

Electricity markets regarding the operational flexibility of power plants

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Electricity market mechanisms designed to steer sustainable generation of electricity play an important role for the energy transition intended to mitigate climate change. One of the major problems is to complement volatile renewable energy sources by operationally flexible capacity reserves. In this paper a proposal is given to determine prices on electricity markets taking into account the operational flexibility of power plants, such that the costs of long-term capacity reserves can be paid by short-term electricity spot markets. For this purpose, a measure of operational flexibility is introduced enabling to compute an inflexibility fee charging each individual power plant on a wholesale electricity spot market. The total sum of inflexibility fees accumulated on the spot markets then can be used to finance a capacity market keeping the necessary reserves to warrant grid reliability. Here each reserve power plant then gets a reliability payment depending on its operational flexibility. The proposal is applied to a small exemplary grid, illustrating its main idea and also revealing the caveat that too high fees paradoxically could create incentives to employ highly flexible power plants on the spot market rather than to run them as backup capacity.

Keywords: electricity markets, market mechanism, operational flexibility of power plants, flexibility measure, renewable energy, capacity market, energy transition

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ACM Classification (1998): J.4

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I. INTRODUCTION

To mitigate the global climate change it is commonly agreed that greenhouse gas emissions, and in particular emissions of CO₂, have to be reduced substantially [11, 17–19, 23, 24]. Since 85% of current primary energy driving global economies are due to the combustion of fossil fuels, and since consumption of fossil fuels accounts for 56.6% of all anthropogenic greenhouse gas emissions, introducing renewable energy sources to support all areas of human life plays an essential role in fighting global warming [8]. In particular, the generation of electricity by renewables will be an important step towards this goal, requiring substantial changes to current grid structures and power plant systems.

If generation and distribution of electricity is to be organized by market principles, a preeminent challenge of a future electricity market mechanism design is to set effective price signals to reward the introduction and the use of renewable energy sources for the generation of electricity, and simultaneously to penalize fossil fuel power plants. However, the physical requirements of electricity grids and the necessities of public life in present societies impose special restrictions on electricity markets. In particular, a necessary condition for grid stability is the reliability of electricity generation and the immediate equality of supply and demand at any instant of time. It is expected that the biggest contribution of renewable energy sources in electricity grids will come from wind turbines and photovoltaic cells [1], both producing electricity only with high volatility. Their widespread installation therefore would challenge the reliability of electricity supply and thus the stability of the grids. Lacking sufficiently large storages for electricity, to warrant reliability in grids with volatile

energy sources power plants with high operational flexibility are required as a power reserve standing in in cases of sudden scarcity of electricity supply or of blackouts. Cramton and Ockenfels [4] proved the “missing money” theorem stating that, in a competitive electricity market, prices are always too low to pay for adequate capacity. In fact, present electricity markets are not perfect efficient markets since both supply and demand are price inelastic, see Figure 1. Future increase of demand elasticity, for instance by smart grids, would relax the difficulties to a certain degree, but inelasticity on the supply-side could only be removed by capacity reserves or huge electricity storages. The first option, however, requires long-term plannings at a magnitude of decades, whereas the second option is technologically not realizable to date. For more details see [5].

Besides these theoretical arguments there also exist empirical clues to doubt that current electricity markets encourage investments in operationally flexible power plants or in the provision of power reserves for cases of emergency or maintenance [2, 7, 9, 27]. Several solutions to this problem have been proposed recently to complement the present “energy-only” markets, ranging from separate capacity markets which trade backup capacity, to strategic capacity reserves usually settled by long-term contracts with national agencies [2, 4, 9, 13, 15, 21, 26, 27].

The main goal of this paper is to propose a solution for the economic problem to finance the necessary capacity reserves guaranteeing grid stability by market principles. One necessary property of a power plant for being part of a capacity reserve is a fast guaranteed operational flexibility. In our opinion the main problem of current market mechanism designs is the fact that market prices do not regard operational flexibil-

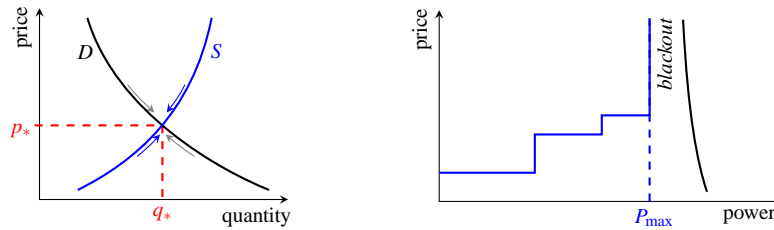


FIG. 1: A perfect efficient market where any demand D meets supply S at a certain equilibrium price p_* and quantity q_* (left hand). On an electricity spot market, a blackout is a market failure due to inelastic demand and supply, with the supply curve given by the merit order of the power plant system (right hand). Here a (“rolling”) blackout occurs if the demand is higher than the total maximum power P_{\max} of all power plants [5]. Increasing the demand-side inelasticity, e.g., by smart grids, could remove the problem on the long run, but in the short run electricity markets require capacity reserves which are not demanded for most of the time.

ity, being determined solely by the marginal costs of electricity generation. Thus the costs of operational inflexibility are market externalities [3, §14], [20, p 125] and reduce welfare. By contrast, a sustainable electricity market mechanism design should induce market prices which take into account both the direct variable production costs and the external ecological costs of electricity production, but also the costs caused by operational inflexibility of each individual power plant. Due to emissions trading [28, §15.4], the first two cost factors are already priced in as marginal costs on present electricity spot markets, but operational flexibility does not play a role for the determination of the spot market prices to date. To internalize it into price calculation, at first we define measure for the operational flexibility of a given power plant. This measure then can be used to compute an inflexibility fee for each power plant. The total of these inflexibility fees then can serve to pay power reserves provided by some given capacity mechanism.

This paper is organized as follows. In section II a general class of functions measuring the operational flexibility of a power plant in dependence to its guaranteed start-up time is defined. In section III the effect of the inflexibility fee on the offer price of a power plant on an electricity spot market is calculated and demonstrated by a prototypical exemplary “toy” grid in Example 1. A way how the accumulated inflexibility fees then can be used to finance a capacity mechanism is described in section IV, before a short discussion concludes the paper.

II. A MEASURE OF THE OPERATIONAL FLEXIBILITY OF A POWER PLANT

We stipulate that the operational flexibility of a power plant depends on its *guaranteed start-up time* $t_s \in [0, \infty)$ which is defined as the time that a power plant requires to supply a guaranteed power of electricity. Moreover, we claim that the measure should be a pure number expressing a degree of flexibility ranging from 0 to 1, with the property that the longer the guaranteed start-up time the smaller the value of flexibility. Consequently, we define a general *measure of operational flexibility* to be a strictly monotonically decreasing function $\varphi : [0, \infty) \rightarrow [0, 1]$ of a single variable satisfying the limit be-

havior

$$\varphi(x) \rightarrow 1 \quad \text{as } x \rightarrow 0, \quad \text{and} \quad \varphi(x) \rightarrow 0 \quad \text{as } x \rightarrow \infty. \quad (1)$$

Here the variable x represents the starting time of the power plant, measured in hours [h]. A simple example of such a measure is the differentiable function

$$\varphi(x) = \frac{1}{x+1}. \quad (2)$$

In the sequel we will use this function to measure the operational flexibility of a given power plant. In Table I there are listed guaranteed start-up times t_s and the respective flexibility measures $\varphi(t_s)$ for some typical power plants. Note that

Power Plant	Guaranteed Start-Up Time [h]	φ	Marginal Costs p^{mc} [€/MWh]
wind turbine	∞	.000	—
hydroelectric power station	0.02	.979	—
gas turbine	0.12	.893	90
cogeneration plant (CHP)	0.17	.855	—
combined cycle gas turbine	5	.167	50
hard coal power plant	6	.143	60
lignite power plant	9	.100	40
nuclear power plant	50	.020	5

TABLE I: Exemplary cold start-up times and their respective operational flexibility measures, as well as exemplary marginal costs (without emissions trading). The values are typical for current German electricity markets. Data from [14, p 71] (start-up times) and [16, pp 13, 19], [29, p 3] (marginal costs).

a wind turbine is assigned a vanishing operational flexibility, since due to the volatility of winds a predetermined amount of energy by a wind turbine cannot be guaranteed at a given future instant. The highest operational flexibilities are exposed by hydroelectric power stations and modern gas turbines.

III. FEES ON OPERATIONAL INFLEXIBILITY

On an wholesale electricity market, each participating power plant operator offers electric power with a sell bid for each of its power plant. The market maker collects all these sell bids and determines the market-clearing price in accordance to the buy bids and the merit order [6, 10, 25, 30], for a theoretical introduction see also [12, §6.5, §7.4.5]. Our main idea now is to rise a fee for operational inflexibility on each power plant, its amount being calculated by the operational flexibility ϕ as part of a factor to a given market-wide reference level. In consequence, the offer price of each power plant must take it into account its operational flexibility.

To be more precise, let p_i^{mc} denote the marginal offer price per energy quantity of the power plant regarding only the marginal costs, including the variable costs of production and emissions trade certificates; this is the price which would be offered for the power plant on a current wholesale spot market [29]. Assume moreover that all power plants participating at the spot market are uniquely numbered by the indices $i = 1, 2, \dots, n$. The spot market offer price p_i of plant i taking into account its operational flexibility ϕ_i then is calculated by the formula

$$p_i = p_i^{\text{mc}} + (1 - \phi_i) p_0. \quad (3)$$

Here p_0 denotes a market-wide constant reference level price, set by the market authority. It therefore is a political or regulatory quantity, not a market-inherent value or immediately economically deducible. It is arbitrary in principle, but the higher its amount the heavier the effect of operational flexibility on the final spot market price. It should be high enough to signal effective incentives to introduce and use operationally flexible power plants for scarcity situations and black-outs, but it must be low enough to avoid a too radical change of the merit order such that too many flexible power plants are operational on the spot market and thus unavailable for a capacity reserve (see Figure 2).

Example 1. Consider a small exemplary grid (called “toy grid” in the sequel) consisting of the eight power plants listed in Table I. The prices resulting from the respective inflexibility fees in dependence to different reference level prices p_0 are listed in Table II. If the reference level price is low (here $p_0 = 10 \text{ €/MWh}$), the modified offer prices do not change the merit order of the power plant system, whereas a sufficiently high reference level price (e.g., $p_0 = 70 \text{ €/MWh}$) changes it, as is depicted in Figure 2. In our toy grid we can recognize that, if the amount of p_0 is too high, the effect may be even counterproductive since the flexible gas turbine is in the money and thus operating at a normal quantity demand, leaving no power plant as a capacity reserve. In case of a sudden scarcity or of a blackout, the grid then would perform worse than with the original merit order.

Moreover we observe that the higher the reference level price p_0 , the higher the spot market price. The amounts, however, are not related to each other in a linear manner, but depend discontinuously on the changes of the merit order. The total amount of inflexibility fees, at last, is directly calculated

to be either 48.4 €/MWh in case of $p_0 = 10 \text{ €/MWh}$, or 339 €/MWh in case of $p_0 = 70 \text{ €/MWh}$.

We finally note that for the demanded quantity q_* depicted in the scenarios in Figure 2, only five power plants are operational. Depending on the reference level price the realized profit then is given by the following tables.

$p_0 = 10 \text{ €/MWh}$		$p_0 = 70 \text{ €/MWh}$	
Power plant	Profit for q_*	Power plant	Profit for q_*
wind turbine	40 €/MWh	wind turbine	27 €/MWh
hydroelectric	50 €/MWh	hydroelectric	95 €/MWh
CHP	0 €/MWh	CHP	37 €/MWh
lignite	2 €/MWh	gas turbine	0 €/MWh
nuclear	37 €/MWh	nuclear	24 €/MWh

Assume for simplicity that the demand remains constantly at q_* during a certain hour and that all power plants yield the same power of 5 MW, say, and let be $q_* = 25 \text{ MW}$ be the demanded electrical power for the hour considered (such that the consumed electricity energy during this period is $E = 25 \text{ MWh}$). Then with Table II the total of the inflexibility fees for the five operational power plants in the money has the amount of

$$C_f = (10 + 1 + 1 + 9 + 10) \cdot 5 = 205 \text{ €/h}, \quad (4)$$

at a reference level price $p_0 = 10 \text{ €/MWh}$, and

$$C_f = (70 + 1 + 8 + 10 + 69) \cdot 5 = 790 \text{ €/h}, \quad (5)$$

at a reference level price $p_0 = 70 \text{ €/MWh}$. The total fee then can be distributed to the power plants participating at a capacity mechanism, paying their time of reliability. \square

The toy grid in Example 1 demonstrates the possible direct consequences of the inflexibility fee to the wholesale electricity market. In essence, by Equation (3) a power plant with a low operational flexibility is penalized more than one with a high operational flexibility. In the limit case that all power plants participating on the spot market are equally operationally flexible, i.e., $\phi_i = \text{const}$, all sell bids are raised by the same amount and the merit order cannot change. On the other hand, if the power plants have different operational flexibilities and the reference price level p_0 is chosen too high, the merit order changes the merit order such that all flexible power plants are operational on the spot market, such that no power plant is left for the capacity reserve necessary to warrant grid reliability.

The total amount of inflexibility fees paid for each power plants participating the spot market now is available for a capacity mechanism, as described in the following section.

IV. ACCUMULATED INFLEXIBILITY FEES PAYING CAPACITY RESERVES

A power plant serving as a power reserve for periods of scarcity or blackouts should have fast and guaranteed start-up times, i.e., should be operationally flexible to a high degree. There exist several proposed capacity mechanisms, for

Power Plant	φ	$1 - \varphi$	Marginal Price	Offer Price	
			p_i^{mc} [€/MWh]	p_i [€/MWh]	
				$p_0 = 10$	$p_0 = 70$
wind turbine	.000	1.000	1	11	71
hydroelectric power station	.980	.020	1	1	2
gas turbine	.893	.107	90	91	98
cogeneration plant (CHP)	.855	.145	50	51	60
combined cycle gas turbine	.167	.833	50	58	108
hard coal power plant	.143	.857	60	69	120
lignite power plant	.100	.900	40	49	103
nuclear power plant	.020	.980	5	15	74

TABLE II: Operational flexibilities, as given by the exemplary data of Table I, and the resulting offer price differences with respect to the reference level prices $p_0 = 10$ €/MWh and $p_0 = 70$ €/MWh.

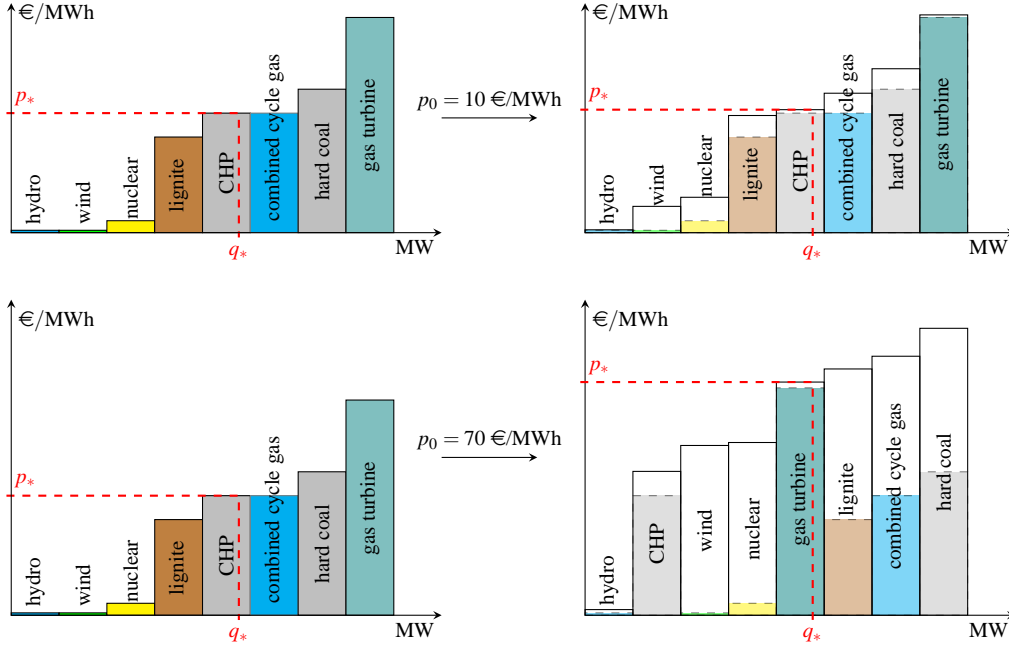


FIG. 2: Effect of the operational inflexibility fee on the price p_* clearing the market consisting of the power plant system in Table II, neglecting operational flexibility (left) and regarding it (right). The reference level price are assumed as $p_0 = 10$ €/MWh and $p_0 = 70$ €/MWh, respectively. For a given demand q_* of electric power, the market-clearing spot price increases more or less slightly, depending on p_0 . For a high operational inflexibility fee, as in the second case, the merit order is changed.

instance capacity markets or a strategic reserve determined by a grid agency. In either of these approaches, we therefore require a power plant to offer capacity reserves to have a high operational flexibility φ , say

$$\varphi > \frac{1}{2}. \quad (6)$$

This value means that the guaranteed start-up time of a power plant participating the capacity mechanism must be less than one hour. A further natural requirement is that a power plant offering its reliability on the capacity market cannot participate on the spot market.

Assume then that there are k power plants participating on the capacity market, each one established with a unique index $i = 1, \dots, k$. Let φ_i and P_i denote the operational flexibility and the capacity (measured in MW) of power plant i , respec-

tively, and let C_f be the total of inflexibility fees accumulated on the spot market in a certain past period, say, the day before. It has the dimension currency per time, for instance €/h. Then the *reliability payment* ρ_i for power plant i in that period is defined as

$$\rho_i = \frac{\varphi_i P_i}{P_{\text{flex}}} C_f \quad \left[\frac{\text{€}}{\text{h}} \right] \quad \text{where} \quad P_{\text{flex}} = \sum_{j=1}^k \varphi_j P_j. \quad (7)$$

Note that by construction $\sum_{i=1}^k \rho_i = C_f$, i.e., the sum over all reliability payments equals the total amount of the inflexibility fees. The quantity P_{flex} is the weighted sum of all available capacities, where the weights are precisely the respective operational flexibilities.

Example 2. Assume the toy grid from Example 1. Then by the requirement (6) only three power plants can participate

at the capacity market, namely the hydroelectric power station, the CHP plant and the gas turbine. In Table III they are listed with their capacities and the resulting reliability payments according to Equation (7) and depending on the amount of total inflexibility fee coming from the spot market. For calculational details refer to the Excel file <http://math-it.org/climate/operational-flexibilities.xls>. \square

V. DISCUSSION

In this paper a proposal has been worked out to integrate operational flexibility into the sell bids of power plants participating wholesale electricity spot markets. The main idea is to calculate a fee for each power plant depending on its operational flexibility. For this purpose the concept of a general measure of operational flexibility of a power plant is introduced here as a strictly monotonically decreasing function φ of the guaranteed start-up time, normed by condition (1). With such a measure, the inflexibility is priced in by Equation (3) to the marginal price determining the sell bid of each power plant at the spot market. The amount depends on a market-wide reference level price p_0 which is set by the market authority or the state. The total operational inflexibility fee C_f accumulated at the spot markets then is spread on the power plants participating in a given capacity mechanism, depending on their operational flexibilities according to Equation (7). Here the power plants forming a capacity reserve should have a very high operational flexibility, to guarantee reliability and stability of the grid. A reasonable value is proposed by inequality (6). A simple example of a measure for operational flexibility is given by Equation (2). Using this measure, the spot market and the corresponding payments to power plants

participating in a capacity mechanism are applied to a simple but prototypical toy grid in Examples 1 and 2.

The most important consequence of our proposal, as viewed from an economic perspective, is the internalization of the negative externality of operational inflexibility of power plants. With the inflexibility fees determined as above, the currently external costs would thus be paid by the spot markets and could be used to pay capacity reserves, be it on a separate capacity market or another capacity mechanism such as a pool of power plants forming a strategic reserve. The inflexibility fee therefore increases welfare without necessarily decreasing dispatch efficiency.

A critical point of our approach, however, is the determination of the reference level price p_0 . It is crucial since it can even change the merit order of electricity markets if it is set very high. Although a change of the merit order in itself does not necessarily imply severe problems, it could nonetheless lead to the paradox that operationally flexible power plants participate in a short-term spot market and therefore could not serve as a capacity reserve. An amount p_0 too high would thus be adverse to the intention to pay a capacity mechanism and thus would even diminish welfare. We therefore are faced with the conflicting objectives of providing enough means to fund the reserves of a capacity mechanism, and of keeping suitable power plants with high operational flexibility as capacity reserve. Although this risk is calculable when choosing the amount for a given grid cautiously such that experiences could be gained over time, a comprehensive theoretical framework to illuminate effects and limits of inflexibility fees on electricity markets should be accomplished. Hints to tackle this problem may be indicated by the optimal taxation due to Ramsey [22], or by regulation theory [28, §13]. Further research in this direction appears worthwhile.

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Power Plant	ϕ	Capacity [MW]	ρ_i [€/h]			
			$C_s = 205 \text{ €/h}$		$C_s = 790 \text{ €/h}$	
hydroelectric power station	.980	5	74	—	284	—
gas turbine	.893	5	67	105	259	404
cogeneration plant (CHP)	.855	5	64	100	247	386

TABLE III: The three power plants participating at the capacity market of our toy grid in Example 2 and their reliability payments ρ in dependence to the total inflexibility fee coming from the spot market.

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