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Policy Implications of a World with Renewables, Limited Dispatchability, and Fixed Load*

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Policy Implications of a World with Renewables, Limited Dispatchability, and Fixed Load*

Mathias Mier†

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Abstract

Most electricity systems face contractual fixed consumer prices in the short term, that is, load and price are fixed before the random supply of renewables like wind or solar realizes. Steam power plants also make production decisions before such a random supply realizes. These capacities cannot react instantly, which creates a demand for gas turbines to balance renewables. We approach these dynamics by considering different types of dispatchability in a more general framework of peak-load pricing and contribute to the debate on market design and capacity payments. Steam power always recovers costs, gas turbines never do so, and renewables might. We describe possible transfer schemes to overcome this problem and provide a more market-oriented solution. However, consumers must always be compensated for lost load.

Keywords: renewable energies, peak-load pricing, electricity market design; missing market; missing money; capacity payments

JEL Classification: Q21, Q41, Q42, Q48, L94, L98

1 Introduction

Electricity markets often provide day-ahead or contractual fixed consumer prices so that load is steady. For steam power, such a price signal is sufficient to recover costs, but it continues to be unclear whether or not gas turbines recover costs. Rising shares of renewables that come at zero marginal costs—which places them at the head of the merit order—substitute for a part of steam power production but require additional gas turbine capacity. In times of low or even zero availability of wind and solar (dark doldrums), steam power and gas turbines can continue

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to produce at full capacity, whereas a higher availability of wind and solar will squeeze out both technologies. This diminishes their capability to recover costs and leads to questions about capacity payments for conventional generators. However, the availability of renewables does not simply fluctuate but is, indeed, uncertain and, thus, only perfectly dispatchable generators like gas turbines are capable of dealing with the stochastic element of renewables. In turn, steam power must be scheduled a certain time ahead of actual production since ramping is either not possible in the necessary time frame or too costly. This brings into doubt whether steam power and renewables are compatible and leads to complications in designing markets to incentivize the necessary gas turbine capacity required to provide resource adequacy.

We contribute to the peak-load pricing literature by raising questions of costs recovery and market design.[1] In particular, we derive policy implications for a regulator who tries to decentralize the efficient capacity mix. We show that steam power and renewables should never be installed together. Steam power can recover costs, gas turbines cannot, and renewables might. The efficient solution could be decentralized by transfers without capacity payments. Transfers could be avoided either by supporting a well-working retail market that balances the real-time supply of producers with consumer load or by a market for imbalance energy. However, the efficient outcome is possible only if consumers are compensated for lost load.

The theoretical model described in this paper introduces three technologies: steam power, renewables, and gas turbines. We cover three technological challenges of electricity systems: (1) stochastic supply of renewable energies, (2) steam power cannot react to the stochastic element of renewables, whereas gas turbines can, and (3) load is steady due to day-ahead or contractual fixed consumer prices (uniform ex-ante price). If production is not sufficient to meet load, consumers suffer surplus losses and disruption costs, for which they need to be compensated. If load would be sufficiently responsive, the market would always clear and consumers would never suffer involuntary rationing (Cramton et al., 2013). However, most electricity markets face low load flexibility (see, e.g., Joskow and Tirole, 2006, 2007), in particular, in real-time (Joskow, 2011).[2]

All technologies face constant marginal production and capacity costs. Marginal disruption costs are assumed to be constant as well, where surplus losses depend on a utility function that fulfills Inada conditions.[3] This paper does not analyze the environmental impact of the three capacities. Environmental externalities are internalized in production costs by a Pigouvian tax and we abstract from less pronounced issue regarding welfare as induced technological change.[4] Subsidies and taxes are implemented only to decentralize the efficient solution.

Our paper builds on the seminal contribution of Eisenack and Mier (2018), who abstract from load issues and focus on supply uncertainty with two polar cases: marginal generating units of one technology are either independent of each other (independence case) or perfectly correlated (perfect

[1] It is questionable whether current market designs are appropriate with high shares of renewables, see, e.g., Fabra et al. (2011); Henriot and Glachant (2013).

[2] There is another factor that drives inelasticities: retail prices and wholesale prices are hugely disconnected since the price that consumers face is largely based on taxes, levies, and network costs. For example, wholesale prices are often only one-fifth of household prices.

[3] The assumption of constant disruption costs is somehow unrealistic but provides (on average) at least the right incentives for resource adequacy.

[4] Benefits from internalizing the (negative) environmental externality are higher than benefits from internalizing the (positive) externality from induced technological change (see, e.g., Parry et al., 2003; Fischer and Newell, 2008).

correlation case). The authors assume that production of different technologies can be adjusted at different speeds. In contrast to the established literature, where all production decisions are made after the random variable realizes, they also account for technologies that need to make production decisions before the random variable realizes. Their main result is that the competition between technologies is much fiercer than in the established peak-load pricing literature.

The idea of peak-load pricing was developed by Bye (1926, 1929); Boiteux (1949); Steiner (1957).[5] Consumers should be charged based on production costs in off-peak periods but based on production and capacity costs in peak periods. The introduction of a more diverse technology mix enhances welfare by smoothing price volatility (see, e.g., Crew and Kleindorfer, 1971). Deterministic models solve the peak-load problem and provide sufficient rules for efficient capacity choices from a regulator's perspective.[6] The literature tends to focus on different rationing schemes as soon as demand uncertainty enters the picture. Brown and Johnson (1969) assume that consumers are served regarding their willingness-to-pay (WTP) without additional costs (perfect load shedding). Visscher (1973) describes two alternative approaches with higher surplus losses from lost load. Either consumers are served randomly or consumers with the lowest WTP are served first. Crew and Kleindorfer (1976) assume that perfect load shedding causes additional rationing costs. Turvey and Anderson (1977) implement constant marginal costs of lost load and abstract from surplus losses due to lost load. Chao (1983) chooses the same setup but additionally assumes that generating units are subject to random failures that are stochastically independent of each other. Kleindorfer and Fernando (1993) model supply uncertainty in the same way but additionally account for surplus losses from lost load and distinguish between rationing and disruption costs. Rationing costs are dedicated to the system operator to obtain perfect load shedding. Disruption costs are dedicated to consumers and reflect that willingness-to-pay is not equal to willingness-to-lose. Our model and that of Eisenack and Mier (2018) choose the same specification of supply uncertainty but relax the assumption of independently distributed marginal generating units. Eisenack and Mier (2018) opt for Chao's rationing approach, whereas we use the Kleindorfer and Fernando formulation but dedicate all costs to consumers.

Whether these efficient pricing rules lead to cost recovery has not been much studied to date. In all deterministic setups, firms could recover costs, but for the stochastic models the outcome is diverse. Perfect load shedding with zero rationing costs as well as random rationing with additive demand uncertainty lead to prices below long-run marginal costs (LRMC) so that costs recovery is not possible. Carlton (1977) shows that random rationing with multiplicative demand uncertainty would permit cost recovery. Serving consumers with the lowest WTP first would even lead to prices above LRMC and profits are possible.

Chao (1983) distinguishes between two polar cases: marginal demand that is independent from total demand and marginal demand that is perfectly correlated to demand. Prices are too low to recover costs for the independence case. For the correlation case, results are inconclusive. The most comprehensive analysis of efficient pricing is by Kleindorfer and Fernando (1993). Additive demand uncertainty will lead to a price weakly lower than LRMC, whereas multiplicative demand

[5] Crew et al. (1995) provide an excellent survey.
[6] See also Houthakker, 1951; Hirshleifer, 1958; Williamson, 1966; Turvey, 1968.

uncertainty might lead to a price above LRMC. It is difficult to conclude whether cost recovery is possible. However, we can conclude that for additive uncertainty, profits are not possible, whereas they are likely for the multiplicative case. The results of Chao (1983) and Kleindorfer and Fernando (1993) coincide with those of Eisenack and Mier (2018), although the latter's uncertainty is on the supply side only. One of their three technologies always recovers costs, whereas another will never do so. The random technology never recover costs for their independence case, whereas it might recover costs for the other polar case.

How to actually implement these rules is not touched upon in the peak-load pricing literature. Borenstein (2016) suggests different approaches for price setting that would allow firms to recover costs. He summarizes that economic efficiency requires pricing equal to short-run marginal costs. The outcome is not efficient when there are externalities or market power or if firms fail to recover costs when price is equal to marginal costs; the latter situation is applicable for our model. However, our focus is different and is not aimed at distorting prices but on using transfers to ensure that short-run marginal cost pricing leads to the efficient outcome.

Chao (2011) links the peak-load pricing literature to the literature on the economics of electricity markets with renewable energies. He considers fossil fuels and one renewables technology, whose (uncertain) supply is inversely correlated with demand, which is a key difference from our paper regarding theoretical modeling. Considering both the independence and the correlation cases is crucial for our results regarding costs recovery, transfer schemes, and market design. Chao (2011) derives efficient pricing and capacity rules under dynamic pricing and uniform ex-ante pricing. He considers surplus losses and rationing/disruption costs in the theoretical part of his work, but abstracts from them to derive results using a numerical simulation with wind power, gas turbines, and combined-cycle power plants. He finds that renewables reduce average market prices and that uniform ex-ante pricing leads to higher average market prices and more investment in renewables. Chao's model is more comprehensive than ours, but he has to rely on the numerical simulation to obtain interpretable results, whereas we can derive policy implications directly from the theoretical model.

Ambec and Crampes (2012) provide a model with a fossil and a renewables technology, whose deterministic availability is either 0 or 1. A uniform ex-ante price for nonreactive consumers leads to overinvestment and no profit in the fossil technology, but underinvestment and profit in the renewables technology, whereas the technology we investigate that is most similar to their fossil one cannot recover costs. Ambec and Crampes (2012) also derive policy implications, but do not contribute to the debate over capacity payments. In contrast to our paper, they assume that reliable capacity must be sufficient to meet load. The same assumption is made by Helm and Mier (2018), who allow the renewables technology to take any value between 0 and 1. They combine reactive consumers that are subject to dynamic pricing and nonreactive consumers that face a uniform ex-ante price. In their model, the efficient solution could be decentralized. In particular, they identified a capacity payment for fossil generators provided through the market. However, their focus is on the efficient diffusion pattern of renewable energies and policy implications are considered only in the case of a price cap. Since dynamic pricing is possible in their setup, they abstract from the core issues of this paper: capacity payments and market design, namely, missing money and missing market. The general issue is that an energy-only market (as in our model) could lead to under-procurement of capacity. Thus, our paper contributes to the discussion on whether capacity payments—as lately implemented by, for example, Great Britain, France, and Australia—are necessary. Newbery (2016) argues that short-term resource adequacy should be ensured by the system operator, whereas long-term resource adequacy is a regulatory and political issue. Investors need a price signal that enables the recovery of costs, where missing money occurs if the price signal is not sufficient. He concludes that missing money problems arise when ancillary services such as balancing, black start capability, and flexibility are insufficiently priced. If the price signal is potentially adequate to recover costs but not perceived either because risks cannot be efficiently allocated or externalities are not properly priced, then we have a missing market problem (Newbery, 2016). However, the border between missing money and missing market is not clear since one might argue that there is a missing market when flexibility is not priced at all or a market for ancillary services is inappropriately designed. Furthermore, one might argue that providing flexibility could be a positive externality, whereas random supply of renewables is the countervailing negative externality.

None of papers just discussed, with the exception of Eisenack and Mier (2018), accounts for different levels of dispatchability; although the topic is highly relevant for the integration of large shares of renewables (see Schill et al., 2017 for start-up costs of thermal power plants), it is only addressed by engineering dispatch models (see, e.g., Wang and Shahidehpour, 1995; Han et al., 2001; Kumano, 2011). Perhaps the theoretical model that comes closest to this topic is that of Green and Léautier (2017) who study inflexibilities—modeled by minimum production levels—of renewables and of conventional capacity. In a numerical simulation they find that higher wind turbine capacities squeeze out inflexible more quickly than flexible nuclear generators, which mirrors our result that the competition between existing technologies is much fiercer than in the established peak-load pricing literature without different dispatchability levels.

Building on Eisenack and Mier's 2018 model, but accounting for surplus losses due to lost load, we find that the exclusion result—steam power and renewables cancel each other in the efficient solution—is even stronger. This result is based on the first two technological challenges covered by our model: (1) random supply of renewables and (2) limited dispatchability of steam power, where the following results are mainly driven by (3) the inflexible load assumption and inability to provide a value-adequate price signal. Steam power always recovers costs; gas turbines never recover costs. In the independence case, renewables will not recover costs since the price is equal to their LRMC but renewables are not fully used for all states. In the correlation case, price is higher by a markup that could be sufficient to recover costs; in fact, under specific distribution assumptions, the mark-up is always sufficient. As soon as renewables enter the market, consumers suffer (involuntary) load management and must be compensated for it. We can implement a value-adequate price signal by employing a specific transfer scheme, including compensation for consumers, without any capacity payments. Combining a real-time wholesale market with a retail market or by supporting a market for imbalance energy would lead to a value-adequate price signal as well. As soon as marginal generating units are not perfectly correlated, even a value-adequate price signal is no longer sufficient to decentralize the efficient solution.

Different levels of dispatchability are reflected by a sequential dispatch decision model. Long-term capacity decisions are made years ahead of actual delivery (Stage 1). At least one day-ahead load is fixed due to contractual fixed consumer prices (Stage 2). In Stages 3 to 5, technologies need to make production decisions. First, production of steam power must be scheduled hours ahead of actual production (Stage 3). Then, minutes to seconds before actual delivery, the random availability realizes and renewables could be dispatched within their capacity constraint in Stage 4. Finally, in Stage 5, gas turbine production is decided in real-time and it might be that lost load occurs if total production is not sufficient to serve load. We use this multi-stage process to determine the efficient solution and a decentralized day-ahead market solution under different levels of enforcement by a benevolent regulator. Even under the benchmark assumption of perfectly competitive markets, the efficient and the day-ahead market outcomes are not equivalent. Consequently, we determine necessary capacity, production, and lump-sum transfers for firms so as to decentralize production and capacity decisions as well as provide for any necessary consumer compensation to decentralize load decisions. We describe one transfer scheme that creates a value-adequate price signal and show how such a price signal could be implemented even without transfers by well-designed markets.

Section 2 introduces the model. Section 3 describes the efficient solution: production, load, and capacities. Section 4 shows describes costs recovery in a day-ahead market. Section 5 develops transfer schemes to decentralize capacity and production decisions. Section 6 derives policy implications that arise from the further analysis. Section 7 concludes.

2 The Model

We consider three types of technologies, $j = r, s, g$. r are renewables technologies like wind turbines and solar PV with random supply. s are steam power technologies. Scheduling steam power requires planning a certain time ahead of actual production (limited dispatchable). g are gas turbines, which are perfectly dispatchable since they can adjust production instantly. Capacity is k_j and production x_j. Steam power and gas turbine production are restricted by capacity, $x_s \leq k_s$, $x_g \leq k_g$, whereas renewables production is restricted by randomly available capacity, $x_r \leq \tilde{x}_r$. Load is D and $x_u = \max\left\{D - \sum_j x_j, 0\right\}$ is lost load. Consumers obtain utility U from load D but suffer utility losses and disruption costs from lost load. Utility is not further specified but fulfills the Inada conditions. In particular, U is concave, i.e., $U^{'} > 0$, $U^{''} < 0$. Note that we consider only one investment and one production cycle. Suppose that $\tilde{x}_r$ is a continuous and continuously differentiable random variable and define it as $\tilde{x}_r := \int_0^{k_r} \omega(z)\, dz$, i.e., $\tilde{x}_r$ is conceived as a continuum of marginal generating units z with random availabilities $\omega(z) \in [0, 1]$. These are stochastically identically distributed random variables. Regarding the correlation of availabilities $\omega(z)$, we consider two extreme cases. The *independence case* is when the availabilities of marginal generating units realize stochastically independently, which we denote *ind*. In the *perfect correlation case*, denoted *corr*, the availabilities of marginal generating units are perfectly correlated.

If weather conditions are the same for each generating unit, we are in the case of perfect correlation. If weather conditions are independent from each other, we are in the case of independence. Of course, these cases are extremes and the reality is in between. However, considering these two extreme cases allow us the derive policy implications applicable to more real-world settings that are neither *ind* nor *corr*.[7]

Assume that $a = E[\tilde{x}_r]/k_r \in (0,1)$ is the *availability factor* of renewables capacity, where E is the expectation operator and $E[\tilde{x}_r]$ expected availability of renewables capacity. Note that $\Omega = [0, k_N]$ is the sample space of $\tilde{x}_r$. For any interval $\Omega_c \subseteq \Omega$, the events $\tilde{x}_r \in \Omega_c$ realize with probability $\Pr_c$. Call $a_c = E[\tilde{x}_r|\Omega_c]/k_r$ the *conditional availability*, where $E[\tilde{x}_r|\Omega_c]$ is expected availability of renewables capacity conditional that Ω_c realizes. To avoid having to show each equation for both extreme cases, we use the dummy $\overline{a}_c := a$ for *ind* and $\overline{a}_c := a_c$ for *corr*.

Marginal production costs c_j and marginal capacity costs b_j are constant. Based in a regular merit-order curve, we assume that renewables have the lowest or even zero marginal production costs, whereas gas turbines have the highest, i.e., $0 \le c_r < c_s < c_g$. To reflect existing structures and to exclude that steam power capacity obviously dominates gas turbine capacity, we have $0 < b_g < b_s$. We assume that long-run marginal costs (LRMC) of gas turbines are the highest, i.e., $\frac{b_r}{a} + c_r,\ b_s + c_s < b_g + c_g$. Otherwise, it might be beneficial to use gas turbines only. Note that renewables capacity has an availability factor of a, i.e., $\frac{1}{a}$ capacity units are needed to provide one available unit in expectations.

We denote the difference between LRMC of steam power and renewables by $\Delta C := b_s + c_s - \frac{b_r}{a} - c_r$. If $\Delta C \le 0$, the LRMC of renewables is higher than that of steam power, whereas the latter technology has no stochastic component and is fully reliable. Consequently, $\Delta C \le 0$ would automatically imply $k_s > 0$ and $k_r = 0$.

Marginal costs of lost load are c_u and dedicated to consumers only, that is, we abstract from rationing costs and consider disruption costs only.[8] Producing one unit with gas turbine capacity is cheaper than accepting one unit of lost load, i.e, $b_g + c_g < c_u$. Otherwise, lost load dominates gas turbine production. Nevertheless, the choice between accepting lost load and providing (often unused) back-up capacities is an optimization problem.

The essential assumption of peak-load pricing models is that capacities k_s, k_r, k_g are fixed in the short-run and load D must be decided before production decisions x_s, x_r, x_g are made under technological restrictions. Steam power production x_s needs to be specified before the random availability of renewables $\tilde{x}_r$ realizes and cannot be changed later. This places steam power earliest in dispatch timing. The merit-order part of steam power capacity must be placed forwardmost as well, which contradicts the merit-order ranking $c_r < c_s < c_g$. To assure that this placement is credible, we assume that the costs of ramping-down steam power are higher than the benefits of replacing steam power with renewables production. Similarly, ramp-ups are technologically not possible in the necessary time frame. After load and steam power production is fixed, renewables availability realizes. If the actual availability of renewables is not sufficient to meet load, gas turbines must be employed or lost load occurs.

[7] One might implement a correlation measure as discussed in Chao (1983).
[8] For a discussion of rationing, disruption, and utility losses by curtailment see Kleindorfer and Fernando (1993).

3 Efficient Solution

In this section we determine the efficient production, load and investment decisions under the technological restrictions described: limited dispatchability of steam power, random availability of renewables, and fixed load due to contractual fixed prices. The efficient solution follows from maximizing welfare J, given by the difference between utility and costs,

$$J = U - \sum_j b_j k_j - \sum_j c_j x_j - c_u x_u, \tag{1}$$

within the constraints of the following decision structure. In Stage 1, a regulator selects capacities k_s, k_r, k_g. In Stage 2, a regulator selects load D. In Stage 3, production of steam power $x_s \leq k_s$ must be decided. Then, the random availability of renewables realize and in Stage 4, production of renewables $x_r \leq \tilde{x}_r$ must be decided. In Stage 5, a regulator selects gas turbine production $x_g \leq k_g$. Finally, lost load $x_u \geq 0$ could incur costs. We consider a one-period setup only, and thus it is sufficient to consider all stage before the random variable $\tilde{x}_r$ realizes as one decision stage (Stages 1 to 3) and maximize expected welfare $E[J]$. The stages after realization of $\tilde{x}_r$ (Stages 4 and 5) constitute another decision stage where we maximize welfare (no expectations necessary but rather conditional results). However, we choose the five-stage setup since this setting best reflects the timing of electricity markets.

Production Decisions. Start with production decisions from Stages 3 to 5. Depending on the realization of the random variable $\tilde{x}_r$, we distinguish between four intervals of events. *Renewables dispatched* occurs for $\tilde{x}_r \in \Omega_1 = [D, k_r]$ and *steam power dispatched* if $\tilde{x}_r \in \Omega_2 = [D - x_s, D)$. *Gas turbines dispatched* realizes for all $\tilde{x}_r \in \Omega_3 = [D - x_s - k_g, D - x_s)$ and *lost load* if $\tilde{x}_r \in \Omega_4 = [0, D - x_s - k_g)$. We call the union of both renewables and steam power dispatched, i.e., $\Omega_{12} = \Omega_1 \cup \Omega_2 = [D - x_s, k_r]$, *excess capacity of renewables*. Similarly, $\Omega_{34} = \Omega_3 \cup \Omega_4 = [0, D - x_s)$ is the union of gas turbines dispatched and lost load, which we call *renewables fully used*. We can use these intervals to derive efficient production decisions as well as the resulting lost load conditional on the interval that might realize as[9]

[9] We omit detailed computations of efficient production decisions and provide intuitive explanations only. For a comprehensive proof, see Eisenack and Mier (2018).

$$x_s = k_s, \tag{2}$$

$$x_r = \begin{cases} \tilde{x}_r & \text{for } \Omega_{34} \\ D - k_s & \text{else} \end{cases}, \tag{3}$$

$$x_g = \begin{cases} k_g & \text{for } \Omega_4 \\ D - k_s - \tilde{x}_r & \text{for } \Omega_3 \\ 0 & \text{else} \end{cases}, \tag{4}$$

$$x_u = \begin{cases} D - k_s - \tilde{x}_r - k_g & \text{for } \Omega_4 \\ 0 & \text{else} \end{cases}. \tag{5}$$

Load is fixed (in Stage 2) when production decisions are made (in Stages 3 to 5). Steam power needs to make production decisions before $\tilde{x}_r$ realizes. As excess capacity of steam power carries no benefit in later stages, production should be increased under the given constraints in order that $x_s = k_s$. After steam power production is fixed and $\tilde{x}_r$ is known, renewables should meet as much of the remaining load $D - x_s$ as they can since they have the lowest marginal production costs. If excess capacity of renewables realizes (Ω_{12}), renewables are not fully needed but if renewables are fully used in Ω_{34}, the total available capacity of renewables is no longer sufficient to meet the remaining load. In Ω_{34}, gas turbines should be used to avoid lost load since $c_g < c_u$, i.e., producing with gas turbines is cheaper than accepting lost load. In Ω_3, gas turbines are dispatched since the total gas turbine capacity is not needed to meet the remaining load $D - k_s - \tilde{x}_r$. The total capacity of gas turbines would be employed if and only if lost load realizes in Ω_4.

Load Decision. In Stage 2, load must be decided. Lost load occurs for all $\tilde{x}_r \in \Omega_4$, i.e., consumers obtain utility from load D if lost load does not occur and from total production if there is unmet load, i.e.,

$$U = \begin{cases} U\left(k_s + \tilde{x}_r + k_g\right) & \text{for } \Omega_4 \\ U\left(D\right) & \text{else} \end{cases}. \tag{6}$$

Using the interchangeability of differentiation and expectations for continuous and continuously differentiable random variables (see Chao, 1983; Eisenack and Mier, 2018), which we will use for the following first-order conditions as well, we can maximize expected welfare with regard to load and obtain the following first-order condition:

$$\frac{\partial E\left[J\right]}{\partial D} = U^{'} \Pr{}_{123} - c_r \Pr{}_{12} - c_g \Pr{}_{3} - c_u \Pr{}_{4} \leq 0 \left[= 0 \text{ if } D > 0\right]. \tag{7}$$

In the model setup, we assumed that the Inada conditions are fulfilled, that is, the first-order condition (Equation (7)) must bind for at least some $D > 0$. Using $U^{'} \Pr_{123} = U^{'} - U^{'} \Pr_4$ to solve the binding first-order condition of Equation (7) for $U^{'}$, enables us to find the necessary marginal utility to maximize welfare with regard to load as

$$U^{'} \quad = \quad c_r \Pr{}_{12} + c_g \Pr{}_3 + c_v \Pr{}_4, \tag{8}$$

where $c_v := c_u + U^{'}$ is the *value of lost load*, that is, the sum of utility losses $U^{'}$ and direct costs c_u from lost load. Equation (8) has both production and consumption components. The production component is given by the first two terms on the right sight, that is, marginal production costs of technologies weighted by the respective probabilities that they will be used as marginal technology. If Ω_{12} realizes, renewables are the marginal technology to serve a marginal unit of load, whereas in the gas turbines dispatched cases (Ω_3), gas turbines are the marginal technology. The consumption component considers that in lost load (Ω_4), consumers suffer the value of lost load c_v.

System Long-Run Marginal Costs. Before turning to efficient capacity decisions in the next subsection we expand on the idea of system costs. Recall that LRMC are defined by $\frac{b_r}{a} + c_r$, $b_s + c_s < b_g + c_g < c_u$, where $\frac{b_r}{a} + c_r \geq b_s + c_s$ immediately implies that no renewables will be installed. Joskow (2011) argues that an output-based metric (as described above) is flawed for variable renewables. Lamont (2008) and Hirth (2013) mention that—from a system perspective—related system costs are relevant. We call LRMC that account for system costs *system LRMC* and denote them by C_j^{sys}.

Steam power capacity is fully used, i.e., $C_s^{sys} = b_s + c_s$. Gas turbines are used only when renewables have been fully used (Ω_{34}). A marginal unit of load in Ω_{12} could be served more cheaply by renewables since there is unused capacity left. We obtain system LRMC that are lower than LRMC, i.e., $C_g^{sys} = c_r \Pr_{12} + b_g + c_g \Pr_{34} < b_g + c_g$ since $c_g > c_r$.

LRMC of renewables are $\frac{b_N}{a} + c_N$. This formulation depicts only the average availability, not the costs caused by variations of $\tilde{x}_r$. We define the system LRMC of renewables as costs to provide a unit of production even in the lost load events (at least in the average of these events), i.e.,

$$C_N^{sys} \quad = \quad \left(\frac{b_r}{\overline{a}_4} + c_r \right) - (c_g - c_r) \frac{\overline{a}_3 - \overline{a}_4}{\overline{a}_4} \Pr{}_3, \tag{9}$$

Note that we use $\overline{a}_c$ as a dummy to distinguish between *ind* and *corr*. The first term covers costs to provide an available capacity unit in Ω_4. The second term is benefits from replacing gas turbine production in Ω_3 by renewables due to the additional capacity installed to provide more available capacity in Ω_4. For the case of independence (*ind*), we have $\overline{a}_4 = \overline{a}_3 = a$ and $C_N^{sys} = \frac{b_N}{a} + c_N$. If a marginal generating unit of renewables behaves stochastically independent, then system LRMC are equal to LRMC. On contrary, for *corr*, all marginal generating units produce less (or more) in the same way and the first element of Equation (9) is higher than the LRMC due to $a_4 < a$.

Capacity Decision. Now consider capacity decisions at Stage 1. We need to maximize welfare from Equation (1) w.r.t. k_s, k_g, k_r by using the expectations. First-order conditions are

$$\frac{\partial E[J]}{\partial k_s} = c_r \Pr{}_{12} + c_g \Pr{}_3 + c_v \Pr{}_4 - b_s - c_s \leq 0 \ [= 0 \text{ if } k_s > 0], \tag{10}$$

$$\frac{\partial E[J]}{\partial k_g} = c_v \Pr{}_4 - b_g - c_g \Pr{}_4 \leq 0 \ [= 0 \text{ if } k_g > 0], \tag{11}$$

$$\frac{\partial E[J]}{\partial k_r} = (c_g - c_r)\,\overline{a}_3 \Pr{}_3 + (c_v - c_r)\,\overline{a}_4 \Pr{}_4 - b_r \leq 0 \ [= 0 \text{ if } k_r > 0], \tag{12}$$

Using $U^{'}$ from Equation (8) and system LRMC as described in the previous subsection, we can rewrite each of these first-order conditions as $\partial E[J]/\partial k_j = U^{'} - C_j^{sys}$. Intuitively, technologies will used if and only if their system LRMC are equal to marginal utility, that is, the benefits from using the respective technology. This immediately implies that system LRMC of each used technology must be same in the efficient solution. This result even holds for applications with more than three technologies and is underlined by Helm and Mier (2018) as well.

First, consider the first-order condition of steam power (Equation (12)). Steam power can substitute for renewables in Ω_{12} and for gas turbines in Ω_3. Steam power is reliable and avoids lost load, i.e., $c_v \Pr_4$ shows benefits from preventing lost load. The sum of these three terms is total benefits and is equal to $U^{'}$ from Equation (8). The last two terms are the system LRMC, which must be subtracted from the benefits. Steam power capacity must be increased as long as the system LRMC C_s^{sys} are lower than the benefits $U^{'}$.

Turn to the first-order condition of gas turbines (Equation (11)). Gas turbine capacity is not fully used in the gas turbines dispatched events (Ω_3) and, thus, gas turbine capacity is beneficial only in lost load (Ω_4). The last two terms are costs. To obtain $\partial E[J]/\partial k_g = U^{'} - C_g^{sys}$ we need to add $c_r \Pr_{12} + c_g \Pr_3$ to the first term and obtain $U^{'}$. Subtracting the same from the latter two terms yields C_g^{sys}.

Finally, consider the first-order condition of renewables (12). Benefits and costs are mixed in the first two terms. c_g, c_v denote benefits from substituting gas turbine production in Ω_3 or preventing lost load in Ω_4, respectively, where c_r are related production costs. Note that the benefit from reducing lost load is smaller than that from using steam power and gas turbines since $\overline{a}_4 < 1$. To obtain $\partial E[J]/\partial k_r = U^{'} - C_r^{sys}$, we must divide Equation (12) by $\overline{a}_4$, add/subtract $c_r \Pr_{123} + c_g \Pr_3$ and do some rearranging.

We would have $U^{'} = C_s^{sys} = C_r^{sys}$, i.e., Equations (10) and (12) are binding simultaneously, only for a boundary case $\Delta C = \Phi$ with

$$\Phi = \frac{a - \overline{a}_3}{\overline{a}_3}\frac{b_r}{a} + \frac{\overline{a}_3 - \overline{a}_4}{\overline{a}_3}(c_v - c_r)\Pr{}_4. \tag{13}$$

From binding Equations (11) and (12) we obtain efficient probabilities that implicitly define capacities of renewables and gas turbines,

$$\Pr{}_4 = \frac{b_g}{c_v - c_g}, \tag{14}$$

$$\Pr{}_3 = \frac{b_r - (c_v - c_r)\,\overline{a}_4 \Pr{}_4}{(c_g - c_r)\,\overline{a}_3}. \tag{15}$$

Using Equation (15) in Equation (8) yields the efficient marginal utility

$$U^{'} = \frac{b_r}{a} + c_r + \Phi. \tag{16}$$

Given that a certain share of renewables is installed, efficient marginal utility must be equal to output-based LRMC of renewables plus a mark-up Φ as described by Equation (13). Steam power will participate if and only if $U^{'} = b_s + c_s$.

In the following we distinguish between the case of independence and the case of perfect correlation since both cases provide different rationales for efficient price setting in the next section.

Case of Independence. Note that for *ind*, we have $\Phi = 0$. Steam power and renewables coexist if the LRMC are equal to each other, i.e., $\Delta C = \Phi = 0 \Leftrightarrow b_s + c_s = \frac{b_r}{a} + c_r$. As argued in Section 2, this cannot be efficient and thus we have $k_s \cdot k_r = 0$.

Case of Perfect Correlation. For *corr*, we have $\overline{a}_c = a_c$. Here, we use the superscript * to denote the efficient variables that maximize expected welfare, e.g. $U^{'*} = \frac{b_r}{a} + c_r + \Phi^*$ is efficient marginal utility, D^* is efficient load and $E\left[x_u^*|\Omega_4\right]$ is the efficient expected lost load conditional on the realization of Ω_4, where $\Pr{}_4^*$ is the efficient probability of lost load. Maximized expected welfare is given by

$$E\left[J^*\right] = U\left(D^*\right) - \left(\frac{b_r}{a} + c_r + \Phi^*\right) D^* - \left(\Delta U_u^* - \left(\frac{b_r}{a} + c_r + \Phi^*\right) E\left[x_u^*|\Omega_4\right]\right) \Pr{}_4^*, \tag{17}$$

where $\Delta U_u^* := U\left(D^*\right) - U\left(k_s^* + a_4^* k_r^* + k_g^*\right)$ is the difference between expected (efficient) utility in Ω_{123} and the expected (efficient) one in lost load events (Ω_4).

Figure 1 shows U, U' on the vertical and D on the horizontal axis. Note the difference between D as variable and D^* as the efficient (fixed) value. The upward sloping curve depicts utility U. The downward sloping curve depicts marginal utility $U^{'}$. Both curves are related via $U = \int_0^D U^{'} d\tilde{D}$.

The areas $ABCL$ are the gross surplus. To obtain consumer surplus (AL), we must subtract the costs of providing the efficient load. Remember, system LRMC C_j^{sys} are the costs of providing the marginal unit of load and must be equal to efficient marginal utility (Equation (16)) as long as $k_j > 0$. So, we must subtract $\left(\frac{b_r}{a} + c_r + \Phi^*\right) D^*$ (see Equation (17)), which is given by the areas BC.

Next, we have to account for possible surplus losses due to lost load. If lost load realizes, consumers suffer losses of $\Delta U_u^* = \int_{D^* - E\left[x_u^*|\Omega_4\right]}^{D^*} U^{'} d\tilde{D}$, which is given by the areas CL. Conversely,

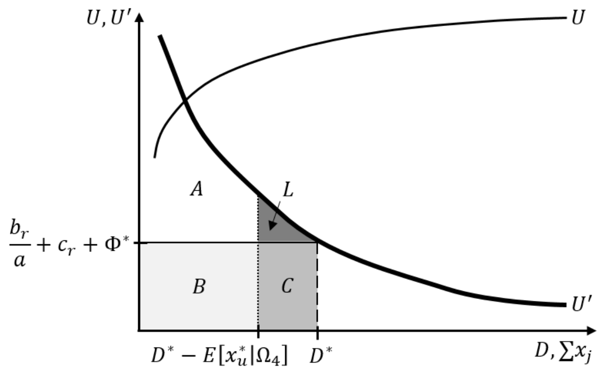

Fig. 1: Illustration of welfare for *corr*

total production costs are reduced by the area C or by $\left(\frac{b_r}{a}+c_r+\Phi^*\right)E\left[x_u^*|\Omega_4\right]$ (see Equation (17)), respectively. So, consumers suffer total losses of $L\,\mathrm{Pr}_4$ in expectation, which is given by the third term in Equation (17).

Note that we assumed positive levels of k_r in the efficient solution, but maximized welfare in a fully reliable system with steam power only would be given by $J^*=U\left(D^*\right)-\left(b_s+c_s\right)D^*$ (dropping the possible realization of Ω_4 in Equation (17)). As soon as renewables enter the system, we have $\mathrm{Pr}_4^*>0$—since providing a fully reliable system cannot be welfare maximizing. Thus, using steam power only would lead to a higher welfare when $\Delta C=\Phi^*\Leftrightarrow b_s+c_s=\frac{b_r}{a}+c_r+\Phi^*$.

Now turn to Φ and note that $\overline{a}_c=a_c$.[10] Obviously, if $a_3<a$, then Φ is positive since $a_3<a_4$. However, $a_3>a$ is possible. Whether $a_3>a$ or $a_3<a$ crucially depends on the shape of the distribution function of $\tilde{x}_r$ and on the total size of k_r.

Start with the size of k_r. For low k_r the occurrence of events for which renewables are not fully used (Ω_{12}) is rare. Conversely, Ω_{34} occurs more often and even a_3 (as the conditional availability factor in gas turbines dispatched events) should be higher. If renewables capacity increases, we would reach $a_3\leq a$ and Φ must be definitely positive. Thus, for k_r close to D (note that $\mathrm{Pr}_{34}<1$ demands for $k_r>D$ since otherwise excess capacity of renewables never occurs) we would have $a_3>a$. Whether such a small k_r is efficient or even the second term in Φ compensates for the negative first term could not be further determined.

It is illuminating to assume uniformly distributed random variables (additionally denoted by superscript *uni*). We can use $a_3\,\mathrm{Pr}_3+a_4\,\mathrm{Pr}_4=a_{34}\,\mathrm{Pr}_{34}$ to obtain

$$\Phi^{corr,uni} = \frac{a-a_{34}}{a_{34}}\frac{b_r}{a}-\frac{a_{34}-a_4}{a_{34}}b_g>0. \tag{18}$$

To conclude, for *corr*, there is strong intuition that Φ is positive but there could be some cases where it is negative.

[10] It is not longer necessary to use $*$.

Summary of Results. We derived efficient production as well as load decision and, finally, determined efficient capacities. We showed that there is an efficient solution for the combination of technologies as long as their system LRMC are equal to efficient marginal utility. Marginal utility shows system marginal costs for all technologies that are employed in the efficient solution. Steam power and renewables will only coexist in the efficient solution for a boundary case $\Delta C = \Phi$. However, welfare has a discontinuity at this boundary (see Eisenack and Mier, 2018) and we need to compare welfare of a fully reliable system with steam power only and of a system with renewables (and lost load). This leads to the conclusion that steam power and renewables cannot coexists in the efficient solution. We summarize this in Lemma 1.[11]

Lemma 1. *Neither for ind nor for corr, is $k_s \cdot k_r > 0$ the efficient solution.*

4 Costs Recovery in a Day-Ahead Market

This paper is not focused on analyzing the efficient solution per se but on how such a solution might be decentralized in a perfect competitive setup with symmetric and profit maximizing firms. We choose this setup as a benchmark in investigating the problem and discuss the policy implications that arise from it.[12]

Our model is comprised of a day-ahead market with steam power, renewables and gas turbine firms. A benevolent regulator (henceforth, the *system operator*) determines the efficient dispatch, that is, efficient production and load, and sets a price in advance of actual delivery. Consumers need to pay this price; firms are obligated to deliver the sold amount of electricity. Steam power production could be decided by firms after the price decision but before the random availability of renewables realizes. Renewables and gas turbine firms in turn make production decisions after the random availability realizes.

Profits of firm i follow from the difference between revenues earned and costs, where x_j^i is production, k_j^i capacity of firm i, and $\tilde{x}_r^i$ is the random availability of renewables capacity. Note that $x_j = \sum_i x_j^i$ is total production of technology j and $k_j = \sum_i k_j^i$ total capacity. We assume that firms do not consider how either own production or own capacity influence total production, total capacity or prices and, thus, the occurrence of events and the related probabilities$\Pr_c$ are given. The decision problem for each firm is to maximize profits, measured as the difference between revenues and costs,

$$\pi_j^i \quad = \quad (p - c_j)\, x_j^i - b_j k_j^i, \tag{19}$$

within the constraint of the following decision structure. In Stage 1, firms select the technology and install k_j^i. In Stage 2, a regulator enforces a uniform ex-ante price $p = U^{'}$ so that load D is

[11] Note that the exclusion result here is even stronger than in Eisenack and Mier (2018), that is, accounting for utility losses due to lost load diminishes the possibility of renewables and steam power coexisting in the efficient solution.

[12] Zöttl (2010) found that—in a setup with fluctuating demand—strategic firms overinvest in baseload capacity (steam power in our model) but total capacities are inefficiently low.

fixed.[13] In Stage 3, steam power firms decide $x_s^i \leq k_s^i$. Then, the random availability of renewables capacity for each firm $\tilde{x}_r^i$ realizes and, in Stage 4, renewables firms decide $x_r^i \leq \tilde{x}_r^i$, whereas in Stage 5 gas turbine firms decide $x_g^i \leq k_g^i$.[14]

Capacity costs from Stage 1 must be considered as sunk costs in later stages and the price p is fixed from Stage 2 onward. Firms' profits manifest as the difference between revenues and production costs, i.e., $\max_{x_j^i} (p - c_j)\, x_j^i$. Decentralization of efficient production (see Equations (2) to (4)) demands for three conditions. First, firms should not produce if doing so is not socially beneficial. This could be incentivized by negative production profits (capacity costs are sunk at the production Stages 3 to 5), i.e., $p - c_j < 0$ would leads to $x_j^i = 0$. Second, firms should not increase production if doing so is beneficial. This occurs when $p - c_j = 0$, i.e., firms would not have an incentive to increase production up to capacity so that $x_j^i < k_j^i$ or $x_r^i < \tilde{x}_r^i$. Third, firms need positive production profits when it is socially beneficial to use the total capacity of the respective technology. This would lead to $x_j^i = k_j^i$ or $x_r^i = \tilde{x}_r^i$, respectively.

Efficient Dispatch. If the price is above the marginal production costs of gas turbines, i.e., $p > c_g$, all firms produce with their whole capacity. In renewables or steam power dispatched events (Ω_1, Ω_2), this would lead to inefficiently high production. If $c_g > p > c_s$, gas turbine firms have no incentive to produce at all. If either $p = c_g$ or $p = c_s$, gas turbine firms or steam power firms, respectively, are indifferent between producing or not. If the price is below the marginal production costs of stream power, i.e., $p < c_g$, not even steam power firms are able to recover short-term costs and have no incentive to produce.

Obviously, a day-ahead price p will never lead to efficient dispatch as long as consumers cannot respond adequately to a price signal. Thus, the efficient production decisions must be enforced. This is not as critical as one might think since system operators often enforce a more (or less) optimal dispatch due to network constraints (and associated balancing costs), which are not internalized by the bids of different generators.

For the analysis in this section, we assume that the price will always be (weakly) above the marginal production costs of gas turbines in order that each technology has at least some incentive to produce in Stages 3 to 5. However, prices will not exceed LRMC of steam power since this is the benchmark price that results from a fully reliable system with steam power only, i.e., $p \in [c_g, b_s + c_s]$.[15]

The dispatch is enforced by setting production limits for each firm. We call $D_j^i\,(\tilde{x}_r|\Omega_c)$ the (conditional) dispatch decision, that is, firm i producing with technology j is allowed to produce $x_j^i \leq D_j^i\,(\tilde{x}_r|\Omega_c)$ conditional on event $\tilde{x}_r$ realizing in Ω_c. Note that this does not cover the whole interval Ω_c but rather refers to one specific realization $\tilde{x}_r$ in Ω_c.

We now take a more detailed look at efficient dispatch and how it could be decentralized by the system operator. In Stage 3, steam power firms are allowed to produce with full capacity, that

[13] There is a long-run or short-run price elasticity determined by $p = U'$ with $U'' < 0$ but no real-time price elasticity (no real-time demand response).
[14] Again, it would be sufficient to differentiate between all stages before and after the random variable.
[15] We assume $p \in [c_g, b_s + c_s]$ to enable the efficient dispatch by setting maximum production limits. However, even $p < c_g$ could be analyzed. The system operator just needs to enforce minimum production levels as well.

is, the system operator sets $D_s^i = k_s$ (independent of $\tilde{x}_r$) and the firms decide for $x_s^i = k_s$ since p exceeds marginal production costs. In Stage 4, renewables firms are allowed to produce at full capacity in the events of gas turbines dispatched and lost load but must reduce production below available capacity in Ω_{12}. Noting that $E\left[D_r^i\left(\tilde{x}_r|\Omega_{12}\right)\right] = E\left[D_r^i|\Omega_{12}\right]$, it is expected that

$$E\left[x_r^i\right] \quad = \quad E\left[\tilde{x}_r^i|\Omega_{34}\right]\Pr{}_{34} + E\left[D_r^i|\Omega_{12}\right]\Pr{}_{12}. \tag{20}$$

In Stage 5, gas turbine firms are not allowed to produce in Ω_{12} since there is already enough production from renewables and steam power. They are only allowed to use total capacity in the events of lost load (Ω_4), where the dispatch decision of the system operator binds in gas turbines dispatched events (Ω_3). Using $E\left[D_g^i\left(\tilde{x}_r|\Omega_3\right)\right] = E\left[D_g^i|\Omega_3\right]$, leads to

$$E\left[x_g^i\right] \quad = \quad k_g^i \Pr{}_4 + E\left[D_g^i|\Omega_3\right]\Pr{}_3. \tag{21}$$

Enforcement of efficient dispatch as described so as to ensure the efficiency of a decentralized solution requires that two additional conditions be met. First, profit-maximizing firms must provide efficient capacity levels (*efficiency condition*, see the first-order conditions of Equations (10) to (12)). Second, each firm's expected profit must be zero (*zero-profit condition*); otherwise efficient capacity decisions are not an equilibrium outcome due to exit or entry.

In the first part of the following analysis, we assume that a regulator enforces efficient capacities in addition to enforcing efficient dispatch (*capacity decisions enforced*). We simply check whether the zero-profit condition is violated or not. In the second part we show the decentralized equilibrium outcome when a regulator no longer enforces efficient capacities (*decentralized capacity decisions*). Finally, we assume that the system operator does not set a price equal to efficient marginal utility (Equation (16)) but, instead, equal to marginal utility (Equation (8)) accounting for distorted capacity decisions of firms (*price adaption*). We use superscript $1st$, $2nd$ and $3rd$ to denote variables for the different system operator actions.

Capacity Decisions Enforced (1st). The system operator enforces efficient capacities and sets $p^{1st} = \frac{b_r}{a} + c_r + \Phi$. Efficient steam power capacity requires $p = b_s + c_s$ and we have $x_s^i = k_s^i$ from efficient production decisions. The zero-profit condition for steam power firms is obviously fulfilled since $E\left[\pi_s^i\right] = \left(b_s + c_s - c_s\right)k_s^i - b_s k_s^i = 0$. Gas turbine firms cannot recover costs—for two reasons. First, they are not operating at fully capacity in Ω_{123}. Second, price is below their LRMC since $p \leq b_s + c_s < b_g + c_g$. Renewables firms are not allowed to use their whole capacity in Ω_{12}. Considering the mark-up Φ, the profits of renewables firms are

$$E\left[\pi_r^i\right] \quad = \quad \frac{b_r}{a}\left(E\left[x_r^i\right] - E\left[\tilde{x}_r^i\right]\right) + \Phi E\left[x_r^i\right], \tag{22}$$

where $E\left[x_r^i\right] < E\left[\tilde{x}_r^i\right]$ in order that the first term is negative. If the mark-up Φ is sufficiently high, renewables firms recover costs. For ind, we know that $\Phi = 0$ and, thus, renewables firms will never recover costs. For $corr$, the mark-up could be positive or negative since $a \lesseqgtr a_3$ as argued before. If, additionally, the random variables are uniformly distributed, the mark-up is positive (Equation (18)) and sufficient to recover costs. Lemma 2 summarizes the results.[16]

Lemma 2. *If a regulator enforces the efficient solution, steam power firms recover costs, whereas gas turbine firms suffer losses, as do renewables firms for ind. For corr, renewables firms might recover costs. For corr and uniformly distributed random variables, renewables firms make profits.*

Decentralized Capacity Decision (2nd). We now analyze firms' capacity decisions when such decisions are not enforced by the regulator. Note that the implication for cost recovery from Lemma 2 does not change since the regulator continues to enforce $p = \frac{b_r}{a} + c_r + \Phi$. Using $x_s^i = k_s^i$ and expected production of gas turbine firms (Equation (21)) yields first-order conditions of profit maximizing steam and gas turbine firms by differentiating expected profits,

$$\frac{\partial E\left[\pi_s^i\right]}{\partial k_s^i} = p - b_s - c_s \leq 0 \left[= 0 \text{ if } k_s^i > 0\right], \tag{23}$$

$$\frac{\partial E\left[\pi_g^i\right]}{\partial k_g^i} = p \Pr{}_4 - b_g - c_g \Pr{}_4 \leq 0 \left[= 0 \text{ if } k_s^i > 0\right]. \tag{24}$$

Let us start with steam power firms. Binding Equation (23) demands for $p = b_s + c_s$, i.e., the efficiency condition is fulfilled if $\Delta C = \Phi$. Next, consider gas turbine firms. Solving the binding first-order condition of Equation (24) yields $\Pr_4 = \frac{b_g}{p - c_g} > 1$ since $p < b_g + c_g$, a contradiction. Thus, no gas turbine capacity will be installed.[17] Note that if $k_g = 0$, there is no longer an efficient solution. All computations without gas turbine capacity are just optimal given that gas turbine capacity is not an option (2nd best).

Turning next to renewables firms, steam power will be used as long as $p = b_s + c_s$ and for all prices $p \leq b_s + c_s$, gas turbine capacity cannot exist in the market. Consequently, $\Pr_3 = 0$ and the first-order condition of renewables—from the perspective of both welfare and profit-maximizing firms—changes to

$$\frac{\partial E\left[J|k_g = 0\right]}{\partial k_r} = (c_v - c_r)\,\overline{a}_4 \Pr{}_4 - b_r \leq 0 \left[= 0 \text{ if } k_s > 0\right], \tag{25}$$

$$\frac{\partial E\left[\pi_r^i|k_g = 0\right]}{\partial k_r^i} = (p - c_r)\,\overline{a}_4 \Pr{}_4 - b_r \leq 0 \left[= 0 \text{ if } k_s^i > 0\right]. \tag{26}$$

Note that, by assumption, $p \leq b_s + c_s < c_v$. Consequently, the price is too low for renewables firms to provide the optimal amount of capacity. The probability of lost load follows from binding

[16] This result is found by Eisenack and Mier (2018) as well. Our setup only differs from their by accounting for the proper value of lost load. However, the proof (see Appendix A) is equivalent.

[17] First-order condition, as well as expected profits would be negative.

Equation (26) and is higher than the optimal one from binding Equation (25). Note that Φ from Equation (13) is general enough to cover situations with $k_g = 0$ as well. Dropping Ω_3, we obtain $\Phi^{2nd} = \frac{a-\overline{a}_4}{\overline{a}_4}\frac{b_r}{a}$. It follows that $p^{2nd} = \frac{b_r}{a} + c_r + \Phi^{2nd}$.

Price Adaptation (3rd). Now we assume that firms' capacity decisions affect price setting by the system operator in Stage 2. Price follows from Equation (8) and not from the efficient marginal utility (Equation (16)), that is, the system operator accounts for different outcomes based on capacity decisions. Still, steam power requires that $p = b_s + c_s$ and gas turbines cannot exist. Using Pr_4 from binding (26), we obtain the adapted price

$$p^{3rd} = \frac{b_r}{a} + c_r + \frac{\frac{c_v - c_r}{p - c_r} a - \overline{a}_4}{\overline{a}_4}\frac{b_r}{a}. \tag{27}$$

Summary of Results. For ind, we have $\overline{a}_c = a$ and all prices are equal to LRMC of renewables. The prices are never sufficient to recover fixed costs of renewables (and gas turbine) firms, whereas steam power firms recover costs if $p = b_s + c_s = \frac{b_r}{a} + c_r \Leftrightarrow \Delta C = 0$.[18] For $corr$, prices differ due to $\overline{a}_c = a_c$. If installing gas turbine capacity is the efficient solution, then we must have $\Phi < \Phi^{2nd}$ and, thus, $p^{1st} < p^{2nd}$.

Moreover, if the system operator adapts the price, it will result in higher prices, $p^{2nd} < p^{3rd}$ since $p < c_v$. A higher price reduces the probability of lost load, which in turn leads to more renewables capacity, i.e., $k_r^{2nd} < k_r^{3rd}$. But—simultaneously—a higher price keeps steam power for lower ΔC (as long as $p = b_s + c_s$) in the market and prevents renewables from entry. We summarize our result in the following Proposition.

Proposition 1. *If a regulator does not enforce efficient capacities, (1) firms will never install gas turbine capacities and (2) renewables firms will install inefficiently low capacity. A price adaption in comparison to the efficient price leads to more renewables capacity if renewables have already entered the market, but prevents renewables from entering at all since steam power remains in the market for lower* ΔC*.*

Note that in the 1st setup, we would not use steam power and renewables together, where in the 2nd and 3rd setup this might be possible. We refrain from analyzing this situation, however, and concentrate next on transfers to decentralize the efficient solution.

5 Day-Ahead Market with Transfers

In this section we show how a regulator can decentralize the efficient solution by implementing transfer schemes. We continue to assume that a regulator enforces the efficient production. However, some of the described transfer schemes will do this automatically. At this point, our multi-stage decision process changes. Before firms choose capacities in Stage 1, a system operator

[18] Notice, for $\Delta C = 0$ the efficient solution demands for $k_s > 0$ and $k_r = 0$.

imposes transfers in order that the *efficiency conditions* as well as the *zero-profit conditions* for each technology type are fulfilled.

Denote technology-specific transfers by τ_j. Positive transfers are subsidies, negative transfers are taxes. We consider transfers on installed capacity, τ_j^k, conditional—meaning that the interval of events Ω_c realizes—production transfers, $\tau_{j,c}^x$, and lump-sum transfers, τ_j^{ls}. Then, the expected profits of representative firm i using technology j after transfers are

$$E\left[\pi_j^{i,\tau}\right] = \sum_c \left(p + \tau_{j,c}^x - c_j\right) E\left[x_j^i|\Omega_c\right] \Pr{}_c - \left(b_j - \tau_j^k\right) k_j^i + \tau_j^{ls}, \tag{28}$$

where $p + \tau_{j,c}^x - c_j$ are *marginal conditional production profits after transfers* and $b_j - \tau_j^k$ are *marginal capacity costs after transfers.*

Steam Power Firms. Steam power firms always operate at full capacity. Note from Section 4 that $p = b_s + c_s$ leads to efficient capacities and steam power firms recover costs. No transfers are necessary.

Gas Turbine Firms. The production schedule for gas turbine firms is given by Equation (21). Using this and assuming that positive levels of gas turbines are installed, maximizing profits w.r.t. k_g^i yields the efficiency condition,

$$\frac{\partial E\left[\pi_g^i\right]}{\partial k_g^i} = 0 \quad \Leftrightarrow \quad b_g - \tau_g^k = \left(p + \tau_{g,4}^x - c_g\right) \Pr{}_4, \tag{29}$$

that is, marginal capacity costs after transfers must be equal to expected marginal production profits if lost load (Ω_4) realizes. We can use this to obtain the zero-profit condition,

$$E\left[\pi_g^{i,\tau}\right] = 0 \quad \Leftrightarrow \quad \tau_g^{ls} = -\left(p + \tau_g^{x,3} - c_g\right) E\left[D_g^i|\Omega_3\right] \Pr{}_3. \tag{30}$$

Efficiency requires that transfers must be chosen so that $\Pr_4 = \Pr_4^*$ (superscript $*$ denotes the efficient solution from Section 3). This is an equilibrium outcome if a lump-sum tax equal to the expected production profits from the gas turbines dispatched events (Ω_3) is imposed. Interestingly, the transfers necessary to fulfill the efficiency condition ($\tau_g^k, \tau_{g,4}^x$) are independent from transfers to fulfill the zero-profit condition ($\tau_{g,3}^x, \tau_g^{ls}$). However, the two conditions Equations (29) and (30) allow for infinite transfer possibilities, which are set out in Table 1. We refrain from showing detailed computations when such is not necessary. However, inserting the values from Table 1 into Equations (29) or (30), respectively, shows that the transfers fulfill the respective conditions.

For the first two schemes, no. 1 and 2, start by assuming that production transfers could not be conditional, i.e., $\tau_g^x = \tau_{g,3}^x = \tau_{g,4}^x$. If capacity is fully subsidized (no. 1), a production transfer

no.	τ_g^k	$\tau_{g,3}^x$	$\tau_{g,4}^x$	τ_g^{ls}
1	b_g	$c_g - p$		0
2	0	$c_v - p$		$-(c_v - c_g) E\left[D_g^i \mid \Omega_3\right] \Pr_3$
3	0	$c_g - p$	$c_v - p$	0

Tab. 1: Transfers for gas turbine firms

of $\tau_g^x = c_g - p < 0$ will be necessary.[19] Given such a production tax no lump-sum transfer is necessary in order that gas turbine firms recover costs. Such a transfer scheme subsidizes total capacity expenses and eliminates all profits or losses, respectively, from production.

If capacity is not subsidized (no. 2), a higher production transfer of $\tau_g^x = c_v - p$ will be required. This subsidy ($c_v > p$ by model assumptions) leads to additional profits in gas turbines dispatched events (Ω_3), which need to be eliminated by a lump-sum tax. Such a lump-sum tax does not distort capacity decisions and eliminates total profits that arise from the (relatively high) production subsidy. If conditional transfers are possible we can avoid capacity as well as lump-sum payments by implementing (no. 3) a subsidy for production during lost load events and a transfer during gas turbines dispatched events. Interestingly, this scheme also leads to efficient production without enforcement by the system operator. Gas turbine firms are indifferent between increasing production or not in Ω_3 since they earn zero marginal production profits, but would operate at full capacity in Ω_4 since they earn $c_v - c_g > 0$.

Renewables Firms. We use the efficient production schedule of Equation (20) to maximize profits w.r.t. k_r^i. If positive levels of renewables capacity were installed by a renewables firm, we obtain the efficiency condition

$$\frac{\partial E\left[\pi_r^i\right]}{\partial k_r} = 0 \quad \Leftrightarrow \quad b_r - \tau_r^k = \left(p + \tau_{r,3}^x - c_r\right) \overline{a}_3 \Pr{}_3 + \left(p + \tau_{r,4}^x - c_r\right) \overline{a}_4 \Pr{}_4. \tag{31}$$

Similar to the situation for gas turbine firms, marginal capacity costs after transfers $(b_r - \tau_r^k)$ must be equal to the expected marginal production profits in the events of full capacity use (Ω_3, Ω_4). Note that efficiency requires that transfers must be chosen so that $\Pr_3 = \Pr_3^*$ and $\Pr_4 = \Pr_4^*$.[20] Since the overall goal is to determine transfers that lead to efficient capacity choices we do not use superscript * in the following since all probabilities refer to the efficient one. We use Equation (31) and obtain the following zero-profit condition for renewables firms:

$$\begin{aligned} E\left[\pi_r^i\right] = 0 \Leftrightarrow \tau_r^{ls} \quad &= \quad -\left(p + \tau_{r,12}^x - c_r\right) E\left[D_r^i \mid \Omega_{12}\right] \Pr{}_{12} \\ &\quad - \left(p + \tau_{r,3}^x - c_r\right)\left(a_3 - \overline{a}_3\right) \Pr{}_3 - \left(p + \tau_{r,4}^x - c_r\right)\left(a_4 - \overline{a}_4\right) \Pr{}_4. \end{aligned} \tag{32}$$

Renewables firms make a profit in Ω_{12} although they are not allowed to use total available

[19] The transfer is a subsidy when $c_g > p$ and a tax when $c_g < p$.

[20] The respective values $\overline{a}_3, \overline{a}_4$ directly follow from $\Pr_3, \Pr_4$ and, thus, we forego denoting them with superscripts.

capacity. These profits must be eliminated by a lump-sum tax. This is equivalent to the lump-sum tax for gas turbine firms. Additionally, profit or loss could occur from events during which renewables firms are operating at full capacity (Ω_3, Ω_4).

For *corr*, we have $\overline{a}_c = a_c$ so that the second line in Equation (32) vanishes and transfers needed to fulfill the efficiency condition are independent from those of the zero-profit condition. For *ind*, in contrast, both conditions are related since the second line could be positive or negative.

Again, we show and discuss only the most relevant and intuitive possibilities (see Table 2). Again, the first two options (no. 1 and no. 2) assume that conditional production transfers are not possible. The third option (no. 3) represents possible solutions for the most intuitive conditional production transfers. Note that we need to distinguish between *ind* and *corr*.

No. 1, no. 2, and no. 3 for *corr* can be proved straightforwardly by inserting the supposed transfers in Equations (31) or (32), respectively. For no. 3 and *ind* Appendix B provides additional computations.

no.		τ_r^k, *ind*	τ_r^k, *corr*	$\tau_{r,12}^x$	$\tau_{r,3}^x$	$\tau_{r,4}^x$	additional transfers
1		b_r		$c_r - p$			*none*
2		ab_g	$a_4 b_g$	$c_g - p$			$\tau_r^{ls} = -(c_g - c_r)\, E\left[D_r^i \vert \Omega_{12}\right] \Pr_{12}$
3	a	0	0	$c_r - p$	$c_g - p$	$c_v - p$	$\tau_{r,12}^{x+} = \frac{1}{E\left[D_r^i \vert \Omega_{12}\right] \Pr_{12}} a_3 k_r^i \gamma$
	b	$\frac{a a_3}{a - a_{34}} \gamma$					$\tau_{r,34}^{x+} = -\frac{1}{(a - a_{34}) k_r^i \Pr_{34}} a_3 k_r^i \gamma$
	c	0					$\tau_r^{ls} = a_3 k_r^i \gamma$
$\gamma = \frac{a - a_3}{a_3} \frac{b_r}{a} + \frac{a_3 - a_4}{a_3} (c_v - c_r) \Pr_4$ for *ind*, $\gamma = 0$ for *corr*							

Tab. 2: Transfers for renewables firms

Given a production transfer of $\tau_r^x = c_r - p$ (which is a tax since $p > c_r$), capacity must be fully subsidized (no. 1), just as was he case for gas turbine firms. Subsidizing the total capacity expenses means that production profits must be fully eliminated by taxing. If the production transfer is higher, i.e., $\tau_r^x = c_g - p$ (could be a tax or a subsidy), capacity must be less subsidized (differently for *ind* and *corr*) but remaining profits must be eliminated by a lump-sum tax (no. 2). If conditional production transfers are possible, capacity subsidies and lump-sum taxation could be fully avoided, at least for *corr*. Note that production transfers from no. 3 are sufficient to fulfill the efficiency condition of Equation (31) for both extreme cases.

For *corr*, even the zero-profit condition is fulfilled since the first line vanishes due to $\tau_{r,12}^x = c_r - p$ and the second line in Equation (32) vanishes due to $\overline{a}_c = a_c$. Moreover, the conditional production transfers enforce the efficient production. In Ω_{12}, renewables firms have no incentives to produce more than actually needed since (marginal) production profits are zero, $p + (c_r - p) - c_r = 0$. In all other situations, renewables produce at full capacity but production profits are highest during lost load events (Ω_4).

For *ind*, in contrast, renewables firms continue to suffer losses since the price is low. Using the transfers defined in Table 2 and substituting them into renewables firm's profit function yields

$$E\left[\pi_r^{i,3,ind}\right] \quad = \quad -a_3 \left[\frac{a - a_3}{a_3} \frac{b_r}{a} + \frac{a_3 - a_4}{a_3} (c_v - c_r) \Pr_4\right] k_r^i + \tau_r^{ls}, \tag{33}$$

where the term in the square brackets is defined (see γ for *ind* in last line in Table 2) similarly to Φ for *corr* (see Equation (13) and the discussion about whether Φ is positive or negative). The difference is that $\Pr_4, a_3, a_4$ refer to the efficient values for *ind*.

Consider high k_r so that $a > a_3$. For both extreme cases, we have $a_4 < a_{34} < a < a_{12}$. Lost load ($\Omega_4$) covers only the lowest realizations of $\tilde{x}_r$, Ω_{34} covers also some higher ones from Ω_3, and Ω_{12} contains only the highest realizations of $\tilde{x}_r$. Additional availability is beneficial only in Ω_{34} because in Ω_{12} there is remaining unused renewables capacity. For *ind*, the marginal performance is always a and, thus, overestimates the ability of the total capacity to produce in Ω_{34}. Thus, *ind* yields too low prices, which does not reflect total costs. For *corr*, the price reflects total costs and no further transfers are necessary to obtain zero-profits.

The problem for *ind* could be solved by implementing an additional production subsidy in Ω_{12} (no. 3a). In the renewables and steam power dispatched events (Ω_{12}), expected production of a renewables firm is $E\left[x_r^i|\Omega_1\right]\Pr_1$. Losses could be avoided by choosing $\tau_{r,12}^{x+}$ (superscript + denotes a production transfer in addition to $\tau_{r,12}^{x}$) so that $\tau_{r,12}^{x+}E\left[x_r^i|\Omega_{12}\right]\Pr_{12} = -E\left[\pi_r^{i,ind,3}\right]$ (see Equation (33)). In total, a renewables firm makes a profit in Ω_{12}, which—again—distorts the production decision because of the incentive to increases production up to the availability restriction. The system operator will need to enforce efficient production.

Two avoid distorting production decisions, the system operator can impose a lump-sum subsidy equal to the losses (no. 3c). However, there is another solution (no. 3b). In Ω_{34}, renewables firms do not need further incentives to produce since marginal profits are already positive. We could decide to eliminate some of the profit. The zero-profit condition would be fulfilled by imposing $\tau_{r,34}^{x+}$, as shown in Table 2. Such a transfer distorts the efficiency condition since capacity is fully used by renewables firms in Ω_{34} so that capacity must be supported by τ_r^k (see Table 2).[21] We summarize:

Proposition 2. *Equations (29) to (32) define transfers for gas turbine and renewables firms such that decentralized capacity choices are efficient and there is an equilibrium outcome (zero profits). Subsidy schemes for both technologies are summarized in Tables 1 and 2.*

6 Policy Implications

Consumers. In the analysis thus, we have ignored consumers' incentives to actually consume the efficient load. Note that the system operator sets a price equal to efficient marginal utility (Equation (16)). So, we need to check whether utility maximization by consumers—given $p = \frac{b_r}{a} + c_r + \Phi$—would lead to efficient load.

We assume that utility maximization of consumers lead to inverse demand $U'(D)$ with $U(D) = \int_0^D U'\left(\tilde{D}\right)d\tilde{D}$. In case of lost load, the system operator curtails consumers with the lowest willingness-to-pay.[22] Call D_u the system operator's dispatch decision, where $x_u = D - D_u$ is

[21] Note that the total transfers paid in nos. 3a, 3b, and 3c (for *ind*) could be calculated by $\tau_{r,34}^{x+}E\left[\tilde{x}_N|\Omega_{34}\right]\Pr_{34} + \tau_r^k k_r^k$, which must be equal to the negative value of the right side of Equation (33).

[22] This is the perfect load shedding developed by Brown and Johnson (1969) and refined by Kleindorfer and Fernando (1993). Note that—in contrast to Kleindorfer and Fernando (1993)—we abstract from rationing costs of the system operator to obtain perfect load shedding and dedicate all additional losses to consumers.

aggregated lost load. Depending on the realization of the random variable $\tilde{x}_r$, consumer surplus, denoted by CS, is given by

$$CS = \begin{cases} U(D_u) - pD_u - c_u(D - D_u) & \text{for } \Omega_4 \\ U(D) - pD & \text{else} \end{cases}.$$

In Stage 2, after price setting by the system operator, consumer decide consumption D, where they take the price as given since the price is set before the load decision. Consumers maximize their expected surplus w.r.t. D. The first-order condition becomes

$$\frac{\partial E[CS]}{\partial D^k} = \left(U^{'} - p\right)\Pr{}_{123} - c_u \Pr{}_4 \leq 0 \; [= 0 \text{ if } D > 0], \tag{34}$$

where we have again used the interchangeability of differentiation and expectation. Note that a price equal to marginal utility, $p = U^{'}$, would imply $\partial E[CS]/\partial D = -c_u \Pr{}_4 < 0$ in order that $D = 0$. The price setting does not account appropriately for direct costs that arise from lost load c_u. To incentivize efficient consumption, that is, aggregate consumption should be equal to efficient load, the system operator should compensate consumers for lost load. Suppose that τ_u^D is the compensation paid to the curtailed consumers conditional on lost load. Obviously, $\tau_u^D = c_u = c_v - p$ would lead to binding Equation (34). We summarize the consumer issues in the following Proposition.

Proposition 3. *Efficient load could be decentralized by a price signal in a fully reliable system without lost load. As soon as renewables reduce system reliability and there is the possibility of lost load, a day-ahead price signal is not longer sufficient to enforce efficient load. A transfer of* $\tau_u^D = c_v - p$ *in case of lost load would circumvent this problem.*

Interestingly, consumers' utility losses due to lost load are already considered by the consumers, where the additional costs of lost load c_u are not taken into account. Intuitively, the ability to curtail consumers if production capability is not sufficient to cover the whole load must be understood in a way similar to the ability of offer an additional production technology. Offering system flexibility requires—in the same way as gas turbines require— compensation or, more precise, a subsidy. Note that such a compensation would not be necessary in a fully reliable system with steam power only. Surplus maximization of consumers would require that $p = b_s + c_s$ so that a system operator could easily set a price to decentralize load decisions.

Value-Adequate Price Signal To this point, the analysis has revealed that a constant price will not lead to efficient capacities (or load). The literature (see, e.g., Joskow, 1976, 2011; Borenstein, 2016) suggests that short-run marginal costs pricing with scarcity rents will create a price signal that reflects the current value of electricity produced and consumed. We call such a price signal *value-adequate* (denoted with superscript va) and define it as the marginal production costs of the last (and most expensive) technology used to serve load (also marginal technology) conditional on the realized interval of events Ω_c. Recall that steam power will never be the marginal generating unit since steam power production cannot be reduced (are only at very high costs) after the random variable realizes. So, a value-adequate price signal distinguishes between three interval of events: $\Omega_{12}, \Omega_3, \Omega_4$, i.e., p^{va} is the value-adequate price signal and p_c^{va} is conditional on the interval of events Ω_c that might realize. In Ω_{12}, there is excess capacity of renewables, which are the marginal technology and, therefore, price should be equal to their marginal production costs c_r. In Ω_3, gas turbines are the marginal capacity type and in Ω_4 consumers are curtailed. We have

$$p^{va} = \begin{cases} c_v & \text{for } \Omega_4 \\ c_g & \text{for } \Omega_3 \\ c_r & \text{for } \Omega_{12} \end{cases}, \tag{35}$$

where $E[p^{va}] = p^*$. Such a price signal could be implemented by transfer schemes no. 3 from Tables 1 and 2 as well as by consumer compensation in case of lost load, that is, $\tau_u^D = c_v - p$. We summarize in Proposition 4.

Proposition 4. *A value-adequate price signal could be implemented by a transfer scheme. For corr, such a transfer scheme enforces efficient dispatch, load, and capacities, but for ind, additional transfers for renewables firms are necessary to ensure efficient capacities and an equilibrium outcome.*

We next question the necessity of complex transfer payments and investigate whether the market could be designed in such a way that transfers would be unnecessary.

Retail Market with Real-Time Wholesale Market In this section we abandon the idea of a day-ahead market. Now, firms not supply consumers directly. Retailers buy from firms on a real-time wholesale market and sell to consumers on a retail market (ahead of actual production). In such a real-time wholesale market the marginal technology sets a price equal to marginal production costs, resulting in a value-adequate price signal as described by Equation (35).[23]

Consider a (perfect competitive) retail market. Representative retailer R sells a fixed amount of load D^R at price p to consumers. The retailer buys the same amount from a wholesale market with real time pricing at price p_c^{va}. Note that $\sum_R D^R = D$ but retailers do not account for their influence on prices (as firms and consumers). Then, representative retailer's profits are

$$E\left[\pi^R\right] = D^R\left(p - p_{12}^{va}\operatorname{Pr}_{12} - p_3^{va}\operatorname{Pr}_3 - p_4^{va}\operatorname{Pr}_4\right). \tag{36}$$

Profit maximization (via differentiation of $E\left[\pi^R\right]$ w.r.t. D^R and if $D^R > 0$) yields a retail price equal to the efficient one, i.e., $p = E[p^{va}]$ (see Equation (8)). Moreover, the zero-profit condition for retailers is fulfilled. We summarize this in the following Proposition. For a proof, see Appendix C.

[23] Note that we need to consider consumers as a fourth technology which operate at costs c_v.

Proposition 5. *A retail market in combination with a real-time wholesale market including involuntary consumer shedding and compensation is equivalent to a transfer scheme with consumer compensation that implements a value-adequate price signal*

Note that firms can recover costs (at least for *corr*) just by allowing real-time pricing. However, such a setup forces consumers involuntarily participate, that is, the market has to pay consumers the compensation described in Proposition 4. Moreover, in the absence of perfect correlation, we need additional transfer to ensure that efficient capacity decisions are an equilibrium outcome.

Over-the-Counter with Market for Imbalance Energy. In the next scenario, there is no retail market, and, once again, firms supply consumers directly. We assume that firms supply consumers *over-the-counter*. Representative firm i using technology j signs contracts with consumers of D_j^i at price p. If firms are not able (or not willing) to produce D_j^i on their own, they would require *imbalance energy*. Conversely, they could offer imbalance energy in the case they experience excess capacity. Denote by $x_{j,im}^i > 0$ imbalance energy sold to other firms, where $x_{j,im}^i < 0$ is imbalance energy purchased. Profits of firm i are

$$E\left[\pi_j^i\right] = pD_j^i + \sum_c p_c^{va} E\left[x_{j,im}^i | \Omega_c\right] \Pr{}_c - b_j k_j^i - c_j E\left[x_j^i\right].$$

Steam power firms will never need or supply imbalance energy, since it is optimal for them to use their total capacity all the time. So, we focus on renewables and gas turbine firms.

If renewables capacity is not fully used (Ω_{12}), both renewables and gas turbine firms offer imbalance energy in total.[24] The marginal suppliers are renewables firms and the price for imbalance energy must be c_r. In Ω_3, renewables and gas turbine firms might offer imbalance energy but the imbalance energy offered from renewables firms is already fully used in order that gas turbine firms are the marginal supplier and the price must be c_g. Note that in Ω_3, renewables firms could also demand (in total) imbalance energy; however, the price implications are the same. If lost load (Ω_4) realizes, the marginal supplier of imbalance energy are consumers, who are dispatched by the system operator at total costs c_v, which is the price for imbalance energy in Ω_4. Thus, a market for imbalance energy leads to a value-adequate price signal as defined in Equation (35) and a consumer price equal to the efficient one, i.e., $p = E\left[p^{va}\right]$. Using this we can make the following Proposition. For a proof, see Appendix D.

Proposition 6. *A market for imbalance energy including involuntary consumer shedding and compensation provides a value-adequate price signal and leads to the same outcome as a retail market in combination with a real-time wholesale market.*

[24] For *ind*, there might be individual demand/supply for imbalance energy for each renewables firm since weather conditions for each might differ. However, price follows from total demand/supply for imbalance energy.

7 Concluding Remarks

We model an electricity system comprised of steam power, renewables, and gas turbines. Steam power is limited dispatchable, renewables supply is stochastic, and load is fixed. We derive the efficient solution (production, load, capacities) and show that steam power and renewables cannot coexists in the efficient solution (Lemma 1). Next, we consider a perfectly competitive day-ahead market with firms acting as price takers. A regulator enforces the efficient price as a uniform ex-ante price. The efficient dispatch must be enforced by the regulator since the uniform ex-ante price is incapable of doing so. When the regulator enforces efficient capacities, steam power recovers costs, gas turbines do not, and renewables do not recover costs when marginal generating units are independently distributed (independence case), whereas they might recover costs in the presence of perfectly correlated marginal generating units (perfect correlation case). For the specific assumption of a uniform distribution, renewables will definitely make a profit (Lemma 2). If the regulator does not enforce efficient capacities, gas turbine capacity will never build and renewables capacity will be inefficiently low. Moreover, if the regulator adapts the efficient price according to efficient pricing rules, the uniform ex-ante price is higher, which allows steam power to stay in the market for greater differences in LRMC of steam power and renewables (Proposition 1).

The regulator can implement capacity, production, and lump-sum transfers to decentralize efficient capacity decisions and ensure an equilibrium outcome, that is, firms make zero profit. We describe different transfer schemes with and without capacity payments (Proposition 2). A transfer scheme subsidizing total capacity expenses might lead to too much capacity; however, an auctioning scheme should avoid this situation. Profits/losses could be eliminated by a lump-sum tax. This solution appears easy to implement in the case of symmetric firms but could be more complicated in a world with asymmetric ones. However, the most intuitive transfer scheme does not involve any capacity payments and lump-sum transfers. To even decentralize efficient load, consumers must be compensated for disruption costs (Proposition 3). Combining the most intuitive transfer scheme with the necessary consumer compensation leads to a value-adequate price signal (Proposition 4). It could be that the system operator must tax consumers for budget compensation, that is, to finance transfers for renewables and gas turbine firms. Shifting surplus from consumers to producers is always possible, either by using lump-sum transfers that does not cause any distortions or by imposing distorting electricity taxes. However, consumer acceptance in the case of switching from a steam power to a renewables-based system can be increased if surplus gains from the switching will not be totally eliminated by the regulator.

Finally, we describe two market designs that allow for a value-adequate price signal although load is still fixed in advance of actual delivery. Supporting a (perfectly competitive) retail market that closes the gap between the fixed load of consumers and simultaneously offers a value-adequate price signal on a real-time wholesale market mitigates the need for complex transfers. Firms that sell to consumers over-the-counter but offer and demand imbalance energy on a market that works in real time leads to as the same outcome the other market design (Proposition 6). However, consumers still need to be compensated (Proposition 5) and face involuntary load management on such markets. The finding regarding the necessary involuntary load shedding of consumers is highly relevant. Under the assumptions of our model, we must curtail consumption to obtain the efficient outcome, which is not good news for the feasibility (regarding social acceptance) of an energy turnaround. However, allowing higher consumer surplus by not eliminating all surplus gains from the energy turnaround might create a countervailing effect.

Note that a regulator can enforce the efficient probability of lost load by enforcing an appropriate "price for lost load". The respective supplier must pay this price to consumers that suffer lost load. The obligation to deliver consumers (and the related risks of lost load) are fully dedicated to the retailers in the setup with a retail market, where the risks are back to the generating firms in the setup with an imbalance energy market. To obtain the efficient result here, we need risk-neutral retailers and generating firms or, at least, the possibility of costless hedging.

Note that, as soon as the perfect correlation case does not apply (not even independence is necessary), firms definitely need additional transfers. The perfectly correlated price signal would allow a value-adequate price signal to decentralize the efficient outcome since total costs are perfectly covered by marginal costs. A price signal on the basis of independently distributed marginal generating units of renewables leads to insufficient prices that do not cover costs since the ability to provide production in events of low availability is overestimated by the marginal perspective.

The are a few limitations of our analysis. For example, we do not model periodic load or the intermittency of renewable energies. Eisenack and Mier (2018) show that this does not change the exclusion result. However, even in a multi-period setup the efficient outcome could be decentralized either by transfer schemes and consumer compensation or by markets that provide a value-adequate price signal. This would prevent steam power from entering the market to provide the efficient outcome again. Furthermore, we consider just the two extreme cases. Following the Chao (1983), one might implement a correlation measure—as he does for demand—on the supply side. However, this would not change the important policy implications of our findings.

That is, a value-adequate price signal (or capacity payments) would still be necessary and only for the perfectly correlated case is such a price signal completely sufficient. Moreover, we use a perfectly competitive market as benchmark, which is far from reality, especially in electricity markets. However, even this strong assumption of perfectly competitive markets dies not cloud the important policy implications of our findings. The impact of imperfect competition might overlap our basic results.

The main restriction is the assumption of very strict dispatchability levels. In reality, steam power is at least partially able to react instantly to stochastic fluctuations in the supply of renewables, albeit at a higher cost. Indeed, modern steam power has higher ramp-up and ramp-down possibilities and lower costs than was formerly the case. Investigating the effect of flexible steam power in a dynamic investment setup with inflexible steam power, renewables and gas turbines would be an interesting and useful topic for future work.

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Appendix

A Proof of Lemma 2

For *corr* and uniformly distributed random variables, we use Equations (18) in (22) to obtain

$$
\begin{aligned}
E\left[\pi_r^i\right] &= \frac{b_r}{a}\left(E\left[x_r^i\right] - ak_r^i\right) + \frac{b_r}{a}\frac{a-a_{34}}{a_{34}}E\left[x_r^i\right] + b_g\frac{a_{34}-a_4}{a_{34}}E\left[x_r^i\right] \\
&= \frac{b_r}{a}\left(\left(\frac{a-a_{34}}{a_{34}} + \frac{a_{34}}{a_{34}}\right)E\left[x_r^i\right] - ak_r^i\right) + E\left[x_r^i\right] + b_g\frac{a_{34}-a_4}{a_{34}}E\left[x_r^i\right] \\
&= \frac{b_r}{a}\left(\frac{a}{a_{34}}E\left[x_r^i\right] - ak_r^i\right) + b_g\frac{a_{34}-a_4}{a_{34}}E\left[x_r^i\right] \\
&= b_r\frac{E\left[x_r^i\right] - a_{34}k_r^i}{a_{34}} + b_g\frac{a_{34}-a_4}{a_{34}}E\left[x_r^i\right] \\
&= b_r\frac{E\left[x_r^i\right] - E\left[\tilde{x}_r^i|\Omega_{34}\right]}{a_{34}} + b_g\frac{a_{34}-a_4}{a_{34}}E\left[x_r^i\right],
\end{aligned}
$$

where the second fraction is positive due to $a_{34} > a_4$ (when $\mathrm{Pr}_3 > 0$ due to $k_g > 0$) and the first fraction is positive as well due to

$$
\begin{aligned}
E\left[x_r^i\right] = E\left[D_r^i|\Omega_{12}\right]\Pr_{12} + E\left[\tilde{x}_r^i|\Omega_{34}\right]\Pr_{34} &> E\left[\tilde{x}_r^i|\Omega_{34}\right] \\
E\left[D_r^i|\Omega_{12}\right] &> E\left[\tilde{x}_r^i|\Omega_{34}\right].
\end{aligned}
$$

In Ω_{12} the firm i is dispatched by the system operator and cannot use their whole production capacity so that the previous inequation holds.

B Calculations for Table 2

We now demonstrate how to calculate Equation (33) and the transfers for no. 3b (for *ind*) from Table 2). Using the conditional production transfers specified in Table 2 and the efficient production schedule Equation (20), from Equation (28) expected profits of a renewables firm are given by

$$E\left[\pi_r^{i,\tau}\right] = (c_g - c_r) E\left[\tilde{x}_r^i|\Omega_3\right] \Pr{}_3 + (c_v - c_r) E\left[\tilde{x}_r^i|\Omega_4\right] \Pr{}_4 - \left(b_r - \tau_r^k\right) k_r^i + \tau_r^{ls}. \quad (37)$$

Note that in Ω_{12} marginal production profits are zero due to $\tau_{r,12}^x = c_r - p$. The efficiency condition in Equation (31) becomes

$$b_r - \tau_r^k = (c_g - c_r)\, a \Pr{}_3 + (c_v - c_r)\, a \Pr{}_4,$$

where $\overline{a}_c = a$ for *ind*. Substituting marginal capacity costs after transfers in Equation (37), we obtain expected profits of

$$E\left[\pi_r^{i,\tau}\right] = -\left[(c_g - c_r)(a - a_3) \Pr{}_3 + (c_v - c_r)(a - a_4) \Pr{}_4\right] k_r^i + \tau_r^{ls},$$

where $E\left[\tilde{x}_r^i|\Omega_3\right] = a_3 k_r^i$ and $E\left[\tilde{x}_r^i|\Omega_4\right] = a_4 k_r^i$. We use $\Pr_3 = \Pr_3^*$ from Equation (15) and—after some rearranging–obtain Equation (33), i.e.,

$$\begin{aligned} E\left[\pi_r^{i,\tau}\right] &= -\left[(c_g - c_r)(a - a_3) \frac{\frac{b_r}{a} - (c_v - c_r) \Pr{}_4}{(c_g - c_r)} + (c_v - c_r)(a - a_4) \Pr{}_4\right] k_r^i + \tau_r^{ls}. \\ &= -\left[(a - a_3) \frac{b_r}{a} + (a_3 - a_4)(c_v - c_r) \Pr{}_4\right] k_r^i + \tau_r^{ls} \\ &= -a_3 \left[\frac{a - a_3}{a_3} \frac{b_r}{a} + \frac{a_3 - a_4}{a_3} (c_v - c_r) \Pr{}_4\right] k_r^i + \tau_r^{ls}. \end{aligned}$$

We now turn to the transfer in subsidy scheme 3b (for *ind*). Accounting for $\tau_{r,34}^{x+}$ and assuming that $\tau_r^{ls} = 0$, expected profits change from Equation (37) to

$$\begin{aligned} E\left[\pi_r^{i,\tau}\right] = {} & (c_g - c_r) E\left[\tilde{x}_r^i|\Omega_3\right] \Pr{}_3 + (c_v - c_r) E\left[\tilde{x}_r^i|\Omega_4\right] \Pr{}_4 - \left(b_r - \tau_r^k\right) k_r^i + \\ & \tau_{r,34}^{x+} E\left[\tilde{x}_r^i|\Omega_{34}\right] \Pr{}_{34}. \end{aligned}$$

Using $\partial E\left[\tilde{x}_r^i|\Omega_{34}\right] / \partial k_r^i = a$, the new efficiency condition becomes

$$b_r - \tau_r^k = (c_g - c_r)\, a \Pr_3 + (c_v - c_r)\, a \Pr_4 + \tau_{r,34}^{x+} a \Pr_{34}.$$

and new expected profits are

$$E\left[\pi_r^{i,\tau}\right] = -a_3 k_r^i \left[\frac{a - a_3}{a_3}\frac{b_r}{a} + \frac{a_3 - a_4}{a_3}(c_v - c_r)\Pr_4\right] - (a - a_{34})\Pr_{34} k_r^i \tau_{r,34}^{x+}$$

This can be solved to obtain the value for $\tau_{r,34}^{x+}$ in Table 2, i.e.,

$$\tau_{r,34}^{x+} = -\frac{a_3}{(a - a_{34})\Pr_{34}}\left[\frac{a - a_3}{a_3}\frac{b_r}{a} + \frac{a_3 - a_4}{a_3}(c_v - c_r)\Pr_4\right].$$

Rearrangering the new efficiency condition by using $\Pr_3 = \Pr_3^*$ and $\tau_{r,34}^{x+}$ yields

$$\begin{aligned}\tau_r^k &= -b_r - (c_g - c_r)\, a \Pr_3 - (c_v - c_r)\, a \Pr_4 \\ &\quad + \frac{a_3}{(a - a_{34})\Pr_{34}}\left(\frac{a - a_3}{a_3}\frac{b_r}{a} + \frac{a_3 - a_4}{a_3}(c_v - c_r)\Pr_4\right) a \Pr_{34} \\ &= \frac{a a_3}{a - a_{34}}\left[\frac{a - a_3}{a_3}\frac{b_r}{a} + \frac{a_3 - a_4}{a_3}(c_v - c_r)\Pr_4\right].\end{aligned}$$

C Proof of Proposition 5

Profits of firm i are

$$\begin{aligned}E\left[\pi_j^i\right] &= (p_{12}^{va} - c_j)\, E\left[x_j^i|\Omega_{12}\right]\Pr_{12} + (p_3^{va} - c_j)\, E\left[x_j^i|\Omega_3\right]\Pr_3 \\ &\quad + (p_4^{va} - c_j)\, E\left[x_j^i|\Omega_4\right]\Pr_4 - b_j k_j^i \\ &= (c_r - c_j)\, E\left[x_j^i|\Omega_{12}\right]\Pr_{12} + (c_g - c_j)\, E\left[x_j^i|\Omega_3\right]\Pr_3 \\ &\quad + (c_v - c_j)\, E\left[x_j^i|\Omega_4\right]\Pr_4 - b_j k_j^i, \end{aligned} \tag{38}$$

where we have used p^{va} from Equation (35). For gas turbine and renewables firms, we have

$$E\left[\pi_g^i\right] = (c_v - c_g)\, k_g^i| - b_g k_g^i \tag{39}$$

$$E\left[\pi_r^i\right] = (c_g - c_r)\, E\left[\tilde{x}_r^i|\Omega_3\right]\Pr_3 + (c_v - c_r)\, E\left[\tilde{x}_r^i|\Omega_4\right]\Pr_4 - b_r k_r^i. \tag{40}$$

Differentiation yields the efficient first-order conditions in Equations (11) and (12). Resubstitution into Equations (39) or (40), respectively, yields zero profits.

D Proof of Proposition 6

Profits of firm i are

$$
\begin{aligned}
E\left[\pi_j^i\right] &= pD_j^i + p_{12}^{va} E\left[x_{j,im}^i|\Omega_{12}\right] \Pr{}_{12} + p_3^{va} E\left[x_{j,im}^i|\Omega_3\right] \Pr{}_3 \\
&\quad + p_4^{va} E\left[x_{j,im}^i|\Omega_4\right] \Pr{}_4 - b_j k_j^i - c_j E\left[x_j^i\right] \\
&= pD_j^i + c_r E\left[x_j^i - D_j^i|\Omega_{12}\right] \Pr{}_{12} + c_g E\left[x_j^i - D_j^i|\Omega_3\right] \Pr{}_3 \\
&\quad + c_v E\left[x_j^i - D_j^i|\Omega_4\right] \Pr{}_4 - b_j k_j^i - c_j E\left[x_j^i\right] \\
&= (c_r - c_j) E\left[x_j^i|\Omega_{12}\right] \Pr{}_{12} + (c_g - c_j) E\left[x_j^i|\Omega_3\right] \Pr{}_3 + (c_v - c_j) E\left[x_j^i|\Omega_4\right] \Pr{}_4 \\
&\quad - b_j k_j^i + \left(p - c_{12}^{va} \Pr{}_{12} - p_3^{va} \Pr{}_3 - p_4^{va} \Pr{}_4\right) D_j^i, \qquad (41)
\end{aligned}
$$

where the last line vanishes due to retailer's maximization problem, i.e., $p = E\left[p^{va}\right]$. Then, Equations (41) and (38) are equivalent.

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