X}_g$ ($\text{conv}(\mathcal{X}_g) = \mathcal{X}_g$) while a non-convex supplier has a non-convex production set $\mathcal{X}_g$. The non-convexities in the model are reflected by the integer variables x, which stand for all the binary variables of the suppliers. Variables q correspond to the energy output. Variables c reflect the supply cost defined within $\mathcal{X}_g$ (for instance, it could be $c_g = \sum_{t \in \mathcal{T}} (MC_g q_{g,t} + v_{g,t} SC_g)$ with MC_g and SC_g being the marginal and start-up costs and $v_{g,t} \subset x_g$ being the startup variables). Let us stress that we assume price-taking agents and truthful bidding.[2] Each supplier g is assumed to maximize its selfish profit function $\mathcal{P}_g(c, q, x, \pi) = \sum_{t \in \mathcal{T}} q_{g,t} \pi_{i(g),t} - c_g$, under market price π and over the production set $(c, q, x)_g \in \mathcal{X}_g$. The system operator is assumed to maximize the value of the network (the "congestion rent", cf. Papavasiliou (2024)) $\mathcal{P}_N(f, \pi) = \sum_{i \in \mathcal{N}, t \in \mathcal{T}} -\pi_{i,t} (\sum_{l \in from(i)} f_{l,t} - \sum_{l \in to(i)} f_{l,t})$, under market price π, and over the (convex) set of network constraints $f \in \mathcal{F}$.

As it is common in power auctions, the auctioneer solves problem (1), thus selecting the as-bid *efficient* allocation (c^*, q^*, x^*, f^*). Then, the auctioneer should announce a market price π. Because of the non-convexities in model (1), a competitive equilibrium is not guaranteed to exist: there may be no price π such that all the individual agents have the right incentives to implement the allocation that maximizes the market surplus.

Example 1. *Let us consider an hourly market with a convex supplier S_1 producing at maximum 30MW for 10€/MWh and a non-convex supplier S_2 producing either 0 or an output between 90MW and 100MW for 20€/MWh. S_2 also faces an avoidable fixed cost (or no-load cost) of 1000€. The demand is fully inelastic and is 110MW. These settings are illustrated in Figure 1. The optimal solution is to produce 90MW with supplier S_2 and 20MW with supplier S_1. The marginal cost price, at the optimal solution, is 10€/MWh: an additional MW of demand means increasing the production of S_1 by 1MW. However, this price ignores the fixed costs, thus S_2 does not break even. A solution to this problem is to price at the average cost of S_2:* 31.11*€/MWh. A concern with this price, however, is that both S_1 and S_2 would have an incentive to produce more than the cleared output. In fact, any price higher than 10€/MWh would incentivize S_1 to produce more than 20MW, while any price lower than 30€/MWh would incentivize S_2 to produce 0MW. Thus there is no equilibrium.*

Even though an equilibrium is not guaranteed to exist in model (1), as illustrated by Example 1, there are cases where an equilibrium exists in a non-convex market. The following proposition provides a *necessary and sufficient* condition for an equilibrium to exist[3].

Proposition 1 (Necessary and sufficient condition for an equilibrium to exist) *There exists a price π^E such that $(\pi^E, (c^*, q^*, x^*, f^*))$ is a competitive equilibrium in model* (1) if and only if (c^*, q^*, x^*, f^*) *is a solution to the convex*

[2]The costs and production constraints are assumed to be available through the bids of the participants. Questions of non-truthful bidding or asymmetry of information are out of the scope of this paper.

[3]This proposition transposes the main result of Bikhchandani and Mamer (1997) to the context of our model (1).

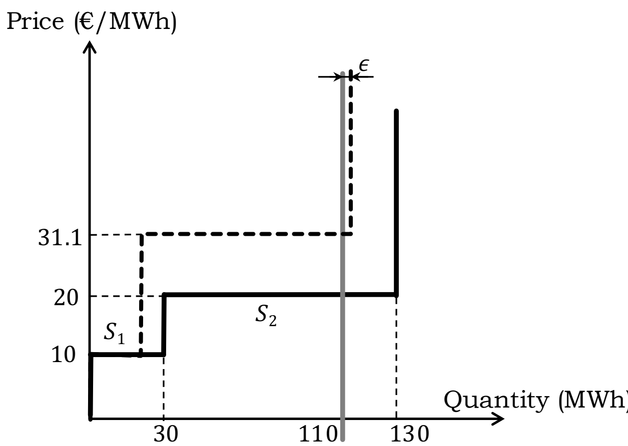


Figure 1: Aggregate marginal cost curve in Example 1.

relaxation of problem (1) in which $\mathcal{X}_g$ are replaced by conv($\mathcal{X}_g$)*, that is, if $z^* = z^*_{CH}$, where z^*_{CH} is the objective solution to this convex relaxation.*

The proof is in Appendix A, along with all the other proofs of the paper. In Example 1, the optimal allocation in the convex hull relaxation problem described in Proposition 1 is for S_1 and S_2 to produce respectively 30 and 80MW. This differs from the primal solution. Thus, as explained in Example 1, and following Proposition 1, there is no equilibrium. If the demand were 130MW instead of 110MW, then S_1 and S_2 would produce respectively at 30 and 100MW in both problems (1) and its convex hull relaxation. Thus, an equilibrium would exist: indeed, a price of $\pi = 30$€/MWh with this allocation would be an equilibrium.

This paper is mostly interested in the cases where the condition of Proposition 1 is not satisfied, thus where an equilibrium does not exist. Two paramount concepts that have been used to characterize how far a price-allocation pair $(\pi, (c^*, q^*, x^*, f^*))$ is from an equilibrium are those of revenue shortfall and lost opportunity costs (Stevens et al., 2024).

Definition 1 (Revenue Shortfall) *Revenue shortfall (RS) corresponds to the payments that are required in order to ensure a non-negative profit. It is defined for each supplier (eq. (2)), for the network (eq. (3)) and in total (eq. (4)).*

$$RS^{gen}_g(\pi) = -\min\left(0,\ \mathcal{P}_g(c^*, q^*, x^*, \pi)\right) \tag{2}$$

$$RS^{net}(\pi) = -\min\left(0,\ \mathcal{P}_N(f^*, \pi)\right) \tag{3}$$

$$RS(\pi) = \sum_{g\in\mathcal{G}} RS^{gen}_g(\pi) + RS^{net}(\pi) \tag{4}$$

Definition 2 (Lost Opportunity Cost) *Lost opportunity cost (LOC) is the difference between the maximum profit and the as-cleared profit under price π. It is defined hereafter for each supplier g (eq. (5)), for the network (eq. (6)) and in total (eq. (7)).*

$$LOC^{gen}_g(\pi) = \max_{\substack{(c,q,x)_g\\ \in\mathcal{X}_g}} \mathcal{P}_g(c, q, x, \pi) - \mathcal{P}_g(c^*, q^*, x^*, \pi) \tag{5}$$

$$LOC^{net}(\pi) = \max_{f\in\mathcal{F}} \mathcal{P}_N(f, \pi) - \mathcal{P}_N(f^*, \pi) \tag{6}$$

$$LOC(\pi) = \sum_{g\in\mathcal{G}} LOC^{gen}_g(\pi) + LOC^{net}(\pi) \tag{7}$$

These two concepts are closely interrelated. In particular, the revenue shortfall should be viewed as a specific type of lost opportunity cost, where the lost opportunity is to exit the market, thus to self-schedule at 0.[4] In a convex economy where agents have the possibility of inaction, there would be a market equilibrium such that both the RS and the LOC are null. While in example 1, S_2 bears a RS (=LOC) of 1900€ at the marginal cost price and S_1 (resp. S_2) bears a LOC of 211€ (resp. 111€) at 31.11€/MWh, the average incremental cost price.

Concretely, revenue shortfall and lost opportunity cost relate to two important concerns in power auctions with non-convexities: make-whole payments and self-scheduling, respectively. Revenue shortfall measures whether the price enable the cleared bids to recover their costs. If it does not, the auctioneer would normally pay discriminatory make-whole payments to the market participants that are unprofitable in order for them to break even. Lost opportunity costs measure whether, given the market price, the market participants have incentives to self-schedule their production in a way that deviates from the cleared allocation—it measures whether the prices "support the cleared allocation". Significant lost opportunity costs would incentivise suppliers to self-schedule, creating the risk for the cleared schedule to unravel.[5]

Some caveats are required regarding lost opportunity costs. An LOC of, say, 10,000€ does not imply that the market participant could realize this lost opportunity in a straightforward way. The timing of the market normally involves three main steps: (i) market participants submit bids, (ii) the auctioneer computes the as-bid surplus-maximizing allocation as well as the uniform price, (iii) the settlement takes place (based on the cleared bids, the market price and other side payments which are calculated by the auctioneer). If, after step (iii), market participants face a LOC, there is no way for them to change their settlement in this market.

[4] In fact, a distinction should be made between the revenue shortfall that corresponds to a lost opportunity and the revenue shortfall that does not, for instance when there is a barrier to exit. We nevertheless omit these subtleties here: the revenue shortfall that we discuss and measure in our numerical results always correspond to a revenue shortfall which is also a lost opportunity. We refer the reader to Stevens et al. (2024) for a detailed discussion on this matter.

[5] Past electricity market experiences have shown the problem of implementing market rules that are not incentive compatible. As Hogan (2002b) puts it: "The move to greater reliance on markets rests on a belief that market participants will respond to incentives. Markets with poorly designed institutions have provided the wrong incentives, and market participants have responded." Hogan (2002b) particularly analyses the perverse incentives created by a price signal that misrepresents transmission constraints. An example is the early market design of PJM. The market participants quickly figured out the profit they could earn by self-scheduling, which led to the collapse of the cleared dispatch. Although the case analysed by Hogan (2002b) is different than the subject matter of our article, it starkly illustrates the importance of taking the incentives of market participants into account when designing pricing policies.

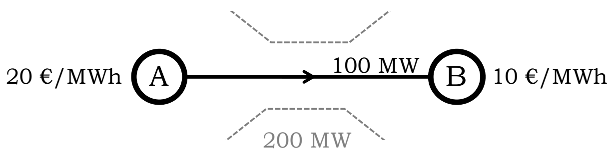


Figure 2: Network LOC illustration.

However, market participants could anticipate their LOC and submit "self-schedule" bids in step (i) of the market: some "must run" quantities bid at the floor price of the auction. Byers and Eldridge (2023) show that in presence of high LOC, market participants can indeed identify profitable self-scheduling opportunities using a basic reinforcement learning algorithm. Thus, although there is no straightforward mapping between LOC and self-scheduling, a high LOC should be understood as an indicator that the pricing rule is *vulnerable to self-scheduling*.

Let us clarify two additional points. First, we take no particular stance on whether the LOC should translate into effective side payments from the auctioneer to the market participants. Nonetheless, when computing the consumers' expenditure in section 4, we assume that the auctioneer only pays make-whole payments (thus only refunds the RS). Second, since the notion of network LOC has occasionally been challenged, it is worth clarifying it and highlighting the importance of this concept. The network LOC formalizes the notion of arbitrage opportunities in the usage of the network resource.[6]

Example 2 (Network LOC) *Let us consider a radial two-node network as illustrated in Figure 2. The line has a capacity of 200 MW. Let us assume an hourly market in which the surplus-maximizing allocation is such that 100 MW flows from node A to node B. Let us consider a hypothetical pricing scheme that would output the following prices: 20€/MWh in node A and 10€/MWh in node B. In this case, there is a price difference between the two nodes while the line is not congested. Furthermore, the power flows from the most expensive node to the least expensive node. This could arguably be contemplated as an undesirable situation, as these prices create certain arbitrage opportunities. Indeed, given these prices, the usage of the grid resource that would maximize its value is to export 200 MW from B to A. The network LOC (eq. (6)), formalizes and quantifies these arbitrage opportunities. In this example:*

$$\begin{aligned} LOC^{net} &= \overbrace{200 \times (20 - 10)}^{\textit{network max value}} - \overbrace{100 \times (10 - 20)}^{\textit{network as-cleared value}} \\ &= 2000 + 1000 = 3000€ \end{aligned}$$

The network LOC thus characterises whether the network flows and the locational prices are "consistent" with one another.

[6] cf. the "no arbitrage condition" as called by Hogan (2002a).

3. AIC pricing

This section introduces Average Incremental Cost (AIC) prices. We start with its formal definition as well as the exposition of a useful Lemma. We then discuss its interpretation with an example before deriving the main property of this pricing mechanism.

Definition 3 (Average Incremental Cost Pricing) *The average incremental cost (AIC) prices are the dual variables π^{AIC} associated to the market clearing constraints of the following problem:*

$$z^{AIC} = \min_{c,q,x,f} \sum_{g \in \mathcal{G}} c_g \tag{8a}$$

$$(\pi^{AIC}) \sum_{g \in \mathcal{G}_i} q_{g,t} - D_t^i = \sum_{\substack{l \in \\ from(i)}} f_{l,t} - \sum_{\substack{l \in \\ to(i)}} f_{l,t} \; \forall i \in \mathcal{N}, t \in \mathcal{T} \tag{8b}$$

$$(c, q, x)_g \in \mathcal{X}_g^{AIC} \quad \forall g \in \mathcal{G} \tag{8c}$$

$$f \in \mathcal{F} \tag{8d}$$

where $\mathcal{X}_g^{AIC}$ is a convex set obtained from $\mathcal{X}_g$ in which each binary variables x_j are relaxed to the continuous interval $0 \le x_j \le x_j^*$, where x_j^* is a parameter corresponding to the optimal solution of problem (1); and in which the production is constrained as follows: $0 \le q_j \le u_j q_j^* + \epsilon$ where u_j are the commitment (on/off) variables ($u_j \subset x_j$).

$\mathcal{X}_g^{AIC}$ is obtained by first relaxing the set $\mathcal{X}_g$ as we consider the LP relaxation of the binary variables, and then restricting the set $\mathcal{X}_g$, as $x \le x^*$ and $q_j \le u_j q_j^* + \epsilon$. Definition 3 and the theory of AIC pricing developed below apply generally to model (1). However, there is one restriction:

Assumption 1. *We assume the model of $\mathcal{X}_g$ is such that $\mathbf{0} \in \mathcal{X}_g$ means "inaction" (no production) and if $\mathbf{0} \in \mathcal{X}_g$ then $\mathbf{0} \in \mathcal{X}_g^{AIC}$.*

The assumption is trivially satisfied for most common models of production $\mathcal{X}_g$. It is however possible to define a model that would violate this assumption.[7] Thus this assumption is made to discard these cases.

Lemma 1 (Pricing dispatch with inelastic load) *With inelastic load, the dispatch and commitment decisions of the suppliers, as well as the flows on the network, computed in the pricing problem (8) are the same as in the primal problem (1), thus $z^* = z^{AIC}$.*

This important observation follows from the fact that, since no unit can produce more in $\mathcal{X}_g^{AIC}$ than in $\mathcal{X}_g$, and since the demand must be met anyway, the dispatch and commitment variables are the same in problems (8) and (1), thus $z^{AIC} =$

[7] For example, with a model including a "non-commitment" variable $y_j \subset x_j$, which equals 1/0 when the supplier is off/on-line, having $0 \le y_j \le y_j^*$ could result into $\mathbf{0} \notin \mathcal{X}_g^{AIC}$. Another case involves initial conditions, which is further discussed on section 5.

z^*. (This property is akin to marginal pricing, where it is also ensured that $z^{MP} = z^*$.) This Lemma also highlights the importance of the constraints $0 \leq q_j \leq u_j q_j^* + \epsilon$ in the AIC pricing Definition 3. Without these constraints, the previous Lemma would not hold, as illustrated in the following example.

Example 3 (Inelastic load with AIC pricing) *Let us consider one more time the settings of example 1. The AIC price is $\pi^{AIC} = 31.11$€/MWh, which reflects the average cost of S_2 at the optimal dispatch. Let us highlight two things: the importance of the constraints on q and u in Definition 3, and the role of the parameter ϵ. If the pricing problem were to include only a constraint on the binary variables (here, $0 \leq u_{S1} \leq 1$), the optimal dispatch in the pricing problem would be to produce 30MW and 80MW with suppliers S_1 and S_2 respectively, which differs from the primal solution. Thus, the output q should be constrained both for convex and non-convex suppliers in Definition 3 for Lemma 1 to hold. Furthermore, without the constraint $q_{S1} \leq u_{S1} q_{S1}^*$, the solution in the pricing problem would be $u_{S1} = 0.9$, which differs from the primal solution, thus violating Lemma 1, and would lead to $\pi^{AIC} = 30$€/MWh. Finally, as far as the parameter ϵ is concerned, without the parameter ϵ, the price in Figure 1 would be $\pi^{AIC} = [31.11, +\infty)$. The parameter ϵ thus resolves the indeterminacy and forces $\pi^{AIC} = 31.11$. We will mostly ignore the parameter ϵ in the analysis of section 4 and delay the analysis of the sensitivity of the AIC price to the choice of the parameter ϵ to section 5.*

As illustrated by Example 3, the AIC price reflects the average cost of the most expensive online unit at its optimal schedule. As a consequence, the revenue shortfall is null. This property holds more generally, as established by the following proposition.

Proposition 2 (AIC) *AIC prices ensure zero revenue shortfall for all the suppliers who have possibility of inaction: $RS_g^{gen}(\pi^{AIC}) = 0 \; \forall g \in \mathcal{G} \mid \mathbf{0} \in \mathcal{X}_g$.*

The proof crucially depends on three main results: the convexity of problem (8), Lemma 1 ($z^* = z^{AIC}$) and Assumption 1 (i.e. the possibility of inaction implies $\mathbf{0} \in \mathcal{X}_g^{AIC}$). Intuitively, since the AIC price reflects the highest average cost of the suppliers *at their optimal dispatch*, it guarantees that they at least break even. This is the cornerstone property of AIC pricing: it eliminates the need for "make-whole payments".

With proposition 2 being established, it is fruitful to think about AIC pricing in contrast to some of its "competitors". In particular, we shall later compare it, in the numerical simulations of section 4, to three alternative pricing approaches: marginal pricing (MP), convex hull pricing (CHP) and minimal make-whole payments (MMWP**) pricing.[8]

[8] We refer the reader to Stevens et al. (2024) for a detailed discussion and a formal presentation of these three pricing schemes. Since Stevens et al. (2024) analyse three different MMWP schemes (called MMWP, MMWP* and MMWP** in Stevens et al. (2024)), we keep the acronym "MMWP**" here to ease the comparison with Stevens et al. (2024).

Marginal pricing sets the price at the marginal cost, ignoring the fixed (non-convex) costs which are thus not reflected in the price signal. This leads to higher revenue shortfall: the marginal price has to be complemented by discriminatory make-whole payments in order for some suppliers to break even. While AIC pricing focuses to a certain extent on revenue shortfalls, aiming at eliminating make-whole payments, convex hull pricing rather focuses on lost opportunity costs. Convex hull prices are indeed the prices that minimize the LOC. Finally, like AIC pricing, several pricing methods have been proposed in the literature in order to minimise the revenue shortfall. MMWP** is one of them.

4. AIC pricing properties

This section analyses how AIC pricing affects the magnitude of the LOC and the RS of the different market participants: the suppliers without a possibility of inaction, the convex suppliers and the network. We first provide a theoretical analysis and establish several key properties. We then conduct a numerical analysis. This numerical analysis has two main objectives. Fist, it illustrates the theoretical properties and it provides to the reader a sense of the order of magnitude that concerns the key metrics that our work focuses on. Second, it also enables a comparison between AIC pricing and certain alternative pricing schemes.

Proposition 3 (Suppliers without a possibility of inaction) *A supplier without a possibility of inaction ($\mathbf{0} \notin \mathcal{X}_g$) could bear a revenue shortfall when facing AIC prices.*

Example 4 (Possibility of inaction) *Let us consider the same settings as in Example 1, except that there is a must-run constraint (for example, due to some initial conditions or constraints) on supplier S_2 such that $u_{S2} = 1$. Then, applying Definition 3, $\pi^{AIC} = 20$€/MWh and S_2 faces a revenue shortfall of 1000€. Intuitively, the possibility of inaction implies that certain costs are sunk and are thus not reflected in the price signal.*

Cases of impossibility of inaction typically result from constraints carried over from previous market sessions that prevent a supplier from disconnecting. Of course, this property could be corrected by changing the Definition 3 of AIC pricing such that $\mathbf{0} \in \mathcal{X}_g^{AIC}$ (concretely, in Example 4, this means removing the must-run constraint in the pricing run). This would lead to a variant of AIC pricing, which departs from Definition 3. Some possible variations of AIC pricing will later be discussed in section 5.

Proposition 4 (Network) *AIC prices ensure zero LOC for the network. If $\mathbf{0} \in \mathcal{F}$ (i.e. $f = 0$ is feasible), this also implies zero RS for the network.*

This proposition establishes the important property that, under AIC pricing, the prices are "locationally consistent", i.e., there are no arbitrage opportunities in the network. Concretely, with AIC pricing, a situation such as the one illustrated in Example 2 could not occur. This property is shared by marginal pricing, which also ensures locational price consistency. This is in contrast with CHP, which does not obey this property in general (Stevens et al., 2024), that turns out to be an important issue in policy discussions in Europe (SDAC, 2023) and in the US (Schiro et al., 2015).

Proposition 5 (Convex suppliers) *AIC prices do* not *guarantee zero LOC for convex suppliers.*

This property is different from marginal pricing, which ensures zero LOC for convex market participants (Stevens et al., 2024). In Example 1, the marginal price equals 10€/MWh, thus the convex supplier S_1 does not bear any LOC. Instead, under AIC pricing, supplier S_1 has an LOC of 211€. Intuitively, two cases occur with AIC pricing. Either a convex unit sets the price, thus the AIC price is the same as the marginal price ($\pi^{AIC} = \pi^{MP}$) and the convex suppliers bear no LOC. Or a non-convex unit sets the price, which implies that the price differs from the marginal price ($\pi^{AIC} \neq \pi^{MP}$). In the latter case, some convex supplier may bear some LOC, as demonstrated in Proposition 5 and observed in Example 1.

Let us illustrate these propositions with numerical simulations. We use the same datasets as in Stevens et al. (2024). The first dataset, later called "FERC dataset", includes almost 1000 power units but does not include a network. The second dataset, later called "CWE dataset", includes a network of 30 bidding zones and 74 power units. Both datasets are used as input to a unit commitment model that includes start-up costs, minimum up and down time constraints, ramp constraints, etc.

Table 1 reports the results of the FERC data set. The table includes the results of AIC pricing (last column) as well as three other pricing methods analysed in Stevens et al. (2024) and briefly introduced in section 3. In the FERC dataset, all suppliers have the possibility of inaction. Thus, as foreseen by Proposition 2, we observe in Table 1 that all the suppliers bear zero revenue shortfall under AIC prices. Mitigating revenue shortfall, however, comes at the cost of increasing the LOC, which is higher under AIC pricing than under marginal pricing or CHP. We further observe that, as anticipated from Proposition 5, both convex and non-convex suppliers bear some LOC under AIC pricing. This is consistent with the analysis of Stevens et al. (2024), and it highlights that aiming for *zero* RS for the suppliers may in turn exacerbate the LOC. On the contrary, as pointed out in Stevens et al. (2024), aiming at minimizing the LOC, as CHP does, does not exacerbate the RS. This important asymmetry follows from the fact that the RS is a particular type of LOC.

Let us turn to the results of the CWE dataset, reported in Table 2. As we observe, introducing network constraints and a locational price signal makes the market more fragmented which enhances the differences between the pricing approaches. There are four main observations that we wish to highlight. Firstly, as noted on the FERC dataset, we observe that AIC pricing tends to exacerbate the LOC with respect to other pricing approaches. This is due to the fact that AIC pricing also leads to a higher price (on average 11% higher than marginal pricing on the CWE dataset), which increases the lost opportunities of some suppliers. Figure 3 also reports the distribution of the LOC among suppliers with a non-zero LOC. This figure should be read as the individual incentives to self-schedule implied by these three pricing schemes. As discussed in section 2, an LOC borne by a supplier does not mean that this supplier could straightforwardly realise this "opportunity"—but it is a threat of self-scheduling. Small

Table 1
Results of the FERC dataset (average over 11 scenarios).[a,b]

		MP	CHP	MMWP**	AIC
Dispatch Cost		29,780,000			
Av. Price		28.8	28.7	28.9	29
Suppl. with LOC		3.4%	1.8%	9.5%	6.8%
Av. LOC per Suppl.		628	19	94	570
Δ Consumer Surplus		0%	0%	−0.3%	−0.7%
LOC	Tot.	37,576	323	14,217	48,029
	Conv.	0	67	79	38
	Non-Conv.	37,576	257	14,137	47,991
RS	Tot.	669	19	0	0
	Conv.	0	0	0	0
	Non-Conv.	669	19	0	0

[a]All figures are in US$. Av. Price is the average uniform price without side payments. The lost opportunity costs (LOC) and the revenue shortfall (RS) are reported for the convex (Conv.) and non-convex (Non-Conv.) suppliers as well as in total (Tot.). Detailed results per load scenario in Table C.3.
[b]For AIC pricing, we use $\epsilon = 0.001$. For the specific instance `2015-09-01_lw`, another $\epsilon^*(= 0.0001)$ has been added to the binary variable relaxation in order to solve infeasibility. In all cases, the shutdown variables w relaxation follows "Option A*", cf. section 5.3.

Table 2
Results of the CWE dataset (average over 11 scenarios).[a,b]

		MP	CHP	MMWP**	AIC
Dispatch Cost		5,489,000			
Av. Price		42.4	43.4	52.6	47.2
Suppl. with LOC		35.1%	38.1%	64.2%	52.1%
Av. LOC per Suppl.		3,620	268	26,975	4,244
Δ Consumer Surplus		0%	−1.8%	−17.1%	−13.1%
LOC	Tot.	92,975	8,353	20,765,110	161,312
	Net.	0	1,267	19,513,628	0
	Suppl.	92,975	7,086	1,251,482	161,312
RS	Tot.	13,224	1,887	0	2,087
	Net.	0	0	0	0
	Suppl.	13,224	1,887	0	2,087
	Suppl. PI.	7,286	1,028	0	0
	Suppl. II.	5,937	859	0	2,087

[a]All figures are in €. Av. Price is the average uniform price without side payments. The lost opportunity costs (LOC) and the revenue shortfall (RS) are reported for the network (Net.), the suppliers (Suppl.) as well as in total (Tot.). The results of the suppliers are further split between suppliers having he possibility of inaction (Suppl. PI.) and the ones who do not (Suppl. II.). Detailed results per load scenario in Table C.4.
[b]For AIC pricing, the simulations use $\epsilon = 0.001$. In all cases, the shutdown variables w relaxation follows "Option A*", cf. section 5.3.

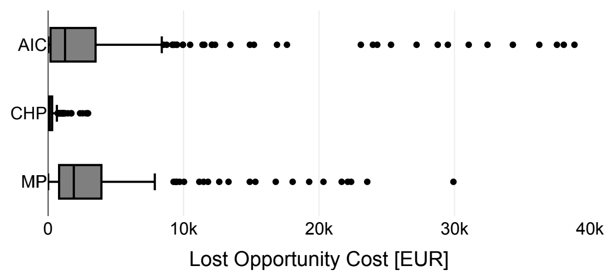


Figure 3: Distribution of LOC among suppliers (CWE cases).

LOC is less of a concern, since market participants are less likely to take the risk to self-schedule for a limited payoff. Instead, high LOC corresponds to more credible threats of self-scheduling. Figure 3 demonstrates that, while CHP leads to a distribution of LOC that eliminates the higher threats of self-scheduling, both marginal pricing and AIC pricing come with a number of market participants who have incentives of 10,000€ or more in a market session to self-schedule.

Second, the price magnitude not only impacts the incentives of suppliers, but also affects the total expenditure of consumers. Both tables 1 and 2 report the impact of the pricing outcome on consumer surplus. This is computed as follows. Since consumers are fully inelastic, a reference point is needed to compare the surplus, which is mathematically infinite. Marginal pricing is chosen as the reference. We thus compute the total consumer expenditure under marginal pricing (let us call it E^{MP}). This includes expenditure from consumption paid at the uniform price ($p^T D$) plus the make-whole payments (RS). We then compute the expenditure for each pricing method, using the same approach (i.e. E^{CHP}, E^{MMWP} and E^{AIC}). Finally, we compute the relative difference between marginal pricing and each of the pricing methods (e.g. $(E^{MP} - E^{CHP})/E^{MP}$), which is the figure reported in Tables 3 and 4. To be clear: a positive number means that the pricing approach leads to a higher surplus for consumers than marginal pricing. On the FERC dataset, consumer surplus is hardly affected by the choice of pricing scheme. On the CWE dataset, the effect remains limited for CHP (-1.8%) while it is more pronounced for MMWP** and AIC pricing. Although AIC pricing eliminates the need for make-whole payments, thus reducing this part of the expenditure of consumers, it does so by means of increasing the uniform price of energy. This, in turn, increases consumer expenditure. The figure shows that this second effect is clearly dominant, as AIC pricing overall leads to an increase of 13.1% of consumers' expenditure. We nevertheless stress that this analysis is only limited to the *short-term* surplus of consumers: as our model does not include investment decisions, it does not say anything about the *long-term* surplus of consumers under the various pricing approaches.

Third, unlike the FERC dataset, the CWE dataset includes suppliers who do not have the possibility of inaction. As foreseen from Proposition 2 and 3, we observe in Table 2 that AIC pricing eliminates revenue shortfall for suppliers *with a possibility of inaction*, while the other suppliers bear some revenue shortfall (cf. row "Suppl. II.").

The fourth noteworthy observation regards the network. As expected from Proposition 4, we observe in Table 2 that AIC pricing leads to zero LOC for the network. This is significantly different from the "minimal make-whole payment" schemes analysed in Stevens et al. (2024) and in particular the MMWP** reported in Table 2. This approach is similar to AIC pricing in the sense that it aims at minimizing revenue shortfall, as opposed to CHP which aims at minimizing the LOC. However, the MMWP approach fails to treat the network properly and therefore leads to extravagant LOC in presence of a network, i.e. significant arbitrage opportunities in the network. AIC pricing overcomes this issue. This locational price consistency is certainly an important advantage of AIC pricing.

5. AIC pricing implementation and its variants

5.1. Formulation dependence

An important caveat to the results of sections 3 and 4 is that AIC pricing is formulation-*dependent*—unlike marginal pricing or convex hull pricing, which are formulation-*independent*.

Proposition 6 (Formulation dependence) *AIC prices are formulation-dependent. Let $\mathcal{X}_g \subset \mathbb{R}^n \times \mathbb{B}^m$, with $\mathbb{B} = \{0, 1\}$, and let P_1 and P_2 be two extended formulations of $\mathcal{X}_g$: $\mathcal{X}_g = proj_{n\times m} P_1 = proj_{n\times m} P_2$, with $P_1 \neq P_2$. Then π^{AIC} is not guaranteed to be the same under P_1 and P_2.*

The proof, in Appendix A, provides an example with the classic *1-bin* and *3-bin* formulations of the unit commitment problem (Knueven et al., 2020). Intuitively, in a multi-period setting, there are several ways of allocating the fixed costs across the periods while satisfying Propositions 2–5. Different formulations (P_1 and P_2) can lead to different ways of reflecting the fixed costs in the price signal, thus differences in terms of price magnitude, consumer surplus, LOC, etc.

In this section we discuss some variants of AIC pricing. Our objective is not to be exhaustive—we rather highlight some important tradeoffs and choices that a modeller might want to consider when implementing AIC pricing. More specifically, we discuss four main topics. We first study the treatment of initial conditions and different ways of relaxing the shut-down variables, as well as their economic interpretation. Then, we discuss the numerical sensitivity of AIC pricing with respect to the choice of ϵ. Lastly, we look at one choice that arises when considering a two-sided auction.

5.2. Initial conditions

In US electricity auctions, model (1) typically corresponds to a unit commitment model. In the classical "3-bin" formulation, the binary variables x include three main sets of variables: commitment (on/off) variables (u), start-up variables (v) and shut-down (w) variables (cf. Knueven et al. (2020) and cf. appendix B which includes an elementary version of a 3-bin unit commitment model), thus $x = (u, v, w)$. Unit commitment models also normally include initial conditions (a unit is initially on-line or off-line). Applying Definition 3, it is natural to relax the shut-down variables w as follows:

- (Option A) $0 \le w \le w^*$

One subtle issue, however, is that in case problem (1) involves initial conditions, using this relaxation may imply that some suppliers with $\mathbf{0} \in \mathcal{X}_g$ have $\mathbf{0} \notin \mathcal{X}_g^{AIC}$, thus violating Assumption 1, with the consequence that these suppliers could bear a positive revenue shortfall (cf. Proposition 3). This is arguably problematic since the key property of AIC pricing is to make sure the market participants have a non-negative profit. The following example illustrates this issue.[9]

Example 5 (Shut-down variable relaxation) *Let us consider the settings of Example 1 with one subtle addition: supplier S_2 now has an initial condition $u^0_{S_2} = 1$ (i.e. S_2 is initially online). From Example 1, the optimal solution is to keep S_2 online such that $w_{S_2} = 0$, $u_{S_2} = 1$ and $q_{S_2} = 90MW$. In the pricing problem, with $0 \le w \le w^* = 0$, then the logical temporal constraint, linking variables w and u (cf. eq. (B.6e) in the appendix), implies that $u_{S_2} = 1$. Then variable u_{S_2} can be eliminated and the no-load cost appears as if it were a sunk cost—while it is not. Thus $\pi^{AIC} = 20$€/MWh and S_2 does not break even.*

A way to fix this problem is the following:

- (Option A*) $0 \le w_{g,t} \le w^*_{g,t}$ $\forall t > 1$ and $0 \le w_{g,t} \le 1$ for $t = 1$.

In Example 5, with $0 \le w \le 1$, this results in $\pi^{AIC} = 31.11$€/MWh, thus S_2 breaks even. Option A* is what has been implemented in our main simulations reported in Tables 1 and 2.

5.3. Average cost pricing *at each hour* or *over a production cycle*

Another natural way of relaxing the shut-down variables w is the following:

- (Option B) $0 \le w \le 1$

Although this slightly departs from Definition 3, Lemma 1 and Propositions 2 to 5 hold with this formulation. Thus options A* and B should be viewed as two variants of AIC pricing. At first glance, the choice between them seems very innocent. However, our simulation demonstrates that it is not: the pricing results vary significantly between these two options. This is illustrated in Tables 3 (FERC dataset) and 4 (CWE dataset) that report the results of Options A, A* and B. Compared to Option A*, Option B leads to a dramatic increase of the AIC price (more than 50% higher, in the CWE datasets) and the associated LOC (more than thirty times higher, in the CWE datasets).

[9] Note that, in our simulations, this issue occurs once: the 15€ in Table 4, row "Suppl. PI.", column AIC Option A.

Table 3
Results of three AIC options over 11 scenarios on the FERC dataset. (Monetary units are US$)

		AIC Options:		
	MP	B	A	A*
Av. Price in $/MWh	28.8	30.1	29	29
Suppl. with LOC	3.4%	21.4%	7.0%	6.8%
Av. LOC/Suppl. in $	628	1,657	543	570
LOC (Tot.) in $	37,576	438,350	48,342	48,029
RS (Tot.) in $	669	0	0	0

Table 4
Results of three AIC options over 11 scenarios on the CWE dataset. (Monetary units are in €)

			AIC Options:		
		MP	B	A	A*
Av. Price in €/MWh		42.4	82.3	54.4	47.2
Suppl. with LOC		35.1%	82.7%	57.4%	52.1%
Av. LOC/Suppl. in €		3,620	92,126	7,850	4,244
LOC in €	Tot.	92,975	5,600,868	333,448	161,312
	Net.	0	0	0	0
	Suppl.	92,975	5,600,868	333,448	161,312
RS in €	Tot.	13,224	88,176	4,828	2,087
	Net.	0	0	0	0
	Suppl. PI.	7,286	0	15	0
	Suppl. II.	5,937	88,176	4,813	2,087

Options A* and B mainly differ in the way they treat the "avoidable fixed costs" (or "no-load costs", cf. NC_g in Appendix B). Roughly put, Options B or A* correspond respectively to having the avoidable fixed costs which are reflected *at each and every hour*, or *over the production cycle*. The intuition is the following:

- $w_{g,t} \le 1$ leads to a price such that each period reflects the average cost of the most expensive online unit. Intuitively, if a plant is online from $t = ts$ to $t = td$, then, in the pricing problem, the plant would have the opportunity to turn off at each hour between ts and td. Thus, the price would reflect the marginal cost and the avoidable fixed costs at each hour. This typically leads to a higher price (higher than what is needed for the agents to break even).

- $w_{g,t} \le w^*_{g,t}$ leads to a price that reflects the average cost *over the entire horizon*. Intuitively this relaxation implies that $w^*_t = 0$ for $t = ts$ to $t = td - 1$. Thus, if a plant is turned on at $t = ts$ in the pricing problem, it can only be turned off at $t = td$, at the end of its "production cycle". The "avoidable fixed costs" are thus not avoidable at each hour, but over the production cycle. In fact, the overall avoidable fixed

Table 5
Sensitivity of AIC results to ϵ-perturbation on both the FERC dataset (`2015-12-01_hw`) and CWE dataset (`SpringWE-24`).

ϵ	w relaxation	FERC dataset z^{AIC} [$]	LOC [$]	RS [$]	$\overline{\pi^{AIC}}$ [$/MWh]	CWE dataset z^{AIC} [€]	LOC [€]	RS [€]	$\overline{\pi^{AIC}}$ [€/MWh]
0.0001	Option A*	17,360,970	3083	0	24.06	4,676,650	128,041	1638	42.40
0.001	Option A*	17,360,970	2978	0	24.06	4,676,639	128,030	1638	42.40
0.01	Option A*	17,360,967	2977	0	24.06	4,676,536	128,023	1638	42.40
0.1	Option A*	17,360,932	3078	0	24.06	4,675,510	123,616	1701	42.05
1	Option A*	17,360,612	2858	0	24.06	4,666,193	106,999 (327)	775	37.81
0.0001	Option B	17,360,970	47,034	0	24.09	4,676,646	5,026,761	87,997	81.25
0.001	Option B	17,360,970	47,034	0	24.09	4,676,611	5,025,595	87,985	81.24
0.01	Option B	17,360,965	47,037	0	24.09	4,676,256	5,014,096	87,866	81.20
0.1	Option B	17,360,913	47,035	0	24.09	4,672,751	4,816,059	85,902	80.41

costs are allocated to the peak-demand hour of the production cycle.

Appendix B provides an illustration of these two formulations and develops a formal argument based on optimality conditions. Let us finally notice that there is no straightforward relationship between the tightness of $\mathcal{X}_g^{AIC}$ (i.e. Option A* adds some valid optimality cuts, and is thus tighter than B) and the lost opportunity costs. In our simulations, Option B clearly leads to higher LOC (cf. Table 4). While in the example of Appendix B, the LOC is smaller with Option B than with Option A*. Thus Option A* does not necessarily outperform Option B in terms of LOC, although it is a clear trend in our simulations.

5.4. Numerical sensitivity

The preceding discussion suggests that AIC prices can be sensitive to some modelling choices. In this last part, we briefly comment on the sensitivity with respect to numerical choices. Because problem (8) is at the edge of infeasibility an "ϵ-perturbation" is introduced on the possible output of suppliers (cf. Definition 3 ; see also (O'Neill et al., 2023)).

Table 5 reports the sensitivity of the AIC results with respect to the ϵ-perturbation for one instance from both FERC and CWE datasets. Let us first analyze the FERC instance. As a point of comparison, on this FERC instance, the average MP is 23.77€/MWh, MP LOC is 447€, and MP RS is 26€. The total cost is 17,360,970€. We observe in Table 5 that for $\epsilon \leq 0.001$, it holds that $z^* = z^{AIC}$: the primal and AIC pricing dispatches are the same, as expected from Lemma 1. When increasing the value of ϵ, the dispatch of the pricing program slightly and monotonically deviates from the primal dispatch. Overall, the results are not significantly sensitive to the choice of ϵ: even an extreme choice of $\epsilon = 1.0$ does not affect the pricing outcome significantly. In particular, on this FERC instance, the RS remains equal to zero for all choices of ϵ.

Let us turn to the CWE dataset. As a point of comparison, on this instance, the primal optimal cost is 4,676,650€, MP LOC and RS are 86,784€ and 1111€ and MP average price is 36.4€/MWh. We observe again in Table 5 that the results are not significantly sensitive to the choice of ϵ, although they are more sensitive than in the FERC dataset. Here, looser choices of ϵ, such as $\epsilon = 0.1$ or $\epsilon = 1.0$ lead to greater variability in the pricing outcome. As an example, $\epsilon = 1.0$ leads to a positive LOC for the network (the 327€ reported in Table 5), thus violating Proposition 4. Nevertheless, as long as ϵ is small enough, the exact choice does not seem to matter much. This contrasts with the way in which the shut-down variables are relaxed, which has a significant impact on the magnitude of prices and thus on the LOC.

5.5. Elastic demand: minimizing RS *vs* zero RS for suppliers

So far, the analysis has been limited to the case of inelastic loads. Although the comprehensive treatment of elastic loads is out of scope for our paper, this section highlights one important choice that arises when elastic loads are included. As we shall see, this sheds some light on the difference between AIC pricing and MMWP pricing that is encountered in the previous section.

Average incremental cost pricing is designed with the very idea of eliminating make-whole payments: as the price reflects the highest average cost of online suppliers, these are guaranteed to at least break even. However, as soon as elastic loads are introduced, the demand side might also face some revenue shortfall and thus require make-whole payments (unlike inelastic loads, which never bear any revenue shortfall). Under these circumstances, fully eliminating make-whole payments for both suppliers and consumers might be infeasible: there are cases in which either the demand or the supply side will face a revenue shortfall whatever the price that is chosen.[10]

The choice that arises in a two-sided market is thus the following: should we select a uniform price that *eliminates the make-whole payments for the suppliers* (pricing at their average cost), or that *minimizes the total amount of make-whole payments* (for suppliers and consumers) that is

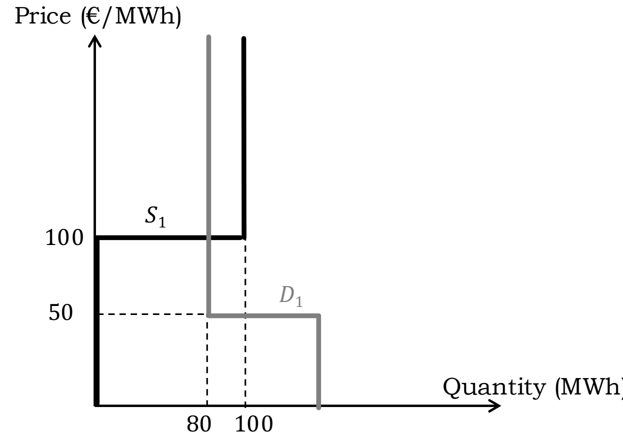
[10] See the discussion and the example in Stevens et al. (2024). O'Neill and Chen (2023) study AIC pricing in a two-sided market in more details. Their approach relies on introducing a second price—thus some discrimination—for the consumers bearing a revenue shortfall.

needed? We view this choice as one important distinction between MMWP and AIC pricing. MMWP aims at minimizing the *total* revenue shortfall: this includes the suppliers, the consumers and the network. Instead, AIC prices reflect the highest average cost of production, leading to zero revenue shortfall *for the suppliers*. With *inelastic* loads only, both approaches lead to zero revenue shortfall for the suppliers. This changes with *elastic* loads. Intuitively, there are cases in which minimizing the total RS implies non-zero RS for the suppliers in order to lower the RS of the loads.

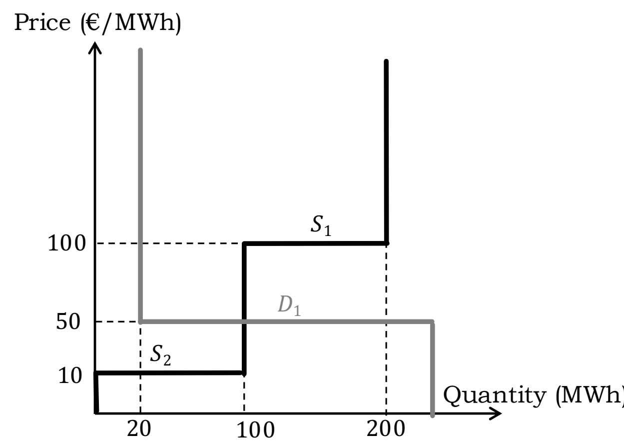
Example 6 (AIC vs MMWP) *Let us consider a market with two periods of one hour as illustrated in Figure 4. Supplier S_1 is non-convex and can produce either 0 or 100 MW at a price of 100€/MWh in both periods. Supplier S_2 is convex and can produce at most 100MW in the second period for 10€/MWh. He is not active in the first period. The demand is partially inelastic but also includes an elastic load D_1 with a willingness-to-pay of 50€/MWh. The optimal dispatch is to clear both S_1 and S_2 entirely. D_1 consumes 20MW in the first period and 180MW in the second period.*

We are interested in the difference between MMWP and AIC prices in this configuration. On the first period $\pi_1^{MMWP} = \pi_1^{AIC} =$ 100€/MWh. This price results in a revenue shortfall of 1000€ *for D_1. However, any lower price would increase the revenue shortfall of S_1 more than it would lower it for D_1. On the second period $\pi_2^{AIC} =$ 100€/MWh (the highest average cost of on-line suppliers) which results in a revenue shortfall of* 9000€ *for D_1. In this case, however, a smaller price would decrease the revenue shortfall of D_1 more than it would increase it for S_1. At $\pi_2^{MMWP} =$ 50€/MWh, the revenue shortfall of S_1 is 5000€.*

Thus in a two-sided multi-period market, an auctioneer who wishes to eliminate revenue shortfalls would face the dilemma of either fully eliminating the revenue shortfalls of suppliers (AIC prices) or minimizing the total revenue shortfall (MMWP prices).



(a) $t = 1$



(b) $t = 2$

Figure 4: AIC vs MMWP pricing in a two-period market.

6. Discussion and conclusions

There are mainly two ways of dealing with (non-convex) fixed costs: (i) inflating the uniform price above marginal cost or (ii) complementing this price with side-payments (multi-part pricing). This leads to three main pricing options. Option one is to fully rely on side payments as marginal pricing does: the uniform price is set to the highest marginal cost and is complemented with make-whole payments. Option two is average incremental cost pricing which relies on the idea of inflating the uniform price so as to fully get rid of make-whole payments. A third option implies a combination of (i) and (ii), such as convex hull pricing: the price is inflated above marginal cost, but not to the extent that it fully eliminates the make-whole payments.

This paper mainly aims at clarifying how the second option, average incremental cost pricing, could be implemented in electricity auctions and what would the consequences be for market participants. Our paper reaches six main conclusions:

- AIC pricing ensures zero RS for suppliers, thus eliminating the need of make-whole payments (Proposition 2)
- But only for suppliers who have possibility of inaction (Proposition 3).
- It eliminates arbitrage opportunities in the network (it guarantees zero “network LOC”, cf. Proposition 4).
- Fully eliminating the RS by means of the uniform price signal, however, can increase the LOC significantly, thus creating the risk of exacerbating self-scheduling behaviour.
- Since it leads to higher uniform prices, the AIC prices tend to lower short-term consumer surplus (although this might also increase investment incentives).
- AIC prices can be sensitive to formulation choices (Proposition 6).

Comparing to other approaches proposed in the literature with the objective of eliminating make-whole payments, we have argued that AIC pricing has the clear advantage of ensuring the locational consistency of prices. However, the fundamental asymmetry identified and analyzed in Stevens et al. (2024) applies to AIC pricing: while minimizing the LOC (focusing on the self-scheduling problem), as convex hull pricing does, leads to low RS (low make-whole payments), minimizing the RS, as AIC pricing does, may exacerbate the LOC significantly.

CRediT authorship contribution statement

Nicolas Stevens: Conceptualization of this study, Methodology, Formal analysis, Software, Writing - Original Draft, Writing - Review and Editing. **Richard O'Neill:** Conceptualization of this study, Methodology, Writing - Review and Editing. **Anthony Papavasiliou:** Conceptualization of this study, Methodology, Writing - Review and Editing.

Declaration of Competing Interest

The authors declare no competing interests.

A. Proofs of the Propositions

PROOF (PROPOSITION 1). Let us first define the following problem:

$$z^*_{CH} = \min_{c,q,x,f} \sum_{g\in\mathcal{G}} c_g \tag{A.1a}$$

$$(\pi^{CH}) \sum_{g\in\mathcal{G}_i} q_{g,t} - D^i_t = \sum_{\substack{l\in\\ from(i)}} f_{l,t} - \sum_{\substack{l\in\\ to(i)}} f_{l,t} \;\forall i\in\mathcal{N}, t\in\mathcal{T} \tag{A.1b}$$

$$(c,q,x)_g \in \mathrm{conv}(\mathcal{X}_g) \;\;\forall g\in\mathcal{G} \tag{A.1c}$$

$$f\in\mathcal{F} \tag{A.1d}$$

The proof relies on two main observations. First, in the convex problem (A.1), a competitive equilibrium exists: let us call $(c^\dagger, q^\dagger, x^\dagger, f^\dagger)$ the solution of problem (A.1), then $(\pi^{CH}, (c^\dagger, q^\dagger, x^\dagger, f^\dagger))$ is an equilibrium. Second, note that $LOC(\pi^{CH}) = z^* - z^*_{CH}$ (the LOC is the duality gap) and π^{CH} (i.e. the convex hull price) is the price that minimizes the LOC, cf. Gribik et al. (2007).

Let us prove that this is a sufficient condition. Since $(\pi^{CH}, (c^\dagger, q^\dagger, x^\dagger, f^\dagger))$ is an equilibrium in model (A.1), and since $(c^\dagger, q^\dagger, x^\dagger, f^\dagger) = (c^*, q^*, x^*, f^*)$ then $(c^*_g, q^*_g, x^*_g) \in \arg\max_{c,q,x} \sum_{t\in\mathcal{T}} q_{g,t}\pi^{CH}_{i(g),t} - c_g$ s.t. $(c,q,x)_g \in \mathrm{conv}(\mathcal{X}_g)$ $\forall g\in\mathcal{G}$. Since $(c^*_g, q^*_g, x^*_g) \in \mathcal{X}_g$ and since $\mathcal{X}_g \subset \mathrm{conv}(\mathcal{X}_g)$, it implies that $(c^*_g, q^*_g, x^*_g) \in \arg\max_{c,q,x} \sum_{t\in\mathcal{T}} q_{g,t}\pi^{CH}_{i(g),t} - c_g$ s.t. $(c,q,x)_g \in \mathcal{X}_g \;\forall g\in\mathcal{G}$. The same holds for the network. By definition of (c^*, q^*, x^*, f^*), the market clears. Thus, $(\pi^{CH}, (c^*, q^*, x^*, f^*))$ is an equilibrium.

To prove that this is a necessary condition, suppose that there is an equilibrium $(\pi, (c^*, q^*, x^*, f^*))$ with some π. Then $LOC(\pi) = 0$. But since π^{CH} minimizes the LOC, it must be that $LOC(\pi^{CH}) = 0$. Thus $(\pi^{CH}, (c^*, q^*, x^*, f^*))$ is an equilibrium.

PROOF (PROPOSITION 2). Let us consider the Lagrangian relaxation $L^{AIC}(\pi)$ of problem (8) in which the market clearing constraint is relaxed. Since this pricing problem is convex, the duality gap is zero: $z^{AIC} = \max_\pi L^{AIC}(\pi)$ and $\pi^{AIC} = \arg\max_\pi L^{AIC}(\pi)$. Furthermore, from Lemma 1, the optimum dispatches, and thus the costs, of both the primal problem (1) (z^*) and the AIC problem of Definition 3 (z^{AIC}) are the same: $z^{AIC} = z^* = \sum_{g\in\mathcal{G}} c^*_g$. Let us denote $\mathcal{G}^{PI}$ (resp. $\mathcal{G}^{II}$) as the subset of the generators which have (resp. do not have) a possibility of inaction: $\mathbf{0} \in \mathcal{X}^{AIC}_g$ (resp. $\mathbf{0} \notin \mathcal{X}^{AIC}_g$). We then write:

$$0 = \sum_{g\in\mathcal{G}} c^*_g - \max_\pi L^{AIC}(\pi) = \sum_{g\in\mathcal{G}} c^*_g - L^{AIC}(\pi^{AIC}) \tag{A.2}$$

$$= \sum_{g\in\mathcal{G}^{PI}} \underbrace{\max_{(c,q,x)_g\in\mathcal{X}^{AIC}_g} \mathcal{P}_g(c,q,x,\pi^{AIC}) - \mathcal{P}_g(c^*,q^*,x^*,\pi^{AIC})}_{\geq 0 \text{ since } (c^*,q^*,x^*)\in\mathcal{X}^{AIC}_g} \tag{A.3}$$

$$+ \sum_{g\in\mathcal{G}^{II}} \underbrace{\max_{(c,q,x)_g\in\mathcal{X}^{AIC}_g} \mathcal{P}_g(c,q,x,\pi^{AIC}) - \mathcal{P}_g(c^*,q^*,x^*,\pi^{AIC})}_{\geq 0 \text{ since } (c^*,q^*,x^*)\in\mathcal{X}^{AIC}_g} \tag{A.4}$$

$$+ \underbrace{\max_{f\in\mathcal{F}} \mathcal{P}_N(f,\pi^{AIC}) - \mathcal{P}_N(f^*,\pi^{AIC})}_{=LOC^{net}\geq 0} \tag{A.5}$$

which is a sum of non-negative terms that is equal to zero. Thus we conclude that each term must be equal to zero:

$$\mathcal{P}_g(c^*,q^*,x^*,\pi^{AIC}) = \max_{(c,q,x)_g\in\mathcal{X}^{AIC}_g} \mathcal{P}_g(c,q,x,\pi^{AIC}) \;\;\forall g\in\mathcal{G}$$
$$\geq 0 \;\;\forall g\in\mathcal{G}^{PI}$$

This last expression derives from Assumption 1 ($\mathbf{0} \in \mathcal{X}^{AIC}_g \;\forall g\in\mathcal{G}^{PI}$).

PROOF (PROPOSITION 3). This proposition directly follows the proof of Proposition 2, which highlights under which circumstances a supplier is guaranteed to bear zero RS under AIC prices.

PROOF (PROPOSITION 4). From the proof of Proposition 2, equation (A.5) implies $0 = \max_{f\in\mathcal{F}} \mathcal{P}_N(f,\pi^{AIC}) - \mathcal{P}_N(f^*,\pi^{AIC}) = LOC^{net}$.

PROOF (PROPOSITION 5). This follows from the fact that the set $\mathcal{X}^{AIC}_g$ is different from $\mathcal{X}_g$ for the convex suppliers as well, because of the additional constraints $0 \leq q_j \leq q^*_j$. This may also be observed in Example 3, where the convex supplier S_1 faces an LOC of 211€.

PROOF (PROPOSITION 6). Let us consider the *1-bin* ($x = u$, the commitment variables) and *3-bin* ($x = (u, v, w)$, the commitment, start-up and shut-down variables) formulations of a unit commitment model. Both models describe the same set $\mathcal{X}_g$ of feasible commitment and output decisions. However, they may result in different AIC prices. The intuition is similar to the one discussed in section 5.3: applying the AIC Definition 3 to the 3-bin formulation results in certain additional constraints on v and w which can impact the way the fixed costs are reflected in the price signal. The reader may check that applying the 1-bin or 3-bin formulation to the example of Appendix B would lead to the same price difference as in Options A* and B discussed therein.

B. Shut-down variable relaxation

This appendix provides an illustration of the two ways of relaxing the shut-down variables, as discussed in section 5. We first provide the example and then we discuss the results more formally.

Example 7. *Let us consider a market with two suppliers (Table B.1) and two periods with inelastic load (Table B.2). We analyse two different load profiles. The optimal dispatch, for both load profiles, is given in Table B.2 together with the AIC prices computed with Options A* and B. As a point of comparison, we also report the marginal prices and "Extended Locational Marginal Prices" (ELMP), an approximation of CHP obtained with the LP relaxation (Stevens et al., 2024).*

In the first load profile, only supplier 1 actually produces energy. His profit is exactly 0 under both Options A and B, although Option A* remunerates the entire fixed costs on period* $t = 1$ *(*$21.58 = 10 + 2 \times 1100/190$*) while Option B split the remuneration over the two periods (*$15.79 = 10 + 1100/190$ *; and* $17.33 = 10 + 1100/150$*). From an economic standpoint, these can be interpreted as two possible variants of "average cost" in this multi-period setting. Mathematically, the so-called "logical temporal constraint" for supplier 1 is* $u_t - u_{t-1} = v_t - w_t$ *(u is the commitment variable, v the start-up variable and w the shut-down variable). Relaxation* $0 \leq w_2 \leq w_2^* = 0$ *implies that* $u_2 = u_1$*. Thus variable* u_2 *can mathematically be eliminated such that the avoidable fixed costs* NC *associated with period 2 fall back to period 1. In the pricing model it is* as if *there was a single decision to produce over the entire production cycle (here, the two periods). Relaxation* $0 \leq w_2 \leq 1$ *implies that* $u_2 = u_1 - w_2$*. Thus variable* u_2 *cannot be eliminated and the avoidable fixed cost is reflected in the price signal in period 2: at each period of the production cycle, the unit has the opportunity to turn off. We refer the reader below to a formal argument based on the full mathematical model and its optimality conditions.*

In the second load profile, supplier 2—who is more expensive—is also active and thus sets the price in period 1 ($100 = 80 + (1000 + 1000)/100$*). The difference lies in period 2: Option B reflects the fixed cost of supplier 1 in the price of period 2, unlike Option A* and although Option A* is enough for the supplier to cover his costs over his production cycle. Indeed, the profit of supplier 1 is 15800 or 16900 with Option A* or B respectively.*

Table B.1
Suppliers in Example 7

Supplier	MC	SC	NC	Q^{min}	Q^{max}	u_0
$S1$	10	1000	1100	100	200	1
$S2$	80	1000	1000	0	200	0

Table B.2
Load, optimal dispatch and AIC prices in Example 7

Supplier	load profile 1 $t=1$	load profile 1 $t=2$	load profile 2 $t=1$	load profile 2 $t=2$
Load	190	150	300	150
q^*_{S1}	190	150	200	150
q^*_{S2}	0	0	100	0
AIC price (Option A*)	21.58	10	100	10
AIC price (Option B)	15.79	17.33	100	17.33
Marginal Pricing	10	10	80	10
ELMP	15.5	15.5	90	15.5

This example shows two things. The first load profile illustrates how Options A* and B can reasonably be viewed as two variants of "average cost" pricing. The second load profile shows why Option B tends to lead to prices which are higher than what is strictly necessary for the market participant to earn a non-negative profit. This, in turn, *might* exacerbate the lost opportunity costs of market participants. This interpretation enables us to intuitively understand the results of Table 4 and why Option B leads to higher prices.

More formally, the AIC pricing (convex) model of Example 7 is

$$\min_{q,u,v,w \geq 0} \sum_{g \in \mathcal{G}} \sum_{t \in \mathcal{T}} (q_{g,t} MC_g + u_{g,t} NC_g + v_{g,t} SC_g) \tag{B.6a}$$

$$(\pi_t) \sum_{g \in \mathcal{G}} q_{g,t} \geq D_t \quad \forall t \in \mathcal{T} \tag{B.6b}$$

$$(\mu_{g,t})\ q_{g,t} \leq u_{g,t} Q_g^{max} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{B.6c}$$

$$(\nu_{g,t})\ q_{g,t} \geq u_{g,t} Q_g^{min} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{B.6d}$$

$$(\lambda_{g,t})\ u_{g,t} - u_{g,t-1} = v_{g,t} - w_{g,t} \forall g \in \mathcal{G}, t \in \mathcal{T}, t > 1 \tag{B.6e}$$

$$(\lambda_{g,1})\ u_{g,1} - u_g^0 = v_{g,1} - w_{g,1} \quad \forall g \in \mathcal{G} \tag{B.6f}$$

$$(\delta_{g,t})\ q_{g,t} \leq u_{g,t} q^*_{g,t} + \epsilon \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{B.6g}$$

$$(\alpha_{g,t})\ u_{g,t} \leq u^*_{g,t} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{B.6h}$$

$$(\beta_{g,t})\ v_{g,t} \leq v^*_{g,t} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{B.6i}$$

$$(\gamma_{g,t})\ w_{g,t} \leq 1 \text{ or } w_{g,t} \leq w^*_{g,t} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{B.6j}$$

where u, v, w and q are, respectively, the commitment, start-up, shut-down and production variables. The optimality conditions are:

$$0 \leq q_{g,t} \perp MC_g - \pi_t + \mu_{g,t} - \nu_{g,t} + \delta_{g,t} \geq 0 \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{B.7a}$$

$$0 \le u_{g,t} \perp NC_g - \mu_{g,t}Q_g^{max} + \nu_{g,t}Q_g^{min} + \lambda_{g,t} - \lambda_{g,t+1} + \alpha_{g,t} - \delta_{g,t}q_{g,t}^* \ge 0 \ \forall g \in \mathcal{G}, t \in \mathcal{T} \quad \text{(B.7b)}$$

$$0 \le v_{g,t} \perp SC_g - \lambda_{g,t} + \beta_{g,t} \ge 0 \ \forall g \in \mathcal{G}, t \in \mathcal{T} \quad \text{(B.7c)}$$

$$0 \le w_{g,t} \perp \lambda_{g,t} + \gamma_{g,t} \ge 0 \ \forall g \in \mathcal{G}, t \in \mathcal{T} \quad \text{(B.7d)}$$

$$0 \le \mu_{g,t} \perp u_{g,t}Q_g^{max} - q_{g,t} \ge 0 \ \forall g \in \mathcal{G}, t \in \mathcal{T} \quad \text{(B.7e)}$$

$$0 \le \nu_{g,t} \perp q_{g,t} - u_{g,t}Q_g^{min} \ge 0 \ \forall g \in \mathcal{G}, t \in \mathcal{T} \quad \text{(B.7f)}$$

$$0 \le \pi_t \perp \sum_{g \in \mathcal{G}} q_{g,t} - D_t \ge 0 \ \forall t \in \mathcal{T} \quad \text{(B.7g)}$$

$$0 \le \delta_{g,t} \perp u_{g,t}q_{g,t}^* - q_{g,t} + \epsilon \ge 0 \ \forall g \in \mathcal{G}, t \in \mathcal{T} \quad \text{(B.7h)}$$

$$0 \le \alpha_{g,t} \perp u_{g,t}^* - u_{g,t} \ge 0 \ \forall g \in \mathcal{G}, t \in \mathcal{T} \quad \text{(B.7i)}$$

$$0 \le \beta_{g,t} \perp v_{g,t}^* - v_{g,t} \ge 0 \ \forall g \in \mathcal{G}, t \in \mathcal{T} \quad \text{(B.7j)}$$

$$0 \le \gamma_{g,t} \perp 1 - w_{g,t} \ge 0 \text{ or } w_{g,t}^* - w_{g,t} \ge 0 \ \forall g \in \mathcal{G}, t \in \mathcal{T} \quad \text{(B.7k)}$$

$$u_{g,t} - u_{g,t-1} = v_{g,t} - w_{g,t} \quad \lambda_{g,t} \text{ free } \forall g \in \mathcal{G}, t \in \mathcal{T}, t > 1 \quad \text{(B.7l)}$$

$$u_{g,1} - u_g^0 = v_{g,1} - w_{g,1} \ \lambda_{g,1} \text{ free } \forall g \in \mathcal{G} \quad \text{(B.7m)}$$

A general observation from these optimality conditions is the following. For a marginal supplier ($Q_g^{min} < q_{g,t} < Q_g^{max}$), we have $\pi_t = MC_g + \delta_{g,t}$ and $\delta_{g,t} = (NC_g + \lambda_{g,t} - \lambda_{g,t+1} + \alpha_{g,t})/q_{g,t}^*$. Then, $q_{g,t} = q_{g,t}^*$, and because of the ϵ, $u_{g,t} < u_{g,t}^*$ and $\alpha_{g,t} = 0$. Because of the logical temporal constraint (B.6e), $w_{g,t} = \epsilon$ and $\delta_{g,t} = NC_g/q_{g,t}^*$ and thus $\pi_t = MC_g + NC_g/q_{g,t}^*$. But this is only possible if $w_{g,t} \le 1$. If $w_{g,t} \le w_{g,t}^* = 0$, then $u_{g,t} = u_{g,t}^*$ and $\delta_{g,t} = 0$, thus $\pi_t = MC_g$.

Let us apply this analysis to Example 7. Let us consider the first load profile (in Table B.2). Since S_2 is offline, we can focus on S_1. We focus on AIC pricing with Option A* ($w_{g,t} \le w_{g,t}^*$). From $w_{g,t} \le w_{g,t}^* = 0$, we deduce: $u_{S1,1} = u_{S1,2} = u$ and $w_{S1,1} = 1 - u$. Thus we can eliminate the variables λ. We can then rewrite conditions (B.7) as follows (using $Q_{S1}^{min} < q_{S1,t} < Q_{S1}^{max}$):

$$0 \le q_{S1,t} \perp MC_{S1} - \pi_t + \delta_{S1,t} \ge 0 \ t \in \mathcal{T} \quad \text{(B.8a)}$$

$$0 \le u \perp 2 \times NC_{S1} + \alpha_{S1} - \delta_{S1,1}q_{S1,1}^* \quad \text{(B.8b)}$$

$$- \delta_{S1,2}q_{S1,2}^* \ge 0 \quad \text{(B.8c)}$$

$$0 \le \alpha_{S1} \perp 1 - u \ge 0 \quad \text{(B.8d)}$$

$$0 \le \delta_{S1,1} \perp uq_{S1,1}^* - q_{S1,1} + \epsilon \ge 0 \quad \text{(B.8e)}$$

$$0 \le \delta_{S1,2} \perp uq_{S1,2}^* - q_{S1,2} + \epsilon \ge 0 \quad \text{(B.8f)}$$

Since $q_{S1,1} = q_{S1,1}^* = 190$MW and $q_{S1,2} = q_{S1,2}^* = 150$, we have $u = (190 + \epsilon)/190$. This implies that constraint (B.8e) is tight (and $\delta_{S1,1} > 0$) while (B.8f) is not tight (and $\delta_{S1,2} = 0$). This leads to $\pi_1 = MC_{S1} + 2 \times NC_{S1}/q_{S1,1}^*$ and $\pi_2 = MC_{S1}$. The avoidable fixed cost is allocated to the period with the highest production.

Under Option B ($w_{g,t} \le 1 \ \forall t$), variables $u_{g,t}$ cannot be eliminated as above. Thus, the avoidable fixed costs are not "aggregated" as a single decision over the production cycle, but are split over the multiple time periods.

C. Detailed Numerical Results

Tables C.3 and C.4 provide the detailed results (per load scenario) of Tables 1 and 2.

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Table C.3
Incentives of market agents on the FERC dataset depending on the pricing scheme (detailed figures per scenario).

		MP	CHP	MMWP**	AIC
2015-02-01-hw	Av. Price	23.1	23.7	23.2	23.7
	Suppl.	7.4%	3.3%	9.1%	7.4%
	Av. LOC per Suppl.	476	22	52	476
	Consumer Surplus	0.0%	1.9%	1.4%	-0.0%
	LOC	32,858	673	4,421	32,866
	RS	0	41	0	0
2015-04-01-hw	Av. Price	19.3	18.9	19.3	19.3
	Suppl.	3.4%	1.2%	8.7%	4.4%
	Av. LOC per Suppl.	265	18	75	185
	Consumer Surplus	0.0%	-2.0%	-2.2%	-2.1%
	LOC	8,734	229	6,360	7,975
	RS	2,426	0	0	0
2015-05-01-hw	Av. Price	24.8	24.7	24.8	24.8
	Suppl.	1.3%	1.3%	4.1%	2.5%
	Av. LOC per Suppl.	68	4	12	35
	Consumer Surplus	0.0%	-0.3%	-0.2%	-0.5%
	LOC	888	60	471	850
	RS	499	0	0	0
2015-06-01-hw	Av. Price	27.2	27.4	27.2	27.4
	Suppl.	2.4%	1.8%	5.2%	2.4%
	Av. LOC per Suppl.	344	15	18	344
	Consumer Surplus	0.0%	0.8%	0.9%	0.0%
	LOC	7,906	271	923	7,906
	RS	0	5	0	0
2015-07-01-lw	Av. Price	32.8	32.9	32.9	32.9
	Suppl.	1.2%	1.1%	5.1%	6.9%
	Av. LOC per Suppl.	231	21	35	118
	Consumer Surplus	0.0%	0.1%	0.0%	-0.1%
	LOC	2,772	241	1,733	7,876
	RS	21	0	0	0
2015-07-01-hw	Av. Price	28.6	27.8	28.7	28.7
	Suppl.	2.4%	3.3%	8.8%	8.1%
	Av. LOC per Suppl.	608	13	42	92
	Consumer Surplus	0.0%	-2.0%	-2.3%	-2.7%
	LOC	13,978	427	3,583	7,282
	RS	3,922	0	0	0
2015-08-01-hw	Av. Price	28	27.2	28.1	27.3
	Suppl.	3.2%	1.4%	11.1%	4.3%
	Av. LOC per Suppl.	749	24	30	574
	Consumer Surplus	0.0%	-1.9%	-1.9%	-0.2%
	LOC	23,217	336	3,327	24,123
	RS	229	12	0	0
2015-09-01-lw	Av. Price	43.3	43	43.6	43.6
	Suppl.	4.1%	2.7%	14.9%	22.6%
	Av. LOC per Suppl.	168	18	99	543
	Consumer Surplus	0.0%	-0.5%	-0.8%	-1.0%
	LOC	6,719	468	14,509	120,049
	RS	233	0	0	0
2015-09-01-hw	Av. Price	35.2	36.9	35.8	36.9
	Suppl.	8.8%	1.3%	21.9%	9.0%
	Av. LOC per Suppl.	3,579	29	511	3,499
	Consumer Surplus	0.0%	3.1%	2.0%	-0.0%
	LOC	307,764	383	109,366	307,949
	RS	0	71	0	0
2015-10-01-lw	Av. Price	30	30.3	30.2	30.3
	Suppl.	2.4%	1.4%	6.4%	2.7%
	Av. LOC per Suppl.	366	26	57	339
	Consumer Surplus	0.0%	1.1%	0.6%	-0.1%
	LOC	8,053	341	3,403	8,463
	RS	0	0	0	0
2015-12-01-hw	Av. Price	23.8	23.8	23.9	24.1
	Suppl.	1.0%	1.0%	9.0%	4.8%
	Av. LOC per Suppl.	50	14	99	66
	Consumer Surplus	0.0%	0.1%	-0.5%	-1.1%
	LOC	447	128	8,286	2,978
	RS	26	85	0	0

Table C.4
Incentives of market agents on the CWE dataset depending on the pricing scheme (detailed figures per scenario).

		MP	CHP	MMWP**	AIC
SpringWE-24	Av. Price	35.6	36.4	50.3	42.4
	Suppl.	31.1%	25.7%	60.8%	50.0%
	Av. LOC per Suppl.	3,773	285	38,787	3,460
	Consumer Surplus	0.0%	1.6%	-29.3%	-20.6%
	LOC	86,784	7,243	27,790,267	128,030
	RS	1,111	1,145	0	1,638
AutumnWE-24	Av. Price	38	37.3	51.2	45.6
	Suppl.	36.5%	27.0%	60.8%	44.6%
	Av. LOC per Suppl.	4,386	179	34,598	9,334
	Consumer Surplus	0.0%	-1.7%	-26.7%	-23.9%
	LOC	118,412	5,130	25,860,062	308,028
	RS	13,896	1,267	0	4,712
SummerWE-24	Av. Price	34.5	34.2	49.5	39.4
	Suppl.	36.5%	27.0%	64.9%	52.7%
	Av. LOC per Suppl.	4,917	544	39,126	6,508
	Consumer Surplus	0.0%	0.1%	-33.4%	-20.6%
	LOC	132,756	12,660	29,231,651	253,829
	RS	9,500	5,369	0	2,712
SummerWE-96	Av. Price	44.3	44.6	51.4	45.9
	Suppl.	39.2%	44.6%	70.3%	55.4%
	Av. LOC per Suppl.	2,659	178	18,266	1,831
	Consumer Surplus	0.0%	0.6%	-8.0%	-2.5%
	LOC	77,107	6,694	15,507,994	75,080
	RS	8,593	2,823	0	2,675
SummerWD-24	Av. Price	35.3	33.8	49.8	39.6
	Suppl.	35.1%	33.8%	64.9%	54.1%
	Av. LOC per Suppl.	3,978	298	37,451	7,968
	Consumer Surplus	0.0%	-4.3%	-37.0%	-22.0%
	LOC	103,440	8,506	29,090,195	318,728
	RS	9,896	1,966	0	3,286
AutumnWD-24	Av. Price	47.9	43.2	55	50.1
	Suppl.	33.8%	43.2%	56.8%	52.7%
	Av. LOC per Suppl.	5,469	446	34,783	2,380
	Consumer Surplus	0.0%	-9.1%	-17.8%	-15.8%
	LOC	136,726	18,936	23,749,608	92,830
	RS	76,993	842	0	3,651
AutumnWD-96	Av. Price	53	52.6	58.1	53.7
	Suppl.	35.1%	55.4%	71.6%	59.5%
	Av. LOC per Suppl.	1,999	152	14,407	1,140
	Consumer Surplus	0.0%	-0.4%	-3.7%	-2.0%
	LOC	51,962	6,625	13,737,122	50,178
	RS	7,886	1,194	0	123
SpringWE-96	Av. Price	44.8	45.3	51.7	46.6
	Suppl.	37.8%	45.9%	68.9%	54.1%
	Av. LOC per Suppl.	2,759	132	17,658	3,129
	Consumer Surplus	0.0%	1.2%	-7.3%	-3.2%
	LOC	77,255	5,498	15,127,962	125,169
	RS	6,657	687	0	824
SummerWD-96	Av. Price	46.7	45.3	53.5	54.4
	Suppl.	35.1%	43.2%	70.3%	59.5%
	Av. LOC per Suppl.	2,687	184	16,068	5,627
	Consumer Surplus	0.0%	-2.1%	-9.1%	-16.4%
	LOC	69,857	6,264	14,933,977	247,605
	RS	2,808	1,325	0	2,840
SpringWD-24	Av. Price	44.5	41.7	53.3	49.4
	Suppl.	29.7%	29.7%	52.7%	45.9%
	Av. LOC per Suppl.	5,451	449	37,436	3,716
	Consumer Surplus	0.0%	-6.4%	-19.8%	-21.0%
	LOC	119,929	10,312	25,414,900	126,354
	RS	14,438	4,021	0	1,021
AutumnWE-96	Av. Price	46	45.2	52.6	47.6
	Suppl.	39.2%	39.2%	64.9%	50.0%
	Av. LOC per Suppl.	2,581	167	18,805	2,840
	Consumer Surplus	0.0%	-1.2%	-8.6%	-5.0%
	LOC	74,843	5,591	14,545,232	105,073
	RS	5,296	1,116	0	1,304
SpringWD-96	Av. Price	50	49.8	55.1	52.1
	Suppl.	32.4%	41.9%	63.5%	47.3%
	Av. LOC per Suppl.	2,776	201	16,313	2,995
	Consumer Surplus	0.0%	-0.0%	-4.3%	-4.2%
	LOC	66,627	6,779	14,192,351	104,837
	RS	1,611	893	0	253