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The Cost of Fairness in Electricity Markets

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The Cost of Fairness in Electricity Markets

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Abstract

European policymakers argue that bidding zones with uniform prices ensure fairness in electricity markets. Since the outcome of such a fair spot market is often infeasible due to network constraints, a second stage is needed: the redispatch. I establish a mechanism design result showing that even a minimal fairness restriction on the first stage strictly increases procurement costs for asymmetric dispatches. In detail, I analyze a market-based redispatch mechanism where inc-dec gaming creates arbitrage profits for those producers that benefit the network the least. These results identify a general cost of fairness in sequential markets and question uniform bidding zones in electricity markets.

Keywords: mechanism design, fairness, electricity market design

JEL codes: D47, D82, L94, Q48

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1 Introduction

European electricity markets are built around the principle of fairness: producers within the same bidding zone receive a uniform spot market price regardless of their location. Most countries therefore maintain a single national bidding zone, with only Norway, Sweden, Denmark, and Italy being divided into multiple zones. This commitment to uniform pricing, however, ignores limited transmission capacities within bidding zones. As a result, the dispatch determined in the spot market is often not physically feasible and must subsequently be corrected through a second market stage: the redispatch. The procurement costs of this redispatch are then shared equally among consumers.

The alternative to this two-stage mechanism is nodal pricing, also known as locational marginal pricing. This one-stage mechanism—used in most regions of the United States—directly delivers feasible dispatches by setting different prices for any two nodes that are connected with congested transmission lines. Similarly, the redispatch could be avoided with a bidding zone split that is fine enough to reflect all transmission constraints.

Economists (Grimm et al. 2024) and transmission system operators (ENTSO-E 2025) have argued that European electricity markets should introduce more local price components and therefore remove the second stage of the market or make it less relevant. This is in line with the economic intuition that prices should reflect local scarcity of a good to create efficient incentives for production, consumption, and investment. Additionally, the theoretical literature on inc-dec gaming—a strategy to increase supply in the first stage and then decrease—finds examples in which arbitrage opportunities between the two stages inflate procurement costs (Holmberg 2026; Holmberg and Lazarczyk 2015; Hirth and Schlecht 2020). Even though inc-dec gaming is not yet thoroughly understood, increasing redispatch costs hint at its practical relevance.[1]

[1] Redispatch costs in the German–Luxembourgish bidding zone increased from 1.3 billion euros in 2019 to 2.8 billion euros in 2024 (Bundesnetzagentur 2025). In the Dutch zone, they increased from 61 million euros in 2019 to 132 million euros in 2025 (TenneT 2020; TenneT 2026).

Still, policymakers insist on maintaining the two-stage mechanism. The central argument in favor of the uniform price is the perceived unfairness of locational price differentiation (Eicke and Schittekatte 2022). Boris Rhein (2025), the Minister-President of the German federal state Hesse, has argued that the uniform price "offers equal opportunities to all citizens and businesses."[2]

This paper analyzes the consequences of maintaining this market design. To satisfy the fairness criterion, a two-stage mechanism must give all players the opportunity to sell electricity in the spot market at a uniform price. How does this fairness restriction affect procurement costs? When and how does inc-dec gaming increase procurement costs?

I contribute to the understanding of the cost of fairness in sequential markets from a mechanism design perspective. I use electricity-market terminology and formulate the model as a procurement problem, but the result has a direct analogue for sequential allocation problems. Absent the fairness restriction, a revelation-principle argument implies that two-stage mechanisms can implement the same social choice functions as one-stage mechanisms. I therefore compare fair two-stage mechanisms with one-stage mechanisms and ask whether imposing fairness on the first-stage market increases the cost of implementing a given final allocation. For general feasibility constraints, I show that any fair two-stage mechanism has weakly higher procurement costs than an appropriate one-stage mechanism that implements the same final allocation. The inequality is strict under a simple asymmetry condition on the allocation. This establishes that the cost of fairness is a general consequence of restricting the intermediate market outcome rather than of a particular redispatch mechanism.

In the electricity-market interpretation, the proof identifies the economic mechanism behind this result. Producers who are unlikely to remain dis-

[2]Germany uses cost-based redispatch instead of market-based redispatch. However, this mechanism may still allow strategic behavior since the redispatch compensation also covers "proven foregone revenue opportunities" (*nachgewiesene entgangene Erlösmöglichkeiten*; § 13a Abs. 2 S. 3 Nr. 3 EnWG).

patched after the redispatch can exploit the fairness restriction by increasing first-stage quantities in anticipation of a profitable downward redispatch. These arbitrage opportunities prevent procurement-cost minimization with uniform spot-market prices.

I then provide an economic interpretation of the general result through a detailed analysis of a specific market-based redispatch mechanism. The model identifies the producers who benefit from the additional rents implied by the general result, explains why these rents accrue to producers with low expected production externalities, and derives implications for bidding behavior, investment incentives, and grid expansion. In particular, arbitrage gains accrue to producers that benefit the network the least because they are located in nodes with abundant supply or have relatively unfavorable cost distributions. Market-based redispatch therefore rewards inefficient production capacities and distorts both investment incentives and the market signals for transmission expansion.

The following section situates my findings in the existing literature. Section 3 develops the general model of sequential market mechanisms using electricity-market terminology. Section 4 establishes the mechanism design result on the cost of fairness and explains the economic mechanism behind it. Section 5 applies this result to a specific market-based redispatch mechanism and derives implications for bidding behavior, investment incentives, and bidding zone design. Section 6 concludes.

2 Related Literature

This paper contributes to the mechanism design literature on fairness and restrictions on discriminatory treatment of market participants. In unconstrained mechanism design, differences in the distributions of private information generally provide a reason to treat participants differently. Myerson (1981), for example, shows that optimal auctions depend on bidders' virtual valuations and therefore need not treat bidders with different type distributions symmetrically.

A central distinction is whether fairness is imposed on the rules of a mechanism or on its equilibrium outcomes. Deb and Pai (2017) and Azrieli and Jain (2018) study restrictions that require auction rules to treat participants symmetrically. They show that, under Bayes–Nash implementation, such restrictions have surprisingly little bite because differences in private-information distributions can generate asymmetric equilibrium outcomes.

Mass et al. (2020) strengthen this approach through imitation perfection, which requires bidders to be able to imitate the allocation and payment opportunities available to others. This restriction ensures non-discriminatory treatment among homogeneous bidders and limits discrimination under heterogeneity, but can be incompatible with efficiency and revenue maximization under heterogeneity. Chen and Knyazev (2026) instead characterize revenue-maximizing auctions within a class of mechanisms that implement discrimination-free social choice functions for heterogeneous bidders. I take a complementary approach. Rather than strengthening symmetry of the mechanism rules or optimizing within a given class of discrimination-free outcomes, I impose fairness directly on the equilibrium outcome of the first stage.

In the sequential setting considered here, fairness requires not only a uniform first-stage price but also effective access to trade at that price, since the value of a first-stage assignment depends on the continuation mechanism. I then ask what this restriction costs the mechanism designer while holding the final allocation fixed. I show that the continuation stage cannot undo the cost of the fairness restriction: for asymmetric dispatches, every fair two-stage implementation has strictly higher procurement costs than an appropriately designed one-stage implementation of the same final dispatch.

The sequential structure is important for this question. In the dynamic mechanism design literature, multiple stages are typically valuable because players learn additional private information over time (Bergemann and Välimäki

2010; Pavan et al. 2014). Here, private information does not change between stages. Then, a revelation-principle argument implies that a one-stage mechanism can implement the same social choice function as an unrestricted two-stage mechanism. Sequentiality matters instead because fairness is imposed on an intermediate market outcome.

Closest to this aspect, Arozamena et al. (2023) study a symmetric procurement auction followed by a prespecified renegotiation game and show how the continuation stage can generate preferential treatment. I allow the designer instead to choose the second-stage mechanism within a general class, subject to voluntary participation. Nevertheless, Proposition 1 shows that every such mechanism with a fair first stage has strictly higher procurement costs than an appropriately designed one-stage mechanism whenever the implemented dispatch is asymmetric. Hence, the cost of fairness does not arise from a particular redispatch or renegotiation procedure, but from imposing fairness on the intermediate market outcome itself.

This mechanism design result advances the understanding of electricity markets by interpreting inc-dec gaming as a manifestation of the cost of fairness in sequential mechanisms. Existing theoretical analyses of inc-dec gaming focus on specific market designs and network structures. Holmberg and Lazarczyk (2015) and Holmberg (2026) study models with a continuum of infinitesimally small producers without private information about production costs and show that export-constrained producers can profit from inc-dec gaming in market-based redispatch. Hirth and Schlecht (2020) obtain a similar result with a finite number of producers, while Ehrhart et al. (2026) identify inc-dec gaming in a setting with private information about production costs.

My analysis differs by separating the general cost created by a fair first stage from the properties of a particular redispatch mechanism. The general mechanism design result does not require a specific network structure or redispatch procedure and provides a necessary and sufficient condition for a fair two-stage implementation to have strictly higher procurement costs than an appropriately designed one-stage implementation. The specific market-based redispatch mechanism analyzed in Section 5 then shows how these additional rents arise through inc-dec gaming and identifies the producers who receive them.

The comparison with Ehrhart et al. (2026) further shows that the design of the redispatch stage matters for the magnitude of procurement costs. Their market-based redispatch mechanism aims to minimize trading in the second stage. In their setting, I show that allowing more extensive redispatch can reduce total procurement costs by changing incentives already in the first stage (Appendix G).

To isolate these strategic effects from allocative inefficiencies, I compare mechanisms that implement a given dispatch function. This differs from Grimm et al. (2022), who analyze a market-based redispatch mechanism that deviates from the efficient dispatch implemented by nodal pricing. Moreover, my analysis does not require specific assumptions about physical feasibility constraints. This allows the general result to apply to network structures for which analytical treatments of Kirchhoff's law and additional security constraints are typically difficult and often require numerical optimization (Neuhoff et al. 2005; Grimm et al. 2016; Egerer et al. 2025).

Finally, the paper relates to the policy debate on investment incentives under different electricity market designs. An argument in favor of market-based redispatch has been the need to preserve efficient investment incentives in grids and production capacities (Haucap and Pagel 2013). I show instead that the arbitrage rents generated by market-based redispatch reward production capacities in export-constrained regions and can therefore distort both generation and transmission investment incentives.

3 Environment

Consider an electricity network consisting of a set of electricity producers $\mathcal{I} = \{1, 2, ..., I\}$. Every producer i can provide one unit of electricity and privately learns her production cost c_i that is independently drawn with probability measure F_i on the support $[\underline{c}, \overline{c}]$ with $\overline{c} > \underline{c} \geq 0$. I assume $F_i(\{\underline{c}\}) > 0$ for all i.[3] Besides the symmetric support, I do not further restrict asymmetries of the distributions. I write c to denote a profile of cost realizations and c_{-i} to denote the costs for all players other than i. I write F and F_{-i} to denote the probability measures of c and c_{-i}. In the spirit of the mechanism design literature, I also refer to c_i as the type of player i.

Total demand for electricity is $D \in \mathbb{N}$. I call y a dispatch if it is an element of the outcome set $Y = \left\{y \in \{0,1\}^I : \sum_{i=1}^{I} y_i = D\right\}$. A dispatch is feasible if it respects the limited capacities of transmission lines between producers. For a general notion of feasibility, I call $\hat{Y} \subset Y$ the set of feasible dispatches. Let $\hat{Y}_{-i}$ be the subset of feasible dispatches that satisfy $y_i = 0$ and let $\hat{Y}_{+i}$ be the subset of feasible dispatches satisfying $y_i = 1$. I assume that for every i the two subsets $\hat{Y}_{-i}$ and $\hat{Y}_{+i}$ are nonempty. This is to avoid that a producer i has infinite market power while also making her production feasible.

An outcome of the electricity market is a tuple $x = (y, t)$ that consists of a dispatch $y \in Y$ and a vector of payments to the producers $t \in \mathbb{R}^I$. Let $\hat{X}$ be the set of outcomes with feasible dispatches and X the unrestricted outcome set.

[3] The lowest possible cost $\underline{c}$ refers to a producer that can generate the unit with variable costs close to zero, as with wind or solar power, and has no possibility to store the electric power. A positive probability mass at $\underline{c}$ is therefore plausible in electricity markets with substantial renewable generation. The assumption is also useful technically: in the proof of Proposition 1, it ensures that the type profile in which all producers have cost $\underline{c}$ occurs with positive probability, so first-stage production at this profile translates into positive interim production probability for type $\underline{c}$. Without such a mass point, an analogous argument would require working with types arbitrarily close to $\underline{c}$ or an appropriate limiting version of the fairness condition. The mass-point assumption should therefore be viewed mainly as a convenient way to formulate the boundary argument rather than as the economic source of the cost-of-fairness result.

4 The Cost of Fairness

4.1 One-stage mechanisms and two-stage mechanisms

To develop my main result, I need to define the classes of mechanisms I compare.

Definition 1 (One-stage mechanisms)**.** *A one-stage mechanism* $M_I = (\mathcal{S}, \mathbf{x})$ *consists of the set of possible action profiles* $\mathcal{S} = \prod_{i=1}^{I} S_i$*, where* S_i *is the action set of player* i*, and an outcome function* $\mathbf{x} : \mathcal{S} \to \hat{X}$*.*

This is the standard definition of one-stage mechanisms. With outcome $(y, t) \in \hat{X}$, the payoff of player i with cost c_i is $-c_i y_i + t_i$.

Definition 2 (Two-stage mechanisms)**.** *A two-stage mechanism is denoted by* $M_{II} = (\mathcal{S}^{(1)}, \mathcal{S}^{(2)}, \mathbf{x}^{(1)}, \mathbf{x}^{(2)}, J)$*. The respective sets of possible action profiles in the first and second stage are* $\mathcal{S}^{(1)} = \prod_{i=1}^{I} S_i^{(1)}$ *and* $\mathcal{S}^{(2)} = \prod_{i=1}^{I} S_i^{(2)}$*. The outcome functions of the first and second stage,* $\mathbf{x}^{(1)} : \mathcal{S}^{(1)} \to X$ *and* $\mathbf{x}^{(2)} : \mathcal{S}^{(2)} \times Y \to \hat{X}$*, give for each player* i *the respective outcomes* $(y_i^{(1)}, t_i^{(1)})$ *and* $(y_i^{(2)}, t_i^{(2)})$ *such that* $t_i^{(1)} = 0$ *when* $y_i^{(1)} = 0$*,* $t_i^{(2)} = 0$ *when* $y_i^{(2)} = y_i^{(1)}$*, and* $t_i^{(2)} \leq 0$ *when* $y_i^{(2)} = 0$ *and* $y_i^{(1)} = 1$*. The profile of signaling functions* J *contains for each player* i *a function* $J_i : \mathcal{S}^{(1)} \to \mathbf{J}_i$ *such that* $J_i(s) = (x_i^{(1)}(s), \gamma_i(s))$ *gives* i*'s outcome of the first stage and potential further signals* $\gamma_i(s)$*.*

With outcomes $(y^{(1)}, t^{(1)}) \in X$ and $(y^{(2)}, t^{(2)}) \in \hat{X}$, the payoff of player i with cost c_i is $-c_i y_i^{(2)} + t_i^{(1)} + t_i^{(2)}$. Without the restrictions that Definition 2 imposes on second-stage transfers, the mechanism designer could circumvent fairness restrictions on the first stage by making it strategically irrelevant. This specification ensures that the first-stage dispatch $y^{(1)}$ matters for producers even though it does not enter payoffs directly. I allow the designer to strategically transmit information about actions and outcomes of the first stage via the signaling function J that is known to all players.

I write a strategy of player i in the one-stage mechanism as a function $\sigma_i : [\underline{c}, \overline{c}] \to S_i$ and in the two-stage mechanism as a tuple of functions $(\sigma_i^{(1)}, \sigma_i^{(2)})$

with $\sigma_i^{(1)} : [\underline{c}, \overline{c}] \to S_i^{(1)}$ and $\sigma_i^{(2)} : [\underline{c}, \overline{c}] \times \mathbf{J}_i \to S_i^{(2)}$. To abbreviate the notation of strategy profiles, I write $\sigma(c)$ in the one-stage mechanism and $\sigma^{(1)}(c)$ and $\sigma^{(2)}\left(c, J(\sigma^{(1)}(c))\right)$ in the respective stages of the two-stage mechanism. From here on, I write y_i, $y_i^{(1)}$, and $y_i^{(2)}$ as the respective parts of the outcome functions from M_I and M_{II} that give the dispatches for player i; and similarly t_i, $t_i^{(1)}$, and $t_i^{(2)}$ for the respective transfer functions. Note that this formulation allows for a broad class of second-stage continuation games and is related to procurement settings with renegotiation as in Arozamena et al. (2023).

It is convenient to define for each player i the (conditional) expectations $\overline{y}_i$, $\overline{t}_i$, $\overline{y}_i^{(1)}$, $\overline{t}_i^{(1)}$, $\overline{y}_i^{(2)}$, and $\overline{t}_i^{(2)}$. For a given strategy profile σ, $\overline{y}_i(c_i)$ and $\overline{t}_i(c_i)$ give the expected quantity and transfer for player i with type c_i in the one-stage mechanism. Similarly, for given strategy profile $(\sigma^{(1)}, \sigma^{(2)})$, I write $\overline{y}_i^{(1)}(c_i)$ and $\overline{t}_i^{(1)}(c_i)$ to denote the expected quantity and transfer for player i with type c_i in the first stage of the two-stage mechanism. I write $\overline{y}_i^{(2)}(c_i, j_i)$ to denote the interim expected quantity for player i with type c_i conditional on observing signal $j_i \in \mathbf{J}_i$ after the first stage of the two-stage mechanism. I define $\overline{t}_i^{(2)}$ analogously. I denote the expected utility from participating in both stages of the two-stage mechanism by $U_i^{II}(c_i)$. The formal definition of (conditional) expectations requires caution with respect to measure-theoretic details that I move to Appendix A.

Definition 3 (Implementation with voluntary participation)**.** *A one-stage mechanism* $M_I = (\mathcal{S}, \mathbf{x})$ *implements a dispatch function* $d : [\underline{c}, \overline{c}]^I \to \hat{Y}$ *with voluntary participation if there is a Bayes-Nash equilibrium strategy profile* σ *of the game induced by* M_I *such that for all* $c \in [\underline{c}, \overline{c}]^I$*, it holds that* $d(c) = y(\sigma(c))$ *and for all* i *and* c_i*, it holds that* $-c_i\overline{y}_i(c_i) + \overline{t}_i(c_i) \geq 0$*. A two-stage mechanism* $M_{II} = (\mathcal{S}^{(1)}, \mathcal{S}^{(2)}, \mathbf{x}^{(1)}, \mathbf{x}^{(2)}, J)$ *implements dispatch function* d *with voluntary participation if there is a Bayes-Nash equilibrium strategy profile* $(\sigma^{(1)}, \sigma^{(2)})$ *of the game induced by* M_{II} *such that*

$$d(c) = y^{(2)}\left(\sigma^{(2)}\left(c, J(\sigma^{(1)}(c))\right), y^{(1)}(\sigma^{(1)}(c))\right) \quad \forall c \in [\underline{c}, \overline{c}]^I$$

and for all i and c_i, it holds that $U_i^{II}(c_i) \geq 0$ and additionally, for all $j_i = ((y_i^{(1)}, t_i^{(1)}), \gamma_i(\sigma^{(1)}(c)))$, it holds that $-c_i\overline{y}_i^{(2)}(c_i, j_i) + \overline{t}_i^{(2)}(c_i, j_i) \geq -c_i y_i^{(1)}$.

I analyze Bayesian implementation with the usual restrictions regarding voluntary participation. In an equilibrium with voluntary participation, the one-stage mechanism cannot give negative expected utility to any type of any player. Similarly, both stages in the two-stage mechanism are voluntary.

In the following, I model the fairness restriction policymakers demand from market mechanisms. Deb and Pai (2017) show that restrictions on the symmetry of outcome function $\mathbf{x}^{(1)}$ impose almost no restrictions on the social choice functions that can be implemented. That is because differences in the distribution of private information parameters allow implementation via asymmetric equilibria. Instead, I impose restrictions on equilibrium outcomes to reflect that spot markets are designed to implement fair allocations in the first stage.

A useful notion of fairness consists of a uniform price condition and additional regularity conditions that prevent the designer from circumventing this uniform price. The core requirement is that producers who sell in the first stage receive the same expected transfer for an assigned unit of production. This captures the uniform pricing rule used in spot markets.

A uniform-price condition alone, however, need not guarantee equal access to trade. This parallels the distinction emphasized by Mass et al. (2020), who show that symmetric auction rules can generate discriminatory equilibrium outcomes and therefore strengthen equal treatment through an imitation requirement: market participants must effectively be able to obtain the allocation and payment opportunities available to others. In the present sequential setting, such an access requirement cannot be formulated solely in terms of first-stage allocations and transfers because the value of a first-stage assignment depends on the continuation mechanism. I therefore impose an outcome-level analogue. A producer must not be denied first-stage trade at the common price when this opportunity would raise her expected utility. Conversely, she must not be assigned first-stage production when the continuation makes this opportunity worse than her equilibrium outcome.

Definition 4 (Fair first stage)**.** *A Bayes-Nash equilibrium of a two-stage mechanism is said to have a fair first stage if there exists a uniform price τ such that, with type $c_i = \underline{c}$, all players*

(i) receive expected transfer τ conditional on $y_i^{(1)} = 1$ in the sense that

$$\frac{\bar{t}_i^{(1)}(\underline{c})}{\bar{y}_i^{(1)}(\underline{c})} = \tau \quad \forall i : \bar{y}_i^{(1)}(\underline{c}) > 0, \tag{1}$$

(ii) receive at least the expected utility from common transfer τ in the sense that

$$U_i^{II}(\underline{c}) \geq \tau - \underline{c} \quad \forall i, \tag{2}$$

(iii) do not sell in the first stage if $\tau - \underline{c}$ would lower their utility in the sense that

$$U_i^{II}(\underline{c}) > \tau - \underline{c} \implies \bar{y}_i^{(1)}(\underline{c}) = 0 \quad \forall i. \tag{3}$$

The restriction to type $\underline{c}$ is deliberate. Conditions (2) and (3) are intended to ensure effective access to trade at the uniform first-stage price, not to require that first-stage trade be equally attractive for every type. For types $c_i > \underline{c}$, the first-stage assignment can itself convey information about the types of other players because it depends on the entire action profile. Being assigned $y_i^{(1)} = 1$ may therefore be good news about the continuation game, while not being assigned may be bad news, or vice versa. Differences in expected utility associated with the first-stage assignment can then reflect this informational content rather than discriminatory access to the uniform price. Imposing analogues of conditions (2) and (3) on all types would consequently rule out such legitimate informational effects. I therefore impose the access requirement only on the boundary type $\underline{c}$. This yields a deliberately weak notion of fairness: Proposition 1 shows that even this minimal restriction is sufficient to increase procurement costs for asymmetric dispatch functions, and the result therefore extends to any stronger notion of fairness that implies Definition 4.

4.2 Main result

First, I define asymmetric dispatch functions. The crucial parameter to evaluate asymmetry of dispatch functions, Ψ_i, is an average of production probabilities of player i weighted across type realizations by the classic envelope formula. Note that Ψ_i is deterministic for a fixed dispatch function.

Definition 5 (Asymmetric dispatch function)**.** *For given dispatch function d, define $\overline{d}_i(c_i) := \int_{[\underline{c},\overline{c}]^{I-1}} d_i(c_i, c_{-i}) dF_{-i}$ and $\Psi_i := \int_{\underline{c}}^{\overline{c}} \overline{d}_i(t)dt$. Let $\Psi_{(k)}$ be the k-th smallest element of $(\Psi_i)_{i=1}^{I}$. Dispatch function d is asymmetric when $\Psi_{(1)} < \Psi_{(D)}$.*

This asymmetry condition is deliberately weak. Roughly speaking, it requires only that the least frequently dispatched producer differs from the D-th least frequently dispatched producer in terms of expected dispatch frequency. The threshold at $\Psi_{(D)}$ reflects that the proof of the main result relies on comparing the least frequently dispatched producer with the set of D producers that receive the uniform first-stage transfer.

Proposition 1 now gives the main result of this paper. Including a *fair* first stage to implement an asymmetric dispatch function comes with increased procurement costs. The proof gives general intuition for inc-dec gaming behavior. Section 5 models a specific market-based redispatch mechanism to add more applied interpretation to this result.

Proposition 1. *Let $\mathcal{M} \neq \emptyset$ be the class of two-stage mechanisms that implement dispatch function d with voluntary participation and fair first stage. There exists a one-stage mechanism that implements d with voluntary participation with strictly lower procurement costs than every $M \in \mathcal{M}$ if and only if d is asymmetric.*

Proof. The proof of Proposition 1 is included in Appendix B. □

In electricity networks that are asymmetric in the distribution of production costs or the set of feasible dispatches, sensible dispatch functions—such as those chosen to minimize procurement costs or maximize societal welfare—are generally asymmetric as they do not satisfy $\Psi_{(1)} = \Psi_{(D)}$. As an example, consider Germany, where electricity demand is high in the south, while supply is high in the north and transmission capacities are limited. For any fixed cost realization c_i, sensible dispatch functions assign a higher probability of being dispatched $\overline{d}_i(c_i)$ if producer i is located in the south. The network is asymmetric. Then, using a *fair* first stage strictly increases procurement costs. Note also that equivalence of procurement costs cannot be recovered by adding efficient producers with high Ψ_i, as Definition 5 is concerned with asymmetry among the low Ψ_i-values.

Since this paper focuses on the shortcomings of the *fair* two-stage mechanism, the main result is based on implementation in Bayes-Nash equilibrium. Refinements such as weak PBE would further narrow the set of social choice functions that can be implemented with a *fair* first stage. However, this equilibrium concept is useful to analyze—as in Section 5—the outcomes of specific two-stage mechanisms.

Proposition 1 speaks in favor of splitting the uniform bidding zones of asymmetric networks. Splitting an asymmetric network into zones that are symmetric in themselves can decrease procurement costs and therefore consumer bills. In a small zone, sensible dispatches can be symmetric. Then, competition among the producers with the lowest Ψ_i-parameters drives procurement costs down such that equivalence with one-stage mechanisms is achieved. Alternatively, policymakers may abandon two-stage mechanisms with *fair* first stage and turn to one-stage mechanisms like nodal pricing.

To illustrate the general mechanism behind Proposition 1, Section 5 analyzes a specific market-based redispatch mechanism. The detailed model identifies the producers who receive the additional rents implied by Proposition 1, explains why these rents arise through inc-dec gaming, and derives further implications for bidding behavior and investment incentives. The following subsection sketches the proof of Proposition 1, which deepens the understanding of inc-dec gaming.

4.3 A general intuition for inc-dec gaming

The economic mechanism behind Proposition 1 is that producers that are rarely dispatched receive more rent than is needed for incentive compatibility. These producers are precisely those with low Ψ_i. There are two natural reasons why a designer might choose such a dispatch function. First, those producers might be located in unfavorable regions with high supply, low demand, and insufficient connections to the rest of the network. Second, those players might have high virtual costs, which make them unattractive for dispatch functions that minimize procurement costs.

Conditional on a given dispatch function, procurement costs are minimized with a no-rent-at-the-bottom condition on transfers. This condition holds when type $\overline{c}$, the least efficient type, has expected utility zero. Two-stage mechanisms with *fair* first stage cannot satisfy this condition when $\Psi_{(1)} < \Psi_{(D)}$ because of the following.

The expected transfer τ for type $\underline{c}$ conditional on $y_i^{(1)} = 1$ has to be sufficiently high to satisfy incentive compatibility and voluntary participation for the player with $\Psi_i = \Psi_{(D)}$. With a *fair* first stage, players with $\Psi_i < \Psi_{(D)}$ and type realization $\underline{c}$ cannot be excluded from this transfer. The first stage is specifically designed to satisfy this notion of fairness. Then, for the players with $\Psi_i < \Psi_{(D)}$, the expected transfer with type $\underline{c}$ is so high that incentive compatibility can only be maintained by sacrificing the no-rent-at-the-bottom condition. The players with $\Psi_i < \Psi_{(D)}$ receive positive expected utility conditional on type realization $\overline{c}$.

When the second stage satisfies the no-rent-at-the-bottom for players with $y_i^{(1)} = 0$, this positive utility must stem from experiencing $y_i^{(1)} = 1$. The players with low Ψ_i accept $y_i^{(1)} = 1$ in anticipation that the second stage sets $y_i^{(2)} = 0$ with high probability. When the received transfer in the first stage outweighs the second-stage payment to go from $y_i^{(1)} = 1$ to $y_i^{(2)} = 0$, the player incurs an arbitrage profit and positive utility. The player increases supply in the first stage and decreases in the second stage, which is exactly the intuition for inc-dec gaming.

5 Nodal pricing and market-based redispatch

Section 4 established that every fair two-stage mechanism implementing an asymmetric dispatch necessarily incurs additional procurement costs. The purpose of this section is to illustrate the underlying economic mechanism with a specific market-based redispatch design in comparison with nodal pricing. In particular, the model identifies the producers who benefit from the additional rents characterized in Proposition 1 and explains how these rents distort bidding and investment incentives.

To apply nodal pricing, I introduce a set of nodes $\mathcal{N} = \{1, 2, ..., N\}$, with a typical node denoted as n. Let $\mathcal{I}_n \subset \mathcal{I}$ be the subset of producers that are located in node n. Every producer is located at exactly one node in the sense that $\cup_{n=1}^{N} \mathcal{I}_n = \mathcal{I}$ and $\mathcal{I}_n \cap \mathcal{I}_m = \emptyset$ for every $m \neq n$.

In the following two subsections, I formalize the specific mechanisms I analyze, as there exist variations to both. The results give valuable policy implications also for mechanisms that have similar outcomes in the sense that they implement roughly efficient dispatches.

5.1 Nodal Pricing and VCG

Nodal pricing mechanisms, also known as locational marginal pricing, are one-stage mechanisms that directly achieve a feasible outcome by setting different prices for subsets of nodes that are connected by congested transmission lines. Liu et al. (2009) show the difficulties and variations in formalizing nodal pricing. I begin with a simple definition.

Definition 6 (Nodal pricing)**.** *An electricity market outcome $x = (y, t)$ resulting from bid profile b satisfies the nodal pricing properties if it satisfies the* *following conditions.*

- *For every node $n \in \mathcal{N}$, it holds that $t_i = t_j := p_n$ for any $i, j \in \mathcal{I}_n$ with $y_i = y_j = 1$.*
- *For every node $n \in \mathcal{N}$ with positive production, it holds that all $k \in \mathcal{I}_n$ with $b_k < p_n$ have $y_k = 1$ and all $k \in \mathcal{I}_n$ with $b_k > p_n$ have $y_k = 0$.*
- *Let there be two producers $i \in \mathcal{I}_n$ and $l \in \mathcal{I}_m$ with $y_i = 0$ and $y_l = 1$ while $b_i < p_m$. Let y' be obtained from y by setting $y'_i = 1$, $y'_l = 0$, and $y'_k = y_k$ for all $k \notin \{i, l\}$. Then, it holds that $y' \notin \hat{Y}$.*

The first condition requires that dispatched producers within the same node receive the same price. The second condition imposes a local merit order: producers bidding below the nodal price are dispatched, while producers bidding above it are not. The third condition captures network congestion: a producer dispatched at nodal price p_m cannot be replaced by a producer bidding below p_m.

In my setting with single-unit production capacities, the VCG mechanism in the spirit of Vickrey (1961) is a nodal pricing mechanism under a plausible assumption on the set of feasible dispatches (Proposition 2). A more specific setting with the same property is analyzed by Ehrhart et al. (2026).

Assumption 1 (Discrete midpoint closure)**.** *Let y and y' be feasible dispatches from $\hat{Y}$. Let $y'' \in Y$ satisfy*

$$\sum_{i \in \mathcal{I}_n} y''_i \in \left\{ \left\lfloor \frac{\sum_{i \in \mathcal{I}_n} y_i + \sum_{i \in \mathcal{I}_n} y'_i}{2} \right\rfloor, \left\lceil \frac{\sum_{i \in \mathcal{I}_n} y_i + \sum_{i \in \mathcal{I}_n} y'_i}{2} \right\rceil \right\}$$

for every node $n \in \mathcal{N}$. Then, $y'' \in \hat{Y}$.

Assumption 1 is a modification of the convexity property to the discrete set of feasible dispatches in my model. The literature on optimal power flow in electricity networks establishes that one may reasonably restrict attention to convex sets of feasible dispatches (Gan et al. 2015; Dymarsky and Turitsyn

2019) and a similar convexity assumption is made by Holmberg and Lazarczyk (2015). When two dispatches are feasible, then it is also feasible to generate in each node the average nodal production of the initial two dispatches without violating transmission constraints. When the average is not an integer, Assumption 1 allows rounding either up or down as long as total production equals demand D such that $y'' \in Y$. Note that the restriction is imposed only on the total production per node and therefore production can be freely reallocated within a node. In particular, by taking the midpoint of some $y \in \hat{Y}$ and y itself, Assumption 1 implies that all dispatches with the same total production per node are also feasible.

In the following, I apply the VCG mechanism to my electricity network and show that it satisfies the nodal pricing property under Assumption 1. Every player i makes a bid $b_i \in \mathbb{R}$. The resulting dispatch is

$$y^{VCG} \in \arg\min_{y \in \hat{Y}} \sum_{i=1}^{I} y_i b_i.$$

As the minimization is on a finite set, there is at least one minimum. In case there are multiple solutions, the mechanism deterministically selects one of them. Random tie-breaking would not change the following results, but deterministic tie-breaking is in line with the class of mechanisms from Section 4.

The intuition of the VCG mechanism is that every producer with $y_i = 1$ receives a payment that equals the size of the (positive) externality her production creates on the (announced) total production costs of others. To quantify the payments, recall that for each producer i the subset of feasible dispatches setting $y_i = 0$ is called $\hat{Y}_{-i}$ and is nonempty. The payment to producer i is then given by

$$t_i = \left(\min_{y \in \hat{Y}_{-i}} \sum_{k \neq i} y_k b_k \right) - \sum_{k \neq i} y_k^{VCG} b_k.$$

Note that, by this definition, it holds that $t_i = 0$ for all producers with $y_i^{VCG} = 0$.

Proposition 2 (VCG is nodal pricing)**.** *Let Assumption 1 be satisfied. Then, every outcome of the VCG mechanism satisfies the nodal pricing property.*

Proof. The proof of Proposition 2 is included in Appendix C. □

Proposition 2 shows that, in the electricity network with single-unit production capacities, the VCG mechanism satisfies the nodal pricing properties. First, producers located at the same node receive the same nodal price for producing a unit, and production within each node follows the local merit order. Second, a producer dispatched at a given node cannot be replaced by a cheaper excluded producer at another node. Differences in nodal prices therefore reflect binding transmission constraints. Roughly speaking, nodal prices are higher in import-constrained than in export-constrained nodes.

5.2 Market-based redispatch

In this subsection, I formalize a market-based redispatch mechanism that implements the same efficient dispatch function as the above nodal pricing mechanism. The following subsection assesses the equilibrium of the mechanism regarding inc-dec strategies and procurement costs and outlines the parallels to the general results from Section 4 while providing additional interpretation. Observation 2 shows that the analyzed equilibrium in the market-based redispatch mechanism has a *fair* first stage. Observation 3 notes that the expected production externality determining the possibility of arbitrage profits through inc-dec gaming is equivalent to the parameter Ψ_i from Section 4 up to an added constant.

In practice, there exists a variety of different market-based redispatch mechanisms. The "global" market-based redispatch I analyze here allows considerable changes compared to the first-stage dispatch. In contrast, the "minimal" market-based redispatch analyzed by Ehrhart et al. (2026) aims to minimize trading in the second stage. In Appendix G, I show that "global" market-based redispatch has lower expected procurement costs than "minimal" market-based redispatch in the setting analyzed by Ehrhart et al. (2026).

In the first stage of a market-based redispatch mechanism, the transmission constraints are ignored and a preliminary outcome $x^{(1)} \in X$ is reached that might not be feasible. Participation in the second stage is voluntary. Thus, a producer only participates in the second stage if she expects a weakly better outcome than $x^{(1)}$.

In both stages, all producers simultaneously make a bid. I write $b_i^{(1)} \in \mathbb{R}$ to denote the bid of producer i in the first stage and $b_i^{(2)} \in \mathbb{R}$ to denote the bid of producer i in the second stage. In the first stage, the lowest D bids are accepted. Let $b_{(D+1)}^{(1)}$ be the $(D+1)$-th order statistic of $(b_i^{(1)})_{i=1}^I$. Then, $y_i^{(1)} = 1$ for all producers with $b_i^{(1)} < b_{(D+1)}^{(1)}$ and $y_i^{(1)} = 0$ for all producers with $b_i^{(1)} > b_{(D+1)}^{(1)}$. Again, ties at $b_{(D+1)}^{(1)}$ are resolved deterministically such that $\sum_{i=1}^I y_i^{(1)} = D$. The first stage sets $t_i^{(1)} = 0$ for all producers with $y_i^{(1)} = 0$ and $t_i^{(1)} = b_{(D+1)}^{(1)}$ for all producers with $y_i^{(1)} = 1$. I call $b_{(D+1)}^{(1)}$ the zonal price in my electricity spot market with a uniform bidding zone. The first stage is a uniform price auction without transmission constraints. In the spirit of the signaling function J_i from Section 4, producer i learns $(y_i^{(1)}, t_i^{(1)})$ from the first stage. That is, producer i learns her allocation from the spot market before bidding in the redispatch stage. For all the following results, it does not matter whether the signaling function J_i reveals further information about the first-stage bids.

I denote the final outcome after the second stage of the market-based redispatch mechanism with $x^{MBR} = (y^{(2)}, t^{(1)} + t^{(2)})$. The total transfer $t_i^{MBR} = t_i^{(1)} + t_i^{(2)}$ is given by the sum of transfers from both stages for each producer. To mimic the nodal pricing mechanism, the second stage sets

$$y^{(2)} \in \arg\min_{y \in \hat{Y}} \sum_{i=1}^{I} y_i b_i^{(2)}.$$

Payments from the second stage are conditional on the redispatch quantities. Players with $y_i^{(1)} = y_i^{(2)}$ receive transfer $t_i^{(2)} = 0$ in the second stage. Again, $\hat{Y}_{-i} \subset \hat{Y}$ is the subset of feasible dispatches setting $y_i = 0$ and $\hat{Y}_{+i} \subset \hat{Y}$ is the subset of feasible dispatches setting $y_i = 1$. Players with $y_i^{(1)} = 0$ and $y_i^{(2)} = 1$ receive as a transfer for the upward redispatch

$$t_i^{(2)} = \left(\min_{y \in \hat{Y}_{-i}} \sum_{k \neq i} y_k b_k^{(2)} \right) - \sum_{k \neq i} y_k^{(2)} b_k^{(2)}.$$

This is equivalent to the definition of the transfers in the nodal pricing mechanism. Players with $y_i^{(1)} = 1$ and $y_i^{(2)} = 0$ receive as a transfer for the downward redispatch

$$t_i^{(2)} = \left(\min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k b_k^{(2)} \right) - \sum_{k \neq i} y_k^{(2)} b_k^{(2)}.$$

Analogously to Proposition 2, it can be shown that, under Assumption 1, producers from the same node receive the same transfers when they engage in the same direction of redispatch. Additionally, it is possible to derive the following relationship between transfers for upward and downward redispatch within a given node.

Observation 1. *Let Assumption 1 be satisfied. Let $y^{(1)}$ and $y^{(2)}$ be the respective dispatches from the first and second stage of the market-based redispatch mechanism and $t^{(2)}$ be the transfers from the second stage. Let i and j be producers from the same node. Let j engage in upward redispatch ($y_j^{(1)} = 0, y_j^{(2)} = 1$) and i engage in downward redispatch ($y_i^{(1)} = 1, y_i^{(2)} = 0$). Then, it holds that $t_i^{(2)} + t_j^{(2)} \geq 0$.*

Proof. The proof of Observation 1 is included in Appendix D. □

In practice and in the equilibrium $b^{(2)} = c$ analyzed in Section 5.3, producers receive positive transfers for upward redispatch and negative transfers for downward redispatch. Observation 1 then implies that, within any node, the transfer producers receive for upward redispatch is higher than the transfer producers pay for downward redispatch.

5.3 Inc-dec gaming and procurement costs

In this section, I show that the crucial parameter for existence and size of arbitrage profits through inc-dec gaming is an expected production externality. Players who, in expectation, do not significantly lower incurred production costs of others with their production have low expected production externalities. Players with the lowest expected production externalities receive the largest arbitrage profits from inc-dec gaming. Existence and size of arbitrage profits depend on the asymmetry of expected production externalities across players.

I begin with the derivation of equilibria.

Proposition 3 (Nodal pricing equilibrium). *The strategies $b_i = c_i$ form a dominant-strategy equilibrium in the nodal pricing mechanism.*

Proof. Recall that nodal pricing is equivalent to the VCG mechanism in this setting. The strategies $b_i = c_i$ are the truthtelling equilibrium in dominant strategies of the VCG mechanism. □

In nodal pricing, producers truthfully report their costs and the outcome is ex-post efficient. Payments are equal to the nodal prices p_n. This is already an argument in favor of nodal pricing mechanisms. It is always possible to achieve, in a dominant-strategy equilibrium, an ex-post efficient dispatch with a nodal pricing mechanism.

Definition 7 (Expected production externality). *For every producer $i \in \mathcal{I}$, define* $\varphi_i := E\left[\min_{y \in \hat{Y}_{-i}} \sum_{k \neq i} y_k c_k - \min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k c_k\right]$.

The expected production externality φ_i measures the expected decrease in production costs that others experience when i participates in production. This parameter is crucial in the analysis of inc-dec gaming in market-based redispatch.

Proposition 4 (Market-based redispatch equilibrium). *Consider redispatch bids $b_i^{(2)}(c_i) = c_i$ and $b_i^{(1)}(c_i) = \varphi_i$. Then, together with any weakly consistent* *belief system, $(b_i^{(1)}, b_i^{(2)})_{i=1}^I$ form a weak perfect Bayesian equilibrium of the market-based redispatch mechanism.*

Proof. The proof of Proposition 4 is included in Appendix E. $\square$

The redispatch stage resembles nodal pricing and achieves an ex-post efficient allocation. Note that, in this equilibrium, the first stage reveals no private information. Every player bids independently of her type realization. The intuition for this is that the first stage only influences utility through its effect on transfers and does not affect the final dispatch. The first-stage dispatch determines whether a player receives a payment for upward redispatch or makes a payment for downward redispatch in the second stage. The proof of Proposition 4 shows that the optimal bid to maximize the sum of expected transfers is independent of the type.

In the following, I evaluate transfers and procurement costs. Note that bids in the first stage depend only on the distributions of other players' cost parameters. No private information is revealed in the first stage. As above, let $\varphi_{(k)}$ denote the k-th smallest element of $(\varphi_i)_{i=1}^I$.

Proposition 5 (Comparison of nodal pricing and market-based redispatch)**.** *Let $x^{nodal} = (y^{nodal}, t^{nodal})$ and $x^{MBR} = (y^{MBR}, t^{MBR} = t^{(1)} + t^{(2)})$ be the respective equilibrium outcomes of nodal pricing and market-based redispatch following from the equilibrium bids described in Proposition 3 and Proposition 4. For every producer $i \in \mathcal{I}$, it holds that $y_i^{nodal} = y_i^{MBR}$ and $E[t_i^{MBR}] - E[t_i^{nodal}] = \max\{0, \varphi_{(D+1)} - \varphi_i\}$. Market-based redispatch has strictly higher expected procurement costs than nodal pricing if and only if $\varphi_{(D+1)} > \varphi_{(1)}$.*

Proof. Let $(b_i^{nodal})_{i=1}^I$ and $(b_i^{(1)}, b_i^{(2)})_{i=1}^I$ be the equilibrium bids described in Proposition 3 and Proposition 4. Recall that $b_i^{nodal} = b_i^{(2)} = c_i$. Then, the equivalence of dispatches follows from the equivalent definitions of y^{nodal} and y^{MBR}. The zonal price in the first stage is equal to $\varphi_{(D+1)}$. Producers with $\varphi_i > \varphi_{(D+1)}$ always receive $t_i^{(1)} = 0$ and therefore $E[t_i^{MBR}] - E[t_i^{nodal}] = 0$ follows from the definition of transfers. The same holds for all producers with

$\varphi_i = \varphi_{(D+1)}$ that receive $y_i^{(1)} = 0$. For all producers with $\varphi_i < \varphi_{(D+1)}$, it holds that $y_i^{(1)} = 1$ and

$$\begin{aligned} E[t_i^{(1)} + t_i^{(2)}|c_i] - E[t_i^{nodal}|c_i] &= \varphi_{(D+1)} + \bar{t}_i^{(2)}(c_i, y_i^{(1)} = 1) - E[t_i^{nodal}|c_i] \\ &= \varphi_{(D+1)} + \bar{t}_i^{(2)}(c_i, y_i^{(1)} = 0) - \varphi_i - E[t_i^{nodal}|c_i] \\ &= \varphi_{(D+1)} - \varphi_i. \end{aligned}$$

The second equality follows from the proof of Proposition 4. Producers with $\varphi_i = \varphi_{(D+1)}$ receive either $y_i^{(1)} = 0$ or $y_i^{(1)} = 1$. Combining the two arguments from above, for those producers it also holds that $E[t_i^{MBR}] - E[t_i^{nodal}] = 0$. Hence, it holds for every producer i that $E[t_i^{MBR}] - E[t_i^{nodal}] = \max\{0, \varphi_{(D+1)} - \varphi_i\}$. The final statement follows immediately. □

Proposition 5 concludes that the possibility of systematic arbitrage payments due to inc-dec gaming depends on expected production externalities φ_i. A producer i makes arbitrage gains in market-based redispatch when $\varphi_i < \varphi_{(D+1)}$. The expected production externality φ_i measures the expected positive welfare effect of i's production on the rest of the network. It is low in nodes with low expected nodal prices and, within a given node, for producers with relatively unfavorable cost distributions. That is, the market-based redispatch mechanism makes excessive payments to the producers who benefit the network the least. Hence, market-based redispatch may be called into question not only because of its excessive procurement costs, but also because of the allocation of the additional payments to producers who are inefficient in terms of production costs and location.

Recall that, in the analyzed market-based redispatch equilibrium, bids in the first stage reveal no private information. Bids are entirely driven by the hunt for arbitrage profits. This model illustrates most strongly the undesirable features of two-stage mechanisms in electricity markets. When the second stage allows changes to the dispatch—partial changes or even complete changes as in the analyzed mechanism—the first stage leaves room for profit maximization beyond the usual information rents for the provided electricity.

In the following, I strengthen the connection to the general result in Proposition 1 by showing that, under Assumption 2, the market-based redispatch mechanism has a *fair* first stage and the crucial asymmetry in φ relates to asymmetry in Ψ.

Assumption 2 (Contribution of (in)efficient producers)**.** *For every producer i and F_{-i}-almost every type profile c_{-i}, it holds that*

$$\underline{c} + \min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k c_k \leq \min_{y \in \hat{Y}_{-i}} \sum_{k \neq i} y_k c_k \leq \bar{c} + \min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k c_k.$$

Assumption 2 states that a producer with the lowest possible cost $\underline{c}$ can be included in an efficient dispatch, while a producer with the highest possible cost $\bar{c}$ can be excluded from an efficient dispatch. The assumption is stated in terms of weak cost comparisons and therefore allows for ties. In particular, it does not require that all producers with cost $\underline{c}$ are dispatched simultaneously. This is crucial, since there can be more than D producers with cost $\underline{c}$ with positive probability.

Observation 2. *Under Assumption 2, the market-based redispatch equilibrium has a fair first stage.*

Proof. Condition (1) is satisfied with uniform spot market price given by $\tau = \varphi_{(D+1)}$. For condition (2), note that it follows from the proof of Proposition 4 that no player with $y_i^{(1)} = 0$ would prefer $y_i^{(1)} = 1$ at this spot market price.

Condition (2) for players with $y_i^{(1)} = 1$ and Condition (3) are proven jointly by showing that, for F_{-i}-almost every c_{-i}, a player with $y_i^{(1)}(\underline{c}, c_{-i}) = 1$ receives exactly utility $\tau - \underline{c}$. To see that this proves condition (3) by contraposition, note that all players with $\overline{y}_i^{(1)}(\underline{c}) \neq 0$ have $y_i^{(1)}(\underline{c}, c_{-i}) = 1$ for all c_{-i}. Then, realized utility of producer i trivially equals $\tau - \underline{c}$ if $y_i^{(2)}(\underline{c}, c_{-i}) = 1$. When

$y_i^{(2)}(\underline{c}, c_{-i}) = 0$, realized utility is equivalently

$$\tau + \left(\left(\min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k c_k \right) - \sum_{k \neq i} y_k^{(2)} c_k \right) = \tau - \underline{c}.$$

To see this, note that $y_i^{(2)}(\underline{c}, c_{-i}) = 0$ implies that

$$\underline{c} + \min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k c_k \geq \sum_{k \neq i} y_k^{(2)} c_k$$

and the first inequality in Assumption 2 implies for F_{-i}-almost every c_{-i} that

$$\underline{c} + \min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k c_k \leq \sum_{k \neq i} y_k^{(2)} c_k.$$

Together, the two inequalities imply equality, and therefore the realized utility is $\tau - \underline{c}$.

□

Observation 3. *Let d be the ex-post efficient dispatch function implemented by the two mechanisms and consider $\Psi_i = \int_{\underline{c}}^{\overline{c}} \overline{d}_i(t)dt$ as in Section 4. Under Assumption 2, expected production externalities satisfy $\varphi_i = \Psi_i + \underline{c}$ for every i.*

Proof. This proof is included in Appendix F. □

Recall that the condition for the cost of fairness in the general model from Section 4 is $\Psi_{(1)} < \Psi_{(D)}$. Since Ψ is a monotone transformation of φ, this is equivalent to $\varphi_{(1)} < \varphi_{(D)}$ and stronger than the condition $\varphi_{(1)} < \varphi_{(D+1)}$ from Proposition 5.[4] However, this result shows that the above market-based redispatch mechanism achieves almost everything that is possible with a *fair* first stage. To prevent inc-dec gaming in asymmetric electricity networks, the *fair* first stage needs to be relinquished. Switching to nodal pricing represents

[4]When $\varphi_{(1)} = \varphi_{(D)} < \varphi_{(D+1)}$, inc-dec gaming and arbitrage profits can be avoided with a mechanism that forces a *fair* first stage upon the players as illustrated in Appendix B.2 with the proof of Proposition 1.

a holistic approach to such a reform. However, bidding zone splits can achieve the same effect in some cases. For example, suppose certain regions are symmetric in themselves in the sense that producers within a region have equal expected production externalities φ_i. Splitting the spot market into such symmetric regions while maintaining a redispatch stage yields the same expected procurement costs as nodal pricing.[5]

Considering dynamic environments, the possibility of arbitrage gains in market-based redispatch creates an incentive to invest in production capacities in nodes that already have abundant supply and insufficient transmission capacities to distribute production to the rest of the network. Inc-dec gaming artificially creates congestion in the spot market in both the short run, with distorted bidding behavior, and the long run, with distorted investment incentives. Then, the spot market sends distorted signals for investments in transmission lines. The need for grid investment in zones with market-based redispatch might be smaller than the spot market signals.

6 Conclusion

European electricity markets justify uniform spot market prices as a fair way to organize trade. This paper shows that this notion of fairness comes at a fundamental cost. More generally, the mechanism design result identifies a cost of imposing fairness on an intermediate outcome in sequential market mechanisms. In the electricity-market application, whenever the efficient dispatch is asymmetric, implementing a fair first stage with a uniform spot market price necessarily increases procurement costs relative to an appropriately designed one-stage mechanism. No redispatch design can fully offset this disadvantage. The underlying mechanism is inc-dec gaming: producers who are unlikely to remain dispatched after the redispatch stage can profit from selling at the uni-

[5] This is because $b^{(1)} = \varphi$ remains an equilibrium in the two-stage mechanism with split spot markets. Since the technical tools used above are sufficient for this result, a dedicated section on bidding zone splits is spared.

form spot price in anticipation that buying back their production in the second stage is cheaper. Thus, the cost of fairness in this setting is the additional procurement cost imposed by the uniform spot market price.

The general model deliberately abstracts from differences in production capacities by assuming that every producer supplies a single unit of electricity. Besides making the analysis tractable, this assumption isolates the procurement-cost effects of inc-dec gaming by giving every producer equal market power. The resulting characterization therefore separates the strategic distortions created by the market design from effects that arise solely from differences in producer size.

The second part of the paper illustrates the general mechanism with a specific market-based redispatch design. It shows that arbitrage profits from inc-dec gaming accrue to producers that contribute least to the network in expectation, either because they are located in export-constrained regions or because they have relatively unfavorable cost distributions. As a result, the mechanism not only increases procurement costs but also creates incentives to invest in production capacities that are inefficient from the perspective of the electricity network. Furthermore, the spot market no longer provides reliable signals for grid expansion, as congestion is driven not only by physical scarcity but may be exaggerated by strategic bidding incentives.

The analyzed redispatch design allows the second stage to reorganize the spot-market dispatch more extensively than market-based redispatch mechanisms studied in the literature. Appendix G shows that this "global" redispatch design can even reduce procurement costs relative to more restrictive redispatch mechanisms. More importantly, it provides a transparent illustration of how inc-dec gaming distorts bidding incentives. In the analyzed equilibrium, spot-market bids become independent of realized production costs and therefore cease to convey private information. While practical redispatch mechanisms typically retain some informational content in spot-market bids, the analysis demonstrates how strongly inc-dec incentives can undermine the informativeness of the spot market.

In conclusion, the paper shows that fairness in electricity markets should be evaluated at the level of the entire market design rather than only at the spot market stage. Uniform spot-market prices may appear fair in isolation, yet they necessitate a redispatch stage that creates strategic distortions and increases procurement costs. These findings strengthen the economic case for more localized pricing through nodal pricing or appropriately designed bidding zone splits.

Appendix

A Conditional expectations

Conditional expectations require careful definition, especially when conditioning on signal realizations j_i that occur with probability zero—cases where Bayes' rule cannot be applied. For an equilibrium strategy profile σ,

$$\overline{y}_i(c_i) := \int_{[\underline{c},\overline{c}]^{I-1}} y_i(\sigma(c))dF_{-i}$$

gives the expected quantity allocated to player i with type c_i in the one-stage mechanism. I define $\overline{t}_i$, $\overline{y}_i^{(1)}$, and $\overline{t}_i^{(1)}$ analogously.

For a given strategy profile $(\sigma^{(1)}, \sigma^{(2)})$, write the expected final quantity for producer i with type c_i in the two-stage mechanism as

$$\overline{y}_i^{II}(c_i) := \int_{[\underline{c},\overline{c}]^{I-1}} y_i^{(2)} \left(\sigma^{(2)}(c, J(\sigma^{(1)}(c))), y^{(1)}(\sigma^{(1)}(c))\right) dF_{-i}$$

and define $\overline{t}_i^{II}(c_i)$ analogously. Then, expected utility from participating in both stages of the two-stage mechanism with strategy profile $(\sigma^{(1)}, \sigma^{(2)})$ is given by

$$U_i^{II}(c_i) := -c_i\overline{y}_i^{II}(c_i) + \overline{t}_i^{(1)}(c_i) + \overline{t}_i^{II}(c_i).$$

Under the mild assumptions of the disintegration theorem, I obtain regularity of second-stage expectations conditional on first-stage signals. These assumptions consist of the action spaces and signal space $\mathbf{J}_i$—equipped with their Borel sigma-algebras—being standard Borel spaces, and the outcome functions, signaling function J, and strategies being Borel-measurable functions. Note that I do not need to restrict attention to settings that satisfy those assumptions. Instead, for the proof by construction in the second part of the proof of Proposition 1 (Appendix B.2), I identify a mechanism that satisfies them.

When the above assumptions hold, conditional on strategies $(\sigma^{(1)}, \sigma^{(2)})$, I can write

$$\overline{y}_i^{(2)}(c_i, j_i) \coloneqq \int_{[\underline{c},\overline{c}]^{I-1}} y_i^{(2)}\left(\sigma^{(2)}(c, J(\sigma^{(1)}(c))), y^{(1)}(\sigma^{(1)}(c))\right) d\mu_{i,c_i,j_i} \tag{4}$$

to denote the interim expected quantity allocated to player i with type c_i conditional on first-stage signal $j_i \in \mathbf{J}_i$. Here, μ_{i,c_i,j_i} is a probability measure from $\Delta([\underline{c},\overline{c}]^{I-1})$ that describes the distribution of types of players other than i conditional on observing c_i and j_i. By the disintegration theorem, for every player i and type c_i, there exists a family of conditional probability measures from $\Delta([\underline{c},\overline{c}]^{I-1})$ denoted by $\{\mu_{i,c_i,j_i}\}_{j_i \in \mathbf{J}_i}$ such that

$$\int_{\mathbf{J}_i} \overline{y}_i^{(2)}(c_i, j_i) d\nu_{i,c_i} = \overline{y}_i^{II}(c_i). \tag{5}$$

Here, I write $\nu_{i,c_i} \coloneqq F_{-i} \circ \left(J_i \circ \sigma^{(1)}(c_i, \cdot)\right)^{-1}$ to denote the probability measure of signal realizations j_i conditional on c_i. Then, equation (5) states that the conditional expectation is consistent with the Law of Iterated Expectations. By the disintegration theorem, the family of conditional probability measures $\{\mu_{i,c_i,j_i}\}_{j_i \in \mathbf{J}_i}$ is ν_{i,c_i}-almost everywhere uniquely determined and therefore the conditional expectation $\overline{y}_i^{(2)}(c_i, j_i)$ is ν_{i,c_i}-almost everywhere uniquely determined. For the analogous definition of $\overline{t}_i^{(2)}(c_i, j_i)$ it is sufficient to additionally assume integrability of the transfer functions. For the definition of implementation with voluntary participation (Definition 3), I say that voluntary participation in the second stage is satisfied when there exist conditional expectations $\overline{y}_i^{(2)}(c_i, j_i)$ and $\overline{t}_i^{(2)}(c_i, j_i)$ as above that satisfy $-c_i\overline{y}_i^{(2)}(c_i, j_i) + \overline{t}_i^{(2)}(c_i, j_i) \geq -c_i y_i^{(1)}$ for all i and all (c_i, j_i). Hence, existence of a set $\mathcal{M}$ of *fair* two-stage mechanisms as in the "if" part of Proposition 1 implicitly assumes that these mechanisms allow taking the relevant conditional expectations.

B Proof of Proposition 1

This proof relies heavily on the techniques by Myerson (1981). I begin with some preliminaries. As defined in Appendix A, I denote, for a given strategy profile $(\sigma^{(1)}, \sigma^{(2)})$, the expected allocation and utility after observing the type realization c_i by $\overline{y}_i^{II}(c_i)$, $\overline{t}_i^{II}(c_i)$, and $U_i^{II}(c_i)$.

For a given social choice function $f = (d, p)$, I write $\overline{d}_i(c_i) := \int_{[\underline{c},\overline{c}]^{I-1}} d_i(c_i, c_{-i})dF_{-i}$ to denote the expected quantity assigned to player i with type c_i and similarly $\overline{p}_i(c_i) := \int_{[\underline{c},\overline{c}]^{I-1}} p_i(c_i, c_{-i})dF_{-i}$ to denote the expected transfer to player i with type c_i. Then, $U_i^f(c_i) := -c_i\overline{d}_i(c_i) + \overline{p}_i(c_i)$ denotes the expected utility of player i with type c_i under social choice function $f = (d, p)$.

By the definition of implementation, an equilibrium of a two-stage mechanism that implements f satisfies $\overline{y}_i^{II}(c_i) = \overline{d}_i(c_i)$ and $U_i^{II}(c_i) = U_i^f(c_i)$ for every i and c_i.

Lemma B.1 (Myerson (1981), Lemma 2)**.** *A social choice function $f = (d, p)$ can be implemented with some one-stage mechanism with voluntary participation if and only if $\overline{d}_i(\cdot)$ is weakly decreasing and for every i and c_i, it holds that*

$$U_i^f(c_i) = U_i^f(\overline{c}) + \int_{c_i}^{\overline{c}} \overline{d}_i(t)dt$$

for some $U_i^f(\overline{c}) \geq 0$.

Lemma B.1 is a standard result from mechanism design.

Lemma B.2 (Incentive compatibility of two-stage mechanisms)**.** *A social choice function $f = (d, p)$ can be implemented with voluntary participation with some two-stage mechanism with fair first stage only if $\overline{d}_i(\cdot)$ is weakly decreasing and for every i and c_i, it holds that*

$$U_i^f(c_i) = U_i^f(\overline{c}) + \int_{c_i}^{\overline{c}} \overline{d}_i(t)dt$$

for some $U_i^f(\overline{c}) \geq 0$.

Lemma B.2 follows from Lemma B.1 with a revelation principle argument. Imposing additionally a *fair* first stage does not change that the above is a necessary condition.

B.1 Proof of "if"

For an implementable dispatch function d, I show that its direct one-stage mechanism with $U_i^f(\overline{c}) = 0$ for all i has strictly lower procurement costs than any implementation via a two-stage mechanism with *fair* first stage when $\Psi_{(1)} < \Psi_{(D)}$. I begin with an auxiliary lemma.

Lemma B.3. *Consider an implementation of d with voluntary participation via a two-stage mechanism with fair first stage. $\Psi_{(1)} < \Psi_{(D)}$ implies that there is at least one player k with $U_k^{II}(\overline{c}) = U_k^f(\overline{c}) > 0$.*

Proof. Consider an implementation of d with voluntary participation via such a two-stage mechanism. Let $\mathcal{I}_{\underline{c}}$ be the set of players with $\overline{y}_i^{(1)}(\underline{c}) > 0$. Note that there are at least D players in this set: at the type profile $(\underline{c}, \dots, \underline{c})$ exactly D players are assigned production in the first stage. Since $F_{-i}(\{\underline{c}_{-i}\}) > 0$, each of these players has $\overline{y}_i^{(1)}(\underline{c}) > 0$. Then, $\Psi_{(1)} < \Psi_{(D)}$ implies that there is a player $i \in \mathcal{I}_{\underline{c}}$ with $\Psi_i > \Psi_{(1)}$. Compare i to player k with $\Psi_k = \Psi_{(1)}$. Conditions (2) and (3) of the *fair* first stage imply that $U_k^{II}(\underline{c}) \geq U_i^{II}(\underline{c}) = \tau - \underline{c}$. Lemma B.2 then implies that $U_k^{II}(\overline{c}) > U_i^{II}(\overline{c}) \geq 0$, which completes the proof. □

For a given social choice function $f = (d, p)$, expected procurement costs are given by the sum of expected transfers to the players. With the integral incentive compatibility conditions, this can be written as

$$
\begin{aligned}
PC(f) &= \sum_{i=1}^{I} \int_{\underline{c}}^{\overline{c}} \overline{p}_i(c_i) dF_i \\
&= \sum_{i=1}^{I} \int_{\underline{c}}^{\overline{c}} \left(U_i^f(c_i) + c_i \overline{d}_i(c_i) \right) dF_i \\
&= \sum_{i=1}^{I} \int_{\underline{c}}^{\overline{c}} \left(U_i^f(\overline{c}) + \int_{c_i}^{\overline{c}} \overline{d}_i(t) dt + c_i \overline{d}_i(c_i) \right) dF_i
\end{aligned}
$$

$$\geq \sum_{i=1}^{I} \int_{\underline{c}}^{\overline{c}} \left(\int_{c_i}^{\overline{c}} \overline{d}_i(t)dt + c_i \overline{d}_i(c_i) \right) dF_i.$$

Hence, the one-stage mechanism that implements d with $U_i^f(\overline{c}) = 0$ for all i has strictly lower procurement costs than the two-stage mechanism that, by Lemma B.3, must set $U_k^{II}(\overline{c}) = U_k^f(\overline{c}) > 0$ for some player k.

B.2 Proof of "only if"

Dispatch functions with $\Psi_{(1)} = \Psi_{(D)}$ can be implemented with minimal costs via two-stage mechanisms with *fair* first stage. I show this by constructing an appropriate two-stage mechanism. For given dispatch function d, let $\mathcal{I}_\Psi$ be some set of D players with $\Psi_i = \Psi_{(1)} = \Psi_{(D)}$. Consider the mechanism that sets $y_i^{(1)}(s) = 1$ and $t_i^{(1)}(s) = \Psi_{(1)} + \underline{c}$ for all players $i \in \mathcal{I}_\Psi$ for any first-stage action profile s. For all other players, the mechanism sets $y_i^{(1)}(s) = 0$ and $t_i^{(1)}(s) = 0$. This mechanism forces a *fair* first stage upon the players.

The second stage follows the intuition of a direct mechanism. For any player i and any action profile s, the signaling function gives $J_i(s) = (x_i^{(1)}(s))$. That is, no additional information about actions is revealed. For any player i, the second-stage action set is given by $S_i^{(2)} = [\underline{c}, \overline{c}]$. For all action profiles $r \in [\underline{c}, \overline{c}]^I$, the outcome function gives dispatch $y^{(2)}(r, y^{(1)}) = d(r)$. For players $i \notin \mathcal{I}_\Psi$, the transfer is $t_i^{(2)}(r, y^{(1)}) = 0$ if $y_i^{(2)}(r, y^{(1)}) = 0$ or $\overline{d}_i(r_i) = 0$ and

$$t_i^{(2)}(r, y^{(1)}) = \frac{\int_{r_i}^{\overline{c}} \overline{d}_i(t)dt}{\overline{d}_i(r_i)} + r_i$$

else. Consider now expected second-stage allocations and transfers—conditional on observing type and the first-stage allocation—$\overline{y}_i^{(2)}(r_i, x_i^{(1)})$ and $\overline{t}_i^{(2)}(r_i, x_i^{(1)})$ as defined in Appendix A. With the simple structure of the first stage, regularity of these conditional expectations is trivial and I can write them as below. I claim that there is an equilibrium where all players truthfully announce their type. A player $i \notin \mathcal{I}_\Psi$ receives $y_i^{(1)} = 0$ and—conditional on truthful play—

receives expected utility

$$\begin{aligned}
U_i^{II}(c_i) &= -c_i \overline{y}_i^{(2)}(c_i, x_i^{(1)}) + \overline{t}_i^{(2)}(c_i, x_i^{(1)}) \\
&= -c_i \overline{d}_i(c_i) + \overline{d}_i(c_i) \left(\frac{\int_{c_i}^{\overline{c}} \overline{d}_i(t)dt}{\overline{d}_i(c_i)} + c_i \right) \\
&= \int_{c_i}^{\overline{c}} \overline{d}_i(t)dt.
\end{aligned}$$

Conditional on truthful play by all other players, it is optimal for a player $i \notin \mathcal{I}_\Psi$ to also play truthfully because the gain from announcing the true type c_i instead of some $c_i' > c_i$ is

$$\begin{aligned}
&- c_i \overline{y}_i^{(2)}(c_i, x_i^{(1)}) + \overline{t}_i^{(2)}(c_i, x_i^{(1)}) - (-c_i \overline{y}_i^{(2)}(c_i', x_i^{(1)}) + \overline{t}_i^{(2)}(c_i', x_i^{(1)})) \\
=&- c_i \overline{y}_i^{(2)}(c_i, x_i^{(1)}) + \overline{t}_i^{(2)}(c_i, x_i^{(1)}) - (-c_i' \overline{y}_i^{(2)}(c_i', x_i^{(1)}) + \overline{t}_i^{(2)}(c_i', x_i^{(1)})) \\
&- c_i' \overline{y}_i^{(2)}(c_i', x_i^{(1)}) + \overline{t}_i^{(2)}(c_i', x_i^{(1)}) - (-c_i \overline{y}_i^{(2)}(c_i', x_i^{(1)}) + \overline{t}_i^{(2)}(c_i', x_i^{(1)})) \\
=&U_i^f(c_i) - U_i^f(c_i') - (c_i' - c_i)\overline{y}_i^{(2)}(c_i', x_i^{(1)}) \\
=&\int_{c_i}^{c_i'} \overline{d}_i(t)dt - (c_i' - c_i)\overline{d}_i(c_i') \geq 0.
\end{aligned}$$

The inequality follows from the fact that $\overline{d}_i$ is weakly decreasing. It can be shown similarly that deviations to $c_i' < c_i$ are not profitable.

Consider now players $i \in \mathcal{I}_\Psi$. Their transfer is set to $t_i^{(2)}(r, y^{(1)}) = 0$ if $y_i^{(2)}(r, y^{(1)}) = 1$ or $\overline{d}_i(r_i) = 1$ and

$$t_i^{(2)}(r, y^{(1)}) = \frac{-\int_{\underline{c}}^{r_i} \overline{d}_i(t)dt - \underline{c} + r_i \overline{d}_i(r_i)}{1 - \overline{d}_i(r_i)}$$

else. Since $\overline{d}_i$ is weakly decreasing, it holds that $\int_{\underline{c}}^{r_i} \overline{d}_i(t)dt \geq (r_i - \underline{c})\overline{d}_i(r_i)$ and this transfer is nonpositive. Conditional on truthful play, expected utility of a player $i \in \mathcal{I}_\Psi$—who receives $y_i^{(1)} = 1$—is then

$$U_i^{II}(c_i) = -c_i \overline{y}_i^{(2)}(c_i, x_i^{(1)}) + \overline{t}_i^{(2)}(c_i, x_i^{(1)}) + \overline{t}_i^{(1)}(c_i)$$

$$= -c_i\overline{d}_i(c_i) + (1-\overline{d}_i(c_i))\frac{-\int_{\underline{c}}^{c_i}\overline{d}_i(t)dt - \underline{c} + c_i\overline{d}_i(c_i)}{1-\overline{d}_i(c_i)} + \int_{\underline{c}}^{\overline{c}}\overline{d}_i(t)dt + \underline{c}$$
$$= \int_{c_i}^{\overline{c}}\overline{d}_i(t)dt.$$

It can be shown as above that deviations are not profitable.

It remains to verify that the first stage is *fair* according to Definition 4. Set $\tau = \Psi_{(1)} + \underline{c}$. For every player $i \in \mathcal{I}_\Psi$, it holds that $\Psi_i = \Psi_{(1)}$ and $y_i^{(1)}(\underline{c}) = 1$. From the expected utility derived above, $U_i^{II}(\underline{c}) = \int_{\underline{c}}^{\overline{c}} d_i(t)\,dt = \Psi_i$. Hence, for every $i \in \mathcal{I}_\Psi$, it holds that $U_i^{II}(\underline{c}) = \Psi_{(1)} = \tau - \underline{c}$, while for every $i \notin \mathcal{I}_\Psi$ it holds that $U_i^{II}(\underline{c}) = \Psi_i \geq \Psi_{(1)} = \tau - \underline{c}$. Thus, all three conditions of Definition 4 are satisfied.

To complete the proof, it remains to be shown that this implementation does not violate participation constraints. The first part can be seen immediately from $U_i^{II}(c_i) = \int_{c_i}^{\overline{c}}\overline{d}_i(t)dt \geq 0$.

To satisfy voluntary participation in the second stage, it needs to be shown that $-c_i\overline{y}_i^{(2)}(c_i, x_i^{(1)}) + \overline{t}_i^{(2)}(c_i, x_i^{(1)}) \geq -c_iy_i^{(1)}$. For players $i \notin \mathcal{I}_\Psi$, I have $y_i^{(1)} = 0$ and the participation constraint is satisfied by

$$-c_i\overline{y}_i^{(2)}(c_i, x_i^{(1)}) + \overline{t}_i^{(2)}(c_i, x_i^{(1)}) = \int_{c_i}^{\overline{c}}\overline{d}_i(t)dt \geq 0 = -c_iy_i^{(1)}.$$

For players $i \in \mathcal{I}_\Psi$, I have $y_i^{(1)} = 1$ and their participation constraint is given by

$$\begin{aligned}-c_i\overline{y}_i^{(2)}(c_i, x_i^{(1)}) + \overline{t}_i^{(2)}(c_i, x_i^{(1)}) &= -c_i\overline{d}_i(c_i) + (1-\overline{d}_i(c_i))\frac{-\int_{\underline{c}}^{c_i}\overline{d}_i(t)dt - \underline{c} + c_i\overline{d}_i(c_i)}{1-\overline{d}_i(c_i)}\\ &= -\underline{c} - \int_{\underline{c}}^{c_i}\overline{d}_i(t)dt\\ &\geq -c_i.\end{aligned}$$

Note that the inequality holds with equality at $c_i = \underline{c}$ and therefore holds also at all $c_i > \underline{c}$ because $\overline{d}_i(t) \leq 1$ at all $t \in [\underline{c}, \overline{c}]$.

C Proof of Proposition 2

I begin with an auxiliary result for the first statement.

Lemma C.1. *Let Assumption 1 be satisfied. For any $b \in \mathbb{R}^I$, let $y \in \arg\min_{y \in \hat{Y}} \sum_{i=1}^I y_i b_i$. Let $y' \in \hat{Y}$. Let $y'' \in Y$ satisfy*

$$\sum_{i \in \mathcal{I}_n} y''_i \in \left\{ \left\lfloor \frac{\sum_{i \in \mathcal{I}_n} y_i + \sum_{i \in \mathcal{I}_n} y'_i}{2} \right\rfloor, \left\lceil \frac{\sum_{i \in \mathcal{I}_n} y_i + \sum_{i \in \mathcal{I}_n} y'_i}{2} \right\rceil \right\}$$

for every node $n \in \mathcal{N}$ and $y''_i = y_i = y'_i$ for all $i \in \mathcal{I}$ with $y_i = y'_i$. Then, the discrete midpoint y'' is weakly preferred to y' in the sense that

$$\sum_{i=1}^I y''_i b_i \leq \sum_{i=1}^I y'_i b_i.$$

Proof. By Assumption 1, the discrete midpoint y'' is feasible. Define the complementary dispatch $y''' := y + y' - y''$. By construction, $y''' \in \{0,1\}^I$. Moreover, for every node $n \in \mathcal{N}$, the aggregate production under y''' is the complementary rounding of the average aggregate production under y and y'. Hence, $y''' \in Y$, and Assumption 1 implies $y''' \in \hat{Y}$.

By construction, $y + y' = y'' + y'''$. Therefore,

$$\sum_{i=1}^I y_i b_i + \sum_{i=1}^I y'_i b_i = \sum_{i=1}^I y''_i b_i + \sum_{i=1}^I y'''_i b_i.$$

Suppose, toward a contradiction, that

$$\sum_{i=1}^I y''_i b_i > \sum_{i=1}^I y'_i b_i.$$

The above identity then implies

$$\sum_{i=1}^I y'''_i b_i < \sum_{i=1}^I y_i b_i,$$

which contradicts the optimality of y. $\square$

Lemma C.1 states that a midpoint of an optimal dispatch y and any alternative dispatch y' is weakly preferred to the alternative dispatch y'. This is helpful to prove Proposition 2. In the following, I write y^{VCG} and t to denote the dispatch and transfers resulting from the VCG mechanism. Begin with the first statement from the definition of the nodal pricing property and suppose, toward a contradiction, that there are two players i and j from the same node with $y_i^{VCG} = y_j^{VCG} = 1$ and $t_i \neq t_j$. Without loss of generality, let $t_i < t_j$.

Then, take any $y' \in \arg\min_{y \in \widehat{Y}_{-i}} \sum_{k=1}^{I} y_k b_k$, which exists because $\hat{Y}_{-i}$ is nonempty and finite. If $y'_j = 1$, set $y^{(-i)} = y'$. Otherwise, $y'_j = 0$. In this case, we can choose a discrete midpoint $y^{(-i)}$ of y^{VCG} and y' such that $y_i^{(-i)} = 0$ and $y_j^{(-i)} = 1$. By Lemma C.1,

$$\sum_{k=1}^{I} y_k^{(-i)} b_k \leq \sum_{k=1}^{I} y'_k b_k.$$

Since $y' \in \hat{Y}_{-i}$ is optimal and $y^{(-i)} \in \hat{Y}_{-i}$, $y^{(-i)}$ is also optimal. Hence,

$$y^{(-i)} \in \arg\min_{y \in \widehat{Y}^{-i}} \sum_{k=1}^{I} y_k b_k \qquad \text{and} \qquad y_j^{(-i)} = 1.$$

Let $y^{(-j)}$ be a dispatch that satisfies $y_k^{(-j)} = y_k^{(-i)}$ for all players $k \notin \{i, j\}$. Set $y_j^{(-j)} = 0$ and $y_i^{(-j)} = 1$. By Assumption 1 on the nature of transmission constraints, I have $y^{(-j)} \in \hat{Y}$. This is because $y^{(-j)}$ has the same level of production per node as $y^{(-i)}$ and can therefore be written as a midpoint of $y^{(-i)}$ and $y^{(-i)}$ itself. This implies that

$$\min_{y \in \hat{Y}_{-j}} \sum_{k=1}^{I} y_k b_k \leq \sum_{k=1}^{I} y_k^{(-j)} b_k.$$

Then, I have

$$t_j \leq \sum_{k=1}^{I} y_k^{(-j)} b_k - \sum_{k \neq j} y_k^{VCG} b_k$$

$$
\begin{aligned}
&= b_j + \sum_{k=1}^{I} y_k^{(-j)} b_k - \sum_{k=1}^{I} y_k^{VCG} b_k \\
&= b_i + \sum_{k=1}^{I} y_k^{(-i)} b_k - \sum_{k=1}^{I} y_k^{VCG} b_k \\
&= \sum_{k=1}^{I} y_k^{(-i)} b_k - \sum_{k \neq i} y_k^{VCG} b_k \\
&= t_i.
\end{aligned}
$$

This gives the desired contradiction.

I proceed with the second statement from the definition of the nodal pricing property. Consider a player $k \in \mathcal{I}_n$ with $y_k^{VCG} = 0$ while there exists some $i \in \mathcal{I}_n$ with $y_i^{VCG} = 1$. Because i and k belong to the same node, replacing i by k leaves production at every node unchanged. Assumption 1 therefore implies that this alternative dispatch is feasible. It follows from the definition of the VCG mechanism that

$$
\begin{aligned}
p_n = t_i &= \min_{y \in \hat{Y}_{-i}} \sum_{j=1}^{I} y_j b_j - \sum_{j \neq i} y_j^{VCG} b_j \\
&\leq b_k - b_i + \sum_{j=1}^{I} y_j^{VCG} b_j - \sum_{j \neq i} y_j^{VCG} b_j \\
&= b_k,
\end{aligned}
$$

which completes the first part of the second statement. Furthermore, it holds by the definition of the VCG mechanism that $\sum_{j=1}^{I} y_j^{VCG} b_j \leq \min_{y \in \hat{Y}_{-k}} \sum_{j=1}^{I} y_j b_j$. This implies for a player k with $y_k = 1$ that

$$
\begin{aligned}
t_k &= \min_{y \in \hat{Y}_{-k}} \sum_{j=1}^{I} y_j b_j - \sum_{j \neq k} y_j^{VCG} b_j \\
&\geq \sum_{j=1}^{I} y_j^{VCG} b_j - \sum_{j \neq k} y_j^{VCG} b_j \\
&= b_k,
\end{aligned}
$$

which completes the second part of the second statement.

I conclude with the third statement. Suppose, toward a contradiction, that $y' \in \hat{Y}$. It follows that

$$
\begin{aligned}
p_m = t_l &= \min_{y \in \hat{Y}_{-l}} \sum_{j=1}^{I} y_j b_j - \sum_{j \neq l} y_j^{VCG} b_j \\
&\leq b_i - b_l + \sum_{j=1}^{I} y_j^{VCG} b_j - \sum_{j \neq l} y_j^{VCG} b_j \\
&= b_i,
\end{aligned}
$$

which contradicts the assumption of the statement.

D Proof of Observation 1

Let $b^{(2)}$ be the vector of second-stage bids. Suppose that an optimal dispatch conditional on including i's production does not involve production by j. Formally, suppose there exists a

$$
y^{(+i)} \in \arg\min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k b_k^{(2)}
$$

with $y_j^{(+i)} = 0$. By Lemma C.1, this would imply that there is also a $\overline{y}^{(+i)}$ from this set with $\overline{y}_k^{(+i)} = y_k^{(2)}$ for all $k \notin \{i, j\}$ and therefore $t_i^{(2)} = -b_j^{(2)}$.[6] From the definition of the dispatch and the transfers, it follows directly that $t_j^{(2)} \geq b_j^{(2)}$ and therefore $t_i^{(2)} \geq -t_j^{(2)}$.

Similarly, suppose there is a $y^{(-j)} \in \arg\min_{y \in \hat{Y}_{-j}} \sum_{k \neq j} y_k b_k^{(2)}$ with $y_i^{(-j)} = 1$. As above, there exists then also such a $y^{(-j)}$ with $y_k^{(-j)} = y_k^{(2)}$ for all $k \notin \{i, j\}$

[6]To see this, note that, under Assumption 1, it is possible to take a feasible discrete midpoint $\overline{y}$ of $y^{(2)}$ and any such $y^{(+i)}$. When $y_j^{(+i)} = 0$, it is possible to take the midpoint such that $\overline{y}_i = 1$ and $\overline{y}_j = 0$ is maintained. After now taking the midpoint of $y^{(2)}$ and $\overline{y}$, and then taking repeatedly the midpoint of $y^{(2)}$ and the previous midpoint while maintaining the dispatch for i and j, after a finite number of repetitions one arrives at some $\overline{y}^{(+i)} \in \hat{Y}$ with $\overline{y}_j^{(+i)} = 0$ and $\overline{y}_k^{(+i)} = y_k^{(2)}$ for all $k \notin \{i, j\}$. Applying Lemma C.1 to each midpoint gives $\sum_k \overline{y}_k^{(+i)} b_k^{(2)} \leq \sum_k y_k^{(+i)} b_k^{(2)}$ and therefore $\overline{y}^{(+i)} \in \arg\min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k b_k^{(2)}$.

and therefore $t_j^{(2)} = b_i^{(2)}$. From the definition of the dispatch and the transfers, it follows that $t_i^{(2)} \geq -b_i^{(2)}$ and therefore $t_i^{(2)} \geq -t_j^{(2)}$.

Again, consider the dispatches $y^{(+i)} \in \arg\min_{y\in\hat{Y}_{+i}} \sum_{k\neq i} y_k b_k^{(2)}$ and $y^{(-j)} \in \arg\min_{y\in\hat{Y}_{-j}} \sum_{k\neq j} y_k b_k^{(2)}$. It remains to be shown that the statement holds when all such $y^{(+i)}$ and $y^{(-j)}$ have $y_j^{(+i)} = 1$ and $y_i^{(-j)} = 0$. In this case, by Lemma C.1, there has to be such a $y^{(+i)}$ with $y_h^{(+i)} = 0$ for some h with $y_h^{(2)} = 1$, while $y_k^{(+i)} = y_k^{(2)}$ for all $k \notin \{i, h\}$.[7] Similarly, there has to be some $y^{(-j)}$ as above with $y_g^{(-j)} = 1$ for some g with $y_g^{(2)} = 0$, while $y_k^{(-j)} = y_k^{(2)}$ for all $k \notin \{j, g\}$. These two statements imply, respectively, that $t_i^{(2)} = -b_h^{(2)}$ and $t_j^{(2)} = b_g^{(2)}$.

Now, take as a feasible midpoint of $y^{(+i)}$ and $y^{(-j)}$ from above the dispatch $\overline{y}$ with $\overline{y}_j = \overline{y}_g = 1$ and $\overline{y}_i = \overline{y}_h = 0$. Since $\sum_k y_k^{(2)} b_k^{(2)} \leq \sum_k \overline{y}_k b_k^{(2)}$, it holds that $b_h^{(2)} \leq b_g^{(2)}$ and therefore $t_i^{(2)} + t_j^{(2)} = -b_h^{(2)} + b_g^{(2)} \geq 0$.

E Proof of Proposition 4

Similarly to the dominant-strategy equilibrium in the VCG mechanism, bidding $b_i^{(2)} = c_i$ maximizes utility independently of beliefs and second-stage behavior of others. Then, bids in the first stage only affect expected profits through the expected transfers from the two stages since the dispatch $y^{(2)}$ is independent of bids $b^{(1)}$. Conditional on $b_i^{(2)} = c_i$ for all i in the second stage, bidding the expected effect on second stage transfers of setting $y_i^{(1)} = 1$ instead of $y_i^{(1)} = 0$ weakly dominates any other first-stage bid for producer i. Again, as defined in Appendix A, let $\overline{y}_i^{II}(c_i)$ be the probability that player i with cost

[7] To see this, note that, under Assumption 1, it is possible to take a feasible discrete midpoint $\overline{y}$ of $y^{(2)}$ and any such $y^{(+i)}$ such that $\overline{y}_i = 1$. One can then repeatedly take a feasible midpoint of $y^{(2)}$ and the previous midpoint such that i remains with dispatch one until arriving at some $\overline{y}^{(+i)}$ that satisfies $\overline{y}_i^{(+i)} = 1$ and $\overline{y}_h^{(+i)} = 0$ for some producer h with $y_h^{(2)} = 1$, while $\overline{y}_l^{(+i)} = y_l^{(2)}$ for all $l \notin \{i, h\}$. By Lemma C.1, I can take $\overline{y}^{(+i)}$ such that $\overline{y}^{(+i)} \in \arg\min_{y\in\hat{Y}_{+i}} \sum_{k\neq i} y_k b_k^{(2)}$.

realization c_i is assigned $y_i^{(2)} = 1$ after the redispatch stage.

$$
\begin{aligned}
b_i^{(1)}(c_i) =&\overline{y}_i^{II}(c_i) E\left[\left(\min_{y\in\hat{Y}_{-i}} \sum_{k\neq i} y_k b_k^{(2)}\right) - \sum_{k\neq i} y_k^{(2)} b_k^{(2)} \middle| c_i, y_i^{(2)} = 1\right] \\
&- \left(1 - \overline{y}_i^{II}(c_i)\right) E\left[\left(\min_{y\in\hat{Y}_{+i}} \sum_{k\neq i} y_k b_k^{(2)}\right) - \sum_{k\neq i} y_k^{(2)} b_k^{(2)} \middle| c_i, y_i^{(2)} = 0\right] \\
=&\overline{y}_i^{II}(c_i) E\left[\left(\min_{y\in\hat{Y}_{-i}} \sum_{k\neq i} y_k b_k^{(2)}\right) - \left(\min_{y\in\hat{Y}_{+i}} \sum_{k\neq i} y_k b_k^{(2)}\right) \middle| c_i, y_i^{(2)} = 1\right] \\
&- \left(1 - \overline{y}_i^{II}(c_i)\right) E\left[\left(\min_{y\in\hat{Y}_{+i}} \sum_{k\neq i} y_k b_k^{(2)}\right) - \left(\min_{y\in\hat{Y}_{-i}} \sum_{k\neq i} y_k b_k^{(2)}\right) \middle| c_i, y_i^{(2)} = 0\right] \\
=&\overline{y}_i^{II}(c_i) E\left[\left(\min_{y\in\hat{Y}_{-i}} \sum_{k\neq i} y_k b_k^{(2)}\right) \middle| c_i, y_i^{(2)} = 1\right] \\
&+ \left(1 - \overline{y}_i^{II}(c_i)\right) E\left[\left(\min_{y\in\hat{Y}_{-i}} \sum_{k\neq i} y_k b_k^{(2)}\right) \middle| c_i, y_i^{(2)} = 0\right] \\
&- \overline{y}_i^{II}(c_i) E\left[\left(\min_{y\in\hat{Y}_{+i}} \sum_{k\neq i} y_k b_k^{(2)}\right) \middle| c_i, y_i^{(2)} = 1\right] \\
&- \left(1 - \overline{y}_i^{II}(c_i)\right) E\left[\left(\min_{y\in\hat{Y}_{+i}} \sum_{k\neq i} y_k b_k^{(2)}\right) \middle| c_i, y_i^{(2)} = 0\right] \\
=&E\left[\left(\min_{y\in\hat{Y}_{-i}} \sum_{k\neq i} y_k b_k^{(2)}\right) \middle| c_i\right] - E\left[\left(\min_{y\in\hat{Y}_{+i}} \sum_{k\neq i} y_k b_k^{(2)}\right) \middle| c_i\right] \\
=&E\left[\min_{y\in\hat{Y}_{-i}} \sum_{k\neq i} y_k c_k - \min_{y\in\hat{Y}_{+i}} \sum_{k\neq i} y_k c_k\right] = \varphi_i
\end{aligned}
$$

In this equilibrium, there is no uncertainty in the first stage. A player with $\varphi_i < \varphi_{(D+1)}$ always receives $y_i^{(1)} = 1$ with bid $b_i^{(1)} = \varphi_i$. Deviating to bids that do not change $y_i^{(1)}$ does not change i's payoff. Deviating to bids $b_i^{(1)} > \varphi_{(D+1)}$,[8] changes the dispatch to $y_i^{(1)} = 0$ and $t_i^{(1)} = 0$. The expected utility gain from this deviation is $\varphi_i - \varphi_{(D+1)} < 0$ as can be seen from the derivation above. Similarly, players with $\varphi_i > \varphi_{(D+1)}$ would make a loss with deviations that change the first-stage allocation. When there are multiple players with $\varphi_i = \varphi_{(D+1)}$, they are indifferent between all possible bids in the first stage.

[8] Or to $b_i^{(1)} = \varphi_{(D+1)}$ when the tie-breaking rule alters the dispatch in this case.

When there is only one player with $\varphi_i = \varphi_{(D+1)}$, this player makes a loss with deviations that change the allocation.

F Proof of Observation 3

It is to be shown that $\varphi_i = \Psi_i + \underline{c}$, or equivalently $\Psi_i = \varphi_i - \underline{c}$. Fix producer i. For a given profile c_{-i}, producer i is included in an efficient dispatch at cost c_i if and only if

$$c_i + \min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k c_k \leq \min_{y \in \hat{Y}_{-i}} \sum_{k \neq i} y_k c_k,$$

up to tie-breaking. Since tie-breaking at equality does not affect the integral over c_i, it follows that

$$d_i(t) = \Pr\left(t + \min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k c_k \leq \min_{y \in \hat{Y}_{-i}} \sum_{k \neq i} y_k c_k \right)$$

for almost every $t \in [\underline{c}, \bar{c}]$. Hence,

$$\Psi_i = \int_{\underline{c}}^{\bar{c}} \Pr\left(t + \min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k c_k \leq \min_{y \in \hat{Y}_{-i}} \sum_{k \neq i} y_k c_k \right) dt.$$

By Fubini's theorem, this equals

$$\mathbb{E}\left[\int_{\underline{c}}^{\bar{c}} \mathbf{1}\left\{ t + \min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k c_k \leq \min_{y \in \hat{Y}_{-i}} \sum_{k \neq i} y_k c_k \right\} dt \right].$$

By Assumption 2, the set of $t \in [\underline{c}, \bar{c}]$ for which the indicator is equal to one has length

$$\min_{y \in \hat{Y}_{-i}} \sum_{k \neq i} y_k c_k - \min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k c_k - \underline{c}.$$

Therefore,

$$\Psi_i = \mathbb{E}\left[\min_{y \in \hat{Y}_{-i}} \sum_{k \neq i} y_k c_k - \min_{y \in \hat{Y}_{+i}} \sum_{k \neq i} y_k c_k \right] - \underline{c} = \varphi_i - \underline{c}.$$

This proves $\varphi_i = \Psi_i + \underline{c}$.

G "Global" market-based redispatch in Ehrhart et al. (2026)

Consider the setting that Ehrhart et al. (2026) use to calculate expected procurement costs of different mechanisms. Nodes (regions) A and B are connected with a transmission line with capacity 1. Demand in node B is two, while demand in node A is zero. There are three producers in A and two producers in B. Each producer i can provide one unit of electricity at cost c_i that is independently drawn from a uniform distribution on the interval $[0, 1]$. Table 1 compares expected procurement costs of "minimal" and "global" market-based redispatch mechanisms in this setting. The design of the "global" market-

Procurement costs	Spot market	Redispatch	total
"Minimal" MBR	0.76	0.42	1.18
"Global" MBR	0.6	0.53	1.13

Table 1: Expected procurement costs

based redispatch also affects bidding in the spot market stage. Even though the "global" market-based redispatch mechanism has higher redispatch costs in this setting, it has lower total procurement costs because of low costs in the spot market stage.

For the sake of completeness, I derive below the results for "global" market-based redispatch. The results for "minimal" market-based redispatch are taken from the paper by Ehrhart et al. (2026). In this setting, "global" market-based redispatch has the same total expected procurement costs as nodal pricing and the VCG mechanism. Hence, total costs can also be taken from the paper by Ehrhart et al. (2026). To calculate the share that stems from the spot market stage, I apply Proposition 4. Bids are equal to expected production externalities. Since all producers have the same distribution of cost parameters, bids are identical within each node. Payments in the spot market equal twice the bid in node A where the expected production externality is lower. To simplify notation, let producers 1, 2, and 3 be in node A and let producers 4 and 5 be in node B.

$$\begin{aligned}
\varphi_1 &= E\left[\min_{y\in\hat{Y}_{-1}}\sum_{k\neq 1} y_k c_k - \min_{y\in\hat{Y}_{+1}}\sum_{k\neq 1} y_k c_k\right] \\
&= (E[\min\{c_4, c_5\}] + E[\min\{\max\{c_4, c_5\}, \min\{c_2, c_3\}\}]) - E[\min\{c_4, c_5\}] \\
&= E[\min\{\max\{c_4, c_5\}, \min\{c_2, c_3\}\}] \\
&= \int_0^1 x(2 + 4x^3 - 6x^2)dx \\
&= 0.3
\end{aligned}$$

For $i \in \mathcal{I}_A$, total payments in the spot market equal $2\varphi_1 = 0.6$.

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