Rational rationing: A price-control mechanism for a persistent supply shock

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Abstract

We propose a simple price-control mechanism correcting for a missing short-run response of demand to prices. It effectively implements an aggregate demand response by a time-varying price cap that optimally adjusts to information on the social value of rationing. A quantification obtains this information from supply and demand bids to the Nordic power market, showing how the mechanism could be incorporated to the market-clearing routines. The mechanism does not bind in normal times but gains traction in a persistent supply shock and stops binding again when the market has adjusted to the new normal.

Keywords: Rationing; price caps; supply shock; electricity market

JEL Classification: D45, D61, Q41, Q48

1 Introduction

> "His Lights Stayed on During Texas' Storm. Now He Owes $16,752."
> —New York Times, March 3/2021

The Texas' Storm in 2021 led to prices that were 100 times higher than anything considered normal. The conflict in Ukraine threatens to disrupt supplies of gas, oil, and electricity in Europe, leading to a chilling prospect that the Texas' Storm type of event could last for, not weeks, but months until the market adjusts. The policy makers in the EU have, among other measures, proposed price controls to protect the economy.[1]

Administratively set price caps are part of the standard design in electricity (wholesale) markets, with the purpose of restoring the equilibrium through rationing in rare situations in which the supply fails to meet the demand. Such caps are typically high, \$9,000/MWh in the Texas' Storm, and intended to bind only in short-lasting events such as production or transmission outages. Once the glitch is resolved, the market is expected to return to the status quo ante. For example, both private and industrial consumers' technology choices or longer-term contracts based on the prevailing spot price can remain unaltered.

The Ukraine shock is different: Supplies are not expected to return back to normal soon, the shock is persistent. In contrast to a one-time anomaly, the demand is expected to adjust but with a delay as not all consumers respond to prices in real time – the short-term demand is sticky in electricity markets.[2] Due to the stickiness, there is a misallocation in the market that cannot be immediately resolved. We show that the efficient intervention corrects for the misallocation by introducing an aggregate "demand response" through rationing not only when the market fails to clear but whenever the market price exceeds the social value of consumption. In our quantification, the efficient policy implements a temporary price cap well below the administrative price caps currently in place.

A persistent shock means persistent over-consumption by the sticky consumers. The

[1] On March 23, 2022, the EU commission outlined the policy options affecting retail and wholesale markets, including a cap on electricity prices. Source: `https://ec.europa.eu/commission/presscorner/detail/en/IP_22_1936`. European Union Agency for the Cooperation of Energy Regulators (ACER, 2022) published a report in April 2022 recommending that "Member States could consider establishing ex-ante a temporary price limitation mechanism kicking in automatically under clearly specified conditions".

[2] Ito et al. (2021) call this "the fundamental inefficiency in electricity markets". They consider an experimental design to deal with it; see also Fowlie et al. (2021)

optimal policy regulates the price of consumption at a level that trades off the surplus from non-sticky (i.e., price-responsive) vs. sticky parts of the demand, together with a rationing protocol to implement the price cap. This non-market mechanism has the same general motivation as, e.g., in Joskow & Tirole (2007), i.e., a market imperfection, but there is an important difference: We introduce the price-control mechanism for all parties in the market.[3] The approach seems unavoidable, e.g., in exchanges where trading takes place with a uniform price without powers to ration consumers individually. In such a situation, we find that the optimal price cap needs to be time-varying, responding to changes in market demand. In particular, the cap starts binding in response to a persistent supply shock, rises to a higher level as the demand adjusts to the shock, and finally stops binding when the demand has adjusted. In this sense, the cap is temporary.

We calculate the social value of rationing using basic price theory. We illustrate it in a specific context, the Nordic market for wholesale electricity. The supply and demand bids to the exchange contain information on the social value of rationing, and they form the basis for calculating the optimal price cap, hour by hour. The bids indicate how the demand changes in response to the shock which is essential for the optimal adjustment of the price cap. In any given hour, if the clearing price rises above the optimal price cap, the mechanism implements the cap by an elimination procedure for the demand bids to obtain the required rationing. We quantify the mechanism using the actual bids in 2019-2022 as data.

We find a number of strong predictions for the optimal intervention. First, in a persistent supply crises, the optimal price cap is only a fraction of the actual harmonized EU price cap. The rudimentary reason for the difference is that the harmonized price cap pays no attention to the welfare gains from a demand response achieved through rationing. The mechanism has no bearing on market clearing in normal times; it gains traction only after the onset of the supply crises in winter 2021-2022. Second, the rationed quantities are minuscule in relation to total volumes in the market suggesting that executing the physical rationing in regions that participate in trading should not be a major hurdle. Third, the intervention has strong distributional implications; a small demand reduction leads to a large price drop. In our stress tests, the policy leads to transfers from producers to consumers measured in billions of euros over a short period of time, although it should be borne in mind that our theory is justified by efficiency and not by redistribution objectives. Finally, the mechanism can be adopted without

[3] In Joskow & Tirole (2007) only the non-responsive individuals, who are thus identified (as a group at least), face rationing with a constant price in all states of the market.

reforming the market clearing rules in place.[4]

The literature on price controls concludes that price caps lead to misallocations in an otherwise competitive market; see Bulow & Klemperer (2012). But if there are misallocations in the market at the outset, non-market mechanisms are needed for efficiency, as in Wilson (1989) and Joskow & Tirole (2006, 2007). In particular, Joskow & Tirole (2007) develop a comprehensive market-design problem when some consumers do not respond to prices, similarly as in Borenstein & Holland (2005). The model lends itself, e.g., to investment analysis (Gowrisankaran et al., 2016).[5] Our insights follow from a simple price theory that applies in uniform-price settings: Whether it is the inability to identify the passive consumers individually (or as a group), the institutional restriction that uniform pricing is a rule (as is the case for electricity in the EU), or that the price cap determination is delegated to an exchange which does not have powers to ration consumers directly, our approach seems relevant.

The results are linked to the literature on welfare impacts of price stabilization; Wright (2001) and, e.g., Newbery & Stiglitz (1979). Sticky demand as a welfare reason for price stabilization does not appear in this literature. The energy transition has led to a revival of interests in the topic.[6]

2 Analytics of the optimal price cap

Consider a share θ of final consumers who respond to any change in the market price by adjusting demand according to marginal utility. Thus, for utility $u(q)$ from consumption q, these consumers' demand $d(p)$ at price p is defined by $u'(q) = p$. The consumers in the remaining share $1-\theta$ are different. Their demand is fixed at $\bar{d}$, following from $u'(\bar{d}) = \bar{p}$, where $\bar{p}$ is what we call a reference price. Think of $\bar{p}$ as the status quo price. The market price p can differ from the reference $\bar{p}$, rendering $\bar{d}$ non-optimal for the consumers who have made 'sticky' choices. The reference quantity $\bar{q}$ and price $\bar{p}$ give a basis for evaluating the welfare losses from stickiness for variations in the actual price

[4]Such reforms may be justified for other reasons, including the regulation of excessive windfall profits, e.g., by clawback mechanisms (Fabra, 2022).

[5]Inefficient price caps distort investments through "the missing money problem" (Joskow, 2008); see Wolak (2022) for the sources of the problem. In our analysis, the policy improves the allocative efficiency and, as such, is not a source of investment distortions.

[6]For example, Ambec & Crampes (2021) study the welfare impact of volatility in a theory model where consumers are risk averse. Bobtcheff et al. (2022) consider instruments to correct for inefficiencies from price caps that are too low.

p.[7]

Total demand $D(p)$ sums the sticky and non-sticky demands:

$$D(p) = (1-\theta)\bar{d} + \theta d(p). \tag{1}$$

Note that if σ is the (local) elasticity of the non-sticky demand $d(p)$, the elasticity of aggregate demand is then $\varepsilon_D = \theta\sigma$ evaluated at $p = \bar{p}$. The same observed elasticity ε_D can thus follow from a high share θ of responsive consumers with low σ, or from a low share θ with high σ. The distinction turns out be important for the optimal price control. We follow, e.g., Bulow & Klemperer (2012) and assume for the non-sticky demand elasticity above one, $\sigma(d) > 1$, for all p high enough,[8] so that utility $u(d)$ and consumer surplus are well defined with normalization $u(0) = 0$.

We envision a social planner who faces only one market distortion to rectify: the sticky demand. The planner has one instrument, $\mu \in [0, 1]$, for rationing the aggregate demand,

$$D_\mu(p) = \mu D(p). \tag{2}$$

The planner thus cannot discriminate between demand sources.[9] If $p = \bar{p}$, the demand choices are optimal, with $D(\bar{p}) = \bar{d}$, and the planner has no reason to ration, $\mu = 1$. If the market price rises sufficiently above $\bar{p}$, the planner optimally sets $\mu < 1$ to prevent the price from exceeding the marginal social value of consumption. Consider next the determination of this social value and the resulting optimal μ.

The market equilibrium adjusts to variations in μ. In any equilibrium, rationed or not, the marginal utility of the non-sticky consumers and marginal costs of production are equal: $u'(d) = C'(D_\mu)$ where C is a strictly convex aggregate costs of production. The derivatives u', u'' are thus evaluated at non-sticky demand d, and costs and its derivatives C', C'' are evaluated at aggregate quantity D_μ. It is easy to establish that when rationing tightens ($d\mu < 0$), aggregate quantity goes down ($dD_\mu/d\mu > 0$), the price

[7] Be it a price expectation obtained from historical prices, a purchasing contract that guarantees a specific price, or fixed regulated retail price (as in electricity markets), the consumers facing the reference price have no incentives to change their demands until the reference itself changes. The reference price allows introducing stickiness without other systematic differences between sticky and non-sticky consumers as in Borenstein & Holland (2005); Joskow & Tirole (2006, 2007).

[8] Any finite demand satisfies $\lim_{d\to 0} \sigma(d) \to \infty$, but a finite elasticity does not require a finite demand. The demand curves we consider satisfy $\lim_{d\to 0} p \to \infty$.

[9] We discuss the alternatives based on priority (Wilson, 1989) in Section 3.

goes down ($dp/d\mu > 0$), and non-sticky demand goes up ($dd/d\mu < 0$).[10]

The policy is set to maximize the total welfare. Let V be the rationed aggregate utility, and W be the aggregate welfare:

$$V = \mu\left((1-\theta)u(\bar{d}) + \theta u(d)\right), \tag{3}$$

$$W = V - C(D_\mu). \tag{4}$$

Taking full derivatives of the welfare with respect to the policy variable μ and the aggregate quantity D_μ, we get:

$$dW = \left[\frac{V}{\mu} - \frac{D_\mu}{\mu}u'\right] d\mu + [u' - C']\, dD_\mu. \tag{5}$$

The last term is zero in equilibrium. The welfare thus increases with rationing, $dW/d\mu < 0$, iff the term between the left square brackets is negative. We thus have a simple condition for the optimal rationing:

Lemma 1 *For the optimal policy it holds that*

$$p^* D_\mu \leq V \perp \mu^* \leq 1, \tag{6}$$

where $p^* = u'(d^*)$, and μ^* is the associated optimal rationing.

The orthogonality symbol tells that rationing applies iff, without rationing, expenditures exceed aggregate utility. The optimal rationing price $p^* = V/D_\mu$ solves a trade-off: Strictly positive consumer surplus for the non-sticky consumers must exactly cancel out negative consumer surplus for the sticky consumers. Formally, when $\mu^* < 1$, it holds that

$$(1-\theta)u(\bar{d}) + \theta u(d^*) = p^*((1-\theta)\bar{d} + \theta d^*) \tag{7}$$

so the price p^* equals the average utility.

We illustrate an optimal rationing situation graphically in Fig 1. The reference equilibrium is F, where the price is $\bar{p}$ and the sticky and non-sticky demands are both equal to $\bar{d}$. In the figure, V equals the area under AF, while pq equals the square with corner at F. Thus, in the reference equilibrium, no rationing is required – condition (6) holds with the left inequality strict, as aggregate utility (i.e., RHS) exceeds expenditures (i.e., LHS) with the right non-strict inequality as equality.

[10] From the aggregate demand (2), we have $dd = -\frac{D_\mu}{\mu^2\theta}d\mu + \frac{1}{\mu\theta}dD_\mu$. From the consumer optimum, $u''dd = C''dD_\mu \Rightarrow \frac{D_\mu}{\mu^2}u''d\mu = \left[\frac{1}{\mu\theta}u'' - C''\right]dD_\mu$, which establishes $dD_\mu/d\mu > 0$, $dp/d\mu > 0$, $dd/d\mu < 0$.

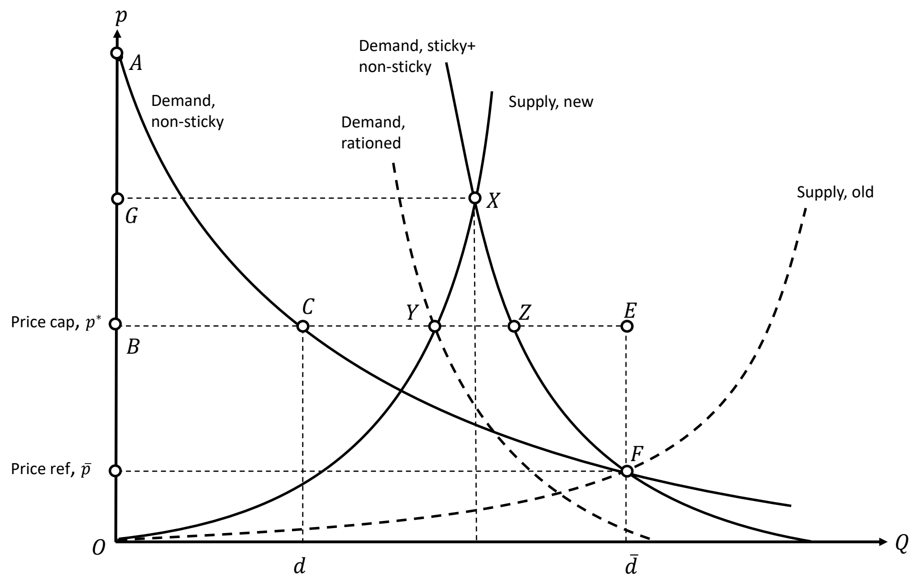


Figure 1: An illustration of optimal price control for a supply shock. Under the optimal price cap p^*, triangles ABC and CEF cover equal areas, the latter weighed by the share of sticky consumers $1-\theta$. Rationing reduces demand at p^* from Z to Y.

Let us then shock the supply to reach a new equilibrium at X. Is it optimal to prevent the price from reaching this new level? Consider that the price is allowed to increase to p^*. The demand by the non-sticky consumers moves to the level indicated by C. Utility V equals the area under AC multiplied by the mass θ plus the area under AF weighed by $1-\theta$. Expenditures equal the rectangular for C weighed by θ plus the rectangular for E weighed by $1-\theta$. The difference between the RHS and the LHS of the condition (6) is the triangle CEF weighed by $1-\theta$ minus the (unweighed) triangle ABC. Graphically, it is obvious that this difference is increasing in the price cap, negative at the reference equilibrium at F and positive at A. There is a unique equilibrium C supported by price p^* such that $\Delta ABC = (1-\theta)\Delta CEF$. If without rationing, $\mu = 1$, the equilibrium price falls short of this p^*, there is no need for rationing. If, as in Fig. 1, the equilibrium price without intervention exceeds p^*, the optimal rationing introduces a "demand response" by decreasing μ to the point where supply can meet demand at price p^*.

There is a unique p^* (independent of μ) such that the left inequality in (6) becomes an equality. This condition is completely characterized by demand. Given such p^*, the supply steps in: The rationing μ is set at a level such that demand equals producers' supply, $D_\mu = S(p^*)$.

We summarize the findings in:

Proposition 1 *For a reference equilibrium $D(\bar{p}) = S(\bar{p}) = \bar{d}$, define a supply shock by a new supply $\underline{S}(p) < S(p)$. Then:*

(i) *there is a unique $p^* > \bar{p}$ and the associated non-sticky demand $d^* < \bar{d}$ given by $p^* = u'(d^*)$ and $(1-\theta)u(\bar{d}) + \theta u(d^*) = p^*((1-\theta)\bar{d} + \theta d^*)$;*

(ii) *if and only if $\underline{S}(p^*) < (1-\theta)\bar{d} + \theta d^*$, it is optimal to implement a binding price cap at p^* with demand rationed by $\mu^* = \underline{S}(p^*)/\left((1-\theta)\bar{d} + \theta d^*\right)$.*

The opptimal rationing loosens and the rationing price increases with an increasing share of non-sticky consumers: $\partial\mu^*/\partial\theta > 0$, $\partial p^*/\partial\theta > 0$.

Proof. We provide a monotonic algorithm for determining p^*, through induction by index k. Start with $p_0^* = \bar{p}$, $d_0^* = \bar{d}$, and then construct interatively $p_{k+1}^* = [(1-\theta)u(\bar{d}) + \theta u(d_k^*)]/[(1-\theta)\bar{d} + \theta d_k^*]$, with updated $d_k^* = d(p_k^*)$ for $k > 0$. For $\theta > 0$, the iteration constructs a monotonic sequence. For $k = 0$, we have $p_1^* = u(\bar{d})/\bar{d} > \bar{p} = p_0^*$. Thus $d_1^* < d_0^*$. As $u(d)/d$ decreases with d, it follows that $p_{k+1}^* > p_k^*$, and subsequently $d_{k+1}^* < d_k^*$. We repeat this ad infinitum. The sequence is bounded for any $\theta < 1$. ■

We now assess the welfare gains from rationing, divided between the consumer and producer surpluses.

Remark 1 *The total increase in welfare is measured by XYZ in Fig 1.*

The result is not obvious, and therefore we develop the changes in consumer and producer surpluses when we move from $\mu = 1$ to $\mu^* < 1$. Define the consumer surplus dependent on prices and rationing:

$$CS(p,\mu) = V - pD_\mu = \mu\left((1-\theta)(u(\bar{d}) - p\bar{d}) + \theta(u(d(p)) - pd(p))\right). \tag{8}$$

Consider a path from the no-rationing to the rationing equilibrium: in Fig 1, consider two segments, first from X to Z and then from Z to Y, described by mapping $f : [0,2] \to (p,\mu)$. Along the first segment, we do not ration but start lowering the price from the equilibrium without rationing, $f(0) = (\widehat{p}, 1)$, to the price consistent with optimal rationing, $f(1) = (p^*, 1)$. That is, we move from X to Z. Along the second segment, we keep prices constant and increase rationing to let demand meet supply, $f(2) = (p^*, \mu^*)$. That is, we move from Z to Y. Along the first segment we have the non-sticky consumers setting marginal utility equal to prices, $u' = p$, thus

$$dCS = \left(-(1-\theta)\overline{d} + \theta(u'd' - pd' - d)\right)dp = -Ddp. \tag{9}$$

Along the second segment, we have $V = pD_\mu$, thus $dCS = 0$. Taken together, the consumer surplus increases by the area $BGXZ$. The producer surplus, on the other hand, decreases by $BGXY$ in Fig 1. Thus, the total increase in welfare is measured by XYZ.

Area XYZ is about half the product of the drop in price and the drop in aggregate demand. The drop in price proxies the rent redistribution. The drop in aggregate demand relates to the efficiency gains by rationing. If the price effect is large but rationing remains modest, the effect is mostly a redistribution effect. If the rationing becomes substantial, there is a pure efficiency gain to be reaped.

Illustration. The constant elasticity of demand, $\sigma = pd'/d$, proves useful in illustrating the information relevant for the optimal price cap policy.

Proposition 2 *For a constant elasticity σ, consider the aggregate elasticity of demand, $\varepsilon_D = \sigma s$ where $s = d/D$. A price cap $p^* > \bar{p}$ is optimal iff the aggregate elasticity exceeds the share of non-sticky consumers, $\varepsilon_D > \theta$, at the reference price $p = \bar{p}$. For the optimal p^* it holds that*

$$\frac{(1-\theta)\left(\frac{p^*}{\bar{p}}\right) + \theta\left(\frac{p^*}{\bar{p}}\right)^{1-\sigma}}{1-\theta+\theta\left(\frac{p^*}{\bar{p}}\right)^{1-\sigma}} = \frac{\varepsilon_D^*}{\varepsilon_D^* - s^*}, \tag{10}$$

with ε_D^* and s^* evaluated at p^*. Moreover, p^* and ε_D^* and s^* all increase in θ.

Proof. We use the condition $p^* = V/D_\mu$ from proposition 1 with $d(p) = \bar{d}\bar{p}^\sigma p^{-\sigma}$ and $u(d) = (\sigma/(\sigma-1))\bar{p}\bar{d}^{1/\sigma}d^{(\sigma-1)/\sigma}$ to obtain, after a few manipulations,

$$\frac{(1-\theta)\psi + \theta\psi^{1-\sigma}}{1-\theta+\theta\psi^{1-\sigma}} = \frac{\sigma}{\sigma-1}, \tag{11}$$

where $\psi = p^*/\bar{p}$ for short. On the right-hand side, $\sigma > 1$ by our assumptions on the finite consumer surplus. The left-hand side is increasing in ψ and maps $\psi \in (1,\infty)$ onto to $(1,\infty)$. There is thus a unique value of ψ defining p^*. The expression in the result follows by $\varepsilon_D = \sigma s$. The ratio on the left decreases in θ, and thus $d\psi/d\theta > 0$ and $dp^*/d\theta > 0$. The expression for s^* is

$$s^* = \frac{\left(\frac{p^*}{\bar{p}}\right)^\sigma}{\frac{1-\theta}{\theta} + \left(\frac{p^*}{\bar{p}}\right)^\sigma}, \tag{12}$$

so thus s^* and $\varepsilon_D^* = \sigma s^*$ are increasing in θ as well. Finally, condition $\varepsilon_D > \theta$ is equivalent to $\sigma > 1$ by $\varepsilon_D = \sigma\theta$ for $p = \bar{p}$. Without this condition holding, the consumer surplus is not finite and losses from any rationing are infinitely large. ■

In normal times $p = \bar{p}$ and, at this price, $\varepsilon_D = \sigma\theta$. The same value of observed demand elasticity ε_D can follow from varied θ and σ, and the optimal intervention depends on the breakdown of sources of the elasticity, with θ increasing the threshold price for intervention. We turn next to our quantification illustrating one approach for obtaining this information.

3 Quantitative Assessment

Data. The data comes from the Nordic day-ahead market for wholesale electricity. It includes all demand and supply bids as price-quantity pairs, and also equilibrium prices and quantities for all hours between 1 Jan 2019 and 9 Apr 2022, with over 44 million bids, on average around 1,500 bids per hour. The Nordic day-ahead market consists of 12 bidding zones: 2 in Denmark, 1 in Finland, 5 in Norway, and 4 in Sweden. Based on the bids, the market clearing algorithm calculates two sets of prices: One for each bidding zone with the actual transmission constraints included, and one for the system level (i.e., system price) without the transmission constrains.[11]

Replication. We construct demand and supply schedules from the data, and, for robustness, replicate the market clearing task to verify that the equilibrium prices and quantities in the data period are consistent with the bid data. We do not have access to the actual code used for market clearing in each historical hour, but our own code replicates the equilibrium outcomes precisely. Imports to the Nordics are added to the supply and exports are added to the demand; in the contrafactual equilibrium with rationing we hold these trade flows as fixed.[12]

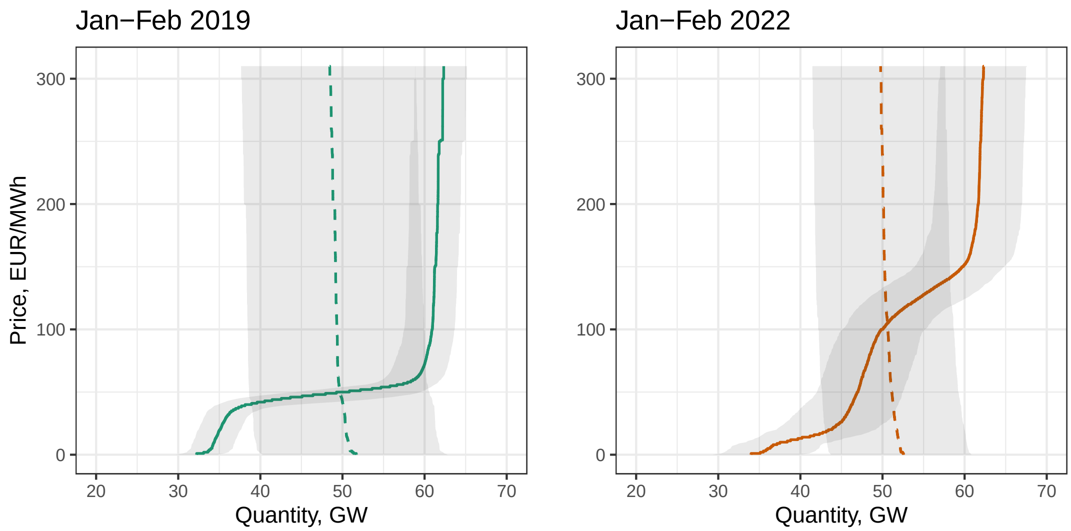
Persistent shock. Fig. 2 depicts the descriptives of the raw bid data by showing average demand and supply schedules in winters 2019 and 2022, with 5% and 95% range of the observed quantities at each price. The persistent supply shock is detectable as a level shift in supply bids due to the record high input prices (natural gas, coal, and the carbon prices in the EU Emissions Trading Scheme). The variation of supply is larger in 2022 due to increased capacity for wind generation between 2019 and 2022. The difference in the demand variation in the two panels is mostly due to temperatures and

[11] Appendix A is the supporting material for this section, including the data description and sources. Data available at Gerlagh et al. (2022).

[12] This is a shortcut that simplifies the allocation task with rationing considerably; otherwise, one needs to compute the EU level equilibrium from the bids to all European bidding zones to determine the change in the trade flows.

exports.

Figure 2: Average bid curves



Notes. Average bid curves in the Nordic market in Jan-Feb 2019 (left panel, green) and in Jan-Feb 2022 (right panel, orange). The shaded areas represent 5% and 95% range of the observed quantities at each price.

Quantification. The price control policy that we propose would implement a counterfactual equilibrium in which the optimal price cap becomes the new equilibrium price. For this counterfactual equilibrium, the market exchange (*exchange*, in short) calculates the social value of rationing and the associated the optimal price cap for each hour from the submitted bids. Rationing means that some demand bids, which would otherwise be activated in equilibrium, are eliminated to attain the price cap; we eliminate quantities from the demand bids on a pro-rata basis.[13]

To implement this procedure, the exchange needs an estimate of the sticky demand share and, in addition, of the non-sticky demand. These are to be identified from the demand bids. Assume that the total demand volume D at price p is approximated by

$$\tilde{D} = \gamma + \eta \exp\left(\frac{-p}{\beta}\right) + \varepsilon \tag{13}$$

[13]This does not require changing the current protocol for dealing with the existing administrative price cap of € 4000/MWh. If the cap is reached, the demand bids are in actuality cut on pro-rata basis to clear the market. Any imbalances then move on to the real-time markets, where the local system operators use contracted reserves or follow their rationing protocols, e.g., rolling black-outs. The pro-rata assumption could be replaced by a market-based rationing for the allocation of the demand curtailment requirement coming from the exchange (e.g., bidding for priority; Chao & Wilson, 1987; Wilson, 1989). The implementation of this design is left open for future research; it appears different from Joskow & Tirole (2007) where the identities of the sticky consumers (or groups of them) are known.

with error ε and parameters γ, η, β to be estimated.[14] Recall that, as the bids define a schedule, we fit (13) to a curve hour by hour using maximum likelihood estimation. Taking the estimated γ, η, β, and the reference price $\bar{p}$, an estimate for the sticky share follows:[15]

$$1 - \theta = \frac{\gamma}{\gamma + \eta \exp(-\bar{p}/\beta)}. \tag{14}$$

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

$$D = (1 - \theta)\bar{d} + \theta \exp\left(\frac{\alpha - p}{\beta}\right). \tag{15}$$

This is now a demand schedule with a sticky part and a non-sticky price-responsive part. The full set of steps for the procedure is:

1. Estimate demand (13) for each hour
2. Take a three-year moving average price as the reference price $\bar{p}$
3. Compute the optimal price cap p^* from Proposition 1 using the estimated D and $\bar{p}$
4. Activate the supply bids with reservation prices (weakly) below p^*
5. Eliminate demand bids (pro-rata) until the demand volume equals the supply volume at p^*.

3.1 Results

Fig. 3 shows the Nordic market price by hour (i.e., system price), the reference price level (i.e., $\bar{p}$ as a rolling three-year average), and the optimal price cap for each hour (i.e., computed by following steps 1-5 above).[16] Consistent with the shift in the supply curve in Fig. 2, in 2022 the market price floated above the reference price that otherwise has been a good basis for sticky demands based on the average price. Clearly, the reference price has been persistently off the actual price development in late 2021 and 2022.

The optimal price cap shown in Fig. 3 varies by the hour because the social value of rationing varies with demand (step 1 above). In contrast, the cap remains unaffected by

[14] Equation (13) implies a convex demand function, a finite demand for zero price, and a minimal demand γ when the price rises without bound.

[15] The reference price $\bar{p}$ gives the expected volume $\bar{d} = \gamma + \eta \exp(-\bar{p}/\beta)$. At a sufficiently high price only the sticky demand remains. This gives the expression.

[16] Appendix B.4 is the supporting material for the results.

shifts in the supply curve; such shifts have an impact on how much rationing is needed to implement any given price cap (in step 4 above). This way, both demand and supply bids contain information necessary for determining the price cap and the associated rationing.

The price cap does not bind in normal times, i.e., when the market price remains close to the reference price. This is as expected. The cap binds at the early stages of the supply shock in late 2021, but then it ceases to bind: The cap escapes the market price by reaching even higher levels. The increase in p^* is almost exclusively explained by changes in the estimated demand parameters α and β; the non-sticky share θ and the reference price $\bar{p}$ are not responsible for the result.[17]

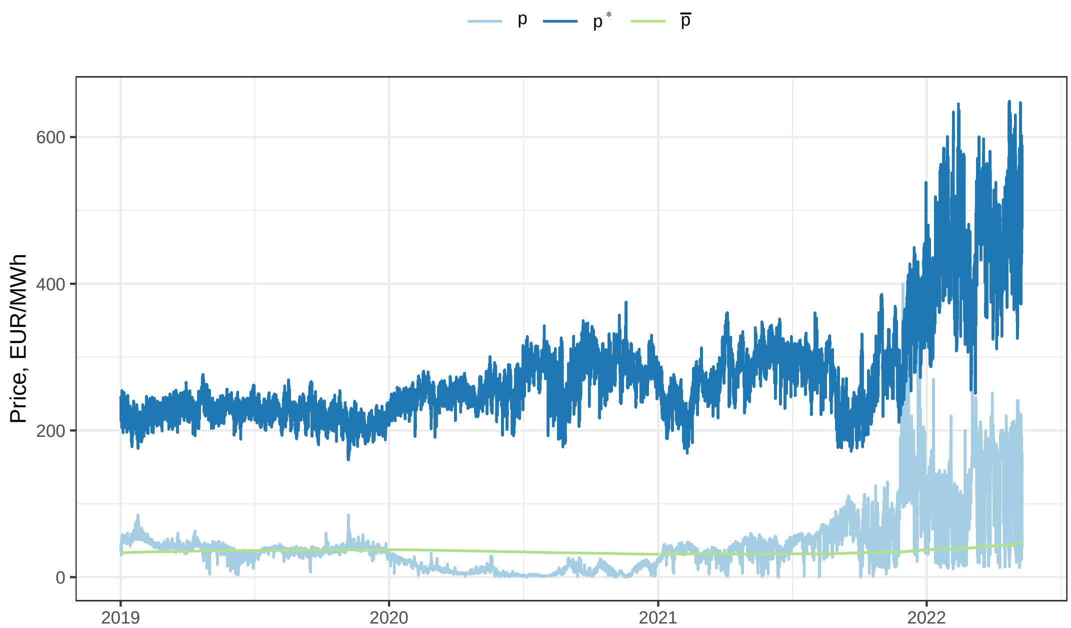
The change in the price cap follows from a change in the demand fundamentals. Parameters α and β are determinants of the demand elasticity, and it would be tempting to conclude that the end-users of electricity have become more attentive to prices in the midst of the crises. However, surprisingly, changes in α and β capture an increase in the demand over a broad range of prices. On reflection, this makes sense: Demand is not isolated from the supply shock because the underlying input-price shock concurrently increases the opportunity cost of electricity demand. For industrial demands, the cost of running in-house generating units goes up, which increases the willingness to pay for the market electricity. For households, the opportunity cost of electric vehicles and heat pumps increases in a similar fashion. Thus, if oil and natural gas are cheap, one can cut electricity at moderate costs. When oil and natural gas are expensive, there is no cheap alternative for electricity. It is then natural that the cost of rationing becomes higher as well. This is exactly what our calculations present.

Table 1 gives a breakdown of winter 2021-2022 results, with two counterfactual scenarios. "Nordic market" shows first the number of observations, and the average hourly quantities and prices in the data period. Then, it reports the results corresponding to Fig. 3 in which the price control is binding in 8 days, in 31 hours in total. Remarkably small rationed quantity, 108 MW or %.2 of the total volume, gives a price reduction of €47/MWh on average. Fig. 4 illustrates, for one hour, why a small policy-induced demand reduction, Δq, leads to such a large drop in the price, Δp: The supply is close to vertical.[18] As a result, the price-control policy leads to a large redistribution from

[17]Given the functional form for the estimated demand, the price cap is a function of the following quartet of parameters: $\alpha, \beta, \bar{p}, \theta$. The contribution of the parameters to the variation in p^* can be evaluated by taking the hourly p^* as the unit of observation and regressing it on the quartet of parameters. From this regression we obtain that α and β explain ca. 99% of the variation in the price cap.

[18]The small horizontal shift in the demand due to rationing is not drawn to maintain clarity.

Figure 3: Market price, price cap, and the reference price



Notes. Optimal price p^*, market price p, and reference price $\bar{p}$ from 1 Jan 2019 to 10 May 2022. The reference price is a rolling three-year average of the historical market prices.

producers to consumers, €85 million in total in 31 hours, while the total efficiency gain, ΔW, remains small. Recall, however, that efficiency is the policy objective in this policy experiment, not redistribution.

"Full export" is a stress-test experiment: The transmission capacities for exporting electricity from the Nordic market to the neighboring regions are assumed to be in full use in this experiment. The idea is to simulate a severe power shortage in central Europe assuming that the Nordic prices remain strictly lower in all hours considered. Given the bids for an hour, the experiment adds the exported quantity as a lump sum to the demand of that hour. It is difficult assess how the bids submitted to the exchange might change in such a scenario but it seems safe to conclude that the price cap binds with much higher frequency: Holding the bids the same with and without the rationing policy, the price cap binds in 635 hours, reducing the price by prodigious €$1,661$/MWh on average in the hours of rationing. The rationed quantity is still modest in comparison to the total volume. There is a large welfare gain from the policy, €708 million, and the distributional impact is large, ca. €62.2 billion.

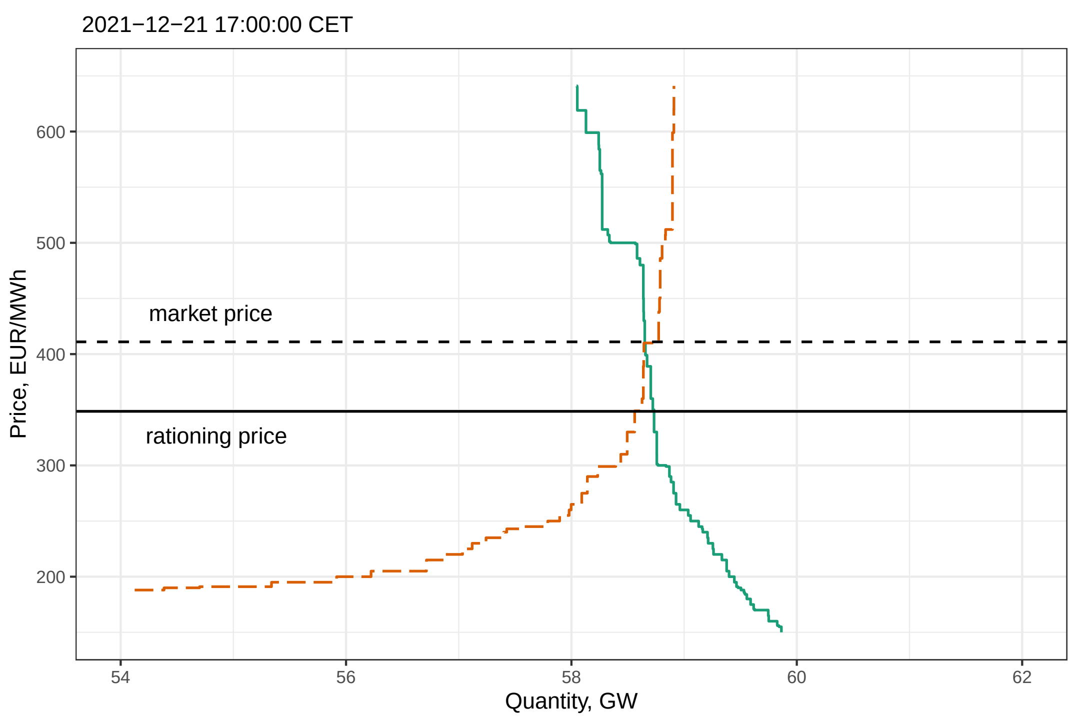
"Finnish area" documents the results for one bidding zone. The exports are added as lump-sum to the demand bids in the Finnish area, and similarly imports are added

Table 1: Price control and rationing in Winter 2021–2022

case	N		Market outcomes		Rationing			Surplus		
	days	hours	q	p	p^*	Δq	Δp	ΔCS	ΔPS	ΔW
Nordic market										
Historical	182	4,327	48,789	116.74						
Rationing policy: yes	8	31	58,097	359.54	312.35	108	-47.18	84.91	-84.67	0.25
Full export										
Rationing policy: no	182	4,327	52,376	415.63						
Rationing policy: yes	63	635	58,109	1,997	335.27	984	-1,661	62,235	-61,527	708
Finland										
Rationing policy: no	182	4,327	8,096	106.56						
Rationing policy: yes	38	254	9,821	363.40	241.92	83	-121.48	317.81	-315.24	2.57

Notes. Table presents the number of days and hours included in the sample, market equilibrium quantities q in MW and prices p in €/MWh, optimal rationing price p^* in €/MWh, the optimal amount of rationing Δq in MW, the change in price Δp in €/MWh, and the change in consumer surplus ΔCS, producer surplus ΔPS, and the change in total welfare ΔW (sum of the surplus changes) in millions of euro. Surplus changes are obtained from the original bid curves. Values reported are the means of the hourly values except for the surpluses which are the sums. Data from 1 Nov 2021 to 30 April 2022.

Figure 4: Demand, supply, and the price cap in an illustrative hour



Notes. Optimal rationing price $p^* = 350$, market price $p = 411$ on hour 5–6pm, 21 Dec 2021.

to the supply bids.[19] Limits on the trade capacity amplify the supply shortages, thereby

[19]Imports and exports are frozen at this level in the equilibrium that follows from the policy interven-

increasing the efficiency gains and distributional impacts from the price control policy.

3.2 Robustness

We obtained a measure of consumer surplus from the demand-side bids by making structural assumptions on how the final aggregate demand is constructed.[20] The data on the entire demand curve, hour by hour, was key in isolating the sticky and non-sticky demands. Although the principles developed here seem general, the same approach may not be feasible in situations where observations are solely equilibrium price-quantity pairs.

The reference price is an input for the optimal price cap: If, after a persistent shock, the reference price is doubled in the new normal, this will accordingly raise the optimal price cap. It is easy to estimate the reference price level from the data as soon as it is explicitly defined, e.g., as a rolling three-year average price or equivalent. The quantitative conclusions we find are not sensitive to changes in this definition, which is reassuring because the relevant reference may differ among end-users, e.g., due to different contractual or technological commitments.

A fundamental question is whether we measure the true social value of rationing. In energy economics, this measure is reported through the value of lost load (VoLL): "[...] markets should be cleared by reductions in demand reflecting the diverse consumers' values of having their demand suddenly curtailed voluntarily or involuntarily" (Joskow, 2022). The common approach to measuring VoLL, often used to justify the administrative price caps in place, is based on surveys estimating a hypothetical valuation for an uninterrupted service. The estimates of VoLL range from close to zero to tens of thousands of euros per MWh, depending on the consumer type, location, frequency of rationing, and time to the interruption.[21]

Analogous to VoLL, our price theory applied to the bid data produces an estimate for the social value of consumption, p^*. It is by definition the social willingness to pay for electricity supply, while VoLL is typically defined as the willingness to accept a cut in supply. We provide next one way of reconciling the two concepts. Consumers should not pay more than their willingness to accept a cut, and therefore we may take VoLL as the reservation value of demand. An estimate of VoLL gives one well-founded price cap when there is not enough supply to all. If the price cap imposed by a policy maker conforms to

tion. The corresponding assumption on trade is made in "Nordic equilibrium"; see fn. 12.

[20] Appendix C is the supporting material for this section.

[21] See CEPA (2018). See also Ambec & Crampes (2018) for an illuminating discussion of the approach. In practise, the price caps often take the firm's profit levels also into consideration; see Section 4.

this idea, suppliers then face a demand effectively truncated at VoLL. At any lower price, $p <$VoLL, the market demand follows the usual marginal utility of non-sticky consumers.

In our empirical case, we do not have information on how much of the demand is in reality valued at VoLL, as this is absorbed into the sticky demand. Adding this information would affect the optimal level of p^* but keep $p^* <$VoLL, because p^* is a mean utility, and the main result would still hold: The intervention is optimal whenever the market price exceeds p^* and some of the price response is sticky.

We propose that $p^* <$VoLL for intervention should be used when a persistent supply shock calls for a structural adjustment in demand. The quantities are small in our case, suggesting that the reserves held by the system operators may have a role in reducing the net demand before consumers are rationed en masse. In contrast, in a one-time blackout situation no *ex post* alterations in the sticky consumption or reference price are needed or expected. Frequent interventions at the level of VoLL are not recommended. Typical VoLL numbers as intervention thresholds are absurd in a supply shock that may last for weeks or months. The electricity factor share can be about 1% of GDP. If VoLL is 100x the normal price, we are willing to give up all income to prevent an uninterrupted service! This may be acceptable in a rare but not in a frequent (i.e., persistent) event.

4 Lessons

Price control and demand response are two sides of the same coin: When demand response is missing, the optimal policy involves price control. While policy makers understand the importance of increasing demand response, policies have not resulted in significant increases of it (e.g., Fabra et al., 2021), and therefore price controls may have their place in policy packages. Price caps are common in electricity markets but not as a tool for active demand management in the sense elaborated in this paper.[22]

It is instructive to review the policies in place in different markets.[23] In the EU, the aim is to implement an energy market where the market price reflects the scarcity of production capacity; the resulting price cap is high, €4,000/MWh. In Texas and Australia, the mechanisms in place monitor the profits of the generators, and curb the prices once the calendar-year profits are deemed to be on a sufficient level. The policies are strikingly different in the implied development of the price cap in a supply crises: The EU rules explicitly call for increasing the price cap in a crises while Texas and Australia

[22]See Neuhoff (2022) for a price-control policy in gas markets.

[23]See Appendix D for an expanded discussion.

implement schemes that control profits by lowering the price. The latter two put a higher weight on distributional concerns and consumer protection; the EU approach is a market-driven approach to the supply problem.

Our insights can put the approaches into a context. First, the market-driven approach to a persistent supply shortage is misguided if there is an imperfection on the demand side: The sticky adjustment of demand calls for a temporary price-control intervention. The intervention is efficient without a redistribution objective. Second, the distributional concerns alone could justify the price cap protocol demonstrated in this paper: Small rationed quantities lead to large redistributions; therefore, the impact on efficiency is small and might even be ignored. Finally, the temporary policy intervention does not distort the private incentives to invest in production capacity: The policy-induced demand response is socially optimal, and therefore it is socially optimal to invest less. After all, this is one of the widely-acknowledged benefits of the increased demand response.

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Online Appendix

Table of Contents

A Data

A.1 Description and data sources

Our main data set consists of bids coming as price-quantity pairs for the Nordic day-ahead market from 1 Jan 2019 to 10 May 2022. There are 29,371 hours with over 45 million bids (28.6 million supply and 16.6 demand bids), on average around 1,500 bids per hour. The Nordic market consists of 12 bidding zones: 2 in Denmark, 1 in Finland, 5 in Norway, and 4 in Sweden. Based on the bids, the market clearing algorithm is used to calculate two sets of prices: One for the *area prices* where the actual transmission constraints are included and one for the *system price* where the internal transmission restrictions within the Nordic area are ignored.

Nord Pool was the sole exchange in the Nordic market until 2 June 2020, and they published the necessary data for the exact replication of the Nordic system price from 1 July 2010 to 2 June 2020[24]. A part of the bid curve data from 3 Jun 2020 to 21 Oct 2021 is missing, because data from a new exchange, Epex Spot, that started on 3 Jun 2020 in the region is available fully only from 22 Oct 2021. We use the partial data for the period prior to 22 Oct 2021 from the *System Price Curves* files published by Nord Pool. The data after 22 Oct 2021 contains bid curves for each Nordic country participating to the system price calculation, these are obtained from Nord Pool and Epex *SCAD* files.

Trade in the day-ahead market is voluntary, and a part of the demand is covered by bilateral contracts or on-site industrial production. The total electricity consumption in the Nordic countries was 405 TWh and the quantity traded in the day-ahead market was 351 TWh in 2020. This market demand includes also the gross exports from the Nordic countries to other regions[25]. In 2020, a total of 80 TWh or 20% of the demand was supplied outside the day-ahead market. Table A.2 provides a breakdown of the annual mean values of the total demand in the region and the demand through the market over the data period, and the export and import means.

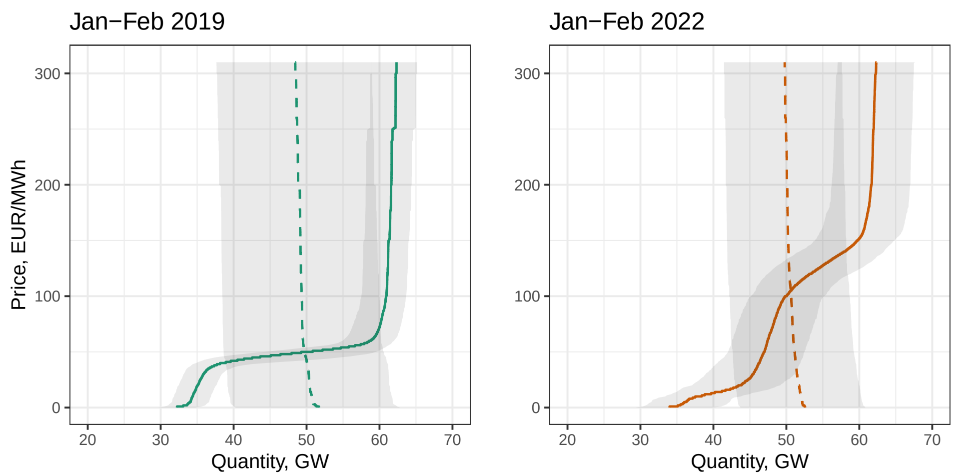
Fig. A.5 reproduces Fig. 2 with 5% and 95% range over the observed quantities at each price level. The increased wind power generation is the most likely explanation for the increased variation in supply from 2019 to 2022. In the Jan–Feb period, the mean wind output increased from 6,154 MW in 2019 to 12,798 MW in 2022, and the maximum

[24] The data consists of supply and demand bid curves and the necessary auxiliary data to account for the accepted volumes from transmission links and block bids.

[25] In 2020 the gross trade away from the Nordics was 26 TWh or 7.4% of the demand contracted through the market. The market operator reports the net flows used in the price calculations.

wind from 12,990 MW in 2019 to 21,187 MW in 2022[26]. Table A.2 summarizes the mean outputs by production technology. The market demand shifts are mostly due to the change in temperatures and exports that are included in the demand curves. Mean temperature in the Nordic capitals in Jan–Feb was .86 °C higher in 2022 than in 2019[27], lowering the demand for electric heating. This if offset by the increase in mean exports from 1,472 MW in Jan–Feb 2019 to 4,157 MW in Jan-Feb 2022. [28]

Figure A.5: Supply shock



Notes. Change in the bid curves in the Nordic market. The curves are averaged over the prices for January and February of 2019 (green) and 2022 (orange).

Table A.2: Mean power output and trade flows in Jan–Feb

	Demand		Generation					Trade	
Year	Total	Market	Hydro	Nuclear	Wind	Thermal	Solar	Export	Import
2018	54,595	50,694	32,232	11,272	4,676	8,221	33	2,495	657
2019	52,260	48,219	27,335	10,968	6,154	8,156	39	1,472	1,080
2020	49,636	44,432	27,069	10,084	9,819	5,499	31	3,163	297
2021	54,230	46,795	32,167	9,660	6,723	7,231	50	2,630	1,028
2022	51,530	46,522	27,050	9,415	12,807	5,736	79	4,157	600

Notes. Total demand, demand cleared at the market place, output by production technology, and exports and inputs from/to the Nordic region in Jan–Feb time period of each year. All reported values are in MW and calculated as means over the hourly data (Source: ENTSO-E Transparency Platform, Nord Pool).

[26]Source: ENTSO-E Transparency Platform.

[27]Source: ECA&D.

[28]Source: Nord Pool.

A.2 Replication

Replication of the historical equilibrium market outcomes is a data robustness check. We use a parsimonious linear program explained in Liski & Vehviläinen (2022) to map the submitted bids to equilibrium prices and quantities hour by hour in the data period. The market clearing protocol is standard but yet it substitutes for the actual program that has been in use in each hour; we have no access to the code used in actuality. We replicate the market prices with a high degree of accuracy, see Table A.3. Reflecting the partially missing data for 3 Jun 2020 to 15 Oct 2021, the mean annual difference between the historical prices and our calculated prices range was €.05/MWh in 2019, increased for 2020–2021 before reducing back to €1.30/MWh in 2022. We take some simplifying steps to deal with the more complex bidding structures, but these do not materially affect the replication outcomes or the usefulness of the bid curves in our main analysis[29].

Table A.3: Historical prices and replicated prices

year	replication	historical	correlation
2019	38.99	38.94	1.00
2020	9.42	10.93	0.94
2021	56.27	62.42	0.99
2022	118.31	117.01	1.00

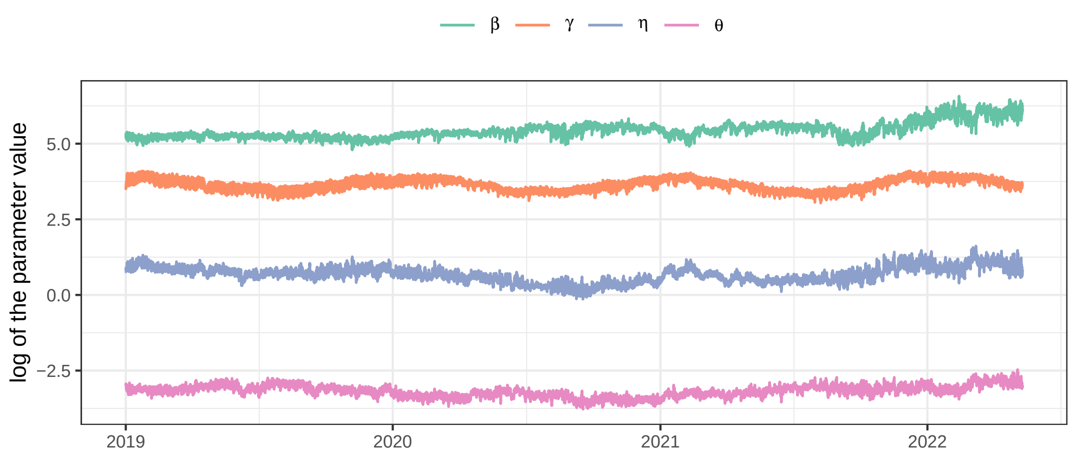
Notes. Table reports the mean values of the hourly prices for each calendar year in €/MWh and the correlation between the hourly values of the historical prices and model prices over each calendar year. Data period from 1 Jan 2019 to 10 May 2022.

[29] The so-called block-bids work as tied bids for several hours: the acceptance of the block is conditional on the mean price over a specified time span, e.g. for the hours 1–24 or 8–20. Although we observe the block bids from data, it is not clear which bids the market clearing algorithm chooses, as tying the bids over hours makes the problem non-convex and the solution is no longer guaranteed to be unique.

A.3 Estimation

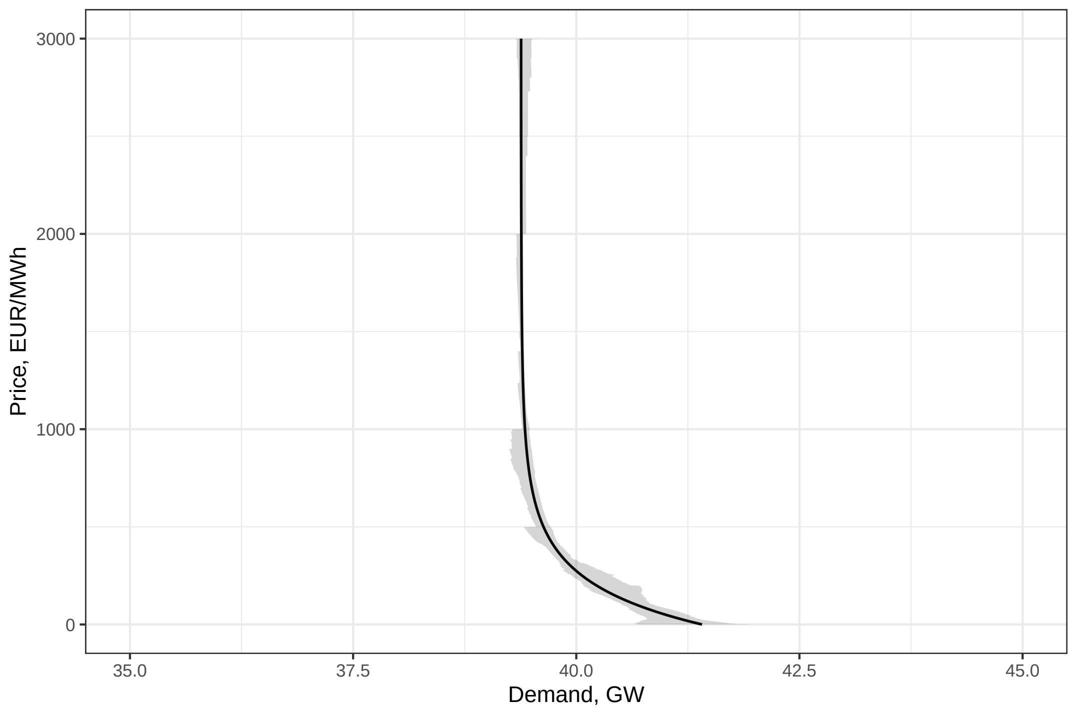
We estimate by maximum likelihood the parameters β, γ, and η to fit the function in (13) to the empirical demand schedule hour by hour. The hourly demand schedule is obtained by stacking the bids in the order of the demand reservation price. The point estimates are reported in Fig. A.6 for all hours. In addition, the figure shows the non-sticky share θ that is calculated from (14) using the point estimates. We do not show the confidence intervals: They are vanishingly small due to the nature of the curve-fitting exercise. A more informative approach to assessing the fit is in Fig. A.7. The figure shows the difference between the predicted demand from the estimated function in (13) and the actual demand at any given price level (mean and the $5-95\%$ range of values).

Figure A.6: Parameter values from the estimation



Notes. Resulting parameter values from the maximum likelihood estimation for each hour in the data set. Parameters β, γ, and η are directly from the estimation and θ is calculated according to Eq. 14. Log-values are reported for all parameters to have them fit the same graph, the means of the parameter values are $\beta = 239.1$, $\gamma = 39.4$, $\eta = 2.02$, and $\theta = .042$. Data period from 1 Jan 2019 to 10 May 2022.

Figure A.7: Accuracy of the demand estimation



Notes. Solid line represents the mean error in the demand estimation over the data period. The shaded area shows the 5% and 95% error values. Data period from 1 Jan 2019 to 10 May 2022.

B Results

B.1 Rationing results by the hour

Table B.4 presents a full account of all the hourly markets where the optimal rationing price would have been binding during 1 November 2021 – 30 April 2022 time span.

B.2 Counterfactual: Full export

The main text reports results from an experiment in which the export links are in full use. In this experiment, we take the bid data of the winter 2021–2022 and adjust the hourly demand curves by adding forced exports out from the Nordics throughout the period. Thus, we are considering a situation where Central Europe faces more sever scarcity than Nordics throughout the winter; as an example such supply shock may result from a full stop in the natural gas and electricity imports from Russia to Europe. Map in Fig. B.8 shows the main export links from the Nordics towards the rest of the Europe and as an illustration the transmission flows on one hour. Fig. B.9 summarizes the historical exports from the Nordics from Central Europe during the winter 2021–2022.

Similar to the main analysis, we 1) collect bid and transmission link data from the market, 2) add to the demand schedule of each hour the exports, this time adjusted to the full export counterfactual, 3) produce a set of market equilibrium outcomes that match the counterfactual situation, and 4) carry out the analysis of the optimal rationing prices and the impacts of rationing. Table B.5 presents a sample of the hourly results.

Table B.4: Impacts of rationing in the main analysis by the hour

	equiilbrium		rationing			surplus		
date.time	q	p	p^*	Δq	Δp	ΔCS	ΔPS	ΔW
2021-11-27 16:00:00	55,284	277.00	273.85	69.30	3.15	0.17	-0.17	0.0002
2021-11-29 07:00:00	56,953	335.20	261.90	176.40	73.30	4.19	-4.17	0.02
2021-11-29 08:00:00	56,979	319.00	260.25	157.50	58.75	3.36	-3.34	0.02
2021-11-29 09:00:00	56,727	299.10	255.80	129.30	43.30	2.47	-2.45	0.01
2021-11-29 10:00:00	56,436	299.90	254.37	129.50	45.53	2.58	-2.56	0.01
2021-11-29 11:00:00	55,996	299.90	252.36	129.40	47.54	2.67	-2.66	0.01
2021-11-29 12:00:00	55,840	315.70	266.23	161.40	49.47	2.77	-2.76	0.01
2021-11-29 13:00:00	56,084	335.50	274.41	159.90	61.09	3.43	-3.42	0.01
2021-11-29 14:00:00	56,324	335.50	270.66	169.40	64.84	3.66	-3.65	0.01
2021-11-29 15:00:00	56,592	379.20	268.54	242.50	110.66	6.28	-6.25	0.03
2021-11-29 16:00:00	56,774	399.90	269.02	299.90	130.88	7.45	-7.41	0.04
2021-11-29 17:00:00	56,756	340.21	272.98	210.30	67.23	3.83	-3.81	0.02
2021-11-29 18:00:00	56,009	291.69	282.90	0.10	8.79	0.49	-0.49	0.0000
2021-12-02 16:00:00	59,532	344.00	332.62	50.10	11.38	0.68	-0.68	0.001
2021-12-06 07:00:00	60,482	384.89	346.88	59.20	38.01	2.30	-2.30	0.002
2021-12-06 08:00:00	60,404	380.00	348.54	59.00	31.46	1.90	-1.90	0.002
2021-12-06 15:00:00	60,772	397.90	341.95	117.40	55.95	3.40	-3.40	0.01
2021-12-06 16:00:00	60,580	380.10	343.63	54.80	36.47	2.21	-2.21	0.002
2021-12-07 07:00:00	61,128	399.90	339.09	82.20	60.81	3.72	-3.71	0.01
2021-12-07 08:00:00	61,234	380.10	339.24	75.70	40.86	2.50	-2.50	0.002
2021-12-21 07:00:00	58,084	387.50	333.97	85.80	53.53	3.11	-3.11	0.002
2021-12-21 08:00:00	58,201	400.10	336.50	91.70	63.60	3.71	-3.70	0.01
2021-12-21 09:00:00	58,189	360.04	334.12	88.80	25.92	1.51	-1.51	0.002
2021-12-21 12:00:00	57,842	350.00	349.54	58.10	0.46	0.03	-0.03	0.0000
2021-12-21 14:00:00	58,462	399.90	344.21	94.80	55.69	3.26	-3.25	0.004
2021-12-21 15:00:00	58,586	400.00	352.93	34.60	47.07	2.76	-2.76	0.003
2021-12-21 16:00:00	58,643	410.10	348.56	82.00	61.54	3.61	-3.61	0.003
2021-12-21 17:00:00	58,500	399.10	367.28	14.80	31.82	1.86	-1.86	0.001
2021-12-22 07:00:00	60,106	404.20	354.51	113.50	49.69	2.99	-2.98	0.004
2021-12-22 08:00:00	60,342	390.00	365.85	87.10	24.15	1.46	-1.46	0.001
2022-03-04 07:00:00	57,165	350.00	340.23	65.60	9.77	0.56	-0.56	0.001
Total	58,097	359.54	312.35	108.07	47.18	84.91	-84.67	0.25

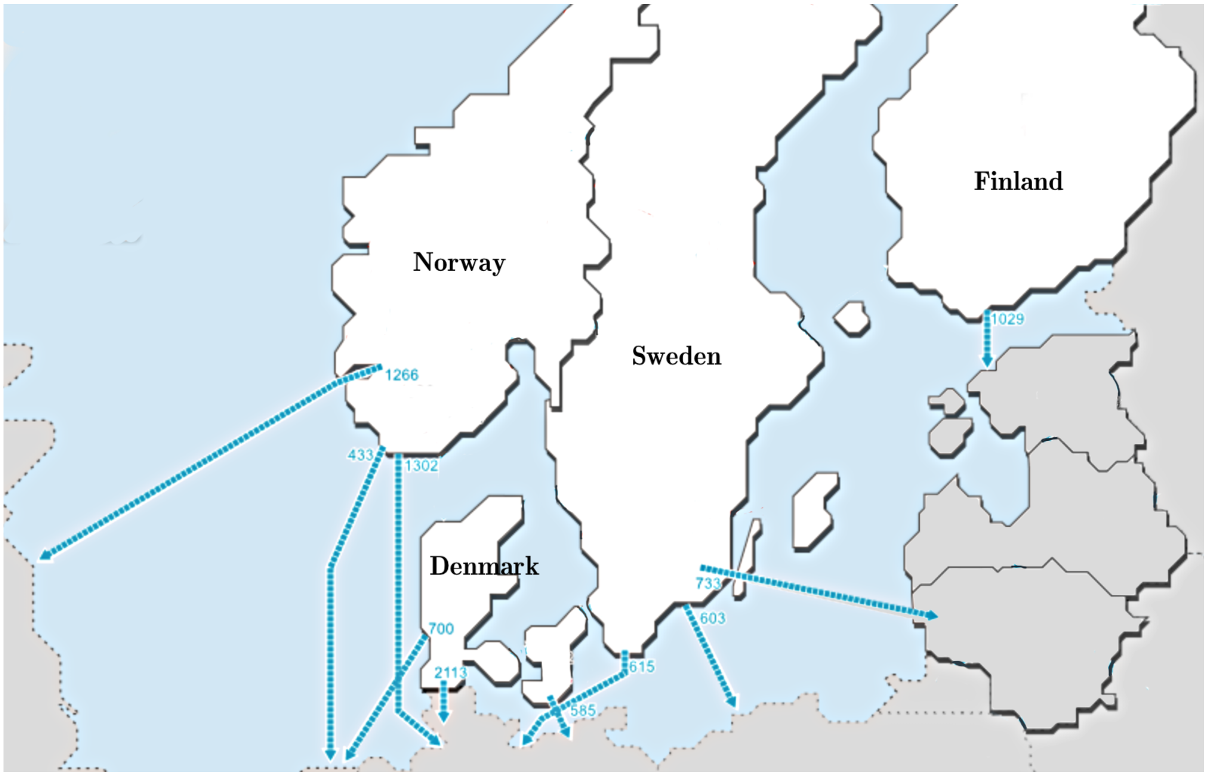
Notes. Table presents the hourly results from optimal rationing over the period 1 Nov 2021 to 30 Apr 2022. Rationing occurs in 8 days for a total of 31 hours. Table presents the replicated market equilibrium quantities q in MW and prices p in €/MWh, the optimal rationing price p^* in €/MWh, the amount of rationing required Δq in MW, the change in price Δp in €/MWh, and the change in consumer surplus ΔCS, producer surplus ΔPS, and the change in total welfare ΔW (sum of the surplus changes) in millions of euro. Surplus changes are measured against the original bid curves. Total row has the mean of the hourly values except for the surpluses where it is the sum.

Table B.5: Impacts of rationing in the full export counterfactual

	equiilbrium		rationing			surplus		
date.time	q	p	p^*	Δq	Δp	ΔCS	ΔPS	ΔW
...								
2021-11-04 06:00:00	52,872	389.92	272.47	749.30	-117.45	6.22	-6.16	0.06
2021-11-04 07:00:00	53,108	976.90	274.24	1093.70	-702.66	37.46	-37.17	0.29
2021-11-04 08:00:00	53,268	500.00	258.39	1149.40	-241.61	12.94	-12.73	0.21
2021-11-04 09:00:00	53,103	413.00	262.39	909.30	-150.61	8.05	-7.92	0.12
2021-11-04 10:00:00	52,943	319.00	252.67	411.30	-66.33	3.53	-3.50	0.03
2021-11-04 11:00:00	52,807	299.00	250.25	356.00	-48.75	2.58	-2.56	0.02
2021-11-04 12:00:00	52,582	275.00	258.91	132.50	-16.09	0.85	-0.84	0.00
2021-11-04 16:00:00	54,162	299.00	260.86	266.70	-38.14	2.07	-2.06	0.01
...								
2021-12-08 06:00:00	64,271	992.00	375.81	870.50	-616.19	39.73	-39.41	0.32
2021-12-08 07:00:00	64,326	3000.00	347.28	1119.90	-2652.72	171.62	-170.02	1.60
2021-12-08 08:00:00	64,400	3000.00	329.47	1132.70	-2670.53	172.99	-171.34	1.65
2021-12-08 09:00:00	64,190	3000.00	337.31	1125.80	-2662.69	171.90	-170.29	1.61
2021-12-08 10:00:00	64,161	3000.00	333.65	1152.30	-2666.35	172.15	-170.43	1.73
2021-12-08 11:00:00	63,837	3000.00	345.11	1147.90	-2654.89	170.59	-168.86	1.73
2021-12-08 12:00:00	63,554	3000.00	359.13	1087.80	-2640.87	168.93	-167.23	1.70
2021-12-08 13:00:00	63,701	3000.00	352.64	1088.90	-2647.36	169.74	-168.02	1.72
2021-12-08 14:00:00	63,801	3000.00	340.34	1182.20	-2659.66	170.80	-169.05	1.76
2021-12-08 15:00:00	63,799	3000.00	334.40	1263.20	-2665.60	171.18	-169.42	1.77
2021-12-08 16:00:00	63,607	3000.00	341.41	1259.70	-2658.59	170.22	-168.42	1.79
2021-12-08 17:00:00	63,384	3000.00	360.95	1162.50	-2639.05	168.36	-166.68	1.68
2021-12-08 18:00:00	63,157	999.90	363.33	951.70	-636.57	40.42	-40.00	0.42
...								
2022-03-31 05:00:00	56,434	1999.90	441.93	1005.30	-1557.97	88.50	-87.60	0.90
2022-03-31 06:00:00	56,322	3000.00	417.26	1232.60	-2582.74	146.82	-144.71	2.10
2022-03-31 07:00:00	55,631	1400.00	384.05	1041.40	-1015.95	56.90	-56.31	0.60
2022-03-31 08:00:00	54,931	948.90	388.97	854.20	-559.93	30.92	-30.63	0.29
2022-03-31 09:00:00	54,386	585.00	389.04	584.40	-195.96	10.69	-10.60	0.09
2022-03-31 10:00:00	53,339	552.90	400.43	424.50	-152.47	8.16	-8.10	0.06
2022-03-31 16:00:00	53,908	500.00	378.67	522.60	-121.33	6.56	-6.51	0.05
2022-03-31 17:00:00	54,241	699.00	409.10	877.90	-289.90	15.76	-15.60	0.16
2022-03-31 18:00:00	54,010	600.10	408.45	582.40	-191.65	10.39	-10.30	0.09
2022-03-31 19:00:00	53,349	585.00	423.79	448.50	-161.21	8.63	-8.56	0.06
...								
Total	58,109	1997	335.27	984.22	-1661	62,235	-61,527	708

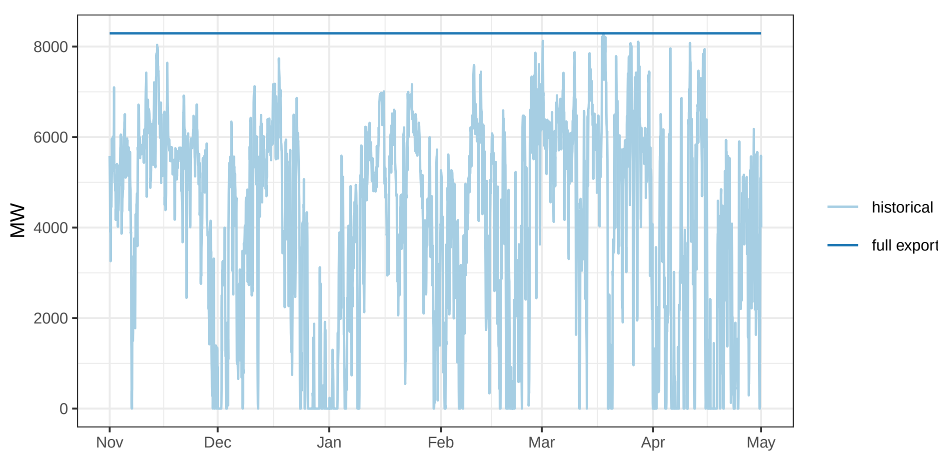
Notes. Table presents an excerpt of the hourly results from optimal rationing in the full exports counterfactual over the period from 1 Nov 2021 to 30 Apr 2022. Rationing occurs in 63 days for a total of 635 hours. The replicated market equilibrium quantities q are reported in MW and prices p in €/MWh, the optimal rationing price p^* in €/MWh, the amount of rationing required Δq in MW, the change in price Δp in €/MWh, and the change in consumer surplus ΔCS, producer surplus ΔPS, and the change in total welfare ΔW (sum of the surplus changes) in million of euro. Surplus changes are measured against the original bid curves. Total row has the mean of the hourly values except for the surpluses where it is the sum.

Figure B.8: Export links from the Nordic market



Notes. Actual export volumes 4:59 am on 18 Mar 2022. Figure: Statnett.

Figure B.9: Exports from the Nordic region to other regions



Notes. Figures shows historical exports from the Nordic region to other regions in MWh/h over the period from 1 Nov 2021 to 30 Apr 2022 and the full export level that matches the maximum observed export level during the time period.

B.3 Finland

The main text reports results for a situation in which rationing is applied in one price zone of the market only: Finland. We cannot repeat this analysis for all price zones in the Nordic region, except for Finland which happens to have only one market area.

We proceed as in the main analysis: 1) we take the bid curve data for the Finnish area, 2) adjust the demand schedules with available data on trade flows, block bids, and the market equilibrium, 3) replicate the historical market prices, and 4) carry out the analysis of the optimal rationing prices and the impacts of rationing. Unlike for the Nordic system price calculation, the market exchanges do not report exactly how the transmission links and the complex bids are handled. In this analysis the bid curves are first constructed from the available data, and any remaining discrepancies are corrected by adjusting the bid curves so that the market clearing prices correspond to the historical equilibria.

Table B.6: Historical prices and replicated prices in the Finnish area

Year	Model	Historical	Correlation
2021	141.88	140.61	0.98
2022	88.51	88.47	1.00

Notes. Table reports the mean values of the hourly prices in each calendar year in €/MWh and the correlation between the hourly values of the historical prices and replicated prices in calendar year. Data period from 1 Nov 2021 to 30 Apr 2022.

Table B.6 shows the resulting price levels from the replication.[30] The counterfactual analysis proceeds with identical steps as in the main analysis. Even though the average prices over the winter 2021–2022 were lower in Finland than in the Nordic area in general, rationing is much more common in Finland (265 hours vs. 33 for the Nordics in the main analysis). A sample of the hourly results is given in B.7.

[30]The remaining differences in prices relate to the fact that for some hours the market price is determined by the vertical part of both curves, leading to ambiguity on which equilibrium price should be picked. The optimization algorithm (Gurobi) we use sometimes ends up with a different price than the market operator's algorithm that uses an undisclosed tie-breaking rule.

Table B.7: Impacts of rationing in Finland by the hour

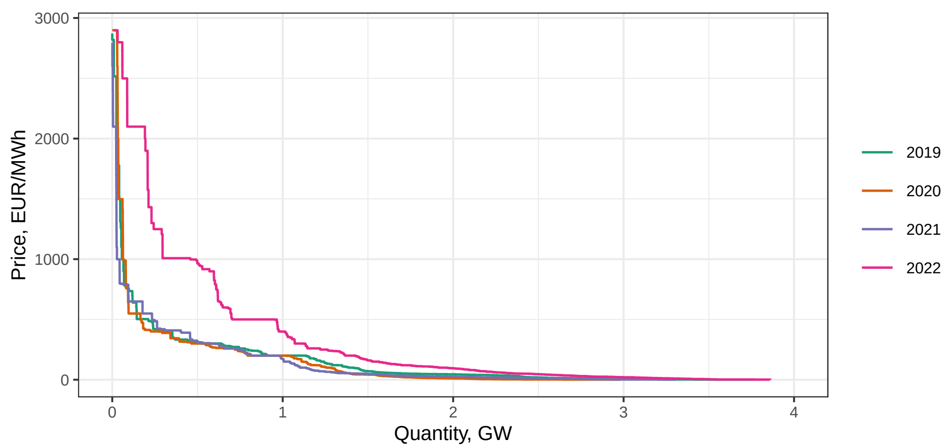
date.time	equiilbrium q	p	rationing p^*	Δq	Δp	surplus ΔCS	ΔPS	ΔW
...								
2021-11-29 05:00:00	9,662	210.00	195.90	32.00	-14.10	0.14	-0.14	0.00
2021-11-29 06:00:00	9,752	299.90	206.35	35.80	-93.55	0.92	-0.91	0.01
2021-11-29 07:00:00	9,712	350.00	200.01	159.00	-149.99	1.47	-1.44	0.03
2021-11-29 08:00:00	9,617	300.10	199.21	113.80	-100.89	0.98	-0.96	0.02
2021-11-29 09:00:00	9,646	299.90	199.51	31.00	-100.39	0.98	-0.97	0.01
2021-11-29 10:00:00	9,646	274.90	203.34	19.70	-71.56	0.69	-0.69	0.00
2021-11-29 11:00:00	9,595	269.90	201.78	19.70	-68.12	0.66	-0.65	0.00
2021-11-29 12:00:00	9,503	300.10	208.05	26.90	-92.05	0.88	-0.87	0.01
2021-11-29 13:00:00	9,635	350.00	206.34	85.40	-143.66	1.39	-1.37	0.02
2021-11-29 14:00:00	9,631	300.10	198.13	41.70	-101.97	0.99	-0.98	0.01
2021-11-29 15:00:00	9,634	399.90	197.88	41.90	-202.02	1.96	-1.94	0.01
2021-11-29 16:00:00	9,539	399.90	191.67	43.40	-208.23	2.00	-1.98	0.01
2021-11-29 17:00:00	9,514	399.90	191.24	44.10	-208.66	2.00	-1.98	0.01
2021-11-29 18:00:00	9,325	399.90	191.61	185.30	-208.29	1.95	-1.92	0.03
2021-11-29 19:00:00	8,864	300.10	189.60	145.60	-110.50	0.99	-0.97	0.02
2021-11-29 20:00:00	9,019	227.70	187.90	22.50	-39.80	0.36	-0.36	0.00
...								
2021-12-06 05:00:00	9,527	269.90	220.48	52.00	-49.42	0.47	-0.47	0.00
2021-12-06 06:00:00	9,667	350.00	212.42	80.90	-137.58	1.34	-1.32	0.01
2021-12-06 07:00:00	9,775	397.90	210.30	51.20	-187.60	1.84	-1.83	0.01
2021-12-06 08:00:00	9,901	397.90	210.68	51.90	-187.22	1.86	-1.85	0.01
2021-12-06 09:00:00	9,979	350.00	210.72	51.20	-139.28	1.40	-1.39	0.01
2021-12-06 10:00:00	10,040	397.90	211.93	83.30	-185.97	1.88	-1.86	0.02
2021-12-06 11:00:00	10,047	345.00	211.54	83.30	-133.46	1.35	-1.34	0.01
2021-12-06 12:00:00	10,056	330.00	211.51	89.20	-118.49	1.20	-1.19	0.01
2021-12-06 13:00:00	10,272	320.00	227.19	96.20	-92.81	0.96	-0.95	0.01
2021-12-06 14:00:00	10,423	450.00	225.29	84.70	-224.71	2.35	-2.34	0.01
2021-12-06 15:00:00	10,380	699.90	207.76	315.90	-492.14	5.12	-5.02	0.10
2021-12-06 16:00:00	10,375	549.90	210.27	202.20	-339.63	3.54	-3.48	0.06
2021-12-06 17:00:00	10,319	350.00	212.11	94.20	-137.89	1.43	-1.42	0.01
2021-12-06 18:00:00	10,151	330.00	211.05	101.40	-118.95	1.22	-1.20	0.01
2021-12-06 19:00:00	9,866	260.00	212.46	38.40	-47.54	0.47	-0.47	0.00
...								
2022-03-09 05:00:00	8,537	250.00	188.22	62.10	-61.78	0.53	-0.53	0.00
2022-03-09 06:00:00	8,651	549.90	184.76	269.30	-365.14	3.17	-3.11	0.05
2022-03-09 07:00:00	8,588	549.90	167.93	267.10	-381.97	3.29	-3.23	0.06
2022-03-09 08:00:00	8,491	249.90	161.94	51.50	-87.96	0.75	-0.75	0.00
2022-03-09 09:00:00	8,424	200.00	159.30	52.80	-40.70	0.34	-0.34	0.00
2022-03-09 16:00:00	8,462	230.00	169.58	163.60	-60.42	0.51	-0.51	0.01
...								
Total	9,821	363.40	241.92	82.64	-121.48	317.81	-315.24	2.57

Notes. Table presents an excerpt of the hourly results from optimal rationing in the Finnish market area over the period from 1 Nov 2021 to 30 Apr 2022. Rationing occurs in 38 days for a total of 254 hours. The replicated market equilibrium quantities q are reported in MW and prices p in €/MWh, the optimal rationing price p^* in €/MWh, the amount of rationing required Δq in MW, the change in price Δp in €/MWh, and the change in consumer surplus ΔCS, producer surplus ΔPS, and the change in total welfare ΔW (sum of the surplus changes) in million of euro. Surplus changes are measured against the original bid curves. Total row has the mean of the hourly values except for the surpluses where it is the sum.

B.4 Impact of the shock on demand

Parameters α_t and β_t are determinants of the demand schedule of an hour t, and changes in these parameters explain the result that the optimal price increases in the supply crises. We argue in the text that the change in the parameters captures a level shift in the price responsive part of the demand. Fig. B.10 illustrates this by showing the average Jan-Feb non-sticky demands in years 2019-2022. A unit of observation is a demand schedule in an hour, net of the estimated sticky demand in that hour. Each curve in the Figure is thus an average of such residual demands. The fuel-price shock increases the opportunity cost of demand sources, which can explain the increase in the willingness to pay.

Figure B.10: Average Jan-Feb non-sticky demands in years 2019-2022.



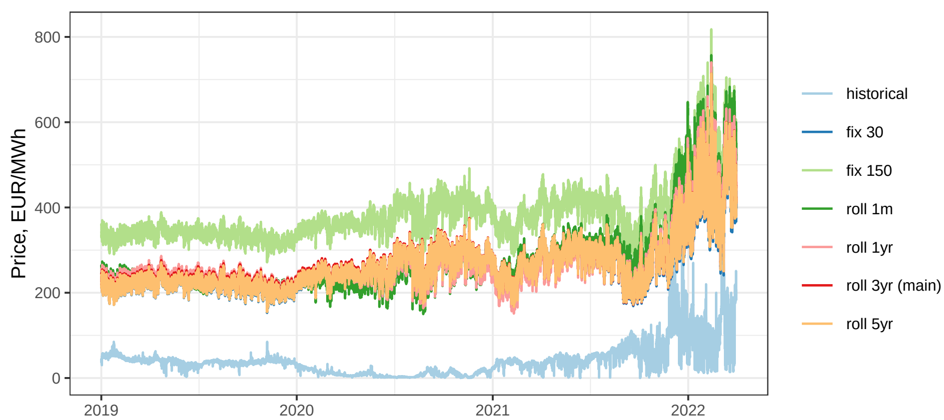
Notes. A unit of observation is a demand schedule in an hour, net of the estimated sticky demand in that hour. Each curve in the figure is an average of such residual demands.

C Robustness

C.1 Reference price

The optimal rationing price p^* depends on the reference price level $\bar{p}$. Our main analysis uses a rolling three-year average to set $\bar{p}$; this smooths out variations, e.g., in hydrological conditions that vary over the years and are an important determinant of the mean price levels. We estimate the optimal rationing price with different ways of defining the reference price $\bar{p}$: fixed at €30/MWh, fixed at €150/MWh, calculated as the rolling average of historical spot price over one month, one year, three years, or five years; Fig. C.11 and Table C.8 present the results. Regardless of the method chosen, the optimal rationing prices follow a similar pattern over time. Prior to the winter 2021–2022 all choices produced rationing prices within 10% of our main choice, except for the (unrealistic) choice of $\bar{p}$ = €150/MWh that shows the potential impact from a level of expectations that matches the highest monthly average in the data period (Dec 2021).

Figure C.11: Impact of the reference price level on the optimal rationing price



Notes. Optimal rationing prices and historical market price P with various methods to set the reference price $\bar{p}$: fixed at €30/MWh (*fix 30*) or €150/MWh (*fix 150*), or calculated as a rolling year average of the historical market prices using one month (*roll 1m*), one year (*roll 1 yr*), three year (*roll 3yr (main)*), or five year (*roll 5yr*) time horizon. Data period from 1 Jan 2019 to 10 May 2022.

Table C.8: Optimal rationing price with different expected price

year	historical	fix 30	fix 150	roll 1m	roll 1yr	roll 3yr (main)	roll 5yr
2019	39.42	217.89	336.32	227.34	231.44	223.82	219.28
2020	9.85	262.39	381.15	244.22	256.42	266.64	263.23
2021	56.65	276.37	394.81	303.18	276.18	278.91	278.74
2022	118.60	441.31	558.49	527.71	483.89	451.88	450.87

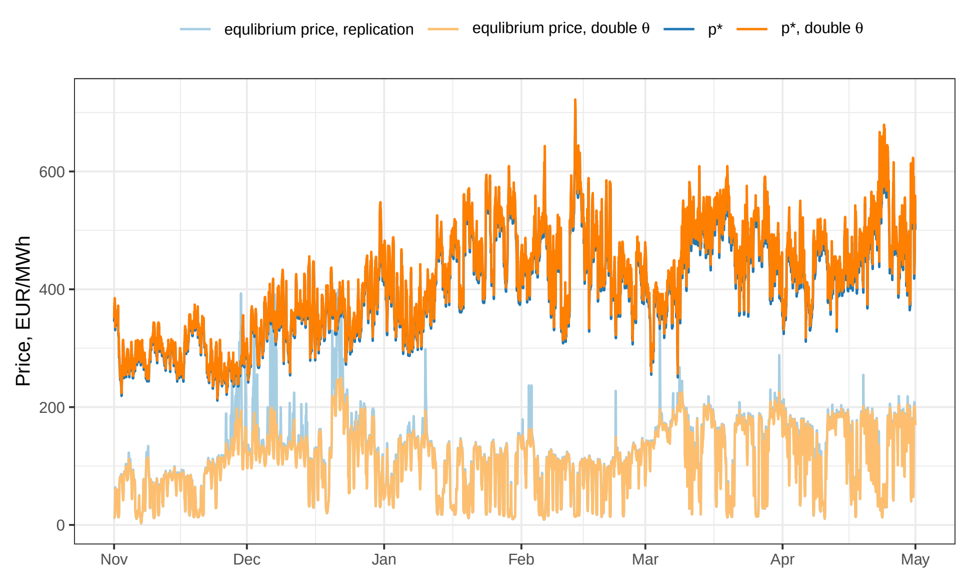
Notes. Historical prices are the actual realizations, other reported prices are the optimal rationing prices using different price expectations. All values in €/MWh.

C.2 Sticky demand

Proposition 2 suggests that the optimal price cap increases in θ. Quantitatively, we gauge the effect by scaling up the estimated values of θ while controlling for the reference price $\bar{p}$ to stay consistent with the reference equilibrium. For each hour t, we double the non-sticky share θ_t and use it to calculate new optimal rationing prices. In effect this increases the demanded non-sticky quantity at each price point by a factor of two. To retain the original reference price and quantity, we reduce sticky demand by a factor of $(1 - 2\theta_t)/(1 - \theta_t)$.

The outcomes of the increased θ are compared to the results in the main analysis that uses historical data in Fig. C.12 and Table C.9. As a result of the doubled θ, the price cap becomes marginally higher but it has the same qualitative variation as in the main case. The higher demand elasticity has an impact on the market equilibrium: price levels are in general lower, in particular during the peaks, as in the winter 2021–2022.

Figure C.12: The impact of θ on the optimal price cap



Notes. The optimal price cap under two demand schedules: the original from the demand curves, and the modified from demand curves with increased share of non-sticky demand obtained by doubling the value of θ for each hour. The equilibrium prices are from the replication of market prices (see Appendix A.2) and the equilibrium prices for the doubled θ follow the same methodology. In both p^* calculations, the reference price is the three-year rolling average price. The data period is from 1 Nov 2021 to 30 Apr 2022.

Table C.9: The impact of θ on the optimal price cap

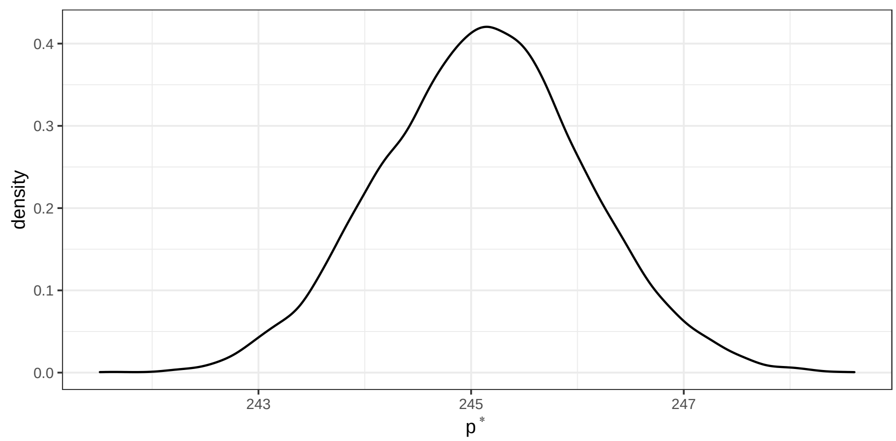
	equilibrium price replication		p^*	
year	main	doubled θ	main	doubled θ
2019	38.99	37.86	223.82	227.25
2020	9.42	8.70	266.64	269.75
2021	56.28	52.73	278.91	283.10
2022	118.33	111.53	451.88	460.25

Notes. The optimal price cap under two demand schedules: the original read from the demand curves and modified demand curves with increased share of non-sticky demand obtained by doubling the value of θ for each hour. The equilibrium prices are from the replication of market prices (see Appendix A.2) and the equilibrium prices for the doubled θ follow the same methodology. In both p^* calculations, the reference price is the three-year rolling average price. The data period is from 1 Jan 2019 to 30 Apr 2022.

C.3 Robustness of the estimation

We use a parametric functional form defined in Eq. 13 to represent the hourly demand schedules. In the main analysis we use maximum likelihood estimation which produces consistently precise point estimates for the parameters of the demand schedule $\tilde{D}_t(p) = \gamma_t + \eta_t \exp(-p/\beta_t)$ in each hour t. This consistency results from the small variation in the underlying data; see Fig. A.7. The precise point estimates result in very tight bounds for the final outcome of interest, i.e. the optimal rationing price, p^*. Fig. C.13 shows an illustration for a typical hour; the optimal rationing price is €245.11/MWh and the 95% confidence interval from bootstrapping [€243.22/MWh, €247.02/MWh].

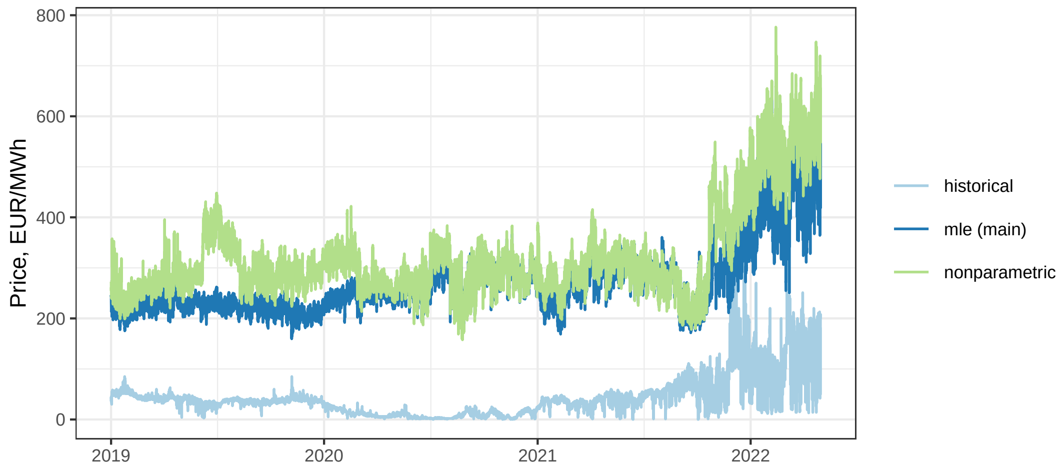
Figure C.13: Bootstrapped values of p^* for a single hour



Notes. Bootstrapped values of p^* in the Nordic market on the first hour of 1 Jan 2019. Bootstrapping uses the point estimates and the covariance matrix of the maximum likelihood estimation of the parameters of Eq. 13.

Despite the consistency of the MLE over the data period, the parametric maximum likelihood estimators are can be inconsistent if the error term distribution is misspecified. Because we observe the hourly demand schedule from data, we can use a discrete approximation of the demand curve as a nonparametric estimator: For each hour, we read the quantity demanded at discrete price points. The sticky part of the demand is given by the quantity demanded at the maximum price, and we interpret the rest of the demand to be non-sticky. Scaling up this non-sticky part so that the demand at the reference price remains intact gives a nonparametric representation of the curve A–F in Fig. 1. Fig. C.14 and Table C.10 present the optimal rationing prices computed from the parametric maximum likelihood estimation and the nonparametric representation of the demand function. Reassuringly, the level and the general shape of the optimal rationing prices from the nonparametric estimation are similar to our main estimation.

Figure C.14: Optimal rationing price with different estimation methods



Notes. The optimal price cap, p^*, when the hourly demand curve has been estimated by maximum likelihood (*mle*) and by the nonparametric estimator (*nonparametric*). In both p^* calculations, the reference price is the three-year rolling average price. The historical prices are shown as reference. The data period is from 1 Jan 2019 to 10 May 2022.

Table C.10: Optimal rationing price with different estimation methods

	equilibrium price	p^*	
yr	replication	parametric (main)	nonparametric
2019	38.99	223.82	290.64
2020	9.42	266.64	288.81
2021	56.28	278.91	309.87
2022	118.33	451.88	547.14

Notes. The optimal price cap, p^*, when the hourly demand curve has been estimated by maximum likelihood *(parametric (main))* and by the nonparametric estimator (*nonparametric*). In both p^* calculations, the reference price is the three-year rolling average price. The replicated equilibrium prices are shown as reference. The data period is from 1 Jan 2019 to 10 May 2022.

D Price cap rules in power markets

In the case the market allocation of electricity fails, the power system operators need to have some mechanism to try to avoid the total collapse of the electricity grid. Such events can be remarkably costly, for example the Finnish TSO Fingrid puts the cost of nation-wide blackout at 100 million euro per hour[31]. We summarize below the relevant legislation for the Nordic market as enacted by the EU[32], and provide an overview of the methods in use in Texas and in Australia. In the EU, the aim is to implement a pure energy-only market so that the market prices reflect scarcity in full and the aim is to minimize any distortions. In Texas and Australia, the mechanisms in place proxy the reasonable profits of the generators, and curb the prices once the calendar year profits are deemed to be on a sufficient level to compensate the capital costs of investments.

D.1 EU

All member states in the EU are subject to the same regulation by the EU Commission that stipulates the general conditions for the European electricity markets. The participation to the market is voluntary and bilateral contracts are not considered in the day-ahead market clearing. As part of the market harmonization, the EU Commission has set the price cap and floor levels for the markets and defined the procedures [33]. In the beginning of 2022 those were set at €$3,000$/MWh and €-500/MWh[34]. These price limits are considered to be "technical", i.e. they are in place to safeguard the price formation but are not considered to reflect the value of lost load or any equivalent definition of the maximum value of electricity. Indeed, the regulation explicitly calls for the removal of all price caps in order to allow for scarcity pricing. In practice, this is implemented with a delay: the price caps are increased automatically after five weeks if the realized market price at any hour in any market area is above 60% of the current price limits (= €$1,800$/MWh in the beginning of 2022).[35]

[31]Source: Fingrid Magazine 3/2012

[32]Although Norway is not part of the EU they follow the same legislation based on the The Agreement on the European Economic Area (EEA).

[33]Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity

[34]Harmonised maximum and minimum clearing prices for single day-ahead coupling in accordance with Article 41(1) of Commission Regulation (EU) 2015/1222 of 24 July 2015 establishing a guideline on capacity allocation and congestion management (CACM Regulation).

[35]Such incident took place on 4 Apr 2022, when the price in France was €$2,987.78$/MWh in the hour 8–9. As a result, the price cap was raised to €$4,000$/MWh on 11 May 2022 (Source: Nord Pool.).

In case of market reaching the price limits, EU regulation requires that the Regional Coordination Centres establish rationing procedures and that any rationing is done in a non-discriminatory manner. In practice for the market places, the rationing (curtailment) has been implemented in the market exchange rules so that all bids are cut on pro rata basis[36].

D.2 ERCOT

The Public Utility Commission of Texas (PUC) is in charge of defining the rules for the market operator in the Texas market, the Electric Reliability Council of Texas (ERCOT). The guiding principles for these rules are that they “should be developed with consideration of microeconomic principles and shall promote economic efficiency in the production and consumption of electricity; support wholesale and retail competition”. [37]

ERCOT operates a voluntary wholesale market for electricity that has a day-ahead clearing and a real-time market. ERCOT has a scarcity pricing mechanism that has been revised after the winter storm in February 2021. The scarcity pricing mechanism consists of two possible levels, High Systemwide Offer Cap (HCAP) of $9000/MWh and Low Systemwide Offer Cap (LCAP) which in 2021 was the maximium of $2000/MWh or 50 times the natural gas spot price at a chosen location. The use of the two depends on the *Peaker Net Margin*, a proxy for the generation costs of a peaking gas power plant. The higher cap is used until a threshold value for a the earnings of a fictitious generator is reached after which the lower cap is adopted. The threshold value in 2021 was $315,000. But because of the exceptionally high gas spot prices, LCAP in February 2021 was higher than HCAP, and so the PUC intervened and HCAP was maintained throughout the scarcity period.

The political backslash from the high consumer costs (see the quote at the start of the article), lead to changes in the scarcity pricing mechanism. The proposed new rule would lower HCAP from $9000/MWh to $5000/MWh and the gas price multiplier from 50 to 10 times the spot price, while retaining the Peaker Net Margin concept as such[38].

[36]Source: Nord Pool.

[37]Public Utility Commission of Texas, Electric Substantive Rules - Chapter 25, §25.501, 18 Apr 2012.

[38]Public Utility Commission of Texas, Electric Substantive Rules - Chapter 25, §25.505, Proposed revision, 21 Dec 2021.

D.3 Australia

There are several regional electricity markets in Australia governed by the same National Electricity Rules set by the Australian Energy Market Commission. These rules define an *Administrative Price Period* (APP), which is activated during a sustained period of high prices. This “safety net” is motivated by the need to alleviate the financial stress that the high prices could cause end users of electricity.

The protocol for the high price control in the spot market is as follows. For a period of seven days leading up to a given time interval the sum of the market prices is calculated, i.e. the spot market prices of each 5 minute interval are summed up. The sum so computed is compared to the *Cumulative Price Threshold* (CPT) that is a value administratively set each year.[39] CPT for 1 July 2022 to 30 June 2023 period is set at \$1,398,100 that corresponds to an average spot price of around \$694/MWh[40]. If the trigger price is exceeded, the market price will be capped at \$300/MWh until the sum of the (uncapped) market prices over the past seven day period falls back below the CPT.

In addition, the market prices are at all times capped at \$$15,500/MWh$, which has been earlier defined based on a Value of Lost Load (VOLL) concept but later renamed to Market Price Cap (MCP). The Cumulative Price Threshold is explicitly linked to the MCP: it is 90 times higher than the price cap (subject to some small differences due to rounding), so for example an event where the price cap is reached for 15 hours in a row would be immediately sufficient to trigger the APP.

[39] Australian Energy Market Operator, Guide to Administered Pricing, July 2021.

[40] Australian Energy Market Commission, Schedule of reliability settings, 24 Feb 2022.