Optimal capacity mechanisms for competitive electricity markets*

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Abstract

Capacity mechanisms are increasingly used in electricity market design around the world yet their role remains hotly debated. This paper introduces a new benchmark model of a capacity mechanism in a competitive electricity market with many different conventional generation technologies. We consider two policy instruments, a wholesale price cap and a capacity payment, and show which combinations of these instruments induce socially-optimal investment by the market. Our analysis yields a rationale for a capacity mechanism based on the internalization of a system-cost externality—even where the price cap is set at the value of lost load. In extensions, (i) we show how increasing variable renewables penetration can enhance the need for a capacity payment under a novel condition called "imperfect system substitutability", and (ii) we outline the socially-optimal design of a strategic reserve with a targeted capacity payment.

Keywords: Investment, wholesale electricity market, capacity mechanism, capacity auction, strategic reserve

JEL Classifications: D41, L94

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1 Introduction

Capacity mechanisms are playing a growing role in electricity markets around the world—and yet their use and design remain hotly debated. In a nutshell, they award generators a capacity payment in exchange for being available to supply at a specified date. Capacity markets, in which this payment is determined by auction, are long-standing feature of several regional US power systems and have more recently been introduced in a number of European countries. At the same time, some jurisdictions rely on an "energy-only" market design without apparent need for capacity payments while other jurisdictions use a strategic reserve to guarantee security of supply.

The justification for a capacity mechanism is often said to arise from the presence of a price cap in the wholesale market. On one hand, a price cap can protect electricity consumers from "too high" prices (perhaps resulting from the exercise of market power). On the other hand, setting it too low leads to underinvestment—known as the "missing money problem" (e.g., Joskow 2008). To this is added that greater renewables penetration reduces the running hours of conventional plant via the much-discussed "merit-order effect". A capacity mechanism, by providing generators with an additional revenue stream, has the potential to resolve the missing-money problem.

In this paper, we introduce a new benchmark model of long-run investment with a capacity mechanism. Our main interest lies in understanding the optimal policy design when the regulator can use multiple instruments: a wholesale price cap and a capacity mechanism. We study three types of capacity mechanism: a capacity payment and capacity auction, both market-wide, and a targeted strategic reserve.

The key features of the model are as follows. First, we consider a wide range—technically, a continuum—of generation technologies, with the standard trade-off that a lower production cost comes with a higher investment cost.[1] This enables us to study how capacity mechanisms affect base-load, mid-merit and peak generation units in potentially different ways. Second, like much of the literature, we assume that demand is price-inelastic. This approximates real-world behaviour and makes the analysis tractable. We allow consumer demand be stochastic (which can also be interpreted as shifts in net demand due to variable renewable generation).[2] Third, if demand exceeds generation capacity, there is forced rationing, in the form of rolling black-outs, leading to a welfare loss for disconnected consumers. Moreover, we consider a system-cost externality which represents lost welfare due to uncontrolled system-wide black-outs or that it is costly for the system operator to conduct controlled rolling black-outs (see also Joskow & Tirole

[1]Electricity markets are commonly characterized by a range of conventional generation technologies such as coal, natural gas, or nuclear. Within each technology, there are different types of plant in terms of size and efficiency. This means that, in practice, there could be a dozen or more individual "technology-types". We use a continuum to approximate this real-world diversity of discrete technologies.

[2]We do not attempt to model demand-side response (which is sometimes interpreted as a form of capacity mechanism).

2007; Fabra 2018; Llobet & Padilla 2018). Fourth, our interest lies in the optimal design of capacity mechanisms for the case of perfect competition among producers.[3] Finally, our setup allows for the presence of a carbon price that is set at the social cost of carbon.

We begin with the first-best benchmark for optimal investment. Social welfare consists of the gross consumer value from electricity minus production costs, investment costs and the expected cost of the system externality. A social planner keeps on investing until the marginal benefits of higher consumer value and a lower system externality are equal to the investment cost. A higher consumer value of lost load (VOLL) and a more pronounced system externality both lead to more investment into peaking plant.

We then study market-based investment under perfect competition. We show that there is a family of combinations of the price cap and capacity payment which achieves the social optimum via the market. One member of this family is setting the price cap at the VOLL and the capacity payment to internalize the system-cost externality. Establishing this policy family makes precise how much "uplift" in a capacity payment is needed to correct for different degrees of missing money.

A key observation is that these policy instruments work solely through their influence on peak plant. For baseload and mid-merit plant, the extra revenue from a higher capacity payment is exactly offset by the reduction in scarcity rent—so the introduce of a capacity mechanism has zero impact on their expected payoffs. The additional revenues, in equilibrium, go solely to financing new investment into peak plant.

In our model, there is a straightforward equivalence between setting a capacity payment that leads to a market-based capacity volume or procuring this capacity volume via a market-based capacity payment—akin to a capacity auction. Moreover, while our main interest is in fully optimal policies, our equilibrium characterization extends to situations in which a country adopts a market design that overprocures investment (relative to the social optimum); in particular, we can derive the second-best optimal combination of the price cap and capacity payment to achieve any given loss of load probability (LOLP).

We present two extensions to the benchmark model. First, we study how the increased penetration of variable renewables can enhance the need for a capacity mechanism. We introduce a new condition called "imperfect system substitutability" that captures how intermittent renewables—compared with conventional plant—achieve a weaker mitigation of the system-cost externality relative to their ability to meet demand. Under this condition, higher renewables penetration raises the social value of investment in peaking plant—which is incentivized by a higher capacity payment.[4]

Second, we outline a new socially-optimal design of a strategic reserve. A capacity payment that discriminates between plants inside and outside the reserve can easily lead to

[3] Some of the finer details of capacity-market design are beyond our scope including the optimal setting of penalties for non-delivery and including reliability options (ROs) in the design.

[4] A grossly sufficient condition is that "firm capacity" from conventional generation acts as a complement to the intermittency of renewables.

market distortions in investment. The key idea of our design is to avoid such inefficiencies by paying an extra-high price to non-reserve plants whenever the reserve is used.

Contribution to the literature. We contribute to a growing theoretical literature on capacity mechanisms. By considering a continuum of generation types, our approach departs from prior work that assumes a single representative technology (e.g., Léautier 2016; Brown 2016; Fabra 2018) or two discrete technologies, sometimes interpreted as conventional and renewable generation (e.g. Llobet & Padilla 2018). Joskow & Tirole (2007) allow for a continuum of technologies but focus on cases with only a few demand outcomes—so producers invest only into 2-3 types of technologies. Moreover, unlike us, previous literature on capacity markets often focuses on issues of market power.

Our work also relates to the classic literature on peak-load pricing which studies investment for a discrete set of technologies (e.g., Crew & Kleindorfer 1976, 1986; Chao 1983). Our approach is similar to the model of Zöttl (2010) which, as far as we know, was first to use a continuous framework to study investment in electricity markets—but does not consider capacity payments or price caps.[5] For markets with inelastic demand, peak-load pricing with discrete technologies corresponds to the "screening curve analysis" which is widely used in the economics of electricity markets (Stoft 2002; Biggar & Hesamzadeh 2014; Léautier 2019). Our work simplifies existing results from this literature and broadens the analysis to include capacity mechanisms and system-cost externalities.

In sum, given these differences, we obtain several novel results including: (i) characterizing the family of socially-optimal combinations of a price cap and capacity payment for markets with multiple generation technologies, (ii) identifying a novel condition of "imperfect system substitutability" between renewables and conventional plant as the key driver of an enhanced need for a capacity mechanism,[6] and (iii) deriving an equivalent socially-optimal design of a targeted strategic reserve.

Plan for the paper. Section 2 begins with additional policy background on the design and use of capacity mechanisms, including a short case study on Great Britain. Section 3 lays out our model, and Section 4 characterizes the first-best outcome. Section 5 studies market-based investment with the policy instruments of a price cap and capacity mechanism. Section 6 analyzes the impacts of increased renewables penetration. Section 7 outlines a socially-optimal design of a strategic reserve. Section 8 concludes, discusses policy implications, and suggests avenues for future research. Proofs are in the Appendix.

[5] Zöttl (2010, 2011) presents theoretical results on investments under Cournot oligopoly with discrete technologies. Pahle, Lessmann, Edenhofer & Bauer (2013) present detailed Cournot simulation results for Germany which focus on the interplay between market power and carbon pricing in driving generation investment but also do not consider the role of capacity mechanisms.

[6] In our model, the increase in renewables penetration is exogenous. In practice, it could be driven by support policies for renewables and/or a decline in renewable technology costs. Bothwell & Hobbs (2017) present an analysis of the ERCOT (Texas) market and characterize investment inefficiencies that arise between renewable and conventional investment.

2 Policy background on capacity mechanisms

This section sets the scene for our modelling. The first part provides an overview of the current state of policy design towards capacity mechanisms—with a particular focus on the EU. The second part illustrates the evolution of policy over time using the case of Great Britain since market liberalization in the 1990s.

2.1 Overview of current policy designs

The need for and design of capacity mechanisms remains one of the biggest questions for the future of electricity markets. Some analysts speculate that wholesale markets will over time be eroded by zero marginal-cost renewables, with virtually all "action" shifting to capacity markets (Helm 2017). Others believe that an energy-only market design is sufficient as long as scarcity pricing is allowed (and credible) such that there is no missing money (Joskow 2008).[7]

Capacity mechanisms are playing a growing role in electricity market design around the world (Bublitz, Keles, Zimmermann, Fraunholz & Fichtner 2019). In the US, capacity auctions are a long-standing feature of several regional power systems such as PJM and the Midcontinent, New England and New York ISOs. Texas is a notable exception with its energy-only market design and no apparent need for capacity payments.[8] Capacity markets also exist in Australia and Colombia.

The policy status in the EU is particularly striking for its cross-country heterogeneity; Figure 1 provides a detailed summary (ACER 2018). There are three broad groups of countries. First, a number of countries are using (or intend to use) capacity auctions, either having newly introduced these (as in Great Britain) or having transitioned from administrative capacity payments (as on the island of Ireland). Second, other countries are instead relying on a strategic reserve; this is long-standing in Finland and Sweden. Finally, a group of countries notably in Central and Eastern Europe operate energy-only markets. In February 2018, the European Commission approved new capacity mechanisms in Belgium, France, Germany, Greece, Italy and Poland.

Nonetheless, with the recent proliferation of national capacity mechanisms, the European Commission has voiced concerns about market fragmentation and potential distortions of competition (EC 2016). Indeed, the EU Target Electricity Model is based on an energy-only market so is arguably inconsistent with any form of capacity mechanism. Recent research has identified significant inefficiencies arising from the lack of coordination in the design of capacity mechanisms within an interconnected European electricity

[7] The debate about capacity mechanisms sits within the wider context of a good market design for a high-renewables electricity system, including flexibility options such as market interconnection (to shift load across space), battery storage (to shift load across time) and demand-side response (Newbery et al. 2018).

[8] At the same time, many other parts of the US still have regulated power markets.

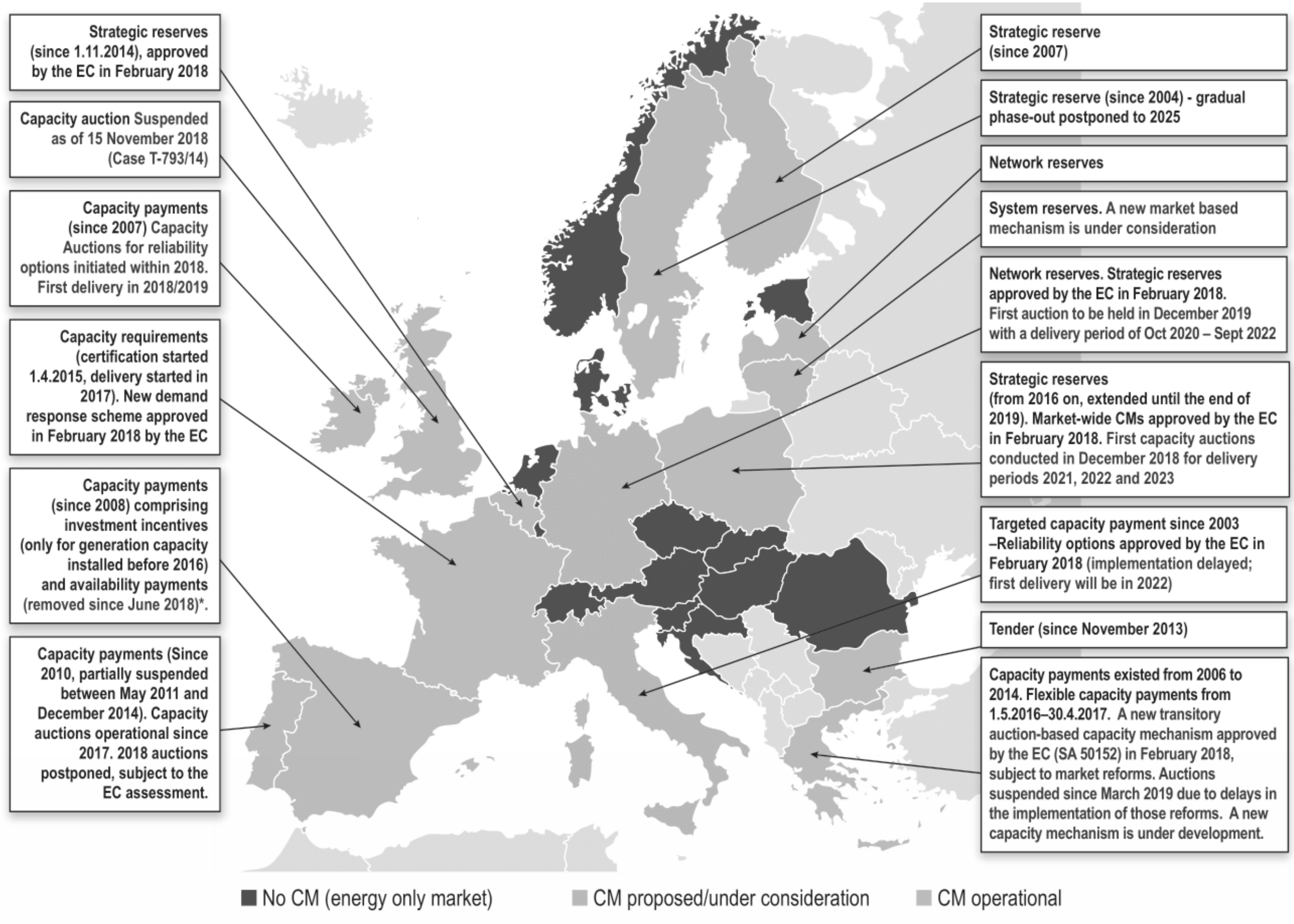

Figure 1: Figure 1: Overview of capacity mechanisms in the EU (ACER 2018)

market (Tangerås 2018; Bucksteeg, Spiecker & Weber 2019; Lambin & Léautier 2019).

2.2 The evolution of British policy since liberalization

Great Britain has been a pioneer of market liberalization, serving as a role model for other jurisdictions. Less widely recognized is how the use of capacity mechanisms has evolved over successive market re-designs since the 1990s. We here sketch the main features of this evolution that are most salient to our analysis.[9]

The evolution of the market can be split into three phases. First, from 1990 to 2000, the original Pool spot market-design was accompanied by an administrative capacity mechanism. Available generation units received a capacity payment equal to LOLP×(VOLL−SMP), where SMP is the system marginal price.[10] These payments were intended to support adequate investment incentives (Helm 2003) and by the mid-1990s made up around 20% of generator revenues (Newbery 2005). Significant regulatory challenges were posed by the calculation of both the LOLP and VOLL. In 1990, VOLL was set to £2000/MWh, and the idea was to uprate this level in line with the price level (Newbery 1997). Pool prices consistently rose after 1990, whereby Ofgem threatened to refer the matter to the Competition Commission (Bower 2002). This threat made National Power and PowerGen promise to keep average prices down.

Second, from 2001 to 2012, chiefly due to concerns about the exercise of market power, the system was re-designed. The New Electricity Trading Arrangements (NETA) moved to a self-dispatched energy-only market that dispensed with capacity payments. NETA itself then underwent several re-designs, plagued by flaws in its short-term balancing mechanism for demand and supply. During these first two phases—Pool and NETA—variable renewables still played a negligible role; since 2005, Britain's electricity generation has been covered by the EU's Emissions Trading Scheme (EU ETS).

Third, since the 2013 Electricity Market Reform (EMR), a system-wide capacity market has become a central pillar of market design. Its stated objective is "to ensure that an adequate level of security of electricity supply is delivered in a way that is cost-effective and complementary to decarbonisation policies"; the government's impact assessment referred explicitly to the missing-money problem and reliability being a quasi-public good as justifications for moving away from an energy-only market (DECC 2012). The GB capacity market operates against the backdrop of a €3,000/MWh price cap in European day-ahead markets and in the shadow of further discretionary price interventions (Joskow 2008).[11]

[9] For wider discussions of British electricity market design and performance since liberalization, see, e.g., Helm (2003), Newbery (2005) and Grubb & Newbery (2018).

[10] In a competitive market, the SMP equals the marginal generator's short-run marginal cost.

[11] Three other points are worth noting. First, in the interim period before the first capacity auction, a strategic reserve was employed as a temporary measure to ensure security of supply. Second, the original intention was for the capacity market to be itself be a temporary policy measure. Third, the level of price

Capacity auctions to date have shown the benefits of competition. The first capacity auction, held in December 2014, for 50 GW of (de-rated) capacity by the winter of 2018/19 cleared below £20/kWyr—well below prior government estimates of around £50/kWyr (Grubb & Newbery 2018). At the same time, partly due to low clearing prices, the auctions have so far incentivized little new-build generation capacity.[12,13]

In sum, the experience with capacity mechanisms shows how design choices can vary widely over time and space. Nonetheless, there appears to be an increasing trend towards the use of some form of capacity mechanism, which policymakers justify mainly by appealing to security of supply—and increasingly also to decarbonization.

Our model will rationalize capacity mechanisms as a possible structural feature of electricity market design, justified by a combination of wholesale price distortions and an externality with public-good character. We also show how socially-optimal capacity payments tend to rise with increased renewables penetration.

3 The model

We consider a two-stage game with investments in Stage 1 and production in Stage 2. We describe the model setup in several steps: technology costs and carbon pricing, demand conditions, and the system-cost externality.

Technology costs. There is a continuum of production technologies with a continuum of marginal costs. We let $k(c)$ be the investment cost per unit of power for a technology with marginal cost $c \in [0, p^*]$, where p^* is the reservation price (value of lost load, VOLL) for consumers. We make a number of technical assumptions to ensure an interesting and well-behaved solution to the model. In particular, we assume that costs satisfy $k(c) \in (0, p^*)$, $k'(c) \in (-1, 0)$ and $k''(c) > 0$ for $c \in [0, p^*]$. We also assume that consumers' VOLL is sufficiently high relative to investment costs, specifically $p^* > p_0^* = k(0)/[-k'(0)]$, which will ensure that generation investment occurs.

The economic intuition underlying these cost assumptions is that they (1) reflect the standard trade-off between production costs and investment costs that is also the basis for screening curve analysis and (2) are necessary for the equilibrium to feature a technology *mix* with investment in multiple generation technologies. First, $k'(c) < 0$ represents the familiar notion that generation technologies with lower marginal cost tend to have higher

caps in the wholesale market featured prominently in the Impact Assessment (DECC 2012).

[12]The design of capacity mechanisms faces a variety of practical challenges. These range from political influence on the volume of capacity procurement, to the appropriate setting of de-rating factors for different generation technologies, to design questions such as criteria for bidder pre-qualificaton and penalties for non-delivery.

[13]In November 2018, the GB capacity market was suspended following a legal challenge over State Aid rules at the EU level. At the time of writing, its legal status remains unclear.

investment costs. Second, it is useful to consider the setup in terms of short-run marginal cost (SRMC) and long-run marginal cost (LRMC): let $v(c) = c + k(c)$ be the LRMC of a technology with a SRMC of c. Our assumptions then boil down to the LRMC $v(c)$ (a) increasing in c with $v'(c) > 0$ (as $k'(c) > -1$) and (b) doing so at increasing rate with $v''(c) > 0$ (as $k''(c) > 0$). The former means that technologies with a higher SRMC also have a higher LRMC. The latter will be a necessary condition for the equilibrium to feature investment in multiple generation technologies—as is typically observed in real-world power systems. These cost assumptions are also consistent with prior literature, e.g. Zöttl (2010), Léautier (2019, especially pp. 40–41).

The total quantity invested in technologies with a marginal cost below c is denoted by $q(c)$. The inverse of this supply function corresponds to a marginal cost curve $C'(q)$. Our assumptions, specifically the convexity property $k''(c) > 0$, will mean that this marginal cost curve is increasing, $C''(q) > 0$—as is a standard feature of the economic analysis of power markets.

Carbon pricing. Our cost assumptions are consistent with the presence of carbon pricing. In particular, we can think of the marginal production cost of each technology as including its carbon costs. To see this for a technology with marginal cost c, let $c = \widetilde{c} + \sigma(\widetilde{c})\tau$ where $\widetilde{c}$ is its marginal cost excluding carbon costs, τ is the carbon price, and $\sigma(\widetilde{c})$ is its emissions intensity (i.e., carbon emissions per unit of production). All else equal, higher carbon costs mean a higher overall marginal cost. We will assume that any carbon price τ is set at the level of the social cost of carbon S (i.e., the monetized value of the damages due to an extra unit of carbon emissions).[14] Further, we assume that carbon pricing does not change the merit order; sufficient conditions for this are that either the carbon price τ is sufficiently small or that higher-cost technologies are also dirtier $\sigma'(\widetilde{c}) \geq 0$.[15,16]

Empirical illustration. We can illustrate our cost assumptions using estimates of the levelized cost of electricity (LCOE) that are commonly used in policy circles. The LCOE represents the overall cost of producing 1 MWh of electricity with different generation technologies such as coal, gas or nuclear. In our context, we can think of LCOE as being equivalent to LRMC, i.e., LCOE $\simeq v(c) = c + k(c)$ for a technology with marginal cost

[14] The carbon price in our setting is best thought of as a carbon tax; we do not consider the free allocation of emissions permits to regulated firms within a cap-and-trade scheme.

[15] In addition, we make the simplifying assumption that a technology with zero marginal cost does not have any emissions, i.e. $\sigma(0) = 0$.

[16] To be able to speak to cases both with and without carbon pricing, our formal proofs require the ordering of technologies in terms of marginal cost to be the same in both cases. The level of carbon prices levied on electricity generation has to date indeed been modest (below around €10/tCO_2) in most jurisdictions—with the principal exception of the EU ETS in the mid-2000s and again more recently since 2018 (World Bank 2019). In general, the degree of merit order changes can also be sensitive to the prevailing level of fuel prices (e.g., coal and natural gas). Nonetheless, we conjecture that our conclusions about social optimality in the presence of carbon pricing would still hold even if changes in the merit order were induced. The reason is that, given a carbon price set at the social cost of carbon, any such changes in the merit order of plant do not constitute an additional market failure.

c.[17] For conventional generation technologies, the main components of the variable cost c are typically fuel costs and carbon costs while the main component of the investment cost k are the so-called overnight investment costs incurred during a plant's construction phase.

Table 1 shows LCOE estimates for Germany, decomposed into values for c and k (IEA 2010). We chose this as an illustrative example mainly because it features a range of conventional generation technologies; of course, the precise numbers will vary both over time and across countries. The LCOE decomposition confirms the trade-off between marginal cost and investment cost, $k'(c) < 0$, and is broadly consistent with the assumptions $v'(c) > 0 \Leftrightarrow k'(c) > -1$ and $v''(c) > 0 \Leftrightarrow k''(c) > 0$.[18] The exception is combined cycle gas turbine (CCGT) generation, which is estimated to have a higher c but a lower LCOE than coal.[19] A richer representation would feature different plant sizes and specifications for each technology, which in our model is approximated by a continuum.

	Marginal cost (without CO_2) ($\widetilde{c}$)	Carbon cost ($\sigma(\widetilde{c})\tau$)	SRMC (c)	Capital cost (k)	LCOE ($c+k$)	Trade-off rate ($\Delta k/\Delta c$)
Nuclear	18.1	0.0	18.1	64.5	82.6	N/A
Lignite	25.3	26.1	51.4	36.0	87.4	–.86
Coal	40.8	22.1	62.9	31.2	94.1	–.42
CCGT	65.3	10.1	75.4	17.4	92.8	–1.10
OCGT	97.9	15.9	113.8	8.8	122.6	–.22

Table 1: LCOE estimates in US$/MWh for Germany (IEA 2010)

Notes: Units are 2008 US$. Assumptions include a 10% discount rate and a US$30/t$CO_2$ carbon price. Fuel price assumptions include US$ 90 per tonne (equivalent to US$ 3.60 per GJ) for hard coal and US$ 10.3 per MMBtu (equivalent to US$ 9.76 per GJ) for natural gas. Operation & maintenance (O&M) are treated as variable costs. See IEA (2010) for further detail.

Demand conditions. At the investment stage, there is uncertainty about consumers' electricity demand. In particular, demand ε follows a probability distribution $F(\varepsilon)$ and density $f(\varepsilon)$ with the support $[0, \overline{\varepsilon}]$ where we assume $f(\varepsilon) > 0$ for $(0, \overline{\varepsilon})$. We can think of

[17] Recall that our LRMC is technology-specific rather than a system-level LRMC of higher electricity production. An important caveat is that neither typical LCOE estimates nor our LRMC feature potential additional grid costs.

[18] Several sources report c in units of \$/MWh and k in \$/kWa units, i.e., in terms of an annuity of kW by year. Going from an investment cost in \$/kW to an annuitized investment cost in \$/kWa requires assumptions on the lifetime of the plant and on the discount rate. The conversion formula to bring the units on a like-for-like basis is: $\frac{1000\times k \text{ (in \$/kWa)}}{\text{full capacity hours per year (in h/a)}} \rightarrow k$ (in \$/MWh).

[19] In a continuous model, a violation of the constraint $k'(c) > -1$ implies a range of technologies for which LRMC decreases with c and for which there will not be any investment. This could be different in practice with a substantial but finite number of different technologies.

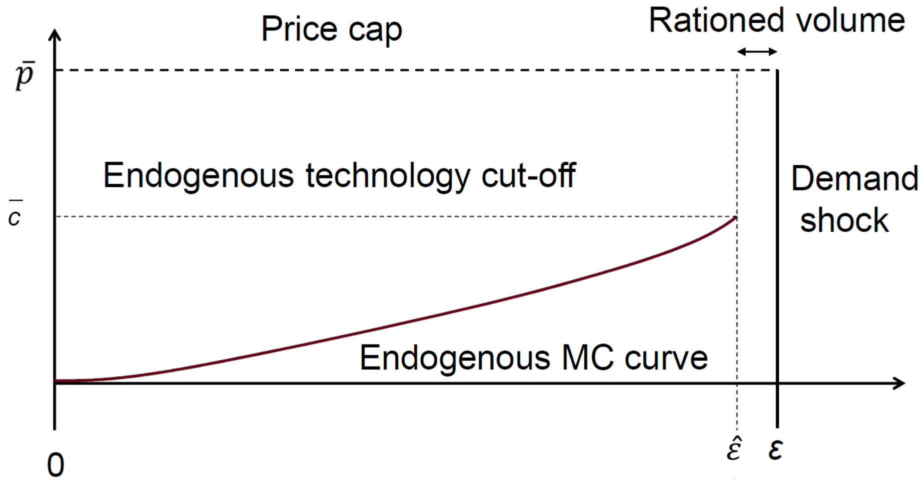

Figure 2: When demand ε exceeds the market capacity $\hat{\varepsilon}$, there is demand rationing and the spot price is at the price cap $\bar{p}$.

$F(\varepsilon)$ as being the fraction of time that demand is less than ε, in which case $F(\varepsilon)$ would be similar to a standard load duration curve.[20]

We let $\overline{c}$ be the highest marginal cost for which there is investment. This technology cutoff is endogenously determined in our model. We let $\hat{\varepsilon} = q(\overline{c})$ be the corresponding total production capacity. As demand is assumed to be price-inelastic, forced demand rationing (rolling blackouts) is needed to keep the system in balance if $\varepsilon > \hat{\varepsilon}$ (that is, demand exceeds capacity). Hence, $1-F(\hat{\varepsilon})$ represents the loss of load probability (LOLP). Figure 2 illustrates our setup in terms of demand and supply.

System-cost externality. We assume that loss of load, in addition to the lost surplus of rationed consumers, has a system externality $M(\hat{\varepsilon})$. This might represent the expected cost of performing rolling black outs. Letting J denote the realized system cost of conducting *controlled* rolling black-outs, which may be a function of the rationed volume $\varepsilon - \hat{\varepsilon}$, we have $M(\hat{\varepsilon}) = \int_{\hat{\varepsilon}}^{\overline{\varepsilon}} f(\varepsilon) J(\varepsilon - \hat{\varepsilon}) \, d\varepsilon$. An alternative interpretation of $M(\hat{\varepsilon})$ is as the (expected) welfare loss due to accidental *uncontrolled* system-wide black outs; more investment then improves system reliability—which is a public good.

We assume that: (i) higher installed capacity reduces the system cost, at a decreasing rate, $M'(\hat{\varepsilon}) \leq 0 \leq M''(\hat{\varepsilon})$; and (ii) to avoid boundary solutions and yield an interesting analysis, the invested capacity $\hat{\varepsilon}$ must lie below $\overline{\varepsilon}$ (the highest demand realization), which will turn out to hold as long as $k(p^*) < [-M'(\hat{\varepsilon})]$.

Finally, it is worth stressing that our system-cost externality $M(\hat{\varepsilon})$ is similar to that considered in work by Joskow & Tirole (2007), Fabra (2018), Llobet & Padilla (2018) and others but is a different concept from the incremental system cost that arises with the integration of intermittent renewables, e.g., due to additional network investment being

[20] The distribution $F(\varepsilon)$ can also be interpreted as *net* demand for conventional generation, taking into account production from renewables; we pursue this analysis further in Section 5.

needed (see, e.g., Ueckerdt, Hirth, Luderer & Edenhofer 2013).

4 Socially-optimal investment and the technology mix

We begin by solving the problem of a social planner who makes investment and production decisions in order to maximize social welfare. Social welfare is comprised of three components. First, it can be shown that the total investment cost in the first stage is given by:

$$K = \int_0^{\overline{c}} k\left(c\right) q'\left(c\right) dc. \tag{1}$$

We see that $q'\left(c\right)$ is essentially a density function. For small Δc, $q'\left(c\right)\Delta c$ is the volume of investment into technologies with marginal costs in the range c to $c + \Delta c$. The associated investment cost is $k\left(c\right) q'\left(c\right)\Delta c$. The total investment cost accounts for all such incremental costs up to $\overline{c}$ (the highest marginal cost for which there is investment).

Second, the social planner in second stage minimizes production cost by starting the cheapest production plants, for which the total output equals the shock ε and subject to the total installed production capacity $\hat{\varepsilon} = q\left(\overline{c}\right)$. It can be shown that the expected total production cost plus system cost is:[21]

$$T = \int_0^{\hat{\varepsilon}} f\left(\varepsilon\right) C\left(\varepsilon\right) d\varepsilon + C\left(\hat{\varepsilon}\right)\left(1 - F\left(\hat{\varepsilon}\right)\right) + M\left(\hat{\varepsilon}\right). \tag{2}$$

The expected production cost has two parts: the first represents outcomes without rationing; the second represents those when forced rationing occurs and production is at full capacity $\hat{\varepsilon}$. Finally, $M\left(\hat{\varepsilon}\right)$ is the system cost at total production capacity $\hat{\varepsilon}$.

For expositional reasons, we develop the welfare analysis in the main text without making explicit the role of the social cost of carbon S. Lemma 1 in Appendix A formally incorporates the environmental externality into the cost calculation; it shows that the expression in (2) remains valid given that the carbon price $\tau = S$ is set at the Pigouvian level and where $c = \widetilde{c} + \sigma(\widetilde{c})\tau$ is marginal cost. Given our assumption that carbon pricing does not change the merit order, the ordering of marginal cost c is the same as that of $\widetilde{c}$ excluding carbon costs.

Third, the expected benefits to electricity consumers in the second stage can be calculated in a similar way:[22]

$$B = p^* \int_0^{\hat{\varepsilon}} f\left(\varepsilon\right) \varepsilon d\varepsilon + p^* \hat{\varepsilon}\left(1 - F\left(\hat{\varepsilon}\right)\right). \tag{3}$$

The social planner chooses the distribution function $q\left(c\right)$ and technology cutoff $\overline{c}$ to

[21] Note that $\int_{\hat{\varepsilon}}^{\overline{\varepsilon}} f\left(\varepsilon\right) C\left(\hat{\varepsilon}\right) d\varepsilon = C\left(\hat{\varepsilon}\right)\left(1 - F\left(\hat{\varepsilon}\right)\right)$.

[22] Note that $\int_{\hat{\varepsilon}}^{\overline{\varepsilon}} f\left(\varepsilon\right) \hat{\varepsilon} d\varepsilon = \hat{\varepsilon}\left(1 - F\left(\hat{\varepsilon}\right)\right)$.

maximize social welfare $W \equiv B - T - K$. We obtain the following result:

Proposition 1 *It is socially-optimal to make generation investments such that the inverse marginal cost curve becomes:*

$$\begin{aligned} q(c) &= F^{-1}(1 + k'(c)) \text{ for } c \in [0, \overline{c}] \\ q(c) &= q(\overline{c}) \text{ for } c \in [\overline{c}, p^*], \end{aligned} \tag{4}$$

where the technology cutoff $\overline{c}$ *is implicitly determined from:*

$$-(p^* - \overline{c})\, k'(\overline{c}) - k(\overline{c}) - M'(q(\overline{c})) = 0, \tag{5}$$

which has a unique solution in the range $[0, p^*]$.

Proposition 1 characterizes socially-optimal investment based on the trade-off between investment and production costs. The condition for optimal investments can be understood by rearranging (4) to give $1 - F(q(c)) = -k'(c)$. Consider a planner choosing between two technologies with a (small) marginal-cost difference Δc. Investing in the technology with lower marginal cost saves $[1 - F(q(c))]\,\Delta c$ in expected production costs, as $1 - F(q(c))$ is the probability that demand will be larger than $q(c)$, i.e. the probability that the plant will be used. On the other hand, this incurs an extra $[-k'(c)]\,\Delta c$ in investment costs. At the optimum, the social planner is indifferent at the margin between such similar investments. Our optimality condition is simpler but results with a similar intuition have been found in a continuous investment framework (Zöttl 2010) and for discrete peak-load pricing (Crew & Kleindorfer 1976).

A key insight from our first-order condition is that neither the VOLL of consumers p^* nor the system cost $M(\cdot)$ have any influence on socially-optimal investments *below* the technology cutoff $\overline{c}$ —though they do affect the cutoff itself. To explore the cutoff condition further, note that (4) holds also at $\overline{c}$, so we can rewrite the condition as:

$$(p^* - \overline{c})(1 - F(q(\overline{c}))) - M'(q(\overline{c})) - k(\overline{c}) = 0. \tag{6}$$

The first term gives the consumer benefit net of production costs from additional investment, and the second term represents the benefit of a lower system cost. The planner continues to invest until these marginal benefits at the optimum $\overline{c}$ are equal to the investment cost $k(\overline{c})$. A higher consumer reservation price (higher p^*) and a steeper decrease in system costs (higher $-M'(\cdot)$) both induce more investment into peaking plant.

Optimality can be expressed in another intuitive form. Let $\eta = [-ck'(c)/k(c)]_{c=\overline{c}} > 0$ denote the elasticity of investment costs with respect to production costs, evaluated at the optimum technology cutoff $\overline{c}$. This is a measure of the technology trade-off: η is larger if a lower production cost comes with a greater increase in investment cost, so technology is less flexible in that sense. This allows us to rewrite (4):[23]

$$\overline{c} = p^* \left[\frac{\eta}{\eta + 1 - \dfrac{-M'\left(F^{-1}\left(1 + k'\left(\overline{c}\right)\right)\right)}{k\left(\overline{c}\right)}} \right] < p^*. \tag{7}$$

We see that the cutoff $\overline{c}$ is higher for higher consumer VOLL (higher p^*) and less flexible available generation technology (higher η); the former makes investment more valuable, and the latter makes it more necessary.[24] The cutoff is also higher with a steeper decrease in system costs (higher $-M'(\cdot)$), as this also makes investment more valuable.

In the special case without a system-cost externality ($M(\cdot) \equiv 0$), the cutoff $\overline{c} = p^*\eta/(\eta+1)$ is *independent* of the distribution of consumer demand $F(\cdot)$. As any changes in the shape of $F(\cdot)$ leave $\overline{c}$ unchanged, it follows directly from (4) that the socially-optimal LOLP is also unchanged. To illustrate, a simple calibration of the IEA generation cost estimates in Table 1 suggests that the technology elasticity η lies in a range of 1–2. Our formula then tells us that the optimal technology cutoff $\overline{c}$ is, roughly, 50–70% of the VOLL. The presence of the system-cost externality pushes this ratio further towards 100%.

5 Market-based investment and capacity mechanisms

We now turn to the investment and technology mix delivered by a competitive market. We assume that the regulator has two instruments: setting a price cap in the wholesale electricity market and designing a uniform market-wide capacity payment. Our main interest lies in deriving the optimal policy design that delivers the social optimum.

5.1 Model setup and additional assumptions

In Stage 2, produced electricity is paid a spot price $p(\varepsilon)$. In a competitive market, the price can be implicitly determined from $\varepsilon = q(p)$, that is, demand equals supply. Moreover, there is a price cap $\overline{p}$ which is the highest spot price allowed by the wholesale market design. In the case of forced demand rationing, the spot price equals the price cap. Our analysis allows for price caps above the VOLL, and we define $\widehat{p} = \min(p^*, \overline{p})$.[25]

[23] Recall that our assumptions ensure that $-M'(\cdot)/k(\overline{c}) < 1$ so that $\overline{c} < p^*$.

[24] As the available technology becomes very flexible with $\eta \to 0$, the trade-off between production cost and investment cost disappears, so the planner can achieve first-best while relying almost only on abundant very low marginal cost generation and so the technology cutoff $\overline{c} \to 0$.

[25] As will become clear, when investments are a public good (via the system externality $M(\hat{\varepsilon})$), it can be socially-optimal to occasionally have prices above the VOLL. It is therefore implicit in our setup that consumers do not quit the market so that the socially-optimal solution can be implemented. Note that consumers' expected utility can still be positive even if prices occasionally exceed the VOLL. Otherwise they could compensated via the wider tax system.

In Stage 1, producers are paid a uniform capacity payment $z \in [0, k(\widehat{p}))$ for each unit of invested capacity.

Our exposition in the following again does not need to make explicit the role of the carbon price τ. As we assume that the carbon price is set at the social cost of carbon, $\tau = S$, there is no additional market or policy failure. Moreover, the carbon costs faced by firms are also government revenue so constitute a transfer in terms of welfare accounting. Therefore, based on our earlier Lemma 1, the following analysis of socially-optimal policies remains valid in the presence of Pigouvian carbon pricing.

5.2 Competitive equilibrium and optimal policy design

In a competitive market, $q(c)$ is the market supply curve, i.e., the market capacity with marginal cost below c. In equilibrium, price equals marginal cost, $p(q(c)) = c$, so a plant with marginal cost c will produce for $\varepsilon \geq q(c)$ which corresponds to $p(\varepsilon) \geq c$.

The expected profit from an investment into a unit of a technology with marginal cost $c \in (0, \overline{c})$ is therefore given by:

$$\pi(c) = z - k(c) + \int_{q(c)}^{\hat{\varepsilon}} (p(\varepsilon) - c) f(\varepsilon) \, d\varepsilon + (\overline{p} - c)[1 - F(\hat{\varepsilon})]. \tag{8}$$

The first two terms are the capacity payment and investment cost; the third is the profit flow from the spot market. The last term is often referred to as the expected scarcity rent (Stoft, 2002). Competitive entry means that the zero-profit condition $\pi(c) \equiv 0$ holds, for every technology $c \in (0, \overline{c})$, in equilibrium.

Our next result derives the policies that achieve the social optimum via the market:

Proposition 2 *Investments are socially optimal when i) the price cap is at or above the socially optimal technology cutoff, i.e. $\overline{p} \geq \overline{c}$, and ii)*

$$z = -M'(q(\overline{c})) - k'(\overline{c})(p^* - \overline{p}). \tag{9}$$

This for example holds when the price cap equals the VOLL, $\overline{p} = p^*$, and the capacity payment internalizes the marginal system-cost externality, $z = -M'(q(\overline{c}))$.

Proposition 2 formalizes how market-based investment, augmented by an optimally-designed price cap and capacity payment, can replicate the socially-optimal technology mix of Proposition 1.

Optimal policy. We derive (9) as the key condition which characterizes the family $(\overline{p}, z)$ of price caps and capacity payments that achieves the social optimum. Figure 3 illustrates. A leading special case is setting the price cap at the VOLL, $\overline{p} = p^*$, and the capacity payment to reflect the marginal system cost, $z = -M'(q(\overline{c}))$. From a policy perspective, this establishes a rationale for the use of a capacity mechanism even where

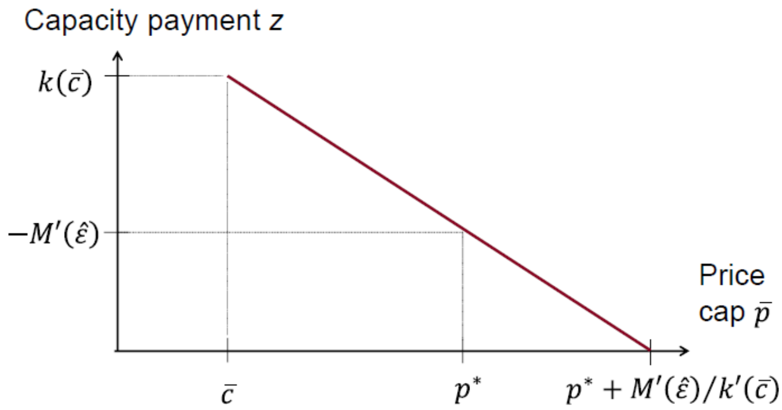

Figure 3: Illustration of the family $(\overline{p}, z)$ of price caps and capacity payments that achieves the social optimum in a competitive market.

the wholesale market design has the "correct" price cap set at the VOLL. The reason is that an additional instrument is needed to correct for the system-cost externality of generation capacity.[26]

The same condition also makes precise how a capacity mechanism can correct for the "missing money problem". Specifically, suppose that for reasons of political economy, the price cap is set too low with $\overline{p} < p^*$; (9) tells us that a capacity payment of $z = -M'(q(\overline{c})) + (p^* - \overline{p})[-k'(\overline{c})]$ restores optimality. From (4), we see that the payment includes an "uplift" of

$$-k'(\overline{c})(p^* - \overline{p}) = LOLP * (p^* - \overline{p}).$$

Hence, the uplift compensates for the scarcity rent lost, in expectation, due to a lower price cap. We realize that the slope in Figure 3 is given by LOLP. Comparing the optimal capacity payment with the capacity payment in the English pool, it seems that the latter was overly generous, but it depends on the size of the system-cost externality in England.

This analysis allows us to place bounds on the required price cap. First, observe that the optimal price cap always satisfies $\overline{p} \geq \overline{c}$. Second, recall from our analysis of the social optimum that the technology cutoff $\overline{c} \geq p^*\eta(\eta+1)$ (for any $-M'(\cdot) \geq 0$). Third, suppose again that available information suggests that the technology elasticity satisfies $\eta \geq 1$. It follows that the optimal price cap must then always exceed 50% of the VOLL as $\overline{p} \geq \frac{1}{2}p^*$. (This condition would be even tighter with (i) higher values of η or (ii) a system-cost externality $-M'(\cdot) > 0$.) Conversely, this simple argument suggests that, in electricity markets with a price cap below 50% of the VOLL, it may be impossible to design capacity payments in a way that fully restores social optimality.

[26] Fabra (2018) obtains a similar finding with a single generation technology and a price cap always set at the VOLL, $\overline{p} = p^*$. See also Llobet & Padilla (2018) for a related result with two generation technologies. Our analysis goes further by characterizing the family of all optimal policy combinations.

Policy equivalence. In our model, it is equivalent for the regulator to set a capacity payment z resulting in market-based invested capacity $\widehat{\varepsilon}$ or to instead set a capacity level $\widehat{\varepsilon}$ which is delivered by a market-based capacity price z in capacity auction. The reason is that producers have symmetric information, so even if there is a demand shock in the spot market, there are no surprises in the capacity market; in equilibrium, producers can predict the outcome of the capacity auction. With symmetric information and small price-taking producers, it is equivalent for the regulator to set "price" (capacity payment) or "quantity" (capacity volume)—akin to the classic analysis of Weitzman (1974).

Generation overinvestment. Our main interest in this paper lies in understanding policy designs that are fully optimal, i.e., restore the social optimum. In practice, policy-makers may have incentives to overprocure generation investment (relative to the social optimum).[27] Our equilibrium characterization extends to such "overinvestment" situations. In particular, we can derive the optimal combination of the price cap and capacity payment to achieve any given level of LOLP, i.e., the values of $(\overline{p}, z)$ themselves do not belong to the family that achieves the social optimum.

We first establish a generalised version of the technology cutoff. For any price $p > p_0^*$ (that lies above the lower bound p_0^* that is necessary for investment to be positive), we can implicitly define a cutoff $\bar{c}(p)$ from

$$-(p - \bar{c}(p))\, k'(\bar{c}(p)) - k(\bar{c}(p)) - M'(q(\bar{c}(p))) = 0,$$

which is a generalised version of (5). The results in Proposition 2 can now be generalised as follows.

Proposition 3 *For the price cap $\overline{p} > p_0^*$ and capacity payment $z = -M'(q(\bar{c}(\overline{p})))$, the technology cutoff for investments is $\bar{c}(\overline{p})$ and the competitive supply function is*

$$q(c) = F^{-1}(1 + k'(c)) \;\; \text{for } c \in [0, \bar{c}(\overline{p})]\,. \tag{10}$$

The same investments would follow for an alternative price cap $\tilde{p} \geq \bar{c}(\overline{p})$, if

$$\begin{aligned} z &= -M'(q(\bar{c}(\overline{p}))) - k'(\bar{c}(\overline{p}))(\overline{p} - \tilde{p}) \\ &= k(\bar{c}(\overline{p})) + k'(\bar{c}(\overline{p}))(\tilde{p} - \bar{c}(\overline{p}))\,. \end{aligned} \tag{11}$$

The technology cutoff $\bar{c}(\overline{p})$ here corresponds to a LOLP level that may itself not be socially optimal. Proposition 3 can thus be interpreted as a characterization of second-best policy in light of a pre-existing constraint on the LOLP level. In particular, the

[27] The cutoff condition in Proposition 1 depend on the VOLL p^* which, in practice, can be difficult to estimate. Cramton and Stoft (2005) recommend that the regulator sets a sufficiently high capacity level $\widehat{\varepsilon}$ to makes LOLP acceptably low—and then procures this using a capacity auction.

condition in (11) defines a family of policy combinations that will result in the same constrained optimum.[28]

Payoff impacts. How does a capacity mechanism affect the overall payoff of producers? On one hand, a higher capacity payment makes outcomes with forced rationing less likely, which reduces producers' expected scarcity rent. On the other hand, a higher capacity payment creates an additional revenue stream. Similarly, a higher price cap means more revenue in the event of forced rationing but also makes this event less likely.

Our next result clarifies the net effect of these two forces:

Proposition 4 *Consider a market with the initial technology cutoff $\overline{c}_0$. If the capacity payment z and/or the procured capacity $\widehat{\varepsilon}$ and/or the price cap $\overline{p}$ is increased, then:*
(i) Total expected revenue from the spot market and the capacity mechanism is unchanged for each plant with a marginal cost below the cutoff $\overline{c}_0$.
(ii) All of the additional expected revenue covers production and investment costs of new generation investments into plant with a marginal cost above $\overline{c}_0$.

Proposition 4 shows that, in equilibrium, a higher capacity payment or price cap have no impact (neither in terms of payoffs or investments) on plant below the technology cutoff. This is consistent with our earlier finding from Proposition 2 that these do not influence investment below the technology cutoff. Given their equivalence, the same conclusion also applies to higher procured capacity. In other words, for baseload and mid-merit plant, the extra revenue from a capacity mechanism is exactly offset by the reduction in scarcity rent. The additional revenues, in equilibrium, go solely to financing new investment into peaking plant at/above the old technology cutoff.[29]

Comparative statics. The model also delivers a number of intuitive comparative statics. For brevity, we here only summarize the main results; the Appendix B contains further technical details. First, a higher capacity payment and a higher price cap both lead to more investment and hence both decrease the LOLP (Proposition 9); in this sense, these policy instruments are substitutes. Second, a higher volume of procured capacity leads both to more investment and a higher capacity payment (Proposition 10). Finally, for a given procurement volume, a higher price cap reduces the "need" for a capacity payment (Proposition 11).

[28] Somewhat similar to our analysis of the social optimum, the equilibrium condition in (10) implies that market-based investments below the technology cutoff $\overline{c}$ do not depend on the price cap $\overline{p}$ or on the capacity payment z. Hence, these policy instruments again influence only investments into peaking plant.

[29] Zöttl (2011) obtains a related result in a two-technology model with imperfect competition.

6 The impact of renewables penetration

A central feature of the future electricity market is that it will be dominated by renewable generation from solar and wind. In the policy debate, the growth of intermittent renewables and its adverse impact on the demand for conventional generation is frequently asserted as a justification for a capacity mechanism. In this section, we use our model to formally characterize the impact of renewables on investment in conventional generation, the socially-optimal LOLP and on the optimal design of capacity mechanism.

6.1 Model setup and additional assumptions

We generalize the model as follows. First, let w denote the (exogenous) level of installed renewables capacity, interpreted as consumers' own production such as rooftop solar power or other intermittent renewable generation such as wind power supplied by an exogenous fringe (with zero marginal cost). Write $F(\varepsilon, w)$ as the probability distribution of *net* demand for conventional plant and assume that the probability that net demand is below some level ε increases with more renewable generation, $\frac{\partial F(\varepsilon;w)}{\partial w} > 0$. We allow the strength of the crowding-out effect to vary along $F(\cdot)$ (e.g., with the time of year). Second, write $M(\hat{\varepsilon}, w)$ as the system-cost externality, where $\hat{\varepsilon}$ is installed conventional capacity.[30] Third, we use $q(c, w)$ to denote socially-optimal conventional supply with marginal cost below c, so $q(c, w) = \varepsilon$ is the condition for market clearing given renewables w.

6.2 Renewables and optimal investment

The optimality conditions from Proposition 1 for investment and the technology cutoff from (4) and (5) are valid for any net-demand distribution F, i.e., it does not matter whether F depends on renewable penetration or not. Hence, for installed wind capacity w, the condition for optimal investment from (4) becomes:

$$1 - F(q(c, w), w) = -k'(c). \tag{12}$$

Similarly, the condition for the optimal technology cutoff $\bar{c}$ from (5) becomes:

$$-(p^* - \bar{c})\, k'(\bar{c}) - k(\bar{c}) - \frac{\partial M(q(\bar{c}, w), w)}{\partial \hat{\varepsilon}} = 0, \tag{13}$$

where $q(\bar{c}, w) = \hat{\varepsilon}$ is total conventional capacity and the LOLP is $1 - F(\hat{\varepsilon}, w)$.

This leads immediately to the following initial finding:

Lemma 1 *At any price $c \in (0, \bar{c})$, higher renewables capacity reduces conventional supply,* $\frac{\partial q(c,w)}{\partial w} < 0$.

[30] For a given level of w, we retain our previous assumptions on $F(\cdot)$ and $M(\cdot)$.

This is an instance of the widely-discussed merit-order effect of renewables penetration. It is a direct consequence of more renewables making low realizations of net demand for conventional plant more likely via $\frac{\partial F(\varepsilon;w)}{\partial w} > 0$.[31]

The further details of the interaction between renewables and conventional plant depend on their relative merits in terms of demand and system costs; the following condition will turn out to be central:

Condition R *Renewables are an "imperfect system substitute" to conventional generation in the sense that:*

$$s^w \equiv \frac{\frac{\partial^2 M(\hat{\varepsilon}, w)}{\partial \hat{\varepsilon} \partial w}}{\frac{\partial F(\hat{\varepsilon}; w)}{\partial w}} \leq \frac{\frac{\partial^2 M(\hat{\varepsilon}, w)}{\partial \hat{\varepsilon}^2}}{\frac{\partial F(\hat{\varepsilon}; w)}{\partial \hat{\varepsilon}}} \equiv s^\varepsilon. \tag{14}$$

If renewable and conventional production could be used interchangeably, i.e., they are perfect substitutes, then Condition R would hold with equality, $s^w = s^\varepsilon$: both would then have the same mitigating impact on the marginal system cost, $\frac{\partial M(\hat{\varepsilon},w)}{\partial \hat{\varepsilon}}$, and the same marginal impact on meeting demand, $F(\hat{\varepsilon}; w)$. It also holds with equality in the special case without a system externality, $M(\hat{\varepsilon}, w) \equiv 0 \Rightarrow s^w = s^\varepsilon = 0$.

More generally, Condition R captures via $s^w \leq s^\varepsilon$ the idea that renewables, due to intermittency, are an imperfect substitute to conventional power. They achieve a weaker mitigation of the system-cost externality relative to their ability to meet demand. This corresponds to that for the same LOLP level, a system with more renewables would have a higher risk of getting a complete system collapse compared to a conventional system. Note that the condition does not make any assumptions on how the *level* of the system cost varies with renewables, i.e., on the sign of $\frac{\partial M(\hat{\varepsilon},w)}{\partial w}$. A grossly sufficient assumption for Condition R to hold is that "firm capacity" acts as complement to the intermittency of renewables, that is, $\frac{\partial}{\partial \hat{\varepsilon}}\left[\frac{\partial M(\hat{\varepsilon},w)}{\partial w}\right] = \frac{\partial^2 M(\hat{\varepsilon},w)}{\partial \hat{\varepsilon} \partial w} \leq 0 \Rightarrow s^w \leq 0 < s^\varepsilon$.[32]

We first characterize the equilibrium impact of more renewables capacity:

Proposition 5 *If Condition R is met, then higher renewables capacity raises the optimal technology cutoff, $\frac{d\bar{c}}{dw} \geq 0$ and reduces the socially-optimal LOLP, $\frac{dLOLP}{dw} \leq 0$. In the special case with no system-cost externality, $M(\hat{\varepsilon}, w) \equiv 0$, the impacts are both zero, $\frac{d\bar{c}}{dw} = 0$ and $\frac{dLOLP}{dw} = 0$.*

The main insight from Proposition 5 is that higher renewables capacity raises the socially-optimal technology cutoff. In other words, it becomes optimal to bring to market some conventional plant technologies with high marginal cost that were previously not

[31] Brown (2018) obtains related results in a model of a capacity auction with imperfect competition and exogenous entry of renewables.

[32] Condition R can also allow to informally think about the role of battery storage in the context of the model. The combination of intermittent renewables plus a "perfect" storage technology would be equivalent to firm capacity, and therefore correspond to a "perfect system substitute", $s^w = s^\varepsilon > 0$.

needed. This formalizes the commonly-expressed view that renewables raise the social value of peaking plant. An immediate implication is that, at the social optimum, the LOLP declines with more renewables.

These renewables impacts hinge crucially on Condition R—imperfect system substitutability, $s^w \leq s^\varepsilon$—which, in turn, requires the presence of the system-cost externality $M(\hat{\varepsilon}, w)$. In its absence, more renewables capacity has zero impact on the technology cutoff or the LOLP—though it does, of course, alter the overall technology mix. This follows directly from Proposition 1: if $M(\cdot) \equiv 0$, optimal investment is independent of the distribution of net demand.[33]

There is a tension underlying these findings. On one hand, the "merit-order effect" from Lemma 6.2 is that, for a given price, renewables reduce conventional supply. On the other hand, the "system-cost effect" from Condition R and Proposition 5 says that renewables raise the optimal technology cutoff $\bar{c}$, so additional peaking plant are needed.

Our next result therefore presents a condition to sign the overall equilibrium impact of renewables on conventional capacity:

Proposition 6 *Higher renewables capacity reduces the socially-optimal conventional capacity,* $\frac{dq(\bar{c},w)}{dw} \leq 0$*, if* $s^w \geq -(p^* - \bar{c})$.

In general, the overall impact, taking into account the knock-on effect of renewables on the optimal technology mix, is theoretically ambiguous. Proposition 6 makes precise when socially-optimal conventional generation capacity declines. The underlying condition is more likely to be met if (i) the system substitutability of renewables s^w is relatively high and (ii) the VOLL p^* is high (compared to the cutoff $\bar{c}$) so that the system externality is relatively less important for optimal investments. A sufficient condition is simply $s^w \geq 0$, i.e., renewables do not require firm capacity as a complement.

6.3 Renewables and capacity-mechanism design

We now turn to characterizing the impact of renewables on the design of a capacity mechanism. Like before, we begin by noting that the result from Proposition 2 on the price cap and capacity payment that achieve social optimality remains valid for any given w. In particular, the family of socially-optimal policy instruments from (9) now becomes:

$$z(w, \overline{p}) + \frac{\partial M(q(\bar{c}, w), w)}{\partial \hat{\varepsilon}} + (p^* - \overline{p}) k'(\bar{c}) = 0, \tag{15}$$

which makes explicit the potential dependency of the capacity payment $z(w, \overline{p})$ on renewables and the price cap.

[33] Biggar & Hesamzadeh (2014, pp. 192-194) obtain an instance of this finding from a graphical screening curve analysis with two conventional technologies.

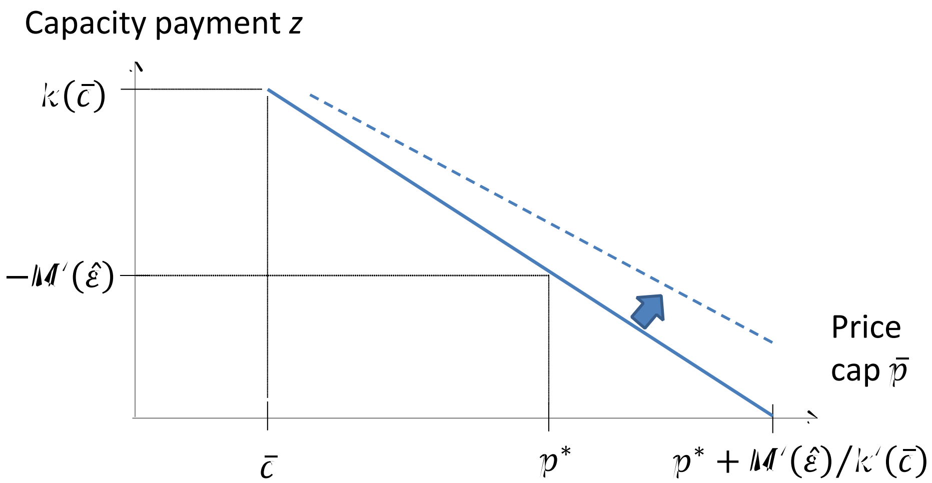

Figure 4: More renewables lead to an outward shift in the socially-optimal family $(\overline{p}, z)$ of price caps and capacity payments.

Our next result formalizes how renewables penetration affects the optimal capacity payment:

Proposition 7 *If Condition R is met, then, for any price cap $\overline{p}$, higher renewables capacity increases the socially-optimal capacity payment, $\frac{\partial z(w,\overline{p})}{\partial w} \geq 0$. In the special case with no system-cost externality, $M(\hat{\varepsilon}, w) \equiv 0$, the impact is zero, $\frac{\partial z(w,\overline{p})}{\partial w} = 0$.*

Proposition 7 shows how increased renewables penetration exacerbates the need for a capacity mechanism. For any given level of the price cap, the socially-optimal optimal capacity payment increases. Hence the optimal family of policy instruments $(\overline{p}, z)$ is pushed outwards as illustrated in Figure 4. The optimal LOLP level is lower with more renewables. Hence, we have that the slope in Figure 4 is less steep for the shifted curve.

This is a direct implication of our finding from Proposition 5 that, given Condition R, renewables increase the social value of peaking plant. For any given price cap, this additional investment is optimally procured by way of a higher capacity payment. Once again, the result hinges crucially on the presence of the system-cost externality.[34]

In sum, our model shows how increased renewables that are an imperfect substitute or a complement to conventional generation raise the social value of peaking plant and can justify higher capacity payments to conventional generation.

[34]Llobet and Padilla (2018) find that capacity payments need to be higher when the volatility of renewables is higher. This is related to our Proposition 7 but also somewhat different; if the system-cost externality were zero in our model, then optimal capacity payments would not depend on the volatility of renewables or on how their output is correlated with demand.

7 An optimally-designed strategic reserve

Some countries use a strategic reserve instead of a market-wide capacity market. A reserve is discriminatory in that a capacity payment is made only to generation units within the reserve. An argument in favour is that this limits the market operations of the system operator (SO) to procuring a (small) reserve. This is an advantage in Europe where a SO often owns the transmission network and accordingly has congestion rents—and the regulator wishes to contain this dominant position. It is less of an issue in restructured US electricity markets with independent SOs (ISOs) that do not own any grid assets.[35]

Yet it is also clear that discriminating between plants inside and outside the reserve can easily lead to market distortions. For example, if plants both inside and outside the reserve are paid the same electricity price when the reserve is used, then the revenue of plants in the reserve are disproportionately large (as they also get a capacity payment) and this can distort investments.

We next present an optimally-balanced market design with a strategic reserve that avoids any such competitive inefficiencies. In a nutshell, this can be achieved by paying an extra-high spot price to non-reserve plants whenever the reserve is used.

7.1 Model setup and additional assumptions

The model is a variation on the previous setup. In Stage 1, plants in the strategic reserve is paid a uniform capacity payment $z \in [0, k(\widehat{p}))$ for each unit of invested capacity. In Stage 2, electricity produced outside the reserve is paid a spot price $p(\varepsilon)$. We let $q(p)$ and $\widehat{\varepsilon}$ denote the supply and total capacity of non-reserve plants, respectively. Hence, for $\varepsilon \in (0, \widehat{\varepsilon})$, the spot price can be implicitly determined from $\varepsilon = q(p)$. The strategic reserve is "triggered" when the non-reserve capacity has been exhausted, i.e., $\varepsilon > \widehat{\varepsilon}$. In this case, the spot price for non-reserve plant is at the price cap $\overline{p}$—irrespective of whether there is demand rationing. This means revenues of non-reserve plants are independent of the size of the strategic reserve. We let $\widehat{\varepsilon}_r$ denote total production capacity including the reserve.

In a competitive market, reserve plant bid and offer at marginal cost. We let $q_r(c)$ be the total market supply curve, including supply from the reserve. If the reserve is used, $\varepsilon > \widehat{\varepsilon}$, but there is no forced rationing, $\varepsilon < \widehat{\varepsilon}_r$, then the clearing price of the reserve p_r is determined from $\varepsilon = q_r(p_r)$. We have $p_r < \overline{p}$, so for the demand range $\varepsilon \in (\widehat{\varepsilon}, \widehat{\varepsilon}_r)$, plants in the reserve are paid a lower spot price than plants outside the reserve. If the reserve is used and there is forced rationing, $\varepsilon > \widehat{\varepsilon}_r$, also plants in the reserve are paid the price cap $\overline{p}$. Let $\overline{c}$ be the highest marginal cost for which there is investment in the conventional market, and let $\overline{c}_r$ be the highest marginal cost for which there is investment

[35] This also explains why US day-ahead markets are centralized and organized by an ISO while markets are more decentralized in Europe (Ahlquist et al. 2019).

in the reserve.

7.2 Competitive equilibrium and optimal policy design

Competitive entry ensures that the zero-profit condition $\pi(c) \equiv 0$ holds in equilibrium, both for plants in the reserve and outside the reserve. Under the above assumptions, we can show that the strategic reserve is equivalent to a market with a uniform capacity payment z and price cap $\overline{p}$:

Proposition 8 *For a market design with a strategic reserve where:*[36]

$$\overline{p} > p_0^* + M'\left(q\left(\bar{c}\left(p_0^*\right)\right)\right)/k'\left(\bar{c}\left(p_0^*\right)\right)$$

(i) There is a highest marginal cost $\overline{c} \in (0, \widehat{p})$ for which there is investment in the non-reserve market, where this cutoff satisfies:

$$-k\left(\overline{c}\right) - \left(\overline{p} - \overline{c}\right)k'\left(\overline{c}\right) = 0. \tag{16}$$

(ii) There is a highest marginal cost $\overline{c}_r > \overline{c}$ for which there is investment in the reserve, where this cutoff is determined from the same condition as for a uniform capacity payment z and a price cap $\overline{p}$:

$$z - k\left(\overline{c}_r\right) - \left(\overline{p} - \overline{c}_r\right)k'\left(\overline{c}_r\right) = 0. \tag{17}$$

(iii) Investments in the non-reserve and the reserve give rise to a total supply curve $q_r(c)$, which below the cutoff $\overline{c}_r$ is determined by:

$$q_r(c) = F^{-1}\left(1 + k'(c)\right). \tag{18}$$

(iv) Investments are socially optimal whenever the price cap $\overline{p}$ and the capacity payment z to the reserve satisfy:

$$z + M'\left(q\left(\overline{c}_r\right)\right) + \left(p^* - \overline{p}\right)k'\left(\overline{c}_r\right) = 0, \tag{19}$$

which for example holds if the price cap equals the VOLL, $\overline{p} = p^*$, and the capacity payment to the reserve internalizes the marginal system-cost externality, $z = -M'\left(q\left(\overline{c}_r\right)\right)$.
(v) When the reserve is used, a non-reserve plant is paid a higher spot price than reserve plant. The difference $\overline{p} - p_r$ is, in expectation, equal to the capacity payment z of the reserve.

[36] Recall that p_0^* is the lowest VOLL level for which we can ensure positive socially optimal investments. Hence, $\bar{c}\left(p_0^*\right)$ and $q\left(\bar{c}\left(p_0^*\right)\right)$ are the socially-optimal technology cutoff and market capacity, respectively, for that lowest VOLL level.

Part (v) is the central result of Proposition 8: it is possible to design a targeted strategic reserve that is as distortion-free as a market-wide capacity payment. As a whole, the market design with a strategic reserve does not discriminate between plants inside and outside the reserve. This non-discrimination property is crucial to avoiding over- or underinvestment in either conventional plants or in the strategic reserve itself.

The optimal design requires that, whenever the strategic reserve is used, the spot price should be at the price cap, while plants in the reserve should be paid the clearing price of the reserve. Given this, the strategic reserve is as efficient as the market design from Proposition 2, with an identical price cap and a discriminatory capacity payment to the strategic reserve at the same level as the previous market-wide capacity payment.

Parts (i)–(iv) are analogs to now familiar conditions from Proposition 2.

This optimal design of a strategic reserve has both similarities and differences relative to how strategic reserves are operated in practice. The underlying principle of trying to isolate the operation of the reserve from the wholesale market appears to be well-understood. A central feature of our design is that reserve plant—in addition to receiving a capacity payment—make competitive bids so there is also a clearing price for the reserve itself. In this sense, our design captures symmetrically the benefits of competition for both non-reserve and reserve plant.

8 Conclusions, policy implications and future research

We have introduced a new benchmark model of long-run investment and the optimal design of a capacity mechanism in a competitive electricity market. Relative to existing literature, the main differentiating features of our approach are: (i) a continuum of generation technologies which represents the range of baseload, mid-merit and peaking plant (ii) joint modelling of two policy instruments: a wholesale price cap and capacity payment, and (iii) an externality arising from the system-wide costs associated with a blackout. We obtained results for three types of capacity mechanism: a market-wide capacity payment and capacity auction as well as a targeted strategic reserve.

From a policy perspective, we obtain a rationale for the use of a capacity mechanism even where the wholesale-market design has the "correct" price cap set at the VOLL. The reason is that an additional instrument is needed to correct for a system-cost externality that arises in the event of a blackout. We showed how socially-optimal generation investment can be achieved through the market using different combinations of a price cap and a capacity payment. Our characterization of the family of optimal policies makes precise how much "uplift" in a capacity payment is needed to correct for different degrees of missing money. It is worth stressing that our analysis is "technology-neutral": we identify optimal policies for wide range of generation technologies that do not by construction favour any particular one of them. More broadly, our analysis suggests that capacity mechanisms may be a longer-term feature of an optimal electricity market design, especially in the presence of high penetration of variable renewables—rather than merely being a fix to a near-term supply crunch.

Future research may wish to build on our benchmark results and take the analysis into other directions. In particular, it would be valuable to extend our characterization of a socially-optimal capacity mechanism in the presence of other market and policy distortions. This could include: (i) market power in the wholesale market and/or in the capacity mechanism itself; (ii) a shortfall in climate policy that leaves the carbon price below its socially-efficient level (though perhaps compensated by an emissions performance standard in the capacity mechanism), and (iii) the presence of cross-border effects with multiple interconnected electricity systems. Finally, given that our paper and other recent literature has highlighted the importance of a system-cost externality related to blackouts, it would be valuable for future research to attempt to derive empirical estimates of it. This would help further strengthen the connection between theoretical research on optimal capacity mechanisms and empirical on how to improve the design of capacity mechanisms in practice.

References

[1] ACER (2018). Market Monitoring Report 2018 – Electricity Wholesale Markets Volume. Agency for the Cooperation of Energy Regulators, 11 November 2019.

[2] Ahlqvist, V., P. Holmberg, and T. Tangerås (2019). "Central- versus Self-Dispatch in Electricity Markets.", IFN Working Paper 1257, Research Institute of Industrial Economics, Stockholm.

[3] Biggar, D.R. and M. R. Hesamzadeh (2014). *The Economics of Electricity Markets.* IEEE Press.

[4] Bothwell, C. and B.F. Hobbs (2017). "Crediting Wind and Solar Renewables in Electricity Capacity Markets: The Effects of Alternative Definitions upon Market Efficiency." *The Energy Journal* 38(SI1): 173–188.

[5] Bower, J. (2002). "Why did electricity prices fall in England and Wales?: Market mechanism or market structure?", Report, Oxford Institute for Energy Studies.

[6] Brown, D.P. (2018). "Capacity Payment Mechanisms and Investment Incentives in Restructured Electricity Markets." *Energy Economics* 74, 131–142.

[7] Bublitz, A., Keles, D., Zimmermann, F., Fraunholz C., and W. Fichtner (2019). "A Survey on Electricity Market Design: Insights from Theory and Real-World Im-

plementation of Capacity Remuneration Mechanisms." *Energy Economics* 80, 1059–1078.

[8] Bucksteeg, M., Spiecker, S., and C. Weber (2019). Impact of Coordinated Capacity Mechanisms on the European Power Market. *The Energy Journal* 40:2, 221-264.

[9] Chao, H.-P. (1983). "Peak Load Pricing and Capacity Planning with Demand and Supply Uncertainty." *Bell Journal of Economics* 14(1), 179–190.

[10] Cramton, P. and S. Stoft (2005). "A Capacity Market that Makes Sense." *The Electricity Journal*, 18(7): 43–54.

[11] Crew, M. and P. Kleindorfer (1976). "Peak Load Pricing with a Diverse Technology." *Bell Journal of Economics* 7(1): 207–231.

[12] Crew, M. and P. Kleindorfer (1986). *The Economics of Public Utility Regulation.* MIT Press.

[13] DECC (2012). Electricity Market Reform – Capacity Market: Impact Assessment (IA). Department for Energy and Climate Change, 27 November 2012.

[14] EC (2016). Final Report of the Sector Inquiry on Capacity Mechanisms. European Commission, SWD (2016) 385 final, Brussels, 30 November 2016.

[15] Fabra, N. (2018). "A Primer on Capacity Mechanisms." *Energy Economics* 75: 323–335.

[16] Grubb, M. and D. Newbery (2018). "UK Electricity Market Reform and the Energy Transition: Emerging Lessons." *The Energy Journal* 39(6): 1–25.

[17] Helm, D. (2003). *Energy, the State, and the Market.* Oxford University Press.

[18] Helm, D. (2017). *Burn Out: The Endgame for Fossil Fuels.* Yale University Press.

[19] Joskow, P.L. (2008). "Capacity Payments in Imperfect Electricity Markets: Need and Design." *Utilities Policy* 16(3): 159–170.

[20] Joskow, P. and J. Tirole (2007). "Reliability and Competitive Electricity Markets." *RAND Journal of Economics* 38(1): 60–84.

[21] Lambin, X. and T.O. Léautier (2019). "Cross-border Effects of Capacity Remuneration Schemes in Interconnected Markets: Who is Free-riding?" *The Energy Journal* 40:6, 79-109.

[22] Léautier, T.-O. (2016). "The Visible Hand: Ensuring Optimal Investment in Electric Power Generation." *The Energy Journal* 37(2): 89–108.

[23] Léautier, T.-O. (2019). *Imperfect Markets and Imperfect Regulation: An Introduction to the Microeconomics and Political Economy of Power Markets*. MIT Press.

[24] Llobet, G. and J. Padilla (2018). "Conventional Power Plants in Liberalized Electricity Markets with Renewable Entry." *The Energy Journal* 39(3): 69–91.

[25] Newbery, D. (2005). "Electricity Liberalisation in Britain: The Quest for a Satisfactory Wholesale Market Design." *The Energy Journal* 26(SI): 43–70.

[26] Newbery, D. (1997). "Pool reform and competition in electricity.", Report, Department of Applied Economics, University of Cambridge.

[27] Newbery, D. and M. Grubb (2015). "Security of Supply, the Role of Interconnectors and Option Values: Insights from the GB Capacity Auction." *Economics of Energy & Environmental Policy* 4(2): 65–82.

[28] Newbery, D., Pollitt, M. and R.A. Ritz (2018). "Market Design for a High-Renewables European Electricity System." *Renewable & Sustainable Energy Reviews* 91, 695–707.

[29] Pahle, M., K. Lessmann, O. Edenhofer, and N. Bauer (2013). "Investments in Imperfect Power Markets under Carbon Pricing: A Case Study Based Analysis." *The Energy Journal* 34(4): 199–227.

[30] Stoft, S. (2002). *Power System Economics: Designing Markets for Electricity*. IEEE Press.

[31] Tangerås, T. P. (2018). "Equilibrium Supply Security in a Multinational Electricity Market with Renewable Production." *Energy Economics* 72: 416-435.

[32] Teirilä, J. and R.A. Ritz (2019). "Strategic Behaviour in a Capacity Market? The New Irish Electricity Market Design." *The Energy Journal*, forthcoming.

[33] Weitzman, M.L. (1974). "Prices vs Quantities." *Review of Economic Studies* 41(4): 477–491.

[34] World Bank (2019). *State and Trends of Carbon Pricing*. Washington DC: World Bank Group.

[35] Zöttl, G. (2010). "A Framework of Peak Load Pricing with Strategic Firms." *Operations Research* 58(6): 1637–1649.

[36] Zöttl, G. (2011). "On Optimal Scarcity Prices." *International Journal of Industrial Organization* 29, 589–605.

Appendix A: Proofs of the main results

Lemma 1 *Carbon emissions externalities are internalized by including them in marginal cost, so that* $c = \widetilde{c} + \sigma(\widetilde{c})\tau$*, with the carbon price* τ *set at the social cost of carbon* S*.*

Proof of Lemma 1. Let $\widetilde{c}$ be the marginal cost excluding carbon costs. For each technology $\widetilde{c}$, let $\check{q}(\widetilde{c})$ be the output from plants with a marginal cost at $\widetilde{c}$, or lower. Using integration by parts, (1) can be rewritten as follows for the case without emissions:[37]

$$T_{noEm} = \int_0^{\overline{\widetilde{c}}} (1 - F(\check{q}(\widetilde{c}))) \widetilde{c}\check{q}'(\widetilde{c})\, d\widetilde{c} + M(\hat{\varepsilon}). \tag{20}$$

This expression can be explained as follows: $1 - F(\check{q}(\widetilde{c}))$ is the probability that demand is above $\check{q}(\widetilde{c})$, and accordingly also the probability that a plant with marginal cost $\widetilde{c}$ will be running. The derivative $\check{q}'(\widetilde{c})$ is the density of plants with marginal cost $\widetilde{c}$, and $\check{q}'(\widetilde{c})\, d\widetilde{c}$ is the (infinitesimally small) volume of such plants. $M(\hat{\varepsilon})$ is the system cost externality.

Next we want to add the social cost of carbon emissions to the production cost. The carbon intensity for technology $\widetilde{c}$ is $\sigma(\widetilde{c})$ and S is the social cost of the carbon externality. Considering the cost of emissions, the total production and system cost becomes:[38]

$$\begin{aligned} T &= \int_0^{\overline{\widetilde{c}}} (1 - F(\check{q}(\widetilde{c}))) \widetilde{c}\check{q}'(\widetilde{c})\, d\widetilde{c} + M(\hat{\varepsilon}) + \int_0^{\overline{\widetilde{c}}} (1 - F(\check{q}(\widetilde{c})))\, \sigma(\widetilde{c})\, S\check{q}'(\widetilde{c})\, d\widetilde{c} \\ &= \int_0^{\overline{\widetilde{c}}} (1 - F(\check{q}(\widetilde{c})))\, (\widetilde{c} + \sigma(\widetilde{c})\, S)\, \check{q}'(\widetilde{c})\, d\widetilde{c} + M(\hat{\varepsilon}). \end{aligned}$$

Now set $\tau = S$ and use that $c = \widetilde{c} + \sigma(\widetilde{c})\,\tau$. Similarly, we define $\bar{c} = \widetilde{c} + \sigma(\overline{\widetilde{c}})\tau$. Let $\varsigma(c)$ be the inverse of this relationship,[39] so that $q(c) = \check{q}(\varsigma(c))$. Hence, $q'(c) = \check{q}'(\widetilde{c})\,\varsigma'(c)$ and $d\widetilde{c} = \varsigma'(c)\, dc$. Hence,

$$\begin{aligned} T &= \int_0^{\bar{c}} (1 - F(q(c)))\, c\frac{q'(c)}{\varsigma'(c)}\varsigma'(c)\, dc + M(\hat{\varepsilon}) \\ &= \int_0^{\bar{c}} (1 - F(q(c)))\, cq'(c)\, dc + M(\hat{\varepsilon}). \end{aligned}$$

Hence, (20) and the optimality conditions that follow from it are valid if we internalize carbon externalities into production costs.

Proof of Proposition 1. The proof for the social optimum proceeds in two main steps. In Step 1, we find the supply function $q(c)$ that minimizes the sum of investment

[37] It has been assumed that $C(q(0))$ is zero. This makes sense as $q(0)$ is assumed to be the supply from plants with zero marginal cost.

[38] To simplify things we set $\sigma(0) = 0$, i.e. we assume that the technology with marginal cost zero does not have any emissions, so that marginal costs are zero also when internalizing emissions.

[39] Our assumption that carbon pricing does not change the merit order ensures that $\varsigma(c)$ exists.

and production costs for a given technology cutoff $\overline{c}$. In Step 2, we find the optimal technology cutoff $\overline{c}$ and corresponding optimal investment level $q(\overline{c})$ that reflect consumer preferences. In the proof, we make use of the function $H(\varepsilon)$, defined such that $H(0) = 0$ and $H'(\varepsilon) = F(\varepsilon)$.

Step 1. We wish to find the function $q(c)$ that minimizes the sum of investment cost K and expected production cost T for a given technology cutoff $\overline{c}$ and the corresponding $q(\overline{c})$. This becomes straightforward once we have an expression that involves $q(c)$ but none of its derivatives; then we can find an optimal $q(c)$ for each c, independently of other marginal-cost levels. Also, we want to get rid of related terms involving $C(\cdot)$ and $C'(\cdot)$.

First, we rewrite the investment cost in this desired form. Using integration by parts, (1) can be rewritten as:

$$\begin{aligned} K &= \int_0^{\overline{c}} k(c)\, q'(c)\, dc = [q(c)\, k(c)]_0^{\overline{c}} - \int_0^{\overline{c}} q(c)\, k'(c)\, dc \\ &= q(\overline{c})\, k(\overline{c}) - q(0)\, k(0) - \int_0^{\overline{c}} q(c)\, k'(c)\, dc. \end{aligned} \tag{21}$$

Second, we use integration by parts to rewrite the expected production cost (2):

$$\begin{aligned} T &= \int_0^{\hat{\varepsilon}} f(\varepsilon)\, C(\varepsilon)\, d\varepsilon + C(q(\overline{c}))\,(1 - F(\hat{\varepsilon})) + M(\hat{\varepsilon}) \\ &= [F(\varepsilon)\, C(\varepsilon)]_0^{\hat{\varepsilon}} - \int_0^{\hat{\varepsilon}} F(\varepsilon)\, C'(\varepsilon)\, d\varepsilon + C(q(\overline{c}))\,(1 - F(\hat{\varepsilon})) + M(\hat{\varepsilon}) \\ &= C(q(\overline{c})) - \int_0^{\hat{\varepsilon}} F(\varepsilon)\, C'(\varepsilon)\, d\varepsilon + M(\hat{\varepsilon}) \\ &= C(q(\overline{c})) - \int_0^{\overline{c}} F(q(c))\, cq'(c)\, dc + M(\hat{\varepsilon}) \\ &= \int_0^{\overline{c}} c\,(1 - F(q(c)))\, q'(c)\, dc + C(q(0)) + M(\hat{\varepsilon}) \\ &= \int_0^{\overline{c}} c \frac{d}{dc}\,[q(c) - H(q(c))]\, dc + C(q(0)) + M(\hat{\varepsilon}) \\ &= [cq(c) - cH(q(c))]_0^{\overline{c}} - \int_0^{\overline{c}} (q(c) - H(q(c)))\, dc + C(q(0)) + M(\hat{\varepsilon}) \\ &= \overline{c}\hat{\varepsilon} - \overline{c}H(\hat{\varepsilon}) + C(q(0)) - \int_0^{\overline{c}} (q(c) - H(q(c)))\, dc + M(\hat{\varepsilon})\,. \end{aligned} \tag{22}$$

We wish to minimize $T + K$ which using (21) and (22) is equivalent to:

$$\begin{aligned} T + K &= q(\overline{c})\, k(\overline{c}) - q(0)\, k(0) + \hat{\varepsilon}\overline{c} + M(\hat{\varepsilon}) - H(\hat{\varepsilon})\, \overline{c} + C(q(0)) \\ &\quad + \int_0^{\overline{c}} \underbrace{H(q(c)) - q(c) - q(c)\, k'(c)}_{=L} dc. \end{aligned} \tag{23}$$

As the remaining terms do not depend on c, we want to find the $q(c)$ that minimizes L for each $c \in [0, \overline{c})$, which can now be done independently of $\overline{c}$ and $q(\overline{c})$. The first- and second-order conditions are:

$$\frac{\partial L}{\partial q} = F(q) - 1 - k'(c) = 0 \text{ and } \frac{\partial^2 L}{\partial q^2} = f(q) \geq 0. \tag{24}$$

The second-order condition ensures that the first-order solution is a global minimum. Hence the first-order condition gives the cost-efficient technology mix.

We can represent this technology mix by the supply function $\hat{q}(c)$, which corresponds to an inverse marginal cost curve. The assumed properties of $k'(c)$ ensure that $F(q) = 1 + k'(c) \in (0, 1)$. Hence, invertibility of $F(q)$ over this range and the support of this function, implies that for every $c \in [0, \overline{c})$ we have a unique solution $\hat{q}(c) \geq 0$. To confirm that $\hat{q}(c)$ is monotonic and therefore a valid solution, we differentiate the first-order condition:

$$f(\hat{q})\,\hat{q}'(c) - k''(c) = 0 \Longrightarrow \hat{q}'(c) = \frac{k''(c)}{f(\hat{q})} > 0. \tag{25}$$

Step 2. We now wish to find the optimal technology cutoff $\overline{c}$ and optimal investment level $q(\overline{c})$. Using (3) and (23) expected social welfare $W \equiv B - T - K$ can be written as:

$$\begin{aligned} W &= p^* \int_0^{q(\overline{c})} f(\varepsilon)\,\varepsilon d\varepsilon + p^* q(\overline{c})\left(1 - F(q(\overline{c}))\right) \\ &\quad - q(\overline{c})\,\overline{c} + H(q(\overline{c}))\,\overline{c} - C(q(0)) - \int_0^{\overline{c}} \left(H(q(c)) - q(c)\right) dc \\ &\quad + q(0)\,k(0) - q(\overline{c})\,k(\overline{c}) + \int_0^{\overline{c}} q(c)\,k'(c)\,dc - M(q(\overline{c})). \end{aligned}$$

Differentiating this expression yields:

$$\begin{aligned} \frac{\partial W}{\partial \overline{c}} &= p^* q'(\overline{c})\,f(q(\overline{c}))\,q(\overline{c}) + p^* q'(\overline{c})\left(1 - F(q(\overline{c}))\right) \\ &\quad - p^* q(\overline{c})\,f(q(\overline{c}))\,q'(\overline{c}) - q'(\overline{c})\,\overline{c} - q(\overline{c}) + \\ &\quad + F(q(\overline{c}))\,\overline{c} q'(\overline{c}) + H(q(\overline{c})) \\ &\quad - \left(H(q(\overline{c})) - q(\overline{c})\right) - q'(\overline{c})\,k(\overline{c}) - q(\overline{c})\,k'(\overline{c}) \\ &\quad + q(\overline{c})\,k'(\overline{c}) - M'(q(\overline{c}))\,q'(\overline{c}) \\ &= p^* q'(\overline{c})\left(1 - F(q(\overline{c}))\right) - q'(\overline{c})\,\overline{c} + F(q(\overline{c}))\,\overline{c} q'(\overline{c}) \\ &\quad - q'(\overline{c})\,k(\overline{c}) - M'(q(\overline{c}))\,q'(\overline{c}) \\ &= (p^* - \overline{c})\,q'(\overline{c})\left(1 - F(q(\overline{c}))\right) - q'(\overline{c})\,k(\overline{c}) - M'(q(\overline{c}))\,q'(\overline{c}) \\ &= q'(\overline{c}) \left(\underbrace{(p^* - \overline{c})\left(1 - F(q(\overline{c}))\right) - k(\overline{c}) - M'(q(\overline{c}))}_{=Y(\overline{c})} \right). \end{aligned} \tag{26}$$

This implies the first-order condition for social welfare is:

$$Y(\overline{c}) = 0. \tag{27}$$

We next confirm that $Y(\overline{c})$ is decreasing when the technology mix is efficient, that is, (24) is satisfied:

$$\begin{aligned} Y'(\overline{c}) &= -(1-F(q(\overline{c}))) - (p^* - \overline{c}) f(q(\overline{c})) q'(\overline{c}) - k'(\overline{c}) - M''(q(\overline{c})) q'(\overline{c}) \\ &= k'(c) - (p^* - \overline{c}) k''(c) - k'(\overline{c}) - M''(q(\overline{c})) q'(\overline{c}) \\ &< 0 \text{ for } \overline{c} \in [0, p^*], \end{aligned}$$

where the simplification makes use of the first-order condition (24) and its derivative in (25). The first-order condition (24) and the assumed properties of $k(c)$ and $M(\widehat{\varepsilon})$ imply that:

$$\begin{aligned} Y(0) &= -p^* k'(0) - k(0) - M'(q(0)) > 0 \\ Y(p^*) &= -k(p^*) - M'(q(p^*)) < 0. \end{aligned}$$

Together with the property $Y'(\overline{c}) < 0$, this ensures a unique solution to $Y(\overline{c}) = 0$ in the range $(0, p^*)$. Since also $q'(\overline{c}) > 0$, it follows from (26) that:

$$\frac{\partial W}{\partial \overline{c}} \geq 0 \text{ for } c \in [0, \overline{c}] \text{ and } \frac{\partial W}{\partial \overline{c}} \leq 0 \text{ for } c \in [\overline{c}, p^*],$$

so we can conclude that the first-order condition $Y(\overline{c}) = 0$ gives a social (global) optimum.

The following lemma is useful when proving Proposition 2, where we e.g. show that the conditions (28) and (29) are satisfied for the markets that we consider.

Lemma 2 *Consider a perfectly competitive market, where the capacity payment is not too low or too high, i.e.*

$$z - k(0) - \overline{p} k'(0) > 0 \tag{28}$$

$$z - k(\widehat{p}) - (\overline{p} - \widehat{p}) k'(\widehat{p}) < 0. \tag{29}$$

In this case, the following can be proven:

1. *There is a highest marginal cost $\overline{c} \in (0, \widehat{p})$ for which there is investment. This cutoff can be uniquely determined from:*

$$z - k(\overline{c}) - (\overline{p} - \overline{c}) k'(\overline{c}) = 0. \tag{30}$$

2. *Investments give rise to a supply curve* $q(c)$*, which can be determined from:*

$$q(c) = F^{-1}(1 + k'(c)) \tag{31}$$

for $c \in [0, \overline{c}]$.

Proof of Lemma 2. With competitive entry, the zero-profit condition $\pi(c) \equiv 0$ is an identity. Hence, since entrants are price takers (so that $p(q(c)) = c$) and using Leibniz' rule, we can differentiate both sides of (8) to get:

$$\begin{aligned} \pi'(c) &= -k'(c) - q'(c)(p(q(c)) - c) f(q(c)) - \int_{q(c)}^{\hat{\varepsilon}} f(\varepsilon) d\varepsilon - (1 - F(\hat{\varepsilon})) \\ &= -k'(c) - (1 - F(q(c))) \\ &= 0, \end{aligned}$$

which is the first-order condition in (10). For the marginal technology $\overline{c}$, we have $\hat{\varepsilon} = q(\overline{c})$ so the zero-profit condition based on (8) simplifies to:

$$\begin{aligned} \pi(\overline{c}) &= z - k(\overline{c}) + (\overline{p} - \overline{c})(1 - F(\hat{\varepsilon})) && (32) \\ &= z - k(\overline{c}) - (\overline{p} - \overline{c}) k'(\overline{c}) && (33) \\ &= 0, && (34) \end{aligned}$$

where the second step uses (10). For given z and $\overline{p}$, we can use this condition to solve for $\overline{c}$. To show that such a solution exists and is unique, let $\overline{\pi}(\overline{c}) = z - k(\overline{c}) - (\overline{p} - \overline{c}) k'(\overline{c})$ and differentiate to get:

$$\overline{\pi}'(\overline{c}) = -k'(\overline{c}) + k'(\overline{c}) - (\overline{p} - \overline{c}) k''(\overline{c}) < 0 \text{ for } \overline{c} \in [0, \widehat{p}).$$

It follows from the conditions in (28) and (29) that:

$$\begin{aligned} \overline{\pi}(0) &= z - k(0) - \overline{p}k'(0) > 0, \\ \overline{\pi}(\widehat{p}) &= z - k(\widehat{p}) - (\overline{p} - \widehat{p}) k'(\widehat{p}) < 0. \end{aligned}$$

These inequalities and $\overline{\pi}'(\overline{c}) < 0$ ensure a unique solution to $\overline{\pi}(\overline{c}) = 0$ in the range $(0, \widehat{p})$.

Proof of Proposition 2. We note that the first-order condition for investments in (31) is identical to that of Proposition (1). Hence, the competitive market yields socially-optimal investments whenever (32) gives the same technology cutoff $\overline{c}$ as the socially-optimal condition from (5), that is, the price cap $\overline{p}$ and capacity payment z are such that:

$$z - k(\overline{c}) - (\overline{p} - \overline{c}) k'(\overline{c}) = -(p^* - \overline{c}) k'(\overline{c}) - k(\overline{c}) - M'(q(\overline{c})),$$

which is the case whenever (9) is satisfied, as claimed.

Next, we wish to establish that the family of socially-optimal instruments $(\overline{p}, z)$ from (9) satisfies the two conditions (28) and (29) in Lemma 2:

Step 1. We start with the regularity condition from (28) that the capacity payment should not be too small, which reads:

$$A = z - k(0) - \bar{p}k'(0) > 0.$$

Using (9) to express the capacity payment z in terms of the price cap $\bar{p}$ yields:

$$A = -M'(\hat{\varepsilon}) - (p^* - \bar{p})\,k'(\bar{c}) - k(0) - \bar{p}k'(0).$$

We wish to find a lower bound on A, that is, a combination of parameter values for which A is at a minimum—from which it follows that indeed $A > 0$. In particular, we look for the "most critical" $\bar{p}$ for given $\hat{\varepsilon}$ and $\bar{c}$.[40] Under these circumstances, we have that:

$$\frac{dA}{d\bar{p}} = k'(\bar{c}) - k'(0) > 0,$$

as $k''(c) > 0$. Hence, for given $\hat{\varepsilon}$ and $\bar{c}$, A is bounded from below by the case where $\bar{p} \searrow \bar{c}$ and so:

$$\begin{aligned} A &> -M'(\hat{\varepsilon}) - (p^* - \bar{c})\,k'(\bar{c}) - k(0) - \bar{c}k'(0) \\ &= k(\bar{c}) - k(0) - \bar{c}k'(0) \\ &> 0, \end{aligned}$$

where the second line follows since we are at a social optimum, (5), and the last line again follows from $k''(c) > 0$. Hence, we conclude that the regularity condition in (28) is satisfied for the socially-optimal instruments from (9).

Step 2. Next we consider the regularity condition from (29) that the capacity payment should not be too large. There are two such cases. First, if $p^* > \hat{p} = \bar{p}$, then (29) can be written as:

$$B = z - k(\bar{p}) < 0.$$

We follow a similar approach to Step 1 but now wish to find an upper bound on B. Again using (9) to express the capacity payment z in terms of the price cap $\bar{p}$ yields:

$$B = -M'(\hat{\varepsilon}) - (p^* - \bar{p})\,k'(\bar{c}) - k(\bar{p}).$$

[40] As we only need to identify a lower bound, we do not need to consider whether the "worst" combination of parameter is actually consistent with some particular demand distribution.

For given $\hat{\varepsilon}$ and $\bar{c}$, we have:

$$\frac{dB}{d\bar{p}} = k'(\bar{c}) - k'(\bar{p}) < 0,$$

as $k''(c) > 0$. Hence, for given $\hat{\varepsilon}$ and $\bar{c}$, B is bounded from above by the case where $\bar{p} \searrow \bar{c}$ and so:

$$\begin{aligned} B &< -M'(\hat{\varepsilon}) - (p^* - \bar{c})\, k'(\bar{c}) - k(\bar{c}) \\ &= 0, \end{aligned}$$

where the second line follows from (5). Hence, we conclude that the regularity condition in (29) is satisfied in this case. Second, and finally, if $p^* = \hat{p} < \bar{p}$, then (29) can be written as:

$$D = z - k(p^*) - (\bar{p} - p^*)\, k'(p^*) < 0.$$

Again using (9) to express the capacity payment z in terms of the price cap $\bar{p}$ yields:

$$D = -M'(\hat{\varepsilon}) - (p^* - \bar{p})\,(k'(\bar{c}) - k'(p^*)) - k(p^*)\,.$$

For given $\hat{\varepsilon}$ and $\bar{c}$, we have:

$$\frac{dD}{d\bar{p}} = k'(\bar{c}) - k'(p^*) < 0,$$

as $k''(c) > 0$. Hence, for given $\hat{\varepsilon}$ and $\bar{c}$, D is bounded from above by the case where $\bar{p} \searrow \bar{c}$ and so:

$$\begin{aligned} D &< -M'(\hat{\varepsilon}) - (p^* - \bar{c})\,(k'(\bar{c}) - k'(p^*)) - k(p^*) \\ &= k(\bar{c}) - k(p^*) + (p^* - \bar{c})\, k'(p^*) \\ &< 0\,, \end{aligned}$$

where the second line follows since we are at a social optimum, (5), and the last line again follows from $k''(c) > 0$. Hence, we conclude that the regularity condition in (29) is satisfied also in this case. Therefore the two regularity conditions in (28) and (29) are both satisfied for the socially-optimal instruments from (9), as required.

Proof of Proposition 3 Assume that $\bar{p} > p_0^*$ is a notional VOLL level that the social planner uses when optimizing investments. Note that the notional level may differ from the true VOLL level. Hence, we can use the results in Proposition 1 to determine a cutoff $\bar{c}(\bar{p})$ from the condition $-(\bar{p} - \bar{c})\, k'(\bar{c}) - k(\bar{c}) - M'(q(\bar{c})) = 0$ and an associated supply curve $q(c) = F^{-1}(1 + k'(c))$, for $c \in [0, \bar{c}(\bar{p})]$. Next, we can use results in Proposition 2 to establish alternative price caps $\tilde{p}$ and capacity payments that will give the same investments as a social planner would for the notional VOLL level $\bar{p}$. Equation (11) follows from the zero-profit condition in (32).

Proof of Proposition 4. Consider first the case where the price cap $\overline{p}$ increases. On one hand, at the margin, this increases the expected revenue to producers from the spot market by $1-F(\hat{\varepsilon})$, the loss of load probability. On the other hand, this raises the market capacity by $\frac{\partial\widehat{\varepsilon}}{\partial\overline{p}}$ which in turn marginally reduces the loss of load probability and thereby reduces payments to producers below the technology cutoff by $(\overline{p}-\overline{c})\, f(\hat{\varepsilon})\frac{\partial\widehat{\varepsilon}}{\partial\overline{p}}$. We now show that the latter effect exactly offsets the former effect, so that the combined impact on any plant with marginal cost below an initial technology cutoff $\overline{c}_0$ is zero.

It follows from (10) that

$$\frac{\partial\widehat{\varepsilon}}{\partial\overline{c}}=\frac{k''(\overline{c})}{f(\hat{\varepsilon})} \tag{35}$$

and we know from (43) that $\frac{\partial\overline{c}}{\partial\overline{p}}=\frac{-k'(\overline{c})}{(\overline{p}-\overline{c})k''(\overline{c})}$, so we can write the latter effect as:

$$\begin{aligned}(\overline{p}-\overline{c})\, f(\hat{\varepsilon})\frac{\partial\widehat{\varepsilon}}{\partial\overline{p}} &= (\overline{p}-\overline{c})\, f(\hat{\varepsilon})\frac{\partial\overline{c}}{\partial\overline{p}}\frac{\partial\widehat{\varepsilon}}{\partial\overline{c}}\\ &= (\overline{p}-\overline{c})\, f(\hat{\varepsilon})\frac{-k'(\overline{c})}{(\overline{p}-\overline{c})\,k''(\overline{c})}\frac{k''(\overline{c})}{f(\hat{\varepsilon})}=-k'(\overline{c})=1-F(\hat{\varepsilon}),\end{aligned}$$

where the last equality uses (10). This shows that the two effects are exactly offsetting.

The argument is similar for the case where the capacity payment z increases. On one hand, at the margin, the capacity payment to production below the technology cutoff $\overline{c}_0$ increases by 1. On the other hand, expected revenues to producers in the spot market decrease by $(\overline{p}-\overline{c})\, f(\hat{\varepsilon})\frac{\partial\widehat{\varepsilon}}{\partial z}$. We again can show that the latter effect exactly offsets the former effect. This here follows directly from (43) and (35).

$$(\overline{p}-\overline{c})\, f(\hat{\varepsilon})\frac{\partial\widehat{\varepsilon}}{\partial z}=(\overline{p}-\overline{c})\, f(\hat{\varepsilon})\frac{\partial\overline{c}}{\partial z}\frac{\partial\widehat{\varepsilon}}{\partial\overline{c}}=\frac{1}{(\overline{p}-\overline{c})\,k''(\overline{c})}\frac{k''(\overline{c})}{f(\hat{\varepsilon})}=1. \tag{36}$$

It follows that, in both cases, any extra revenue due to the higher price cap and/or capacity payments goes solely to covering the production and investment costs of new investments above the initial technology cutoff $\overline{c}_0$.

Proof of Lemma 6.2. Differentiating the condition for optimal investment from (12) shows the impact of more renewables, for any technology level c, is given by:

$$-\frac{\partial F(q(c,w);w)}{\partial\varepsilon}\frac{\partial q(c,w)}{\partial w}-\frac{\partial F(q(c,w);w)}{\partial w}=0,$$

so that:

$$\frac{\partial q(c,w)}{\partial w}=-\frac{\partial F(q(c,w);w)}{\partial w}\Bigg/\frac{\partial F(q(c,w);w)}{\partial\varepsilon}<0. \tag{37}$$

as $\frac{\partial F(q(c,w);w)}{\partial\varepsilon}<0$ and $\frac{\partial F(q(c,w);w)}{\partial w}>0$ are assumed.

Proof of Proposition 5. First, we differentiate the optimality condition (12) to obtain:

$$-\frac{\partial F\left(q\left(c,w\right),w\right)}{\partial \varepsilon}\frac{\partial q\left(c,w\right)}{\partial c}=-k''\left(c\right)\Longrightarrow\frac{\partial q\left(c,w\right)}{\partial c}=k''\left(c\right)\Bigg/\frac{\partial F\left(q\left(c,w\right),w\right)}{\partial \varepsilon}>0. \tag{38}$$

Next, differentiating the condition for the socially-optimal technology cutoff $\overline{c}$ from (13) shows that the impact of w on $\overline{c}$ satisfies:

$$\begin{aligned}0 &= \frac{d\overline{c}}{dw}k'\left(\overline{c}\right)-\left(p^{*}-\overline{c}\right)k''\left(\overline{c}\right)\frac{d\overline{c}}{dw}-k'\left(\overline{c}\right)\frac{d\overline{c}}{dw}\\ &\quad -\frac{\partial^{2}M\left(q\left(\overline{c},w\right),w\right)}{\partial\hat{\varepsilon}^{2}}\left(\frac{\partial q\left(\overline{c},w\right)}{\partial c}\frac{d\overline{c}}{dw}+\frac{\partial q\left(\overline{c},w\right)}{\partial w}\right)-\frac{\partial^{2}M\left(q\left(\overline{c},w\right),w\right)}{\partial\hat{\varepsilon}\partial w}.\end{aligned}$$

Using (37), this can be rearranged to give:

$$\frac{d\overline{c}}{dw} = -\frac{\frac{\partial^{2}M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}^{2}}\frac{\partial q(\overline{c},w)}{\partial w}+\frac{\partial^{2}M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}\partial w}}{\left(p^{*}-\overline{c}\right)k''\left(\overline{c}\right)+\frac{\partial^{2}M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}^{2}}\frac{\partial q(\overline{c},w)}{\partial c}} \tag{39}$$

$$= \frac{\frac{\partial^{2}M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}^{2}}\frac{\partial F(q(c,w);w)}{\partial w}\Big/\frac{\partial F(q(c,w);w)}{\partial\varepsilon}-\frac{\partial^{2}M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}\partial w}}{\left(p^{*}-\overline{c}\right)k''\left(\overline{c}\right)+\frac{\partial^{2}M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}^{2}}\frac{\partial q(\overline{c},w)}{\partial c}}, \tag{40}$$

and so, as the denominator is always positive, $\frac{d\overline{c}}{dw}\geq 0$ if $s^{w}\equiv\frac{\frac{\partial^{2}M(\hat{\varepsilon},w)}{\partial\hat{\varepsilon}\partial w}}{\frac{\partial F(\hat{\varepsilon};w)}{\partial w}}\leq\frac{\frac{\partial^{2}M(\hat{\varepsilon},w)}{\partial\hat{\varepsilon}^{2}}}{\frac{\partial F(\hat{\varepsilon};w)}{\partial\hat{\varepsilon}}}\equiv s^{\varepsilon}$, which is Condition R. Again using (12), the socially-optimal loss of load probability satisfies $LOLP=1-F\left(\hat{\varepsilon},w\right)=-k'\left(\overline{c}\right)$ and so differentiation yields:

$$\frac{dLOLP}{dw}=-\frac{dk'\left(\overline{c}\right)}{dw}=-k''\left(\overline{c}\right)\frac{d\overline{c}}{dw}\leq 0.$$

Finally, for the special case with $M(\hat{\varepsilon},w)\equiv 0$, it follows by inspection that $\frac{d\overline{c}}{dw}=0$ and so also $\frac{dLOLP}{dw}=0$.

Proof of Proposition 6. The overall impact of renewables on the socially-optimal conventional capacity is given by:

$$\frac{dq\left(\overline{c},w\right)}{dw}=\frac{\partial q\left(\overline{c},w\right)}{\partial c}\frac{d\overline{c}}{dw}+\frac{\partial q\left(\overline{c},w\right)}{\partial w}. \tag{41}$$

We have already derived the first term $\frac{\partial q(\overline{c},w)}{\partial\overline{c}}$ in (38), the second term $\frac{d\overline{c}}{dw}$ in (39), and the third term $\frac{\partial q(\overline{c},w)}{\partial w}$ in (37). Using these results gives:

$$\begin{aligned}\frac{dq\left(\overline{c},w\right)}{dw} &= -\frac{\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}^2}\frac{\partial q(\overline{c},w)}{\partial w}+\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}\partial w}}{\left(p^*-\overline{c}\right)\frac{\partial F(q(c,w),w)}{\partial\varepsilon}+\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}^2}}+\frac{\partial q\left(\overline{c},w\right)}{\partial w}\\ &= \frac{-\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}\partial w}+\frac{\partial q(\overline{c},w)}{\partial w}\left(p^*-\overline{c}\right)\frac{\partial F(q(c,w),w)}{\partial\varepsilon}}{\left(p^*-\overline{c}\right)\frac{\partial F(q(c,w),w)}{\partial\varepsilon}+\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}^2}}\\ &= -\frac{\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}\partial w}+\frac{\partial F(q(c,w);w)}{\partial w}\left(p^*-\overline{c}\right)}{\left(p^*-\overline{c}\right)\frac{\partial F(q(c,w),w)}{\partial\varepsilon}+\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}^2}},\end{aligned} \tag{42}$$

which is negative if $\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}\partial w}+\frac{\partial F(q(c,w);w)}{\partial w}\left(p^*-\overline{c}\right)\geq 0$, or equivalently, $-\left(p^*-\overline{c}\right)\leq \frac{\frac{\partial^2 M(\hat{\varepsilon},w)}{\partial\hat{\varepsilon}^2}}{\frac{\partial F(\hat{\varepsilon};w)}{\partial\hat{\varepsilon}}}\equiv s^w$, as claimed.

Proof of Proposition 7. The family $(\overline{p},z)$ of socially-optimal policies is defined by the condition in (15) so, for a fixed $\overline{p}$, we have:

$$\frac{\partial z\left(w,\overline{p}\right)}{\partial w}=-\frac{\partial^2 M\left(q\left(\overline{c},w\right),w\right)}{\partial\hat{\varepsilon}^2}\frac{dq\left(\overline{c},w\right)}{dw}-\frac{\partial^2 M\left(q\left(\overline{c},w\right),w\right)}{\partial\hat{\varepsilon}\partial w}-\left(p^*-\overline{p}\right)k''\left(\overline{c}\right)\frac{d\overline{c}}{dw}.$$

Using the expressions for $\frac{dq}{dw}$ and $\frac{d\overline{c}}{dw}$ from (42) and (39), respectively, we obtain:

$$\begin{aligned}\frac{\partial z\left(w,\overline{p}\right)}{\partial w} &= \frac{\partial^2 M\left(q\left(\overline{c},w\right),w\right)}{\partial\hat{\varepsilon}^2}\frac{\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}\partial w}+\frac{\partial F(q(c,w);w)}{\partial w}\left(p^*-\overline{c}\right)}{\left(p^*-\overline{c}\right)\frac{\partial F(q(c,w),w)}{\partial\varepsilon}+\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}^2}}-\frac{\partial^2 M\left(q\left(\overline{c},w\right),w\right)}{\partial\hat{\varepsilon}\partial w}\\ &\quad -\left(p^*-\overline{p}\right)\frac{\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}^2}\frac{\partial F(q(c,w);w)}{\partial w}-\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}\partial w}\frac{\partial F(q(c,w),w)}{\partial\varepsilon}}{\left(p^*-\overline{c}\right)\frac{\partial F(q(c,w),w)}{\partial\varepsilon}+\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}^2}}\\ &= \left(\overline{p}-\overline{c}\right)\frac{\left[\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}^2}\frac{\partial F(q(c,w);w)}{\partial w}-\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}\partial w}\frac{\partial F(q(c,w),w)}{\partial\varepsilon}\right]}{\left(p^*-\overline{c}\right)\frac{\partial F(q(c,w),w)}{\partial\varepsilon}+\frac{\partial^2 M(q(\overline{c},w),w)}{\partial\hat{\varepsilon}^2}},\end{aligned}$$

which is positive if $s^w\equiv\frac{\frac{\partial^2 M(\hat{\varepsilon},w)}{\partial\hat{\varepsilon}\partial w}}{\frac{\partial F(\hat{\varepsilon};w)}{\partial w}}\leq\frac{\frac{\partial^2 M(\hat{\varepsilon},w)}{\partial\hat{\varepsilon}^2}}{\frac{\partial F(\hat{\varepsilon};w)}{\partial\hat{\varepsilon}}}\equiv s^\varepsilon$, which is Condition R. Finally, for the special case with $M(\hat{\varepsilon},w)\equiv 0$, it follows by inspection that $\frac{\partial z(w,\overline{p})}{\partial w}=0$.

Proof of Proposition 8. Under the design laid out in Section 6.1., the non-reserve market is independent from the reserve market. Hence, revenues for plants in the energy-only market are identical to those in a competitive market with the same price cap $\overline{p}$ and no capacity payment.[41] Hence, the invested capacity $\widehat{\varepsilon}$, technology cutoff $\bar{c}$ and

[41] Recall that p_0^* is the lowest VOLL level for which we can ensure positive socially optimal investments. Hence, $\bar{c}\left(p_0^*\right)$ and $q\left(\bar{c}\left(p_0^*\right)\right)$ are the technology cutoff and market capacity, respectively, for that lowest VOLL level. It follows from Proposition 2 that those investments will also occur for $\bar{p}=p_0^*+M'\left(q\left(\bar{c}\left(p_0^*\right)\right)\right)/k'\left(\bar{c}\left(p_0^*\right)\right)$ when $z=0$. We need $\bar{p}>p_0^*+M'\left(q\left(\bar{c}\left(p_0^*\right)\right)\right)/k'\left(\bar{c}\left(p_0^*\right)\right)$ to make sure

technology mix will also be the same. When solving for investments into the reserve, we can take investments into the non-reserve market as given. We know from Proposition 4 that even if a capacity payment z was introduced, this would not change the technology mix and supply below the marginal cost $\bar{c}$. It follows that revenues for reserve plant are identical to those for plant in the capacity range $[\widehat{\varepsilon}, \widehat{\varepsilon}_r]$ of a capacity market with a uniform capacity payment z. Hence, the technology mix for that range and the technology cutoff $\bar{c}_r$ follow from our previous results for a market-wide capacity payment. Therefore, in sum, statements (i)-(iv) follow from Proposition 2. Finally, we verify using comparative statics the statement (v) that the payment difference $\overline{p} - p_r$ (which energy-only plant make relative to reserve plant, in situations when the strategic reserve is used) is equal in expectation to the capacity payment z to reserve plant. By the arguments of (36), a marginally higher capacity payment to reserve plant would lower their spot-market revenues by $(\overline{p} - \overline{c}) f(\hat{\varepsilon}) \frac{\partial \widehat{\varepsilon}}{\partial z} = 1$, so that expected profit remains zero. The spot price for energy-only plants does not change when the capacity payment z to reserve plants increases. Hence, the payment difference $\overline{p} - p_r$ will, in expectation, give an extra payment to non-reserve plant (relative to reserve plant) that increases at the same rate as z.

Appendix B: Comparative-statics results

Results

The following comparative statics results make use of the conditions established in connection with Proposition 3. The reason is that these conditions also apply to values of $(\overline{p}, z)$ that do not necessarily belong to the family that achieves the social optimum.

Comparative statics: Capacity payment and price cap

Proposition 9 *Consider a capacity mechanism where the capacity payment z is set by the market design:*
(i)The technology cutoff $\overline{c}$ increases for a higher capacity payment z:

$$\frac{\partial \overline{c}}{\partial z} = \frac{1}{(\overline{p} - \overline{c})\, k''(\overline{c})} > 0 \tag{43}$$

and for a higher price cap $\overline{p}$:

$$\frac{\partial \overline{c}}{\partial \overline{p}} = \frac{-k'(\overline{c})}{(\overline{p} - \overline{c})\, k''(\overline{c})} > 0. \tag{44}$$

that investments are non-negative.

(ii) The loss of load probability, $1 - F(q(\overline{c}))$, decreases for a higher capacity payment z:

$$\frac{\partial (1 - F(q(\overline{c})))}{\partial z} = -f(q(\overline{c}))\, q'(\overline{c}) \frac{\partial \overline{c}}{\partial z} < 0$$

and decreases for a higher price cap $\overline{p}$:

$$\frac{\partial (1 - F(q(\overline{c})))}{\partial \overline{p}} = -f(q(\overline{c}))\, q'(\overline{c}) \frac{\partial \overline{c}}{\partial \overline{p}} < 0.$$

Proposition 9 shows that a higher capacity payment and price cap both raise investment and decrease the LOLP. In this sense, these two policy instruments are substitutes.

Comparative statics: Capacity volume and price cap

Proposition 10 *Consider a capacity mechanism where the capacity volume $\hat{\varepsilon}$ is set by the market design and the capacity payment z is endogenously determined. A higher procured capacity $\hat{\varepsilon}$ raises the technology cutoff $\overline{c}$:*

$$\frac{\partial \overline{c}}{\partial \hat{\varepsilon}} = \frac{f(\hat{\varepsilon})}{k''(\overline{c})} > 0, \tag{45}$$

and raises the capacity payment z:

$$\frac{\partial z}{\partial \hat{\varepsilon}} = (\overline{p} - \overline{c})\, f(\hat{\varepsilon}) > 0. \tag{46}$$

Proposition 10 shows how a capacity auction that procures more capacity investment brings a higher technology cutoff and requires a higher capacity payment. The first part of the result, $\partial \overline{c} / \partial \hat{\varepsilon} = f(\hat{\varepsilon}) / k''(\overline{c}) > 0$, follows directly from the condition (10) which ensures that producers are indifferent between investment alternatives. To understand the second part, if investments increase by a (small) $\Delta \widehat{\varepsilon}$, producers will now be paid $\overline{c}$ instead of the higher price cap $\overline{p}$ for shocks in the range $[\hat{\varepsilon}, \hat{\varepsilon} + \Delta \widehat{\varepsilon}]$. Shocks are in this range with probability $f(\hat{\varepsilon})\, \Delta \widehat{\varepsilon}$. Therefore, to ensure that the expected profit from marginal investments remains zero, a competitive market adjusts the capacity payment upwards by $(\overline{p} - \overline{c})\, f(\hat{\varepsilon})\, \Delta \widehat{\varepsilon}$.

Proposition 11 *Consider a capacity mechanism where the capacity volume $\hat{\varepsilon}$ is set by the market design and the capacity payment z is endogenously determined. For a given procured capacity $\hat{\varepsilon}$, a higher price cap $\overline{p}$ has no impact on the technology cutoff $\overline{c}$:*

$$\left. \frac{d\overline{c}}{d\overline{p}} \right|_{\hat{\varepsilon} \text{ fixed}} = 0, \tag{47}$$

and reduces the capacity payment z:

$$\left.\frac{dz}{d\overline{p}}\right|_{\hat{\varepsilon}\ fixed} = k'(\overline{c}) < 0. \tag{48}$$

The first part of Proposition 11 again follows directly from (10); the technology cutoff is unchanged if invested capacity is unchanged. The second part can be understood by using $[1 - F(\hat{\varepsilon})] = -k'(\overline{c})$ from (4) to rewrite (48) as $[dz/d\overline{p}]_{\hat{\varepsilon}\text{ fixed}} = -[1 - F(\hat{\varepsilon})]$. Producers are paid the price cap $\overline{p}$ when there is demand rationing, which occurs with probability $1 - F(\hat{\varepsilon})$. Hence, if the price cap is increased by a (small) $\Delta\overline{p}$, then the capacity payment must decline by $\Delta\overline{p}[1 - F(\hat{\varepsilon})]$ to keep expected profit from marginal investments at zero.

Proofs

Proof of Proposition 9. For the statement in part (i), implicit differentiation of (11) with respect to the capacity payment z yields:

$$\begin{aligned} 1 - k'(\overline{c})\frac{\partial\overline{c}}{\partial z} + \frac{\partial\overline{c}}{\partial z}k'(\overline{c}) - (\overline{p} - \overline{c})k''(\overline{c})\frac{\partial\overline{c}}{\partial z} &= 0 \\ 1 - (\overline{p} - \overline{c})k''(\overline{c})\frac{\partial\overline{c}}{\partial z} &= 0 \Longrightarrow \frac{\partial\overline{c}}{\partial z} = \frac{1}{(\overline{p} - \overline{c})k''(\overline{c})} \geq 0. \end{aligned}$$

Similarly, implicit differentiation of (32) with respect to the price cap $\overline{c}$ yields:

$$\begin{aligned} -k'(\overline{c})\frac{\partial\overline{c}}{\partial\overline{p}} - \left(1 - \frac{\partial\overline{c}}{\partial\overline{p}}\right)k'(\overline{c}) - (\overline{p} - \overline{c})k''(\overline{c})\frac{\partial\overline{c}}{\partial\overline{p}} &= 0 \\ -k'(\overline{c}) - (\overline{p} - \overline{c})k''(\overline{c})\frac{\partial\overline{c}}{\partial\overline{p}} &= 0 \Longrightarrow \frac{\partial\overline{c}}{\partial\overline{p}} = \frac{-k'(\overline{c})}{(\overline{p} - \overline{c})k''(\overline{c})} \geq 0. \end{aligned}$$

The statement in part (ii) follows straightforwardly using the results from part (i).

Proof of Proposition 10. The first-order condition in (10) also holds at $\overline{c}$ and for marginal changes in $\hat{\varepsilon}$. Hence differentiating with respect to capacity $\hat{\varepsilon}$ gives:

$$-k''(\overline{c})\frac{\partial\overline{c}}{\partial\hat{\varepsilon}} + f(\hat{\varepsilon}) = 0 \Longrightarrow \frac{\partial\overline{c}}{\partial\hat{\varepsilon}} = \frac{f(\hat{\varepsilon})}{k''(\overline{c})} \geq 0.$$

Moreover, implicit differentiation of (11) with respect to $\hat{\varepsilon}$ yields:

$$\begin{aligned} 0 &= \frac{\partial z}{\partial\hat{\varepsilon}} - k'(\overline{c})\frac{\partial\overline{c}}{\partial\hat{\varepsilon}} + \frac{\partial\overline{c}}{\partial\hat{\varepsilon}}k'(\overline{c}) - (\overline{p} - \overline{c})k''(\overline{c})\frac{\partial\overline{c}}{\partial\hat{\varepsilon}} \\ &\Longrightarrow \frac{\partial z}{\partial\hat{\varepsilon}} = (\overline{p} - \overline{c})k''(\overline{c})\frac{\partial\overline{c}}{\partial\hat{\varepsilon}} = (\overline{p} - \overline{c})f(\hat{\varepsilon}) \geq 0. \end{aligned}$$

Proof of Proposition 11. The first-order condition in (10) also holds at $\overline{c}$ so $\overline{c}$ is fixed if $\hat{\varepsilon}$ is fixed: $\left.\frac{d\overline{c}}{d\overline{p}}\right|_{\hat{\varepsilon}\text{ fixed}} = 0$. Implicit differentiation of (11) shows that $\left.\frac{dz}{d\overline{p}}\right|_{\hat{\varepsilon}\text{ fixed}} = k'(\overline{c}) < 0$.