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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. Several pricing mechanisms that deal with this issue have emerged from the literature. We analyze 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 behavior. 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

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 organized 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 both the physical constraints of production as well as 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. Concretely, the auctioneer cannot find an allocation and a price that are an equilibrium (Starr, 1969; Bikhchandani and Mamer, 1997). Marginal pricing in these auctions fails to support the efficient allocation of resources as it does not account for the fixed costs in the price signal.

In economics, this relates to the broader problem of fixed cost recovery. Although marginal pricing is often considered as a cornerstone principle of microeconomic theory, it is also well known that there can be *optimal* departures from marginal cost pricing (Baumol and Bradford, 1970). Two classic examples include Ramsey-Boiteux pricing and Coase multi-part pricing. In the first, a regulated firm or the State 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 second — and related — problem is analyzed 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. Notice that indivisible fixed costs as well as increasing returns to scale are typical examples of non-convexities in production processes. The two solutions we have just described involve either inflating the commodity price above marginal cost or complementing this uniform price with side payments.

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[1] By "fixed costs", we will 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.

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Although non-convexities exist in many markets, and have therefore attracted some general attention in auction theory (Milgrom, 2017; Milgrom and Watt, 2025; Day and Lubin, 2025), electricity auctions turn out to be a place where the defect of the convexity assumption, and the possible remedies to it, has fed a particularly dynamic stream of research. Indeed, this has led to various heterogeneous practices implemented by electricity auctioneers, as well as a number of possible solutions that are advocated in the scientific literature.[2] 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. More specifically, three main pricing approaches have emerged: (i) *marginal pricing*, complemented by — eventually large — side-payments (O'Neill et al., 2005); (ii) *convex hull pricing* (Gribik et al., 2007), which aims at finding prices that minimize the incentives agents have to deviate from the cleared allocation (formally, that minimize *lost opportunity costs*, cf. Section 2), complemented by — typically lower — side payments, and (iii) pricing schemes that ensure that all market participants are profitable without the need for discriminatory side-payments (formally, that minimize, or eliminate *revenue shortfall*, cf. Section 2). The third category includes several variants (Madani and Papavasiliou, 2022; Bichler et al., 2022). 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, a pricing scheme belonging to category (iii), 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. Intuitively, large discriminatory payments lead to a pricing scheme that resembles less to *uniform* pricing and more to *pay-as-bid* pricing. Our paper aims at formalizing the AIC approach as well as understanding its economic consequences on the incentives of market participants.

More specifically, the material of the paper is organized 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 characterize how these prices affect suppliers, consumers and the network operator. One important result that we establish is that AIC prices guarantee locational price consistency: they ensure that 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 allows for 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, and it provides a sense of the expected magnitude 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 behavior. 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 modeling choices and implementation choices. Section 6 discusses the main findings and concludes.

2. The model

Let us consider the following electricity auction model:

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

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

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

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

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^i_t in each node i of the network and each period t. Although inelasticity of demand is a simplification, it is general enough to describe most of the trade-offs that exist between the possible pricing schemes. Nevertheless, we offer a brief treatment of demand elasticity in Section 5.2. Suppliers are modeled 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 $\mathcal{X}_g$ ($\mathrm{conv}(\mathcal{X}_g)=\mathcal{X}_g$) while a non-convex supplier has a non-convex production set $\mathcal{X}_g$. Electricity markets are indeed not pure combinatorial auctions: they typically include a mix of non-convex or partly non-convex bids, often linked to thermal power plants, as well as convex bids often linked to either renewable assets or to pure financial trading. 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.[3] 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 $f\in\mathcal{F}$. In other words, the system operator plays the role of a "spatial arbitrager".

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 market surplus.

Example 1. Let us consider an hourly market with a convex supplier S_1 producing at maximum 30 MW for 10 €/MWh and a non-convex supplier S_2 producing either 0 or an output between 90 MW and 100 MW for 20 €/MWh. S_2 also faces an avoidable fixed cost (or no-load cost) of 1000 €. The demand is fully inelastic and is 110 MW. The optimal solution is to produce 90 MW with supplier S_2 and 20 MW with supplier S_1. The marginal cost price, at the optimal solution,

[2] We refer the reader to Stevens et al. (2024) for an overview of this literature and for a historical account of the US and Europe. See also Ahunbay et al. (2025), and the main references cited below. Hübner (2025) provides an analysis of the empirical magnitude of these issues in the European market.

[3] The costs and production constraints are assumed to be available through the bids of the participants. Questions of non-truthful bidding or strategy-proofness of the mechanisms are out of the scope of this paper and left for future research.

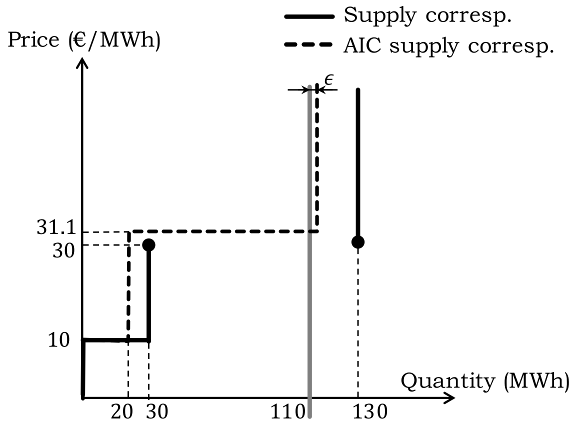

Fig. 1. Supply correspondences in Example 1.

is 10 €/MWh: an additional MW of demand means increasing the production of S_1 by 1 MW. 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 20 MW, while any price lower than 30 €/MWh would incentivize S_2 to produce 0 MW. Thus there is no equilibrium. This is graphically illustrated in Fig. 1 which shows the demand and supply correspondences: the leap in the supply correspondence implies supply and demand do not cross, thus there is no equilibrium. (The AIC supply correspondence will be explained later on in Section 3.)

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.[4]

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 relaxation of problem (1) in which $\mathcal{X}_g$ are replaced by $\mathrm{conv}(\mathcal{X}_g)$, 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 80 MW. This differs from the primal solution. Thus, as explained in Example 1, and following Proposition 1, there is no equilibrium. If the demand were 130 MW instead of 110 MW, then S_1 and S_2 would produce respectively at 30 and 100 MW 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)).

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

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

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

These two concepts are closely interrelated. In particular, revenue shortfall should be viewed as a specific type of lost opportunity cost, where the lost opportunity is not to produce, thus to self-schedule at 0.[5] In a convex economy where agents have the possibility of inaction, there would be a Walrasian 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 allows 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. In PJM, for instance, the day-ahead plus real-time make-whole payments average $13 million per month over the period from 2017 to 2024, according to PJM data. Although significant, this is less than 0.5% of consumer total energy expenditures. In the European electricity market, institutional arrangements imply that make-whole payments should be zero, which led the power exchanges to adopt a pricing rule that fully avoids discriminatory payments (NEMO Committee, 2020).[6]

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 incentivize suppliers to self-schedule, creating the risk for the cleared schedule to unravel.[7]

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

[5] 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 corresponds 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.

[6] From this perspective, the European pricing rule bears some resemblance with AIC pricing. The main difference is that, by design, AIC pricing clears the surplus maximizing allocation, while European pricing rule may clear a sub-optimal allocation.

[7] 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 analyzes 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

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) 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: the LOC is an *ex-post* measure of how much market participants would have liked to deviate from the cleared schedule. 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.[8] It is worth noting that self-scheduling is a significant phenomenon in PJM, as well as in other ISO markets. According to PJM data, suppliers' self-scheduling stands for ∼70% of the load in real-time, over the period from 2017 to 2024.[9] Byers and Eldridge (2023) use a basic reinforcement learning algorithm to show that in the presence of high LOC, market participants can indeed identify profitable self-scheduling opportunities. 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. Nevertheless, when computing the consumers' expenditure in Section 4, we assume that the auctioneer only pays make-whole payments, thus only refunds the RS, as this is a common practice among US ISOs—although some ISOs, such as ISO-NE, also pay LOC to committed units (EPRI, 2019). 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.[10]

Example 2 (*Network LOC*)**.** Let us consider the radial two-node network illustrated in Fig. 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:

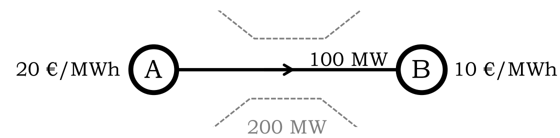

Fig. 2. Network LOC illustration.

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

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

3. AIC pricing

This section introduces Average Incremental Cost (AIC) prices. We start with the formal definition of the method 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:

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

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

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

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

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

The set $\mathcal{X}_g^{AIC}$ is obtained by first relaxing the set $\mathcal{X}_g$, as we consider the LP relaxation of the binary variables, and then by 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). That is, we do not require any assumption regarding the specific model behind $\mathcal{X}_g$, except:

Assumption 1. We assume that 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.[11] Thus this assumption is adopted so as to discard these cases.

they could earn by self-scheduling, which led to the collapse of the cleared dispatch. Although the case analyzed by Hogan (2002b) is different than the subject matter of our article, it clearly illustrates the importance of taking the incentives of market participants into account when designing pricing policies.

[8] In general, generation resources are allowed to self-schedule in ISO markets. For instance, PJM enforces physical suppliers to bid into the auction, but allows them to either submit a "dispatchable bid" or "self-schedule bid" which corresponds to offering a quantity at arbitrarily low price (PJM, 2024). The main restriction to self-scheduling is that these bids are not compensated for their losses in the market, thus they are not eligible to receive make-whole payments (Monitoring Analytics, 2024).

[9] These self-scheduling are obviously not all related to LOC. Although explaining self-scheduling behavior is not obvious, reasons of self-scheduling might for instance include a short-sighted market horizon or some limitations of the market products.

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

[11] 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 in $\mathbf{0}\notin\mathcal{X}_g^{AIC}$. Another case involves initial conditions. This case is further discussed in the Online Appendix.

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 $z^{AIC} = z^*$. (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. Graphically, Definition 3 corresponds to drawing the "AIC supply correspondence" in Fig. 1, where supply and demand intersect at $\pi^{AIC} = 31.11$ €/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 30 MW and 80 MW 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 Fig. 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 paramount alternative pricing approaches that have emerged in the literature: marginal pricing (MP), convex hull pricing (CHP, cf. Gribik et al. (2007)) and minimal make-whole payments pricing (MMWP**, cf. Bichler et al. (2022)).[12] 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 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 minimize the revenue shortfall. MMWP** is one of them.

4. AIC pricing properties

This section analyzes 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 (Propositions 3 to 5). We then conduct a numerical analysis. This numerical analysis has two main objectives. First, 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 impossibility 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. ISOs typically have specific rules to deal with these cases (for instance, in PJM or in NYISO, a unit is not eligible for uplift payments if its minimum run time exceeds 24 h). Of course, this property could be corrected by changing 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.

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). This turns out to be an important issue in policy discussions in Europe (SDAC, 2023) and in the US (Schiro et al., 2015). Let us illustrate this property with an Example.

Example 5 (*Network AIC*). Let us consider the radial network of Example 2. There are hourly loads of 250 MW in node A and 150 MW in node B. There is a convex supplier in node A, G_A, with a capacity of 350 MW and a marginal cost of 20 €/MWh. There are two suppliers in node B: G_{B1} who can produce either 0, or an output in $[900, 1000]$ MW for 10 €/MWh ; and G_{B2} who can produce either 0, or an output in $[25, 200]$ MW for 25 €/MWh with a start-up cost of 1000 €. The cost-minimizing allocation is to produce 350 MWh with G_A and 50 MWh with G_{B2} (although G_{B1} is cheaper, its inflexibility renders it more expensive, all things considered). The reader may check that CHP

[12] 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) analyze 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).

leads to $\pi_A^{CHP} = 20$ €/MWh and $\pi_B^{CHP} = 10$ €/MWh, as in Example 2 (this happens because the line is congested from B to A in the CHP relaxed problem). Here, there are arbitrage opportunities in the network ($LOC^{net}(\pi^{CHP}) = 3000$ €). This does not happen with AIC pricing ($\pi_A^{AIC} = \pi_B^{AIC} = 45$ €/MWh, $LOC^{net}(\pi^{AIC}) = 0$) nor with marginal pricing ($\pi_A^{MP} = \pi_B^{MP} = 25$ €/MWh, $LOC^{net}(\pi^{MP}) = 0$).

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

This property is illustrated in Example 1. There, the marginal price equals 10 €/MWh, thus the convex supplier S_1 does not bear any LOC (this holds in general: marginal pricing ensures zero LOC for convex market participants Stevens et al., 2024). By contrast, 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. Concretely, in a US market, these convex suppliers are for instance the "virtual bids" which correspond to pure financial trading. Proposition 5 then implies that a virtual bid could face lost opportunities.

Let us illustrate these propositions with numerical simulations. We use the same datasets as in Stevens et al. (2024). The first dataset, later referred to as "FERC dataset", includes almost 1000 power units but does not include a network (Krall et al., 2012; Knueven et al., 2020). The second dataset, later referred to as "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 analyzed 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* — a fundamental take-away of our analysis — follows from the fact that the RS is a particular type of LOC. Intuitively, when a tiny expensive unit (say, of size ϵ), with high fixed costs (say $FC \gg 0$), is dispatched because of some inflexibility in the system, its average cost ($\sim FC/\epsilon$) can be enormous, thus it can significantly inflate the uniform price if taken into account, as AIC pricing does. This in turn exacerbates the LOC of other suppliers. Instead, CHP would rather compensate this unit by discriminatory payments (equal to FC), in order to prevent the LOC from skyrocketing.

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. Fig. 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 realize this "opportunity"—but it is a threat of self-scheduling. Small LOC is less of a concern, since market participants are less likely to risk self-scheduling for a limited pay-off. Instead, high LOC corresponds to more credible threats of self-scheduling. Fig. 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 result in a number of market participants facing incentives of 10,000 € or more per 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

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

		MP	CHP	MMWP**	AIC
Dispatch cost [$]		29,780,000			
Av. Price [$/MWh]		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] 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 Online Appendix.
[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 relaxation of shutdown variables w follows "Option A*", see Online Appendix.

Table 2
Results of the CWE dataset (average over 12 scenarios).[a,b]

		MP	CHP	MMWP**	AIC
Dispatch Cost [€]		5,489,000			
Av. Price [€/MWh]		42.4	43.4	52.6	47.2
Suppl. with LOC		35.1%	38.1%	64.2%	52.1%
Av. LOC per Suppl. [€]		3620	268	26,975	4244
Δ Consumer surplus		0%	−1.8%	−17.1%	−13.1%
LOC [€]	Tot.	92,975	8353	20,765,110	161,312
	Net.	0	1267	19,513,628	0
	Suppl.	92,975	7086	1,251,482	161,312
RS [€]	Tot.	13,224	1887	0	2087
	Net.	0	0	0	0
	Suppl.	13,224	1887	0	2087
	Suppl. PI.	7286	1028	0	0
	Suppl. II.	5937	859	0	2087

[a] 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 Online Appendix.
[b] For AIC pricing, the simulations use $\epsilon = 0.001$. In all cases, the shutdown variables w relaxation follows "Option A*", cf. Online Appendix.

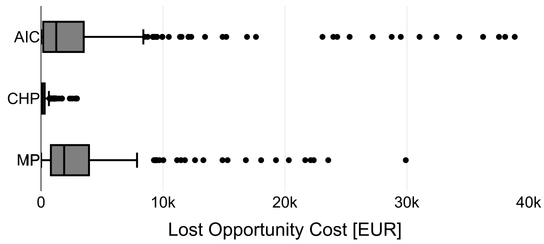

Fig. 3. Distribution of LOC among suppliers (CWE cases).

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 1 and 2. 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 Propositions 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 analyzed 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 the presence of a network, i.e. significant arbitrage opportunities with respect to locational price differences. AIC pricing overcomes this issue. This locational price consistency is certainly an important advantage of AIC pricing.

5. AIC pricing implementation

Sections 3 and 4 have described the main economic properties of AIC pricing. This section discusses challenges linked to its implementation. Sections 5.1 and 5.2 add two important caveats to the preceding discussion: the formulation-dependence of AIC pricing results and a new set of issues that arises when demand elasticity is introduced. Section 5.3 discusses institutional and technical challenges.

5.1. Formulation dependence

An important qualification 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 to 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 particular, our analysis leads to three main take-aways. First, we find that the results of AIC pricing can be sensitive to some apparently innocent modeling choices. In a unit commitment model that includes binary shutdown variables, our simulations show that the way in which these variables are relaxed when computing the AIC prices, although not affecting the validity of Propositions 2 to 5, leads to significantly different outcomes in terms of average price magnitude, LOC, etc. The Online Appendix provides an extensive discussion of these findings and their economic interpretation. Briefly stated, different models lead to different interpretations of what "average cost" means: for instance, whether it means having the avoidable fixed costs which are reflected *at each and every hour*, or *over the production cycle* of a power plant.

Second, we find that there is no straightforward relationship between the tightness of $\mathcal{X}_g^{AIC}$ and the resulting LOC. In our simulations reported in the Online Appendix, tighter formulations clearly lead to lower LOC. Instead, an example, also developed in the Online Appendix, shows that the opposite can also be true.

Third, we investigate the *numerical sensitivity* of the results with respect to the choice of the parameter ϵ involved in the definition of AIC pricing. 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)). Here, we find that the results are fairly robust: as long as ϵ is sufficiently small (10^{-4} to 10^{-2}), the exact choice does not matter much. This contrasts with the *modeling sensitivity* just discussed. The Online Appendix reports the detailed results with different choices of ϵ on both the FERC and CWE datasets.

5.2. Demand elasticity

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 discussed in the previous section.

Average incremental cost pricing is motivated by 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.[13]

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 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.

[13] 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 detail. Their approach relies on introducing a second price — thus some discrimination — for the consumers bearing a revenue shortfall.

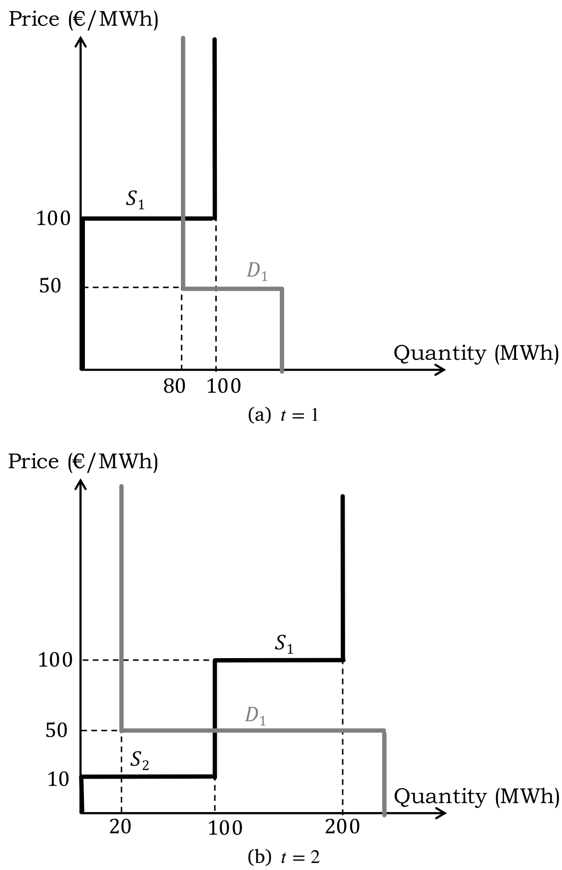

Fig. 4. AIC vs. MMWP pricing in a two-period market.

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 Fig. 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 100 MW 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 20 MW in the first period and 180 MW 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).

With elastic demand, AIC pricing becomes *asymmetric* in the sense that it treats supply and demand differently. This is another difference with both CHP and MMWP** which treat supply and demand *symmetrically*.

5.3. Institutional and technical challenges

Let us finally comment on the institutional challenges that the implementation of AIC pricing could face, both from a technical and a market acceptance point of view. First, from a technical perspective, calculating the AIC prices, thus solving problem (8), is computationally straightforward—more straightforward than solving the non-convex problem (1). Indeed, model (8) is a convex problem that can be solved by any commercial mathematical programming solver. On a personal computer (Apple M4 with 16 GB of RAM) using Gurobi 12 with an implementation in Julia (JuMP), the AIC prices are computed in, on average, 0.75 s (FERC datasets) and 0.12 s (CWE datasets). In fact, among the four pricing schemes discussed in Section 4, the only computationally challenging approach is convex hull pricing, which requires a specific algorithm to solve the Lagrangian relaxation problem implied by its formulation—although this can be solved on a personal computer in a matter of minutes (Stevens and Papavasiliou, 2022).

A reader might ask "if the goal is to find prices that satisfy a number of requirements, such as zero RS (Proposition 2) or zero LOC for the network (Proposition 4), why not simply write an optimization model that achieves this directly (i.e. $\min_\pi ||\pi||_2$ s.t. $RS(\pi) = 0$ and $LOC^{net}(\pi) = 0$) instead of taking the detour of model (8)?" The answer is that, although writing a mathematical program that achieves zero RS is straightforward (Bichler et al., 2022), including constraints on the LOC leads to a *bilevel optimization model*, which is not tractable. By contrast, as noted before, solving problem (8) is computationally straightforward.

Second, regarding the market acceptance of AIC pricing, based on the evidence of Section 4, we observe that it leads to higher prices than its alternatives. For the suppliers, provided the as-bid allocation is the same, this implies higher short-term profit, which is unlikely to raise resistance. Our results nevertheless show that it also implies higher LOC, thus some frustrated suppliers. If these LOCs are concentrated on a small set of suppliers, it could raise some resistance from them. The major resistance is likely to come from consumers as the higher prices undercut their short-term surplus. As already noted, the implication on long-term surplus is however ambiguous and more work would be required to quantify it.

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).[14] 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 by make-whole payments. Option two is average incremental cost pricing which relies on the idea of inflating the uniform price so as to fully eliminate 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 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 the consequences could be for market participants. Our paper reaches six main conclusions:

[14] A third way, which we do not discuss here, relies on a sub-optimal allocation, as in the European market.

- 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 behavior.
- Since it leads to higher uniform prices, AIC pricing tends to reduce short-term consumer surplus (although this might also increase investment incentives).
- AIC prices can be sensitive to formulation choices (Proposition 6).

Compared to other approaches proposed in the literature with the objective of eliminating make-whole payments, such as the "MMWP" approach, 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: Writing – original draft, Writing – review & editing, Software, Methodology, Formal analysis, Conceptualization. **Richard O'Neill:** Writing – review & editing, Methodology, Conceptualization. **Anthony Papavasiliou:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Proofs of the propositions

Proof of Proposition 1. Let us first define the following problem:

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

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

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

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

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 $z^* = z^*_{CH}$ is a *sufficient* condition for an equilibrium to exist in model (1). 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 $z^* = z^*_{CH}$ is a *necessary* condition for an equilibrium to exist in model (1), 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, and $z^* = z^*_{CH}$.

Proof of 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:

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

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

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

Proof of 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 of 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 5.1 and developed in the Online Appendix: applying the AIC Definition 3 to the 3-bin formulation results in certain additional constraints on v and w which can impact the way that fixed costs are reflected in the price signal. The reader may check that applying the 1-bin or 3-bin formulation to Example C.1. of the Online Appendix would lead to the same price difference as in Options A* and B discussed therein.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2025.109047.

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