Pricing in Crisis

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Abstract

When demand aggregates both price-sensitive and price-insensitive behaviors, uniform pricing becomes a deficient market design that generates negative surplus during extreme-price events. We develop a price-control mechanism that efficiently resolves the tradeoff between protecting consumers and limiting rents. The mechanism implements a dynamic price cap that responds to demand adjustments and induces truthful supply through incentive payments. In a quantitative application to the French wholesale electricity market during the 2022–2023 energy crisis, the mechanism would have lowered expected procurement costs by roughly €200 billion, about two-thirds of total projected costs in this central scenario.

1 Introduction

Markets in which a homogeneous good is traded at a uniform price often aggregate buyers with heterogeneous abilities to adjust their demand in response to price changes. Some buyers can flexibly reduce or shift their quantities when prices fluctuate, while others cannot, either because of technological rigidities, contractual obligations, or the essential nature of the good. This mixture of elastic and inelastic demands is a structural feature of many high-stakes markets. When supply is tight, the clearing

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price can rise to extreme levels because aggregate demand reflects the willingness to pay only of those who are able to adjust.

From a welfare perspective, this creates a fundamental tension. Leaving prices unconstrained exposes inelastic buyers to shocks, leading to large transfers and inefficient destruction of surplus, while constraining prices too much eliminates incentives for efficient allocation on the responsive margin. Because discrimination between demand types is often infeasible or undesirable, policies such as price control and rationing cannot be targeted to specific groups. The central design challenge is therefore to balance protection of inelastic demand with the preservation of efficiency on the responsive margin.

We start by noting that this problem has, in principle, a simple structure. For any realized demand state (i.e., demand schedule), there exists a unique price threshold at which total consumer surplus is zero, aggregating both the inelastic and elastic components. Under standard regularity conditions, capping the price at this threshold and rationing total demand to clear the market maximizes total surplus. Crucially, this threshold depends only on the composition of demand, not on the shape or level of supply. It can therefore be computed directly whenever the demand schedule is observable and decomposable into responsive and inelastic components.

This result implies a transparent rule for price control: the optimal price cap adjusts dynamically with changes in demand composition, tightening when inelastic demand dominates and relaxing when elastic demand expands. Such a rule cushions price shocks without suppressing the information contained in prices and preserves incentives for efficient adjustment.

Our analysis is cast in general terms, taking as primitives demand and supply schedules as in market exchanges. Electricity markets provide a leading example: our main quantitative application is to the European energy crisis of 2022-2023, discussed below. But price caps are also in everyday use in other high-stakes markets, including short-term money markets. In these markets, a significant share of liquidity demand is effectively exogenous in the short run—arising from payment obligations, collateral needs, and reserve requirements—while the remainder adjusts elastically to interest rates. A central bank enforces the ceiling on the overnight rate by supplying liquidity elastically. In the short run, this masks the rationing implied by the cap. In the long run, however, the central bank's capacity to absorb shocks is limited by balance sheet, risk, and political constraints. When these constraints bind, rationing reemerges through collateral requirements, counterparty access restrictions, or segmentation in the interbank market.[1]

This paper makes the following contributions. First, we characterize the welfare-maximizing price cap in uniform-price markets with elastic and inelastic demand and provide an algorithm to compute it from observed demand schedules. Second, we provide a mechanism-design foundation for the price-cap algorithm by developing an auction mechanism that induces truthful supply behavior. Third, we allow for heterogeneity in buyers' welfare weights and endogenous selection into price responsiveness and show that the price-cap mechanism remains implementable and optimal. Fourth, we apply the theory to the European wholesale electricity market during the 2022 energy crisis, focusing on France, and quantify its implications.

Empirical case. We use hourly market outcomes for 2023 to quantify the drivers of the high contract prices observed in fall 2022. The combination of the EU price-capping protocol then in place and the sharp reduction in nuclear availability—due to systemic technological problems emerging in 2022—together account for the escalation in expected procurement costs, which approached €330 billion for France for 2023 (assuming 70% nuclear availability and €7,000/MWh cap). Applying our price-control mechanism to the same counterfactual generates time-varying caps that would have reduced expected procurement costs by about €200 billion, substantially mitigating the threat to market stability. Under a more adverse 60% availability scenario, expected procurement costs fall by roughly €475 billion. Notably, while rationing is more frequent under the optimal policy, the amount rationed is not materially higher than implied by the prevailing EU protocol. We also compute the incentive payments required to sustain truthful supply of marginal capacity. Under the optimal price-cap policy, these payments fall sharply—to only a few euros per MWh—and are fiscally negligible relative to suppliers' revenues from sales at market prices.

Related literature. Our work contributes to several strands of the literature.

A first strand concerns price controls and rationing as exogenous institutions. A

[1] A related logic appears in fiscal policy. In the model of Halac and Yared (2018), fiscal rules place state-contingent limits on policy instruments to balance flexibility and commitment. This is conceptually similar to a price cap: the rule protects against extreme realizations while preserving responsiveness within the allowed range. In both settings, the cap is a mechanism to structure trade-offs between protection and efficiency.

classic contribution is Weitzman (1977), showing how rationing can improve allocation when some buyers cannot afford essential goods (see also Sah, 1987; Wijkander, 1988). Other studies highlight the distributional and efficiency properties of rationing in the management of common resources (e.g., Donna and Espin-Sanchez, 2023; Ryan and Sudarshan, 2022). In contrast to this literature, which typically treats rationing or price control as exogenous, our result shows that a rationing rule—implemented together with an optimal price cap—arises endogenously as a welfare-maximizing policy even in the absence of distributional weights or externalities. This result reflects the presence of a committed component of demand, which may itself be technologically or institutionally determined, and contrasts with the large price-theory literature emphasizing the efficiency losses from rationing (e.g., Bulow and Klemperer, 2012). The key novelty is that the optimal rationing rule and price cap emerge directly from demand primitives, without invoking additional policy objectives or institutional assumptions.

A second strand of the literature concerns price formation and scarcity pricing in electricity markets. These analyses emphasize that when some consumers cannot respond to price changes, efficiency requires treating demand types differently: inelastic consumers should face fixed prices and be rationed when needed, while elastic consumers should continue to face market prices that guide efficient adjustment (e.g., Wilson, 1989; Joskow and Tirole, 2006, 2007; Borenstein and Holland, 2005; Gowrisankaran et al., 2016). In practice, however, electricity *wholesale* markets clear all demand, derived from different sources, at a single uniform price and do not distinguish between demand types at the market-clearing stage. Our planner would like to follow the explicit discrimination policy but must work with aggregate demand to infer the demand composition for obtaining the welfare-maximizing price cap.[2]

A third literature concerns mechanisms that address market power and informational distortions on the supply side. Within a price-theory framework, efficient allocations can be implemented by clearing the market $n + 1$ times based on the submitted bids. The n counterfactual clearings generate discriminatory unit prices that effectively transform the setting into a Vickrey auction (Vickrey, 1961) with VCG payments, as in Montero (2008). This avoids the inefficiencies of pay-as-bid

[2]The literature on activating consumer price-sensitivity identifies a related but distinct distortion (Fowlie et al., 2021; Ito et al., 2023). Our mechanism remains optimal even after correcting for possible behavioral biases in consumer selection into price-sensitivity; we assume no behavioral biases but only differing private costs of technologies.

auctions (cf. Ausubel et al., 2014). While multi-unit Vickrey auctions are uncommon (cf. Hortaçsu and McAdams, 2018), we find that the two instruments—price caps to buyers and incentive payments to suppliers—jointly solve the trade-off between protecting consumers and limiting producers' rents. Their optimal joint use further makes the design more attractive by reducing the incentive payments required to sustain truthful supply. In extreme-price events when the cap binds, firms receive no incentive payments beyond their market revenue; *the mechanism thus optimally limits rents in times of scarcity*, in contrast to settings without a cap.

A fourth strand studies mechanism design under distributional objectives. Recent contributions have shown how welfare weights shape optimal market designs (e.g., Dworczak et al., 2021; Akbarpour et al., 2024; Pai and Strack, 2022; Tokarski et al., 2023). We allow for heterogeneity in buyers' value of money and for endogenous selection into price responsiveness. In this setting, welfare weights shift the optimal price cap downward when the planner places higher value on inelastic buyers, while responsiveness externalities raise the cap. Despite these additional forces, the mechanism remains tractable and implements the constrained-efficient allocation.

2 Optimal Price Control in a Competitive Market

2.1 Environment

Demand and Supply. The policymaker observes the aggregate demand and supply schedules prior to market clearing. It is useful to think of these schedules as bids submitted to an exchange where the policy is implemented. Let $D_x(p)$ denote aggregate demand in demand state x, differentiable and strictly decreasing in price p, and let $S_y(p)$ denote aggregate supply in supply state y, differentiable and strictly increasing in p.[3]

The joint market state $z = (x, y)$ is drawn from a commonly known joint distribution. The demand function $D_x(p)$ satisfies decreasing differences in (p, x): a higher price reduces demand more in a higher-demand state. The supply function $S_y(p)$ satisfies increasing differences in (p, y): a higher price increases supply more in a higher-supply state. The model therefore allows for shocks to demand, supply, or

[3] We use differential methods for the analytical results; the empirical application implements these objects as step-functions, as observed in the data.

both.

The policymaker does not need to know the functional dependence of these schedules on the underlying states x and y; it is sufficient that the realized schedules are observable as data containing quantities demanded and supplied at each price. We may think of each market opening as a new draw of z and its corresponding schedules. The policy described below specifies how outcomes are chosen in each such realization.

The policymaker controls a single instrument, a *rationing rule* $\mu_z \in [0,1]$, that scales the aggregate demand schedule:

$$D_z(p) = \mu_z D_x(p). \tag{2.1}$$

Given $D_z(p)$ and $S_y(p)$, the market clears at the equilibrium price p_z satisfying

$$D_z(p_z) = S_y(p_z).$$

We assume that this equation defines a unique equilibrium price $p_z > 0$ for every state z, and that the expected values $\overline{p} = \mathbb{E}[p_z]$ and $\overline{p}_x = \mathbb{E}[p_z \mid x]$ remain bounded for all admissible choices by the agents.[4]

Sticky and Non-sticky Demands. Consumers differ in how their individual demand responds to market prices. A share $\theta \in [0,1]$ of consumers are *responsive*, and the remaining $1 - \theta$ are *sticky*. When responsive, a consumer's private demand is $d_x(p)$, a strictly decreasing and differentiable function of price p in any demand state x. When sticky, the consumer does not observe the realized market price but forms rational expectations $\overline{p}_x$. Sticky demand is fixed at the expected-price level $d_x(\overline{p}_x)$, denoted $\overline{d}_x$ for short. Sticky consumers thus understand how their preset demand varies across states and how it correlates with prices, even though it does not adjust to the realized price.[5]

The aggregate demand in any state x can then be written as

$$D_x(p) = (1 - \theta)\,\overline{d}_x + \theta\, d_x(p), \tag{2.2}$$

[4]We omit the subscript z from expectations when no confusion arises.

[5]We collapse the indexation of realized demand schedules D_x and price expectations $\overline{p}_x$. More generally, one can let x determine D_x while forming expectations with respect to an information set X_x such that $x \in X_x$, so that $\overline{p}_x = \mathbb{E}[p_z \mid X_x]$. We suppress this distinction.

where θ is the share of responsive consumers. The policymaker can identify the two components, $\overline{d}_x$ and $d_x(p)$, from observed aggregate data $D_x(p)$ if information on $\overline{p}_x$ is available—for instance, from contract prices or from expert evaluations linking expected prices to demand covariates.

Given $D_x(p)$ and $\overline{p}_x$, identification of sticky demand follows from $D_x(\overline{p}_x) = d_x(\overline{p}_x)$, which pins down $\overline{d}_x$. The share $\theta > 0$ can be inferred from $\lim_{p\to\infty} D_x(p) = (1-\theta)\,\overline{d}_x$, and the responsive demand from

$$d_x(p) = \frac{D_x(p) - (1-\theta)\,\overline{d}_x}{\theta}.$$

With this information, the policymaker can evaluate welfare effects of alternative policies.

To ensure that the welfare evaluations are well defined, we assume that the elasticity of the responsive demand satisfies $\sigma(d_x) > 1$ for sufficiently high p in every state x. This guarantees that the indirect utility from responsive consumption, $u_x(d)$, is finite at $d = 0$. Normalizing $u_x(0) = 0$, utility can be written as

$$u_x(d_x(p)) = p\,d_x(p) + \int_{p' \geq p} d_x(p')\,dp'.$$

Understanding how the concept of utility follows from observables, we move on to the planner's problem.

2.2 Planner's Problem

The planner observes the aggregate demand and supply schedules before market clearing and can influence the market outcome through a rationing rule $\mu_z \in [0,1]$. We also introduce a per-unit tax or subsidy τ_z on consumption, an auxiliary instrument that aids interpretation. Formally, for a given τ_z, we continue to denote the demand by $D_z(p) = \mu_z D_x(p + \tau_z)$.

Aggregate utility in state z is given by

$$U_z = \mu_z\big[(1-\theta)\,u_x(\overline{d}_x) + \theta\,u_x(d_x)\big], \tag{2.3}$$

where $d_x = d_x(p_z + \tau_z)$ is the demand of non-sticky consumers. Because rationing applies uniformly, total utility scales proportionally with μ_z.

Aggregate welfare is

$$W_z = U_z - C_y(D_z), \tag{2.4}$$

where $C_y(D_z)$ is the total cost of supplying quantity D_z, strictly convex and differentiable.

2.3 Main Characterization

Using $d_x = [D_z/\mu_z - (1-\theta)\bar{d}_x]/\theta$, substitute into (2.4) to express welfare as a function of (D_z,μ_z,τ_z). Differentiating yields

$$dW_z = \left[u'_x - C'_y\right] dD_z + \left[\tfrac{U_z}{\mu_z} - \tfrac{D_z}{\mu_z} u'_x\right] d\mu_z, \tag{2.5}$$

where u'_x is the marginal utility of non-sticky consumers, evaluated at $d_x(p_z + \tau_z)$, and C'_y is the marginal cost of total supply D_z.

Equation (2.5) shows how welfare changes with aggregate demand and rationing. The planner can vary demand dD_z through τ_z. Trading sets $u'_x - C'_y = \tau_z$ and it follows immediately that it is not optimal to distort the choices at the adjusting margin by a consumption tax or subsidy.

Proposition 2.1 (Optimal Policy)**.** *The optimal policy does not use taxes or subsidies, $\tau_z = 0$, and regulates the market solely through rationing μ_z. For every state z, the optimal pair (p^*_z,μ^*_z) satisfies*

$$p_z D_z(p_z) \le U_z \ \perp \ \mu_z \le 1. \tag{2.6}$$

That is, rationing applies if and only if consumer surplus is zero at the equilibrium price.

Proof. The first term in (2.5) shows that introducing a tax τ_z would create a gap between u'_x and C'_y, lowering welfare. The first term thus shows that $\tau_z = 0$. The market equilibrium adjusts to variations in μ_z. The second term implies that welfare increases with μ_z when $\frac{U_z}{\mu_z} - \frac{D_z}{\mu_z} u'_x > 0$ and decreases otherwise, establishing the complementarity condition in (2.6). □

Condition (2.6) defines a state-contingent price boundary p^*_z, implemented as a price cap. Because both U_z and D_z scale proportionally with μ_z, the boundary depends only on the demand state x, denoted p_x^*. Thus, remarkably, the optimal policy implies that the planner needs only information about demand to derive the price boundary. When binding, the price cap equates the average utility per unit of consumption,

$$p_x^* = \frac{(1-\theta)\, u_x(\overline{d}_x) + \theta\, u_x(d_x^*)}{(1-\theta)\, \overline{d}_x + \theta\, d_x^*}, \tag{2.7}$$

where $d_x^* = d_x(p_x^*)$. Intuitively, the price p_x^* prevents a negative surplus by balancing the positive consumer surplus from non-sticky consumers and negative surplus from sticky ones.

Implementation of the Optimal Policy. We can now state the rationing policy in full:

Proposition 2.2. *Assume that the demand and supply schedules, $D_x(p)$ and $S_y(p)$, are observable. Then:*

(i) *For each demand state x, the unique optimal price cap p_x^* derived from $D_x(p)$ satisfies (2.7) with $d_x^* = d_x(p_x^*)$, and the relevant utility terms are identified from the observed $D_x(p)$.*

(ii) *For each x, there exists a unique supply state y_x^* such that*

$$S_{y_x^*}(p_x^*) = (1-\theta)\, \overline{d}_x + \theta\, d_x^*.$$

If and only if $y < y_x^*$, it is optimal to implement a binding price cap at $p = p_x^*$ with demand rationed by

$$\mu_z^* = \frac{S_y(p_x^*)}{D_x(p_x^*)}.$$

The optimal rationing loosens, and the rationing price increases, with the share of non-sticky consumers:

$$\frac{\partial \mu_z^*}{\partial \theta} > 0, \qquad \frac{\partial p_x^*}{\partial \theta} > 0.$$

Proof. The planner observes $D_x(p)$ and can identify the sticky and non-sticky shares and the corresponding demands and utilities as described above. To simplify notation, suppress the index x, since the argument is identical for each demand state. We provide a monotone algorithm for determining p^* by induction on index k. Start with

$p_0^* = \overline{p}$ and $d_0^* = \overline{d}$, and construct iteratively

$$p_{k+1}^* = \frac{(1-\theta)u(\overline{d}) + \theta u(d_k^*)}{(1-\theta)\overline{d} + \theta d_k^*}, \qquad d_k^* = d(p_k^*).$$

For any $\theta > 0$, the sequence $\{p_k^*\}$ is monotone. At $k = 0$, $p_1^* = u(\overline{d})/\overline{d} > p_0^* = \overline{p}$, implying $d_1^* < d_0^*$. Because $d'(p) < 0$ and $u(d)/d$ decreases in d, it follows that $p_{k+1}^* > p_k^*$ and $d_{k+1}^* < d_k^*$. The sequence converges for any $\theta < 1$, and the comparative statics follow directly from the limit expression for p^*. The second part of the proposition follows from $S_y(p)$ being strictly increasing in y. □

Figure 1 illustrates an optimal rationing situation for two supply states, $y' < y$, and one demand state. The figure is drawn so that equilibrium F corresponds to the reference equilibrium: sticky and non-sticky demands both equal $\overline{d}_x$ at the reference price $\overline{p}_x$. In this equilibrium, no rationing is required—condition (2.6) holds with strict inequality on the left, as aggregate utility exceeds expenditures.

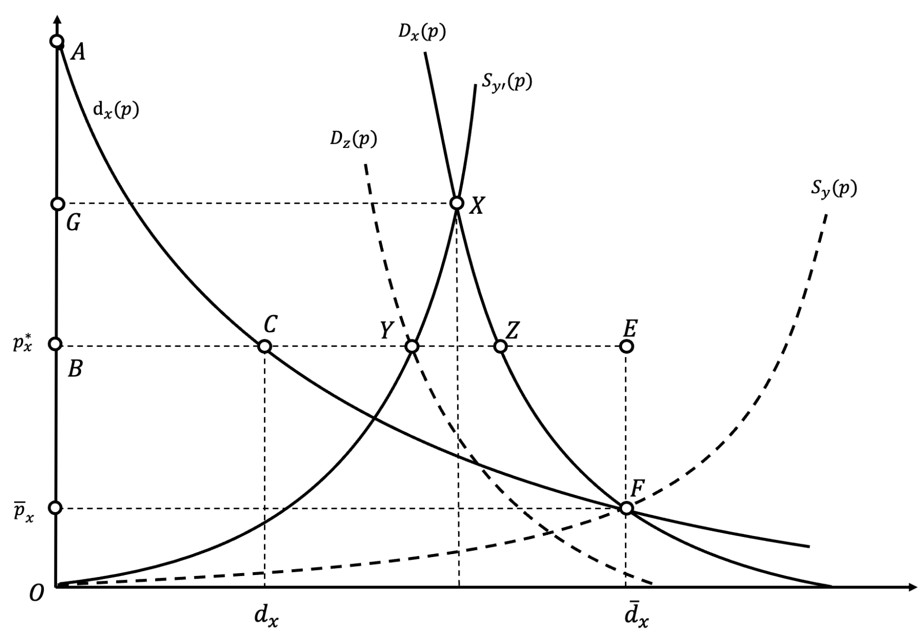


Figure 1: An illustration of the optimal price-control and rationing policy for two supply states. Under the optimal price cap p_x^*, triangles ABC and CEF have equal areas, the latter weighted by the share of sticky consumers $(1-\theta)$. Rationing reduces demand at p_x^* from Z to Y.

Now consider a negative supply shock, from y to y', which moves the equilibrium from F to X. Is it optimal to allow the price to rise to this new level? Under the price cap p_x^*, the demand of non-sticky consumers adjusts to point C. Aggregate utility U_z equals the area under AC, weighted by θ, plus the area under AF, weighted by $(1-\theta)$. Expenditures equal the corresponding rectangles, yielding the difference between the right- and left-hand sides of condition (2.6) as the triangle CEF weighted by $(1-\theta)$ minus the triangle ABC. Graphically, this difference increases with the price cap: it is negative at F and positive at A. Hence, there exists a unique p_x^* such that $\Delta ABC = (1-\theta)\Delta CEF$. If, without rationing, $\mu_z = 1$, the equilibrium price is below p_x^* and no rationing is needed. If the unregulated price exceeds p_x^*, as in Figure 1, optimal rationing reduces demand to ensure that supply meets demand at the capped price.

There is therefore a unique p_x^* (independent of μ_z) such that the left inequality in (2.6) binds. This condition is fully determined by the demand schedule. Given p_x^*, the corresponding optimal rationing rate μ_z^* is set so that demand equals supply, $D_z = S_y(p_x^*)$. The same logic applies for any realization of demand; the price cap is state-contingent in x.

2.4 Parametric Demands

To illustrate the mechanism in a tractable form, consider a class of semi-log demand functions, to be estimated in the empirical application. We suppress the state notation (z,x,y) when not essential.

Proposition 2.3 (Semi-log case)**.** *For the semi-log demand function*

$$d(p) = \exp\left(\frac{\alpha - p}{\beta}\right), \tag{2.8}$$

with non-negative parameters α, β, the optimal rationing price satisfies

$$p^* = \lambda(\theta)\,\beta + \overline{p}, \tag{2.9}$$

where $\lambda(\theta)$ solves

$$(\lambda - 1)\,e^{\lambda} = \frac{\theta}{1-\theta}. \tag{2.10}$$

Proof. The semi-log specification implies the inverse demand $p = \alpha - \beta \ln d$, with elasticity p/β. Utility follows as $u = \beta d + pd$, yielding indirect utility

$$u = v(p) = (\beta + p)\,\exp\left(\frac{\alpha - p}{\beta}\right).$$

Following the iterative procedure from Proposition 2.2, the updating rule for the optimal price cap is

$$p^*_{k+1} = \frac{(1-\theta)(\beta + \overline{p})\exp\left(\frac{\alpha - \overline{p}}{\beta}\right) + \theta(\beta + p^*_k)\exp\left(\frac{\alpha - p^*_k}{\beta}\right)}{(1-\theta)\exp\left(\frac{\alpha - \overline{p}}{\beta}\right) + \theta\exp\left(\frac{\alpha - p^*_k}{\beta}\right)}. \tag{2.11}$$

Defining $\lambda_k = (p^*_k - \overline{p})/\beta$, this recursion becomes

$$\lambda_{k+1} = 1 + \frac{\theta\,\lambda_k\,e^{-\lambda_k}}{(1-\theta) + \theta\,e^{-\lambda_k}}. \tag{2.12}$$

Starting with $\lambda_0 = 1$, the sequence $\{\lambda_k\}$ is strictly increasing and converges to the unique fixed point $\lambda(\theta)$ satisfying (2.10). □

The optimal rationing price in (2.9) depends only on the expected price $\overline{p}$, the semi-log slope parameter β, and the share of non-sticky consumers θ. In empirical implementation, θ is identified jointly with α and β from estimated demand schedules. Proposition 2.3 shows directly how θ shifts the price cap: $\lambda(0) = 1$, $\lambda'(0) = 1/e \approx 0.368$, $\lambda(0.05) = 1.019$, $\lambda(0.1) = 1.039$, and $\lambda(0.5) = 1.28$. Hence, a 10% share of responsive consumers raises the distance between the optimal price cap and the reference price $\overline{p}$ by roughly 4%. For any demand state x, the price cap increases one-to-one with $\overline{p}$ and decreases with higher elasticity (lower β).

Finally, the policy can be expressed equivalently in terms of demand:

$$d^* = e^{-\lambda(\theta)}\,\overline{d}. \tag{2.13}$$

Thus, for this class of demand functions, the relative reduction of non-sticky demand before the price cap binds depends only on the share of responsive consumers. Non-sticky demand falls by at least 63% before rationing becomes active.

Consider next iso-elastic demand with $\sigma = p\,d'(p)/d(p)$.

Proposition 2.4 (Isoelastic case)**.** *For a constant elasticity of individual demand*

$\sigma > 1$, let the aggregate elasticity of demand be $\varepsilon_D = \sigma s$, where $s = d/D_x$ denotes the share of responsive consumption in total demand. At the optimal p^*, it holds that

$$\frac{(1-\theta)\left(\frac{p^*}{\overline{p}}\right) + \theta\left(\frac{p^*}{\overline{p}}\right)^{1-\sigma}}{1-\theta+\theta\left(\frac{p^*}{\overline{p}}\right)^{1-\sigma}} = \frac{\varepsilon_D^*}{\varepsilon_D^* - s^*}, \tag{2.14}$$

where ε_D^* and s^* are evaluated at p^*. Moreover, both p^* and ε_D^* increase with θ.

We omit the proof – the result follows after a few steps from $p^* = U_z/D_z$ in Proposition 2.1.

The same observed ε_D can arise from different combinations of σ and θ, and therefore the policy depends on the decomposition between intrinsic elasticity σ and the share of responsive consumers θ. A higher θ raises the threshold price for intervention.

The price cap is minimal when all demand is sticky ($\theta = 0$), the result implies in that case that prices can increase by a factor $\sigma/(\sigma-1)$ before rationing becomes optimal:

$$p^* = \frac{\sigma}{\sigma - 1}\,\overline{p}.$$

The associated reduction in non-sticky demand is

$$d^* = \left(\frac{\sigma-1}{\sigma}\right)^{\sigma}\overline{d},$$

so $d^*/\overline{d} < 1/e$ and $d^*/\overline{d} \to 1/e \approx 0.368$ as $\sigma \to \infty$. The demand ratio $d^*/\overline{d}$ increases with elasticity σ: non-sticky demand falls by at least 63% before the price cap binds, as in the case of semi-log demand.

The parametric demands show that the price cap policy remains well-defined even when all demand is inelastic ($\theta = 0$). To clarify the total welfare gain from the policy in this case and in general, it proves useful to state:[6]

Remark 2.1. For given demand D_x and supply S_y schedules and state z, the total increase in *ex post* surplus due to the policy is measured by XYZ in Fig 1.

[6]We omit the proof, which is not immediate; the complete argument appears in the working paper version of this paper.

2.5 Discussion and Roadmap

The main characterization establishes a simple rule: the planner regulates solely through a state-contingent rationing policy and a price cap. The cap p_x^* is pinned down by the average utility per unit of total demand; rationing μ_z^* is chosen to clear the market at p_x^* for the realized supply. Proposition 2.1 gives the complementarity condition: ration only when aggregate consumer surplus would turn negative. Proposition 2.2 shows how to implement the rule state by state, including comparative statics in the share of non-sticky consumers θ. The parametric illustrations (semi-log and iso-elastic) provide formulas for p_x^*.

The remainder of the theory section extends and applies this rule along three main margins. First, in Section 3 we relax the assumption of marginal-cost supply. As a baseline, we introduce the incentive payments for truthful supply first without a price cap (Section 3.1) and then with a cap (Section 3.2), and then introduce investments that materialize the supply (Section 3.3). Second, Section 4 extends the framework to endogenous selection into stickiness. Third, Section 5 incorporates distributional concerns and selection externalities.

3 Incentive Payments for Efficient Supply

When supply is competitive, the planner can set the price cap based solely on demand: the equilibrium price always reflects marginal cost. This assumption is unrealistic when suppliers hold market power, leading reservation prices to deviate from true marginal costs. Such strategic behavior would not matter if marginal costs were observable and truthful supply bids could be enforced. But even in this case, firms may have private information about investments that determine their marginal costs.

The incentive payments considered next provide a solution to both problems.

3.1 Incentive Payments without a Price Cap ($\theta = 1$)

Consider n firms $i = 1, \ldots, n$ with cost functions $C_i(\cdot)$. Each firm submits a non-decreasing supply schedule $\hat{s}_i : \mathbb{R}_+ \to \mathbb{R}_+$. Aggregate supply is $\hat{S}(p) = \sum_{i=1}^{n} \hat{s}_i(p)$, and the market clears at the price $\hat{p}$ solving $\hat{S}(\hat{p}) = D(\hat{p})$. For each firm i, define the counterfactual clearing price $\hat{p}_{-i}$ from

$$\sum_{j \neq i} \hat{s}_j(\hat{p}_{-i}) = D(\hat{p}_{-i}),$$

and define the residual demand

$$D_i(p) = D(p) - \sum_{j \neq i} \hat{s}_j(p).$$

In addition to market revenue, firm i receives a side transfer,

$$T_i(\hat{p}, \hat{p}_{-i}) = \begin{cases} \displaystyle\int_{\hat{p}}^{\hat{p}_{-i}} D_i(p')\,dp', & \text{if } \hat{p}_{-i} > \hat{p}, \\ 0, & \text{otherwise,} \end{cases}$$

so its payoff is

$$\pi_i = \hat{p}\,\hat{s}_i(\hat{p}) - C_i(\hat{s}_i(\hat{p})) + T_i(\hat{p}, \hat{p}_{-i}).$$

Recall that each C_i is differentiable and strictly convex. In addition, we require that each $\hat{s}_i$ is right-continuous and non-decreasing. Together with continuous demand, these conditions ensure existence and uniqueness of $\hat{p}$.

Proposition 3.1 (Incentive payments without a price cap)**.** *Under the mechanism above:*

(i) ***Dominant-strategy truthfulness.*** *Each firm's dominant strategy is the truthful schedule $s_i^*(p) = (C_i')^{-1}(p)$. At the realized clearing price $\hat{p}$,*

$$\frac{d\pi_i}{ds_i(\hat{p})} = \hat{p} - C_i'(\hat{s}_i(\hat{p})),$$

so the best response satisfies $C_i'(\hat{s}_i(\hat{p})) = \hat{p}$, independently of others' bids.

(ii) ***Efficiency.*** *With truthful bids, the allocation maximizes total welfare*

$$W = \int_0^Q D^{-1}(q)\,dq - \sum_{j=1}^{n} C_j(q_j), \quad Q = \sum_{j=1}^{n} q_j.$$

(iii) ***Payoff equals marginal contribution.*** *Under truthful bidding,*

$$\pi_i = W - W_{-i},$$

where W_{-i} is welfare when firm i is removed and the market re-clears at $\hat{p}_{-i}$.

Proof. See Appendix F □

The proof follows (relatively) standard arguments for Vickrey–Clarke–Groves (VCG) mechanisms. The transfers $T_i(\hat{p},\hat{p}_{-i})$ top up firms' market revenues so that each firm's total payoff equals its marginal contribution to welfare. Under strictly increasing marginal costs ($C_i'' > 0$), these contributions are subadditive, $\sum_i (W - W_{-i}) < W$; hence total transfers remain below aggregate surplus. Intuitively, the loss from removing one firm is partly offset by re-optimization of remaining suppliers.

The strong efficiency properties hinge on private information residing on the supply side while the planner observes demand. If both sides held private information, total surplus from trade would generally be insufficient to finance the transfers (Krishna and Perry, 1998), leading to a multi-unit version of the Myerson–Satterthwaite Theorem (Myerson and Satterthwaite, 1983).

3.2 Incentive payments with a price cap ($\theta < 1$)

We now extend the mechanism to the case of sticky demand ($\theta < 1$). The cap p^* is designed under the assumption of truthful supply. We therefore focus on mechanisms that ensure this assumption holds: they induce truthful supply when p^* binds.

When $\theta < 1$ but the cap does not bind, Proposition 3.1 applies as such. Assume thus that the cap binds. When firm i is removed, rationing must increase and production falls to $Q - \Delta$, defined by

$$C'_{-i}(Q - \Delta) = p^*.$$

The associated welfare change can be decomposed into two parts:

$$A = \int_0^{Q-\Delta} \big(C'_{-i}(q) - C'(q)\big)\, dq, \qquad B = \int_{Q-\Delta}^{Q} \big(p^* - C'(q)\big)\, dq.$$

Term A represents the pure cost savings generated by firm i. The firm receives the full value of these savings at the constant price p^*. Term B captures the net surplus from firm i's participation, that is, the additional output enabled at price p^*. This surplus is also fully compensated through market revenue. Therefore, when the cap binds, no additional transfer is required, and the optimal mechanism sets $T_i = 0$.[7]

Proposition 3.2 (Incentive payments with $\theta < 1$)**.** *Suppose p^* is the welfare-maximizing price cap. Under the Groves–Clarke pivot rule, if p^* binds:*

(i) Truthful supply is a dominant strategy for each firm,

(ii) Each firm's payoff equals its marginal contribution to welfare

$$\pi_i = W - W_{-i} = A + B,$$

(iii) $T_i = 0$.

If p^* does not bind, Proposition 3.1 applies.

The incentive payments defined here can therefore be implemented in the same way as under Proposition 3.1, but when the cap binds, the required transfer is zero.

The mechanism admits two implementation properties.

(i) Simplicity. The mechanism relies exclusively on repeated applications of the standard market-clearing rule. The planner computes the equilibrium price once with all firms and n additional times, each time removing a single firm to obtain the counterfactual equilibrium. These counterfactuals determine transfers but do not affect the final allocation or price.

(ii) Transfer reduction through price caps. In tight markets, counterfactual prices may rise substantially, implying large transfers in the absence of price regulation.

[7] If the cap does *not* bind with C but *does* bind with C_{-i}, we need to modify "$A + B$" slightly. Let $P(q)$ be inverse demand. Define Q by $C'(Q) = P(Q) = p_0 < p^*$ (the cap does not bind), let Q' satisfy $P(Q') = p^*$ (so $Q' < Q$), and let $Q' - \Delta$ satisfy $C'_{-i}(Q' - \Delta) = p^*$ (so $\Delta > 0$). Rationing takes place over $[Q - \Delta, Q']$ and surplus change over $[Q', Q]$ is given by the Harberger triangle

$$B' \equiv \int_{Q'}^{Q} \big(P(q) - C'(q)\big)\, dq.$$

Thus, the total welfare change is $A + B + B'$.

A binding welfare-maximizing price cap limits this escalation and, as shown in Proposition 3.2, reduces transfers to zero. Firms are fully compensated for their marginal contributions through the capped market price. By this property, the mechanism is financially more disciplined than a system of incentive payments without the cap policy.

A large policy and regulatory literature, mostly in the electricity context (see Fabra, 2018), views price caps and capacity remuneration mechanisms as complementary instruments: caps limit exposure to high prices and market power, while capacity payments restore the scarcity rents needed for investment. In our framework, by contrast, the price cap p^* arises as the welfare–maximizing response to sticky demand under uniform pricing. This distinction is central for the investment stage: as we show next, the mechanism aligns firms' investment incentives with social welfare without relying on separate capacity payments. A broader discussion appears in the concluding section.

3.3 Investments on the Supply Side

The mechanism described above applies without an investment stage, but it is natural to ask how the price-cap policy affects producers' investment decisions that determine the observed supply schedules $S_y(p)$. We now introduce an investment stage preceding the realization of the market state $z = (x,y)$.

Each firm $i = 1, \ldots, n$ chooses an investment level K_i at cost $G_i(K_i)$, where $G_i(\cdot)$ is convex and differentiable. Investment shifts the firm's operating cost function $C_i(q_i; K_i)$, which is convex in output and nonincreasing in K_i. The aggregate supply schedule is

$$S_y(p) \;=\; \sum_{i=1}^{n} s_{i,y}(p; K_i),$$

with each $s_{i,y}$ strictly increasing in price and in the supply state y.

Proposition 3.3 (Ex ante investment efficiency)**.** *Suppose the planner implements the ex post rationing policy (p^*_x, μ^*_z), defined in Propositions 2.1–2.2, and firm-specific incentive payments defined in Proposition 3.2. Under uniform pricing and non-discriminatory rationing, the policy (p^*_x, μ^*_z, T_i) maximizes expected welfare ex ante, subject to voluntary firm investment decisions with general convex costs $G_i(\cdot)$.*

Proof. Firm i's profit in state z equals its marginal contribution to total welfare:

$$\pi_{i,z}(K) \; = \; W_z(K) - W_{z,-i}(K_{-i}).$$

Taking expectations over market states, firm i chooses its investment K_i to solve

$$\max_{K_i} \; \mathbb{E}_z[\pi_{i,z}(K)] - G_i(K_i).$$

The first-order condition for this problem coincides with the planner's maximization problem

$$\max_{K} \; \mathbb{E}_z[W_z(K)] - \sum_i G_i(K_i),$$

so equilibrium investment is efficient ex ante. In equilibrium, each firm invests until its private marginal benefit—its expected contribution to total welfare—equals its marginal investment cost. Since transfers ensure that firms internalize their marginal contributions, no other uniform-price mechanism can improve expected welfare. □

Interpretations of investment. The investment variable K_i can be interpreted broadly as any firm-specific decision that shifts the cost function $C_i(q_i; K_i)$ or its curvature. In the simplest case, K_i represents capacity expansion that enlarges the feasible output set, as in traditional capacity investment. More generally, K_i may capture a technology choice, or an improvement in operational reliability that increases the expected availability of capacity while reducing its variance. It can also be viewed as a flexibility investment that flattens marginal costs and enables faster response to supply shocks, or as a hedging investment that reduces exposure to the carbon price by lowering the emissions intensity of production. Regardless of interpretation, all these decisions enter the market stage through the cost function $C_i(\cdot; K_i)$. Because the mechanism rewards each firm according to its marginal contribution to social welfare, $\pi_i = W - W_{-i}$, firms internalize the full social value of their investments. Hence, the same dominant-strategy property that guarantees efficiency ex post also ensures efficient investment ex ante, independent of the particular technological form of K_i.

Remark. If the market is perfectly competitive and firms are small (so investments are continuous and nonlumpy), marginal contributions are already internalized through the price mechanism, and efficient investment arises without additional transfers. This result parallels Makowski and Ostroy (1995), where agents rewarded according to their marginal contributions implement efficient allocations. The present setting, with incentive payments designed by the planner, achieves this principle more generally: they provide each firm with its marginal contribution to social surplus, ensuring efficiency both ex post and ex ante.

A parallel issue arises on the demand side: consumers may choose whether to be price–responsive, and this choice is itself a welfare–relevant margin (e.g., Ito et al., 2021). In environments where the planner can discriminate among demand types, the efficient policy would ration only the sticky consumers—an insight going back to Wilson (1989) and Joskow and Tirole (2007). In our setting, however, uniform pricing rules out such discrimination. Given this constraint, the induced selection between responsive and sticky consumers is efficient under the ex post policy derived above. The next section establishes this result and after this we show how distortions arise once distributional objectives are introduced.

4 Endogenous Selection into Stickiness

The planner commits to the ex post policy characterized in Propositions 2.1–3.2 and applies it in every realized state $z = (x,y)$ using observed market schedules (D_x,S_y) to implement (p^*_z,μ^*_z). Consumers choose whether to be price–responsive before z is realized and form rational expectations over the induced distribution of equilibrium prices p_z.

Let each consumer draw a private cost $c \geq 0$ from a continuous CDF H on $\mathbb{R}_+$ for observing and responding to price. This is the cost from becoming non-sticky. For demand state x, write the indirect (gross) surplus at price p as

$$\phi_x(p) \;\equiv\; \int_{p' \geq p} d_x(p')\, dp',$$

well-defined under the assumptions stated. A responsive consumer attains $\phi_x(p_z)$ at the realized price; a sticky consumer consumes $\bar{d}_x = d_x(\bar{p}_x)$, where $\bar{p}_x \equiv \mathbb{E}[p_z \,|\, x]$, and attains $\phi_x(\bar{p}_x)$. Ex ante (before z is realized), the expected surplus gain from responsiveness is

$$\Delta \;\equiv\; \mathbb{E}_z\big[\phi_x(p_z)\big] \;-\; \mathbb{E}_z\big[\phi_x(\bar{p}_x)\big],$$

where the expectation is over the joint distribution of (x,y).

Proposition 4.1 (Efficiency of endogenous responsiveness)**.** *Fix the optimal ex post policy rule* (p_z^*,μ_z^*)*, applied in every realized state* z*. Then the competitive equilibrium ex ante selection into responsiveness maximizes welfare achievable under uniform pricing. In equilibrium, consumers become responsive if and only if* $c \leq \Delta$*, so that*

$$\theta \;=\; H(\Delta).$$

Proof. (i) Ex post efficiency given θ*.* By Propositions 2.1–3.2, for each realized z the allocation induced by (p_z^*,μ_z^*) maximizes W_z subject to uniform pricing and the rationing rule, taking the aggregate demand generated by the current share θ as given and with truthful supply ensured.

(ii) Planner's ex ante marginal condition. Consider increasing the share of responsive consumers by a marginal amount $d\theta$ before z is realized. Because the realized allocation in each z is already efficient conditional on θ (envelope logic with quasi-linearity and truthful supply), the first–order effect on expected welfare equals the expected gross surplus gain of converting one marginal consumer from sticky to responsive:

$$\frac{d}{d\theta}\,\mathbb{E}_z[W_z(\theta)] \;=\; \mathbb{E}_z\big[\phi_x(p_z^*)\big] \;-\; \mathbb{E}_z\big[\phi_x(\overline{p}_x)\big] \;=\; \Delta. \tag{4.1}$$

The social marginal cost of increasing θ is the cost of the marginal type, which equals $H^{-1}(\theta)$. Thus the planner's FOC is $\Delta = H^{-1}(\theta)$.

(iii) Private choice and rational expectations. A consumer with cost c becomes responsive iff $c \leq \Delta$, so in equilibrium the marginal type satisfies $c^* = \Delta$ and the induced share is $\theta = H(c^*) = H(\Delta)$. Hence the private cutoff condition coincides with the planner's FOC, implying ex ante efficiency of the equilibrium θ. □

This result formalizes the idea that stickiness need not be an anomaly in this setting: the planner applies the ex post policy state by state, consumers anticipate the induced price distribution and optimally choose their responsiveness, and the resulting composition θ of sticky and responsive demand is welfare-optimal ex ante under uniform pricing.

5 Inequality-aware welfare objective

We now extend the planner's objective to account for heterogeneity in the marginal value of money. The idea is that the planner may be more concerned about the welfare of certain consumer types, as in Dworczak et al. (2021), Akbarpour et al. (2024), Pai and Strack (2022), and Ahlvik et al. (2024). Each individual has a welfare weight ω, which reflects the planner's valuation of a unit of monetary surplus accruing to that individual. We assume that ω is unobservable at the individual level but that the planner knows its distribution. In particular, the planner observes the average welfare weights $\bar{\omega}_s$ and $\bar{\omega}_r$ for sticky and non-sticky consumers, respectively, and uses these weights to evaluate utility in a quasi-linear setting.

Based on the analysis of strategic supply, it is without loss of generality to describe the price-cap policy assuming truthful supply. We start by assuming that the investments have already been made and thus technology choices are given. The aggregate utility is modified as:

$$U_z^{\omega} = \mu_z \Big((1-\theta)\bar{\omega}_s \, u_x(\overline{d}_x) + \theta \bar{\omega}_r \, u_x(d_x) \Big), \tag{5.1}$$

and the planner's welfare objective becomes:

$$W_z^{\omega} = U_z^{\omega} - C_y(D_z). \tag{5.2}$$

This leads to the following extension of the optimal policy condition (proof omitted for brevity):

Proposition 5.1 (Inequality-aware price cap)**.** *Under the inequality-weighted welfare objective, the optimal policy satisfies:*

$$p_z D_z(p_z) \leq U_z^{\omega} \;\perp\; \mu_z^* \leq 1. \tag{5.3}$$

If the price cap binds, the optimal price satisfies:

$$p_z^* = p_x^{*,\omega} = \frac{(1-\theta)\bar{\omega}_s \, u_x(\overline{d}_x) + \theta \bar{\omega}_r \, u_x(d_x^*)}{(1-\theta)\overline{d}_x + \theta d_x^*}, \tag{5.4}$$

where $d_x^* = d_x(p_x^{*,\omega})$.

The optimal price cap $p_x^{*,\omega}$ equates the welfare-weighted average utility per unit of demand across consumer types. If $\bar{\omega}_s > \bar{\omega}_r$—that is, if the planner places greater weight on sticky consumers who are less price responsive and more vulnerable—then the optimal price cap is lower than in the unweighted case.[8] This reflects the increased importance of shielding inelastic consumers from high prices when the planner values distributional equity.

However, once investments that determine responsiveness are endogenous, the distributive objective alters the nature of the optimal policy. In contrast to the main setting, the ex post price-cap mechanism may no longer coincide with the ex ante optimal mechanism. As shown, for instance, in Laffont and Tirole (1993) and Pavan et al. (2014), when early-stage decisions affect later allocations, the planner may wish to distort continuation policies to influence investment incentives. In Appendix F we show that, in the natural benchmark where the planner applies the same welfare weight to the self-selection cost and to surplus from market interaction, no such distortion is optimal: the optimal price-cap rule is unchanged.

6 Application: Energy crisis, France 2022–2023

6.1 Background

The European energy crisis emerged following the onset of the war in Ukraine, which disrupted supplies of gas, oil, and electricity and led to widespread economic impacts due to a surge in energy prices. Figure 2 illustrates the timeline and evolving expectations of the crisis's severity, as reflected in France's electricity prices. It shows the prices at which electricity for 2023 delivery were contracted in 2021–2022. Contract prices rose to more than ten times (!) their usual levels prior to 2022, imposing insurmountable cost burdens on entities needing to procure electricity in advance, such as those serving final consumers. The crisis threatened the stability of Europe's integrated electricity market by endangering the solvency of firms with contractual commitments, with potential collateral demands exceeding one trillion euros.[9] To avert a "Lehman Brothers scenario in the energy sector," governments

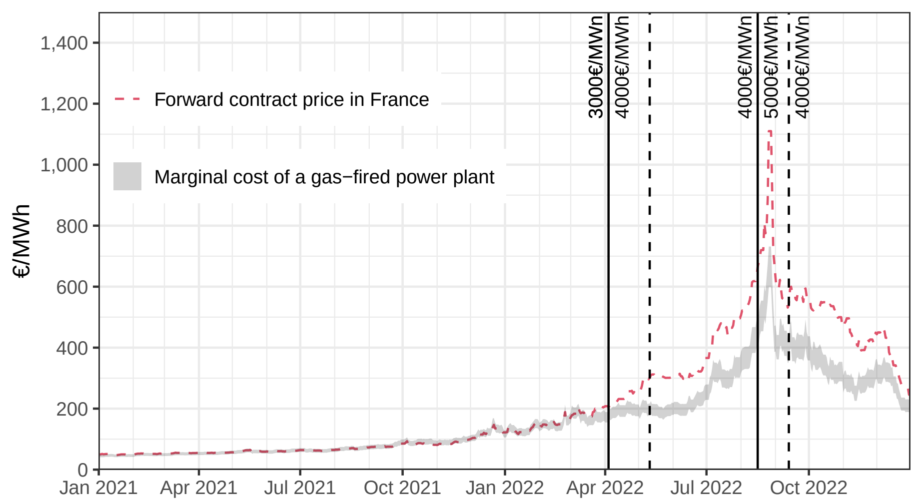
[8]Formally, this can be shown by using our fixed-point iteration $p_{k+1} = \Phi_\kappa(p_k) \equiv \frac{u(\bar{d})+\kappa\, u(d(p_k))}{\bar{d}+\kappa\, d(p_k)}$, in which $\kappa \equiv \frac{\bar{\omega}_r}{\bar{\omega}_s} \cdot \frac{\theta}{1-\theta}$, and observing that the fixed point is strictly increasing in κ.

[9]See *Bloomberg News*, "Energy Trading Stressed by Margin Calls of \$1.5 Trillion," September 6, 2022. Available at `https://www.bloomberg.com/news/articles/2022-09-06/energy-trade-risks-collapsing-over-margin-calls-of-1-5-trillion`.

committed tens of billions in loans and guarantees.[10]

Prices decoupled from expected marginal costs of production. A central factor behind this decoupling was the EU policy for setting and updating a price cap for wholesale electricity across the entire EU region. On April 4, 2022, the hourly wholesale price of electricity in France reached a critical level, prompting the EU protocol to automatically raise the maximum clearing price permitted under EU rules from €3,000/MWh to €4,000/MWh (CRE, 2022). According to the protocol, the maximum price would be automatically raised again under the same procedure if the crisis were to unfold towards Winter 2022/23. Seen through the lens of Summer 2022, such a development was expected, and it prompted a hike in prices for future guaranteed-supply contracts: contract prices carried a markup reaching nearly 40%. The market anticipated power supply shortages where prices would be determined by the cap rather than by marginal costs.[11]

Figure 2



Notes. Electricity forward market price for 2023 and the marginal cost in France in 2021-2022. The marginal cost of a gas-fired power plant with a 45–55% efficiency using 2023 forward price for gas. Source: own calculations. Vertical lines indicate the EU price cap revisions for wholesale electricity.

[10]See Tom Wilson and Philip Stafford, "Why are Europe's power producers running out of cash?," *Financial Times*, September 6, 2022. Available at `https://www.ft.com/content/3a188669-7eeb-4154-91a8-f808ed8ced71`.

[11]In September 2022, the rule for further price cap increases was suspended, and the cap was set back to €4,000/MWh (as indicated by the last vertical line).

6.2 Crisis quantification

We begin by quantifying the expectations shown in Fig. 2, disentangling the contributions of three drivers: (i) input price developments (notably natural gas), (ii) capacity shortages in nuclear production, and (iii) the EU price-cap rule. The war in Ukraine led to a reduction in gas supply and raised the marginal cost of thermal generation. Independently, France's nuclear fleet, normally inframarginal, encountered a potentially systemic stress-corrosion problem (corrosion-induced cracking), taking out about 40% of nuclear capacity at that time and creating uncertainty about its near-term availability (CRE, 2022). Together, these factors contributed to expectations that a supply crisis might emerge in 2023, particularly during the winter.

To analyze the three drivers, we consider hourly electricity prices for 2023 both as they occurred and in counterfactual situations capturing factors (i)-(iii). The actual prices (and quantities) come as data from year 2023, but we also reproduce them using hourly demand and supply schedules. For counterfactuals, we hold the hourly demand schedules as given and construct the supply curve for each hour of the year from engineering estimates combined with the counterfactual scenario assumptions. The constructed supply curve allows analyzing separately the effect of higher input prices and reduced nuclear availability.

The data are drawn from the French day-ahead wholesale electricity market. For each hour between 1 January and 31 December 2023, we observe the complete set of demand and supply bids, price–quantity pairs, together with the market-clearing price and quantity. The dataset contains approximately 4.3 million anonymous bids, averaging about 500 per hour. We use unit-level information for 57 fossil-fuel plants obtained from RTE, the French transmission system operator, to build the supply estimates that depend on fossil inputs. These data report nameplate capacity (MW), technology, e.g., combined cycle gas turbine (CCGT) or steam turbine (ST), and commissioning year. We match technology and vintage to engineering-based heat-rate estimates to recover marginal cost curves. Appendix B provides details, but two features are noteworthy. First, marginal-cost estimates combined with observed demands reproduce the baseline 2023 hourly equilibrium once we include markups with magnitudes similar to those documented in Reguant (2014). Positive markups are not inconsistent with efficiency, as generators face start-up costs. Second, not all supply and demand clear through the exchange. To obtain an aggregate representation, we adjust the bid schedules using day-ahead forecasts of both total demand and supply;

this procedure replicates the equilibrium outcomes up to rounding error.

The observed prices in 2023 yield a mean of €96/MWh. Table 1 contrasts this baseline with our quantification of crisis expectations. The first row reports the effect of higher gas input prices, set to the forward contract input prices observed in August 2022; these values exceed the input prices that ultimately materialized in 2023. Under this counterfactual, the mean expected price rises to €155/MWh. The columns report results for alternative price-cap levels, reflecting the range of outcomes that the EU's administrative price-cap protocol could have generated by 2023. Across these caps ranging from 3,000 to 7,000 €/MWh, expected prices remain unchanged: the increase in input costs does not raise the market price sufficiently for the cap to bind in any hour. We conclude that higher gas prices alone, while raising expected prices by roughly 60%, are insufficient to account for the expectations depicted in Fig. 2.

Table 1: EU price cap: Counterfactual mean hourly prices in 2023

Nuclear	Price cap (€/MWh)					Share of hours
availability	3,000	4,000	5,000	6,000	7,000	rationing
100%	155	155	155	155	155	0
90%	203	206	210	214	218	0.004
80%	298	316	335	353	372	0.019
70%	482	537	592	646	701	0.055
60%	844	999	1,153	1,308	1,462	0.155

Notes. The table reports simulated 2023 market outcomes by nuclear availability (rows) and price caps (columns). The share of hours with rationing applies to all columns 2–6. Input prices are fixed at 25 August 2022 closing levels. Nuclear availability is relative to realized 2023 nuclear generation. All prices are in €/MWh.

As expected, as nuclear availability for 2023 declined from 100% to 60%—the level observed in August 2022—expected market prices rise sharply. In this table, input prices are held constant at their August 2022 forward levels, so variation across rows reflects only changes in nuclear availability relative to actual 2023 production. At full (100%) availability, the expected price remains €155/MWh across all price-cap levels. At 90% availability, expected prices rise to €203–€218/MWh, and at 80% they move into the €298–€372/MWh range. Further reductions generate steep increases: at 70% availability, expected prices lie between €482 and €701/MWh, and at 60% availability they reach €844–€1,462/MWh. The sensitivity of expected prices to the price-cap level also increases as availability falls. Although in August 2022 expected forward prices briefly exceeded €1,000/MWh and nuclear availability was close to 60%, we take 70% availability as a central scenario for 2023 expectations and use the €7,000/MWh cap as our benchmark.

Scarcity drives prices away from marginal cost. When the unconstrained market-clearing price exceeds the administrative ceiling, the cap sets the price, so expected prices reflect both marginal unit costs and the frequency with which the cap binds. This mechanism generates the nonlinear relationship between the expected price and the price cap shown in Table 1. The last column reports the share of hours in which the cap binds.[12] Notably, even a 5% share of binding-cap hours implies that rationing is anticipated as a regular event—about one hour per day on average. The mean rationed quantity in binding-cap hours remains below 10% of total load in all cases; in 95% of binding-cap hours, the rationed quantity is below 16% of load (Appendix E).

6.3 Optimal price cap

We apply the optimal price-control mechanism to the 2023 fundamentals. In this counterfactual equilibrium, the price cap is set at its optimal level rather than the EU cap, yielding a new counterfactual mean price for 2023. This mean price is the contract price that market participants should have expected under the optimal policy.[14] We implement the mechanism in two ways that yield essentially the same results. First, we compute the counterfactual equilibrium numerically using the raw demand bid data and our counterfactual supply estimates. Second, instead of using the raw step-function bid schedules, we fit a parametric demand curve to each bid schedule and run the mechanism using the fitted curves. The parametric approach links the empirical analysis more directly to the theory and clarifies the quantitative determinants of the optimal cap.

For each hour, we observe a demand schedule as a step function constructed from a set of bid price-quantity pairs, denoted $(p_i, D_{xi})_i$, where i indexes points along the demand curve for any given hour x. We approximate this schedule using the

[12] This share is almost invariant across price cap levels in columns 2–5. That is, a higher price cap level does not increase supply but increases the price to be paid for the available supply.

[14] Here, as in Fig. 1, contract is a futures contract on a fixed quantity at a fixed price.

parametric form:

$$D_{xi} = \gamma_x + \eta_x \exp\left(-\frac{p_i}{\beta_x}\right) + \varepsilon_{xi}, \tag{6.1}$$

where γ_x, η_x, and β_x are parameters to be estimated for each hour x, and ε_{xi} is an error term. We drop subscripts x,i below. We fit the formula in (6.1) to a curve, as the bids define a schedule, using maximum likelihood estimation. Taking the estimated γ, η,β, and the reference price $\overline{p}$, the expected volume from (6.1) is $\overline{d} = \gamma + \eta \exp(-\overline{p}/\beta)$, which gives the sticky volume for $\overline{p} \to \infty$ and thereby the sticky share follows:

$$1 - \theta = \frac{\gamma}{\gamma + \eta \exp(-\overline{p}/\beta)}. \tag{6.2}$$

By defining $\alpha = \beta \ln(\eta/\theta)$ we can rewrite an estimate for the demand in terms of θ,α,β:

$$D = (1 - \theta)\overline{d} + \theta \exp\left(\frac{\alpha - p}{\beta}\right). \tag{6.3}$$

This is now a demand schedule with a sticky part and a non-sticky price-responsive part, with $d(p)$ taking a semi-log form as in (2.8) of illustration 2 in Section 2.4. The full set of steps for the procedure is:

1. Estimate demand (6.1) for each hour.

2. Impute the reference price $\overline{p}$. [16]

3. Compute the optimal price cap p^* as in Proposition 2.3 using the estimated demand parameters.

4. If p^* binds:
   (i) activate the supply bids with reservation prices (weakly) below p^*, and
   (ii) eliminate demand bids (pro-rata) until the demand volume equals the supply volume at p^*.

[16] The reference price anchors the sticky demand, reflecting consumption commitments made in the past: we construct the reference price as a rolling one-year average of realized market prices.

The key features of the estimated demand schedules can be summarized briefly. The mean estimated parameters are $\gamma \approx 46.0$ GW, $\eta \approx 8.0$ GW, and $\beta \approx 140.4$ €/MWh in 2023. The parametric form fits the bid schedules closely: replicating market outcomes using the estimated demand schedule, instead of the actual bids, leaves hourly equilibria nearly unchanged.

The elasticity of total demand takes a convenient form,

$$\varepsilon_D(p) \;=\; \frac{\eta\, p}{\beta\big(\eta + \gamma e^{p/\beta}\big)},$$

which simplifies to $\varepsilon_D = p/\beta$ for the non-sticky component ($\gamma = 0$). To illustrate the ballpark magnitudes, we compute the optimal price cap using the mean estimated demand parameters ($\gamma \approx 46.0$, $\eta \approx 8.0$, and $\beta \approx 140.4$) and the average non-sticky demand share ($\theta \approx 0.026$). Substituting this value of θ into the defining equation $(\lambda - 1)e^{\lambda} = \theta/(1-\theta)$ yields $\lambda(\theta) \approx 1.01$, which implies $\lambda(\theta)\beta \approx 142$ €/MWh. By Proposition 2.3, the corresponding optimal cap is therefore approximately 142 €/MWh above the reference price $\overline{p}$. This calculation is purely illustrative: in the empirical analysis we compute p^* separately for each hour of 2023 using the hour-specific demands, with details reported in the Appendix.

Table 2: Optimal price cap: Counterfactual mean market prices in 2023

Nuclear availability	Optimal price cap (€/MWh)	Market price (€/MWh)	Share of hours rationing
100%	573	154	0.011
90%	597	190	0.030
80%	626	242	0.082
70%	659	331	0.201
60%	718	443	0.387

Notes. The table reports the optimal price cap, the resulting mean market price, and the share of hours in which rationing occurs in simulations for 2023. Input prices are fixed at 25 August 2022 closing levels. Nuclear availability is expressed relative to realized nuclear generation in 2023. All prices are in €/MWh.

Table 2 presents the expected 2023 market prices under the optimal cap as supply conditions tighten, mirroring the structure of Table 1. The cap in each hour is determined from the same demand schedules in each scenario, but the reference price varies across scenarios: as capacity becomes scarcer, the reference price rises, shifting up the implied cap. The number of hours in which the cap binds increases with the nuclear shortfall and is now well above the levels in Table 1, exceeding 20 % of hours under 70% availability. However, the quantities rationed in binding-cap hours still remain on average close to 10 percent of total load (Appendix E). Intuitively, when the supply curve is steeply rising, a relatively small reduction in demand lowers the price to the desired level. The difference in the rationed amount required to bring the price down by hundreds is only a few percentage points.

Table 3 shows how the price-cap mechanism affects the wholesale cost of procuring electricity. In the central case (70% availability), the optimal price-cap rule lowers expenditures by about two-thirds relative to a fixed €7,000/MWh cap—roughly €200 billion.

Table 3: Total Expenditures (million €)

Nuclear availability	Price cap rule: Fixed at €7,000/MWh	Price cap rule: Optimal	Difference
100%	65,910	64,889	1,021
90%	97,239	79,108	18,131
80%	177,477	100,555	76,922
70%	333,096	133,745	199,351
60%	647,283	171,175	476,108

Notes. Expenditures are the wholesale cost of procuring total electricity consumption in France at market prices for the hours for which we have full data (N = 7,488), scaled to a full-year equivalent (N = 8,760). The difference column reports the savings from optimal rationing relative to the fixed price-cap rule at €7,000/MWh. Input prices are fixed at 25 August 2022 closing levels. Nuclear availability is expressed relative to realized nuclear generation in 2023. All values are in millions of euros.

6.4 Incentive payments

We compute the incentive payments required to support truthful supply. The calculation uses the observed demand and estimated marginal-cost schedules to evaluate each marginal unit's contribution to total surplus for each hour. A unit's marginal contribution equals the market revenue it receives at the clearing price plus any additional payment needed to align its compensation with the social value it generates.

Table 4 reports the incentive payments for the main marginal unit types in 2023 under two scenarios for nuclear availability (100 percent and 70 percent). For each scenario, we compare a *baseline* case, in which the anticipated EU price cap of €7,000/MWh applies, with the *optimal* price-cap policy documented in Table 2. For each unit type, we also report the corresponding price–cost margin under the two policies.

Two patterns emerge. First, the optimal price control substantially reduces markups, especially under lower nuclear availability: for example, the markup for combined-cycle gas falls from €3,000/MWh to €200/MWh at 70% availability. Second, the incentive payments required to implement truthful bidding remain small in all cases. Even at 70% availability, the plant level payments remain below 15 euros per MWh under the optimal policy—an order of magnitude smaller than the corresponding markups[17]. This reflects that most compensation is provided through market revenues and that the presence of many inframarginal units limits the marginal value of any individual generator.

Table 4: Price–cost markups and incentive payments under baseline and optimal cap

		Markup (€/MWh)		Incentive payments (€/MWh)	
Units	Nuclear	Baseline	Optimal	Baseline	Optimal
Coal	100%	203.2	155.9	13.5	6.1
Gas, CCGT	100%	13.4	19.2	25.0	2.3
Gas, ST	100%	16.7	17.6	31.7	3.0
Oil	100%	206.7	131.0	2.4	1.6
Coal	70%	1,530.4	272.8	13.9	6.4
Gas, CCGT	70%	3,001.0	206.2	13.8	8.5
Gas, ST	70%	4,389.6	236.8	3.4	14.8
Oil	70%	1,211.1	209.1	5.6	2.8

Notes. "Baseline" refers to the anticipated EU price cap (€7,000/MWh). "Optimal" refers to the optimal rationing mechanism. Values are simulated mean outcomes for 2023 under the specified nuclear availability, expressed relative to realized nuclear generation in 2023. Input prices are fixed at 25 August 2022 closing levels.

[17] Table 4 shows that incentive payments can be higher under optimal rationing than in the baseline. This is driven by a change in dispatch composition: high-cost gas units run fewer hours under optimal rationing.

7 Conclusion

Many markets combine uniform pricing with buyers who must commit before the realized price is known. In short-term funding, banks must obtain secured overnight funding to meet liquidity obligations, generating inelastic demand for the high-quality collateral used in repo transactions (Krishnamurthy et al., 2014). In housing, turnover units reprice, so posted rents reflect conditions faced by movers while most tenants remain bound by leases (Genesove, 2003). In health insurance, employees choose annual plans and deductibles before medical needs and out-of-pocket prices are realized (Handel, 2013). In transportation, peak-period demand is nearly inelastic because schedules are fixed and congestion tolls cannot easily be avoided (Arnott et al., 1993). In all these cases, a flexible margin sets the market-clearing price, while much of demand is effectively inelastic in the short run.

When committed and flexible agents are pooled under a single price, price control can improve efficiency. In the cases above, instruments such as rent stabilization, regulated copays, and peak-fare caps can thus be viewed as efficiency responses rather than purely distributive ones (cf. Dworczak et al., 2021). We characterize this logic, deriving the optimal state-contingent cap and rationing rule.

A broader question is when inequality of outcomes makes uniform-price markets unacceptable. The Atkinson–Stiglitz theorem implies that if substitution patterns across goods are similar across the income distribution, the desired equity–efficiency compromise can in principle be implemented through income taxation or targeted transfers, making commodity-specific interventions redundant (Atkinson and Stiglitz, 1976). When this condition fails—as is plausible for essential services such as electricity, which are consumed both by households and as intermediate industrial inputs—the redistribution problem becomes a market-design problem. Our analysis characterizes optimal price caps and rationing as one response to this tension. A fuller treatment of inequality-aware market design may require instruments that condition directly on income or other observables (e.g., differentiated tariffs or targeted mechanisms); see Ahlvik et al. (2024, 2025) for discussion. We leave this open for future research.

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Part I

Appendix

Table of Contents

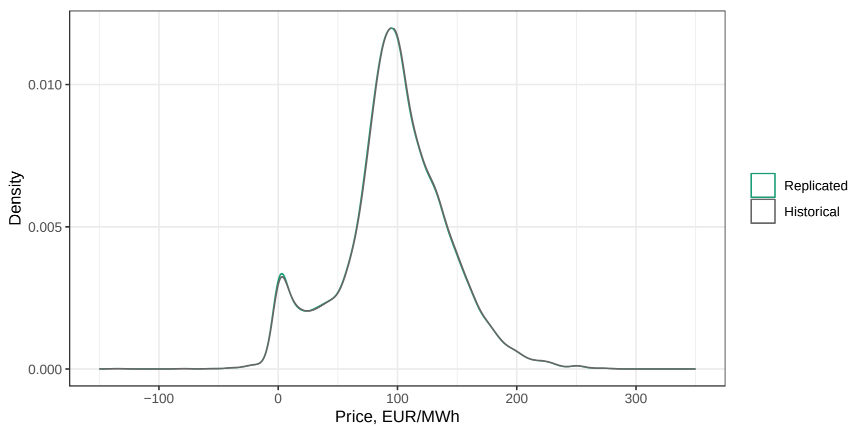
A Data and replication package

Available in Gerlagh et al. (2025)

B Day-ahead market

Market data. Our quantification builds on the actual bids submitted to the French day-ahead market. Bid data is obtained from the European common electricity market's Single Day-Ahead Coupling (SDAC) files, accessed through one of the common market operators, Nord Pool.

Figure B.1: Market price replication



Notes. Density plots of the historical hourly day-ahead spot prices in France in 2023 and the market prices as replicated by our model.

Replication. We construct price-responsive demand schedules from bid curves with price–quantity pairs and replicate market outcomes using similarly constructed supply bids. Replication of the historical equilibrium market outcomes is a data robustness check. We use a parsimonious linear program explained in Liski and Vehviläinen (forthcoming) to map the submitted bids to equilibrium prices and quantities hour by hour over the sample period. The bid curves do not contain all information required for a full replication of aggregate market outcomes, due to imports, exports, non-standard bids, and transactions outside the exchange. We therefore level-adjust demand and supply bid curves so that the aggregate equilibrium quantity matches the day-ahead load forecast—information available at the time bids are submitted (data from ENTSO-E Transparency Platform). In the counterfactual equilibrium with rationing we hold these adjustments fixed. This shortcut simplifies allocation under rationing, though a regulator with full access to the algorithm could implement the mechanism EU-wide. Our model reproduces historical market prices with high accuracy, see Fig. B.1.

C Parametric demand estimation

We estimate the parametric form in Section 6.3, hour by hour, using each hour's bid-curve data, i.e., the price (p_i) and quantity (D_{xi}) pairs. Table C.1 reports summary statistics for the MLE estimates of the parameter values, γ_x, η_x, and β_x, and for the imputed non-sticky demand share θ_x. To assess fit, we substitute the observed demand bid curve with the hour-specific parametric demand and recompute the market price for each hour, holding market supply as in data. As shown in Fig. C.2, the use of parametric demand yields prices broadly consistent with historical outcomes, with greater variation at the extremes.

Table C.1: Parameter demand estimates

Statistic	N	Mean	St. Dev.	Min	Max
γ	8,760	45.971	10.051	23.425	80.531
η	8,760	8.049	4.767	0.112	26.350
β	8,760	140.400	159.663	12.593	2,605.899
θ	8,760	0.026	0.017	0.00000	0.112

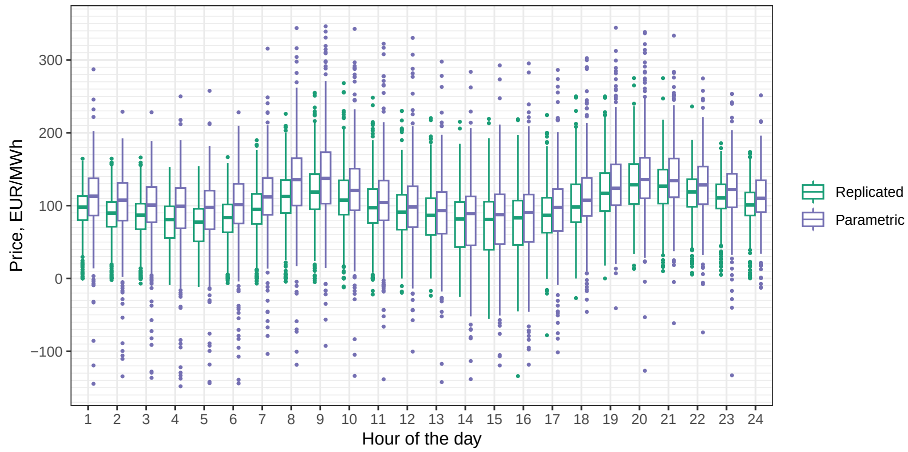
Notes. The table reports mean, standard deviation, and the minimum and maximum values of the estimated parameter values γ, η, and β, and the imputed value of θ, for the N hours in the data.

D Marginal cost supply

The counterfactual supply curve is constructed from plant-level data for large fossil-fuel units and aggregate production by energy source for other generation: hydro, nuclear, wind, solar, and bio/waste and other small units.

The marginal costs of fossil-fuel plants depend on fuel and carbon prices and heat rates (electric efficiency). Plant-level data are from RTE, the French TSO, and include

Figure C.2: Replicated market prices and parametric demand prices



Notes. The Figure compares 2023 French day-ahead spot prices from the replication with prices computed using the estimated parametric demand. For each hour of the day, the plot shows a box that represent the middle 50% of data, a line inside for the median, whiskers drawn at most 1.5 times the interquartile range from the box, and outliers beyond the whiskers as individual data points (further 135 outliers are cropped from view).

start date of operation, maximum capacity in megawatts (MW), and technology (combined cycle, steam turbine, and cogeneration status). RTE data do not report fuel sources. We use the Global Bioenergy Power Tracker (Sep 2025) and the Global Oil and Gas Plant Tracker (Jan 2025) to map plants with a capacity of over 20 MW to their fuel sources (combustion turbines can use coal or bio/waste; steam turbines can use natural gas or oil).

For input fuel and carbon prices, we use daily settlement prices from Refinitiv Eikon as follows: ICE Rotterdam Coal front-month futures for coal, EEX TTF Gas Day-ahead for natural gas, Brent FOB for oil, and EU ETS spot for carbon. Dollar values are converted to euros using the USD/EUR rate obtained through the European Central Bank API, and fuel energy content is converted to MWh using calorific values of 6,000 kcal per tonne of coal, 11.63 MWh per tonne of oil, and 7.37 barrels per tonne of oil. We obtain heat rates by mapping RTE technology and start date to the engineering values in Mier (2024), which provide typical heat rates by five-year construction cohort.

Supply costs include start-up and ramp-up costs and possibly other variable operation and maintenance costs. Firms may use block bids and other non-standard bid structures to recover the start-up costs, but their precise formulation is unobserved in the data. Start-up and ramping-up constraints generate an hourly pattern: nighttime and midday prices deviate downward, while morning and evening peak prices deviate upward, relative to daily marginal costs. We capture this pattern using the difference between a dynamic estimation that includes start-up costs and the competitive static estimate from Reguant (2014) (Markup 3 in Fig. 8) to capture this pattern. To account for marginal costs beyond fuel and carbon, we scale the markups in Reguant (2014) by 1.5, increasing the mean bid-cost markup from .09 to .14.

The final fossil-fuel plant–level data set contains plant ID, nameplate capacity, fuel source and the associated emission factor, heat rate, and markup as defined above. Combined with the input price data, these variables yield plant-level reservation bids as quantity–price pairs. We account for outages via the ENTSO-E Transparency Platform, which reports unavailabilities for larger plants with capacities above 100 MW; smaller plants are assumed continuously available.

We recompute the 2023 market prices using observed demand bids and substituting market supply with cost-based reservation prices. These counterfactual prices align closely with the historical means and daily pattern, as shown in Fig. D.3. The main differences are at the low end, which is unsurprising since we do not explicitly model the bidding by typically infra-marginal hydro, nuclear, and other assets. We validate the approach by comparing annual shares of marginal technologies from our simulation with the reported values by CRE, the French regulator: in 2023, gas fired technologies were marginal for 30% of hours in our simulation (30% for CRE), coal 10% (coal + borders 13%), and oil less than 1% (< 1%) in 2023[18].

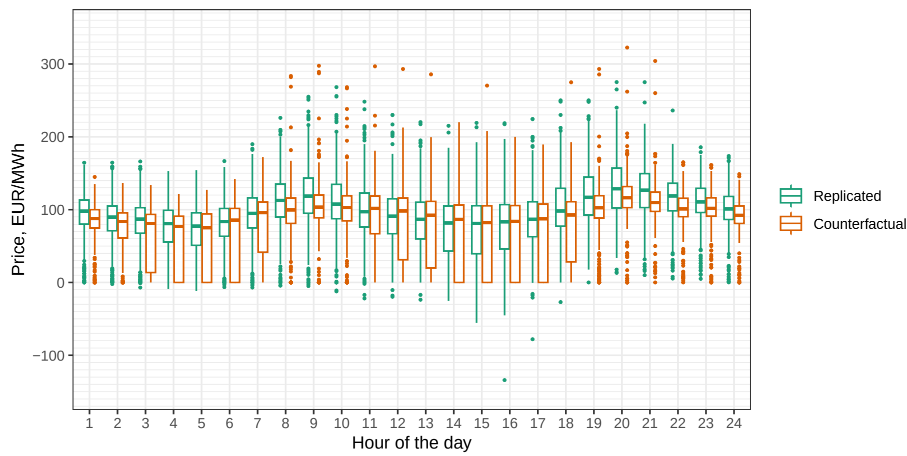
E Counterfactual simulations

The counterfactual simulations in the main text use observed market demand and the marginal-cost supply construction described above. They differ from the historical counterfactuals in three ways: (i) input prices are fixed fixed at crisis-peak levels; (ii) nuclear availability is scaled back; and (iii) the price cap rule is varied.

Fixed input costs. The counterfactual simulations fix input prices for all days at their levels on 25 August 2022. For reference, the settlement price for a futures contract for electricity delivery in 2023 was €888/MWh (EEX), close to the mean

[18] CRE, The monitoring and functioning of wholesale electricity and natural gas markets in 2023.

Figure D.3: Historical market prices and marginal cost based prices



Notes. Comparison of 2023 French day-ahead spot prices: replicated market outcomes vs. counterfactual marginal-cost-based supply. For each hour, the plot shows a box that represent the middle 50% of data, a line inside for the median, whiskers drawn at most 1.5 times the interquartile range from the box, and outliers beyond the whiskers as individual data points.

closing price that week. On that date, input prices were €285.45/MWh for natural gas (TTF 2023 futures), $368/t for coal, and $102.58/bbl for oil; USD/EUR rate was .997. These input prices are used to construct plant-level bids for the fossil-fuel fleet, as in the marginal-cost supply curve above.

Nuclear availability. The counterfactuals vary nuclear availability in 2023. For each scenario, we rerun the hourly market clearing by scaling the historical hourly nuclear output profile down by a fixed percentage across all hours. As a reference, when technical issues affecting much of the French nuclear fleet emerged in 2022, expected 2023 output was revised from 340–370 TWh to 300–330 TWh (February 2022).[19] Realized nuclear output was 275 TWh in 2022 and 316 TWh in 2023.[20]

Fixed price cap. We run counterfactuals under two price-cap rules: a fixed, predetermined cap and our optimal rationing rule. Under the fixed cap, we hold the cap constant throughout the year and vary its level; sticky demand is assumed to bid at the cap. We evaluate caps from €3,000/MWh to €7,000/MWh in €1,000/MWh increments. At the start of 2022, the price cap was €3,000/MWh with an automated

[19]EDF press releases, 11 Feb 2022, 18 May 2022, 3 Nov 2022.

[20]Source: ENTSO-E Transparency Platform.

rule: the cap increases by €1,000/MWh/MWh after five weeks if any hourly price in any market area exceeds 60% of the cap (=€1,800/MWh at the time).[21] This threshold was met on 4 April 2022, when France reached €2,987.78/MWh in hour 8–9, triggering a raise to €4,000/MWh on 11 May 2022.[22] A second trigger occurred on 17 August 2022 when Baltic prices hit the EU ceiling, lifting the cap EU-wide to €5,000/MWh.[23] The last increase was revoked before entering into force.[24]

Optimal price cap. The optimal rationing rule updates the price cap for each hour. We calculate the optimal price cap directly based on the observed demand bid data by minimizing the trade-off between utility and expenditures, $\Delta ABC = (1-\theta)\Delta CEF$ in Fig. 1. Table E.2 shows the summary statistics of the counterfactual market prices and the optimal price cap.

Table E.2: Optimal price cap

Statistic	N	Mean	St. Dev.	Min	Max
Market price	7,488	154.013	100.516	0.000	777.943
Price cap	7,488	572.535	211.043	202.033	2,840.000

Notes. The table reports mean, standard deviation, and the minimum and maximum values of the counterfactual market clearing price and the optimal price cap for the N hours in the data.

Table E.3 compares the share of quantity rationed with the fixed price cap rule and the optimal pricing rule as the nuclear supply reduces. In our central scenario on the crisis expectations, 70% of nuclear availability and €7,000/MWh fixed price cap, the mean rationed quantity, if rationing occurs, would have been 3,447 MWh. In the same scenario with our optimal price cap, the mean quantity rationed would have been 4,038 MWh.

[21] Regulation (EU) 2019/943 and Commission Regulation (EU) 2015/1222 (CACM).
[22] SDAC Communication Note, 11 Apr 2022.
[23] SDAC Communication Note, 23 Aug 2022.
[24] ACER Decision 01/2023.

Table E.3: Quantities rationed.

Nuclear availability	Price cap rule	
	Fixed at €7000/MWh	Optimal
100%	0 (0-0)	0.034 (0.001-0.076)
90%	0.017 (0.003-0.035)	0.051 (0.004-0.126)
80%	0.032 (0.002-0.078)	0.057 (0.004-0.153)
70%	0.051 (0.005-0.123)	0.071 (0.006-0.181)
60%	0.061 (0.003-0.155)	0.093 (0.008-0.217)

Notes. Table reports mean and 5%–95% interval of ratios between the quantity rationed to quantity demanded without rationing, calculated for each hour when rationing occurs, in different nuclear availability scenarios. Input costs are fixed to 25 August 2022 levels.

Pricing in Crisis

Reyer Gerlagh et al., December 2025

SUPPLEMENTARY MATERIAL

F Supplementary online material

Proof of Proposition 3.1

Proof. We prove (i)–(iii) in order.

Step 1 (via a local variation at the clearing price). Fix opponents' bids $\hat{s}_{-i}$. Let $\hat{p}$ be the clearing price under $\hat{s}_i$. Consider a small variation of $\hat{s}_i$ that changes only the offered quantity at the realized clearing price, i.e., $\hat{s}_i^\varepsilon(p) = \hat{s}_i(p) + \varepsilon\phi(p)$ where ϕ is a smooth bump around $p = \hat{p}$ with $\int \phi = 1$. Denote by $\hat{p}(\varepsilon)$ the new clearing price and write derivatives at $\varepsilon = 0$.

Revenue term:

$$\frac{d}{d\varepsilon}\big[\hat{p}(\varepsilon)\, \hat{s}_i^\varepsilon(\hat{p}(\varepsilon))\big]_{\varepsilon=0} = \hat{s}_i(\hat{p})\, \hat{p}'(0) \;+\; \hat{p}\, \frac{d\hat{s}_i(\hat{p})}{d\varepsilon}.$$

Cost term:

$$\frac{d}{d\varepsilon} C_i\big(\hat{s}_i^\varepsilon(\hat{p}(\varepsilon))\big)_{\varepsilon=0} = C_i'\big(\hat{s}_i(\hat{p})\big)\, \frac{d\hat{s}_i(\hat{p})}{d\varepsilon}.$$

Transfer term (note $\hat{p}_{-i}$ does not depend on $\hat{s}_i$):

$$\frac{d}{d\varepsilon} T_i(\hat{p}(\varepsilon),\hat{p}_{-i})\big|_{\varepsilon=0} = -\Big[D(\hat{p}) - \sum_{j\neq i} \hat{s}_j(\hat{p})\Big]\hat{p}'(0) = -\,\hat{s}_i(\hat{p})\, \hat{p}'(0),$$

using market clearing $D(\hat{p}) = \hat{s}_i(\hat{p}) + \sum_{j\neq i} \hat{s}_j(\hat{p})$.

Summing the three derivatives, the $\hat{p}'(0)$-terms *cancel*, yielding the Gateaux derivative

$$\frac{d\pi_i}{d\varepsilon}\Big|_{\varepsilon=0} = \Big[\hat{p} \;-\; C_i'\big(\hat{s}_i(\hat{p})\big)\Big]\, \frac{d\hat{s}_i(\hat{p})}{d\varepsilon}.$$

Thus, at the realized price $\hat{p}$, increasing quantity raises profit iff $\hat{p} > C_i'$, and lowers profit iff $\hat{p} < C_i'$. Hence the unique best response at $\hat{p}$ satisfies

$$C_i'\big(\hat{s}_i(\hat{p})\big) = \hat{p},$$

independently of $\hat{s}_{-i}$. Because opponents' bids can make the clearing price equal to any p in the support, the only strategy that is optimal for every possible $\hat{p}$ is the pointwise truthful schedule $C_i'(\hat{s}_i(p)) = p$ for all p. This proves (i).

Step 2 (Efficiency under truthful bidding). If each firm bids $s_i^*(p) = (C_i')^{-1}(p)$, then $\hat{S}(p) = \sum_i (C_i')^{-1}(p)$ is the aggregate marginal-cost schedule. The clearing condition

$\hat{S}(\hat{p}) = D(\hat{p})$ is the first-order condition for maximizing W: set total quantity Q so that $D^{-1}(Q)$ = common marginal cost = $\hat{p}$, with quantities allocated across firms by $C_i'(q_i) = \hat{p}$. By strict convexity of costs and strict monotonicity of demand, the solution is unique and efficient. This proves (ii).

Step 3 (Payoff equals marginal contribution under truthful bidding). We establish the "area identity," then conclude. Under truthful bids,

$$q_j = \hat{s}_j(\hat{p}) = (C_j')^{-1}(\hat{p}), \qquad q_j^{-i} = \hat{s}_j(\hat{p}_{-i}).$$

A change of variables $q = D(p)$ gives

$$\int_{Q_{-i}}^{Q} D^{-1}(q)\, dq = \int_{\hat{p}_{-i}}^{\hat{p}} p'\, D'(p')\, dp' = \Big[p' D(p')\Big]_{\hat{p}_{-i}}^{\hat{p}} - \int_{\hat{p}_{-i}}^{\hat{p}} D(p')\, dp'. \tag{F.1}$$

For $j \neq i$, convexity and truthfulness imply

$$C_j(q_j) - C_j(q_j^{-i}) = \int_{q_j^{-i}}^{q_j} C_j'(q)\, dq = \int_{\hat{p}_{-i}}^{\hat{p}} p'\, d\hat{s}_j(p') = \Big[p' \hat{s}_j(p')\Big]_{\hat{p}_{-i}}^{\hat{p}} - \int_{\hat{p}_{-i}}^{\hat{p}} \hat{s}_j(p')\, dp'. \tag{F.2}$$

Summing (F.2) over $j \neq i$ gives

$$\begin{aligned} \sum_{j\neq i} \big[C_j(q_j) - C_j(q_j^{-i})\big] &= \Big[p' \sum_{j\neq i} \hat{s}_j(p')\Big]_{\hat{p}_{-i}}^{\hat{p}} - \int_{\hat{p}_{-i}}^{\hat{p}} \sum_{j\neq i} \hat{s}_j(p')\, dp' \\ &= \hat{p}\,[D(\hat{p}) - \hat{s}_i(\hat{p})] - \hat{p}_{-i} D(\hat{p}_{-i}) - \int_{\hat{p}_{-i}}^{\hat{p}} \sum_{j\neq i} \hat{s}_j(p')\, dp'. \end{aligned} \tag{F.3}$$

Subtracting (F.3) from (F.1) yields

$$\begin{aligned} \int_{Q_{-i}}^{Q} D^{-1}(q)\, dq - \sum_{j\neq i}[C_j(q_j) - C_j(q_j^{-i})] &= \Big(\hat{p} D(\hat{p}) - \hat{p}_{-i} D(\hat{p}_{-i})\Big) - \Big(\hat{p}[D(\hat{p}) - \hat{s}_i(\hat{p})] - \hat{p}_{-i} D(\hat{p}_{-i})\Big) \\ &\quad - \int_{\hat{p}_{-i}}^{\hat{p}} D(p')\, dp' + \int_{\hat{p}_{-i}}^{\hat{p}} \sum_{j\neq i} \hat{s}_j(p')\, dp'. \end{aligned}$$

The boundary terms simplify to $\hat{p} D(\hat{p}) - \hat{p}[D(\hat{p}) - \hat{s}_i(\hat{p})] = \hat{p}\, \hat{s}_i(\hat{p})$. The integral terms combine as

$$-\int_{\hat{p}_{-i}}^{\hat{p}} D(p')\,dp' + \int_{\hat{p}_{-i}}^{\hat{p}} \sum_{j\neq i} \hat{s}_j(p')\,dp' = -\int_{\hat{p}_{-i}}^{\hat{p}} \Big[D(p') - \sum_{j\neq i} \hat{s}_j(p')\Big]\,dp' = \int_{\hat{p}}^{\hat{p}_{-i}} D_i(p')\,dp',$$

where $D_i(p') = D(p') - \sum_{j\neq i} \hat{s}_j(p')$ is the residual demand for i. Therefore,

$$\int_{Q_{-i}}^{Q} D^{-1}(q)\,dq - \sum_{j\neq i}[C_j(q_j) - C_j(q_j^{-i})] = \hat{p}\,\hat{s}_i(\hat{p}) + \int_{\hat{p}}^{\hat{p}_{-i}} D_i(p')\,dp'.$$

Subtracting $C_i(q_i) = C_i(\hat{s}_i(\hat{p}))$ from both sides gives

$$W - W_{-i} = \hat{p}\,\hat{s}_i(\hat{p}) - C_i(\hat{s}_i(\hat{p})) + \int_{\hat{p}}^{\hat{p}_{-i}} D_i(p')\,dp' = \pi_i,$$

as claimed. This proves (iii). □

Proof of ex-ante optimality of price cap rule for heterogeneous welfare weights in Section 5.

Let the demand state x be continuously distributed with full support over a compact interval. Assume also that the price-cap rule p_x^* is a continuous and differentiable function. The planner applies this rule ex post in each state, but anticipates its ex ante impact on responsiveness and investment. The planner's problem is

$$\max_{\{p_x^*\}} \quad \mathbb{E}_z[W_z^\omega] - \int_0^{c^*} \omega(c)\,c\,dH(c), \tag{F.4}$$

where

$$W_z^\omega = \mu_z(p_x^*)\Big[(1-\theta)\bar{\omega}_s(\theta)\,u_x(\bar{d}_x) + \theta\bar{\omega}_r(\theta)\,u_x(d_x(p_z))\Big] - C_y(D_z), \tag{F.5}$$

with conditional welfare weights

$$\bar{\omega}_r(\theta) = \frac{1}{\theta}\int_0^{c^*} \omega(c)\,dH(c),$$
$$\bar{\omega}_s(\theta) = \frac{1}{1-\theta}\int_{c^*}^{\infty} \omega(c)\,dH(c),$$

and with the selection margin satisfying $\theta = H(c^*)$.

After perturbing the optimal (differentiable) rule in a given state x, the first-order condition can be written as

$$\frac{\partial \mathbb{E}_z[W_z^\omega]}{\partial p_x^*} + \Big(\frac{\partial W_z^\omega}{\partial \theta} - \omega(c^*)\, c^*\Big) h(c^*) \frac{\partial \Delta}{\partial p_x^*} = 0, \tag{F.6}$$

where

$$\frac{\partial c^*}{\partial p_x^*} = \frac{\partial \Delta}{\partial p_x^*}, \qquad \frac{\partial \theta}{\partial p_x^*} = h(c^*) \cdot \frac{\partial c^*}{\partial p_x^*}.$$

To interpret the condition, note that (F.6) decomposes the planner's first-order condition into two channels (separated by the plus sign). The first measures the deviation from the ex-post optimal price cap (5.4). The second measures the deviation from optimal endogenous selection of responsiveness for uniform consumer weights (4.1). That is, the FOC informs us that if heterogeneous welfare weights change the optimal selection of responsiveness θ, the optimal price cap rule (5.4) must be adjusted as well. Yet as we will see, such is not the case. The optimal price cap rule is preserved.

The first term in brackets of (F.6) reflects the social benefits of adding the marginal consumer $c^* = \Delta$ from sticky to responsiveness. As we have seen in (4.1), the social value equals the private costs, denoted by the second term in brackets of (F.6). Heterogeneous weights does not change that, as both benefits and costs receive the same marginal consumer's weight. Thus the term in brackets is zero, and thus the ex-post optimal price cap rule is also preserved ex-ante.