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Resilience regulation: An incentive scheme for regulated electricity network operators to improve resilience

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Abstract: This paper presents an approach for resilience incentives in the regulation of electricity network operators. Resilience is the ability of the power system to deal quickly and efficiently with large-scale and long-lasting power interruptions. It comprises two related aspects: minimizing the damage caused by an outage and increasing the robustness of the system. The resilience regulation proposed in this paper contains two complementary parts. First, a resilience incentive mechanism, which aims at internalizing external effects of resilience improvement. This part relies on so-called duration-dependent consumer damage functions (CDFs). Second, a forward-looking budget approach with a sharing factor to strengthen incentives for resilience expenses within regulatory constraints.

Keyword: resilience, electricity, network, regulation

JEL-classification: K23, L5, L94,

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1 Introduction

Resilience of electric power systems has recently gained attention and importance (cf. EU Council, 2021; acatech, 2020). With resilience of an electric power system, we mean the ability of the power system to deal quickly and efficiently with *large-scale* and *long-lasting* power interruptions. These are described in the literature as being caused by high-impact, low-frequency (HILF) events (cf. e.g. NERC, 2010). Examples are cyber-attacks, extreme seismic events or simultaneous behavior of a large group of market players using comparable algorithms (cf. acatech, 2020).

Although many stakeholders somehow affect the resilience of the system, the electricity network operators are particularly well placed to retain or improve network- and system-resilience. However, resilience is not well established in the regulation of the network operators. Network regulation usually contains an element for quality regulation, which incentivizes network operators to retain the quality level of the network. Although quality and resilience are related, there are important differences. Quality regulation is not well equipped to deal with long and large disturbances related to extreme situations because these are often exempted from liability. It also does not aim at restoring the system after a breakdown occurs. As a result, we conclude that quality regulation is not well suited to cover resilience. Therefore, we propose resilience regulation in addition to quality regulation. The two schemes are similar at first sight, but details differ critically.

The presented incentive mechanism is in addition to the base regulation; we do not suggest changing the base regulatory model. Although our analysis is largely theoretical, the proposed mechanism has been designed explicitly with the aim that it can be implemented in practice. Regulatory systems differ strongly between various countries. The mechanism proposed here, was designed with the regulatory system in Germany in mind, but was framed such that it is applicable to other regulatory systems as well.

The proposed mechanism relies on the concept of the consumer damage functions (CDFs) (cf. Anderson et al., 2019). A CDF is a dynamic extension of the static concept of the Value of Lost Load (VoLL). Whereas the VoLL (per kWh) is calculated regardless of the duration of outage, the CDF (per kWh) explicitly makes the calculation dependent on the outage duration. This is useful for resilience regulation, precisely because resilience is defined in relation to large-scale and long-lasting outages, which makes it critical to take duration into account.

The paper is structured as follows. Section 2 discusses the background problem and the main concepts. Section 3 presents the resilience regulation proposed in this paper. It contains two parts: first, a resilience incentive scheme and second, a forward-looking budget approach with a sharing factor. These two parts are complementary, not different options. Section 4 gives concluding remarks.

2 Background and problem description

2.1 Resilience and HILF-events

As mentioned above, resilience describes the electric power systems ability to deal quickly and efficiently with *large-scale* and *long-lasting* power interruptions (cf. acatech, 2020), also described as being caused by high-impact, low-frequency (HILF) events (cf. e.g. NERC, 2010). We will follow this notation and focus on interruptions due to HILF-events.

Importantly, resilience covers two related aspects. First, resilience means increasing the robustness of the system, such that HILF-events are unlikely to occur or to cause damage in the first place. Second, resilience means minimizing the damage caused by a HILF-event and restoring the system optimally. Concerning the latter, Pechan et.al. (2023) propose an auction for priority positions to optimize outage costs. The figure below illustrates these two aspects of resilience. The incentive mechanism, which will be presented below, covers both aspects.

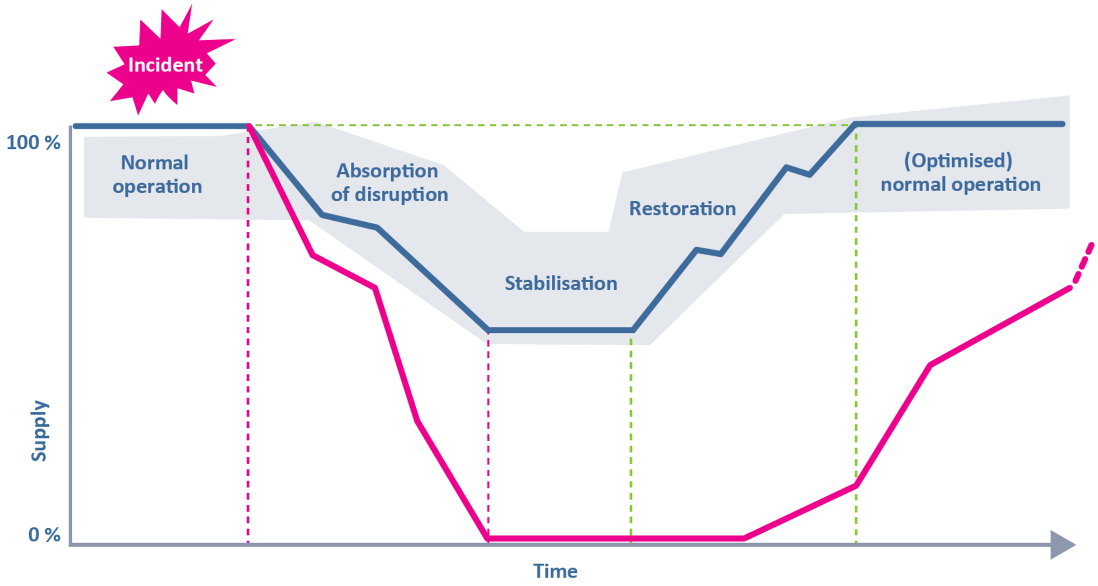

Figure 1: Illustration of resilience.
Source: Babazadeh et al, 2018, p. 32.

Resilience of the electric power system and HILF-events have gained attention in recent times (cf. acatech, 2020). Because of the large impact, the mere threat suffices to raise attention. We observe several sources for the recent attention:

- The system is becoming more decentralized and consequently more complex; hence, it gets more difficult to control the system technically. Liberalization and the energy transition allowed the emergence of many, widely diverse third parties: the industry changed from a top-down closed hierarchy, to a bottom-up, open market-based system. Subsequently, coordination has become a challenge (cf. Brunekreeft et al., 2016).
- The system is becoming increasingly digital. This affects the infrastructure itself, but also the numerous users of the infrastructure. The users are increasingly interconnected regardless of heterogenous private interests and across different markets. Moreover, the interconnection of internet-suitable devices (e.g. heat pumps or electric vehicles connected to the wide area network) creates vulnerabilities for cyber-attacks.
- Digitalization has a significant impact on transactions and interactions; for instance, it may increase simultaneity of the (automated) actions of large groups of small users, which may have a destabilizing effect on the system. Simultaneous behavior may especially be triggered if devices use the same standards or traders use the

same algorithms. Well known is the case of solar panels, which were programmed to disconnect from the system at a certain frequency level; clearly, with substantial solar capacity, this would destabilize the system.

We should stress that the effects described above on the risk of HILF-events and the resilience of the system are ambiguous on balance. For instance the presence of a wide group of interconnected small users may be a risk, but can also improve the resilience of the system. The same holds for digitalization: an increasingly digital system makes the same system more vulnerable to cyber-attacks, but at the same time improves the possibilities to counter cyber-attacks and restore the system.

Electricity network regulation typically has an element to improve quality of the network, also known as quality regulation (cf. e.g. CEER, 2022). Quality regulation is widely applied in regulation, particularly in price-based models, such as price- or revenue caps. The theoretical foundation was made by Spence (1975, p. 420, fn. 5), who notes: “of somewhat less interest is the case where price is fixed or taken as given. In that case, the firm always sets quality too low”. In a nutshell, Spence notes that under a price cap, the firm cannot fully recoup the value creation of increased willingness to pay (analytically, a shift of the demand curve) induced by higher quality and will therefore invest too little in quality. This is different for cost-based regulatory approaches, where an increase in costs triggers higher prices. This has become the justification for explicit quality incentives in addition to the price-based models. The same principle holds for resilience and resilience regulation. Yet, for a number of reasons, the details of quality regulation do not readily carry over to incentives to improve resilience against HILF-events, as defined above:

- Quality typically concerns short and local interruptions; HILF-events, and thus resilience regulation, concern long and large disturbances.
- Quality disturbances are typically caused by technical reasons under “normal” circumstances, related to the age and maintenance of the infrastructure devices. Old lines have a higher probability of breaking down. HILF-events are related to service interruptions in extreme situations, which tend to be excluded from quality measures and regulation; force majeure is usually exempted from liability.
- Quality disturbances occur often; improving quality means to reduce outages, not to avoid them altogether. HILF-events hardly occur and the aim is to avoid the

events altogether. This implies that details of quality regulation may not apply to resilience incentives.

- The focus of improving quality is to reduce outage frequency to an optimal level. The focus of resilience incentive mechanisms is to restore the system optimally after the breakdown occurs.

In section 3, we will develop an incentive mechanism to supplement network regulation to improve resilience. The reader may note that at first glance the mechanism has similarity to the usual quality mechanism (as these are basic incentive mechanisms), but details matter and differ significantly.

2.2 From a static VoLL to duration-dependent CDFs

Quality regulation typically relies on the concept of Value of Lost Load (VoLL), which is a static value per kWh. For almost all consumers, the security of electricity supply is a public good. A supply interruption is a non-market good and does not have a "listed price". Instead, the cost of supply interruptions (usually expressed as the VoLL) should be estimated. Basically, there are two general methods to estimate the VoLL. Either it can be estimated indirectly, e.g. from consumption- and production-data using macro-economic assumptions. Or the consumers can be asked directly to reveal their willingness to pay, using a conjoint statistical analysis (cf. e.g. Nooij et al., 2007).

The VoLL has been studied extensively and is widely used in the quality-element of regulation of electricity networks (cf. CEER, 2022). Typically, the VoLL is estimated regardless of the duration of outage. For quality regulation, which focuses on relatively short outage durations, taking the VoLL as a static parameter is useful. Things change for HILF-events precisely because these have long durations.

To take account of the effect of duration on the outage costs, the concept of consumer damage function (CDF) was developed. In essence, a CDF is a duration-dependent VoLL and is therefore well suited for use in resilience incentive mechanisms. The CDF can be estimated for different user groups and different regions. The method to estimate CDFs is explained well in the work of NREL in the US (see especially Ericson & Lisell, 2018). These authors estimate outage-cost-functions comprising three elements: fixed costs, flow costs and stock costs. The latter two are a function of outage duration. This results in a non-constant VoLL as a function of outage duration, called consumer damage function.

Anderson et al. (2019) illustrate the concept for a case study with grid-scale production costs. The case study examines the outage costs of a disturbance at the TSO grid level: it optimizes constrained dispatch in the transmission grid (running the system up and down) at bus-level to which the power plants and the distribution networks are connected. At the costs of more computing power, this can be differentiated for lower levels in the grid.

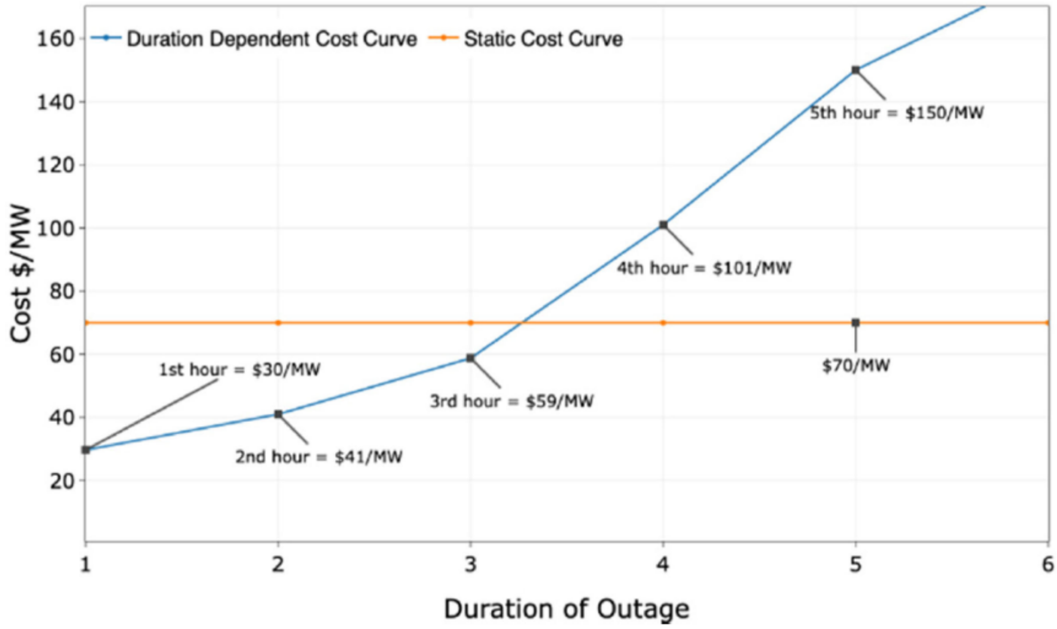

Figure 2: Outage costs as a function of duration.
Source: Anderson et al. (2019, p. 3, fig. 2).

Figure 2 shows the result for the case study in Anderson et al. (2019). The outage costs are expressed per kWh. The horizontal orange line is the static VoLL; it is constant number regardless of duration. The upward sloping blue line is the CDF: it shows how the outage costs per kWh increase with duration. The figure suggests an internal relation between the VoLL and the CDF: the VoLL seems to be a hypothetical average of a specific time frame for the CDF (in figure 2 the static cost curve, i.e. VoLL, corresponds approximately to the average outage costs for the first 5 hours). Importantly, the CDFs are context-dependent. This function in figure 2 holds only for this case study; another case study could result in a different CDF, possibly with a different shape (downward sloping or an inverse U-shaped).

The main advantage of using user-group specific and duration-dependent CDFs over the static VoLL is that it allows better optimization of rationing and running up the system after a (part) black-out, or put differently, it allows to improve resilience by minimizing the outage costs. The CDF-based dispatch is more refined and allows for better fine-tuning than the VoLL-based dispatch. As mentioned above, for local outages of short duration this is quantitatively not relevant; with HILF-events, where outages are large-scale and of long duration, it will have a potentially large quantitative impact. Anderson et al. (2019, p. 5, table 3) continue to show that the use of CDF would indeed significantly improve the efficiency of dispatch after the disturbance, as compared to using a static VoLL. The incentive mechanism we will propose below exploits precisely this idea.

2.3 Network regulation

Resilience affects the entire electricity supply system and involves many agents. A pivotal role, however, is for the network operators, both in transmission and distribution. In this paper, we focus on the regulated network operators. As expressed in the introduction, the main aim of this paper is to design incentives for electricity network operators as part of the network regulation to improve resilience of the system.

Electricity network operators are considered natural monopolies and profits are usually capped with some kind of network regulation: price- or revenue-capping, cost-plus approaches, or hybrid forms. Modern regulation aims to implement incentive mechanisms: the key notion is to design a regulatory framework which allows the regulated firm to maximize profits under the regulatory constraint, while doing so is also good for society. Basically thus, an incentive mechanism aligns the interests of the firm and society. This is easier said than done, as effective design depends on many details. In practice, we observe many hurdles to optimal behavior.

We differentiate between internal and external hurdles (cf. Brunekreeft et al., 2021), as the hurdles in these two dimensions require different regulatory approaches; our approach for resilience regulation, using the two components with a resilience incentive mechanism and a budget approach, relies on precisely this distinction. Internal means that costs and benefits of an action are primarily incurred by the decision-maker. External means that costs and/or benefits are (partly) incurred by third parties and not by the decision-maker. It is important to make this distinction in order to be able to incentivise investments into resilience appropriately, since incentive biases as well as proposed solutions differ accordingly. Below, we discuss these two different dimensions and the regulatory challenges that arise in this context with a focus on resilience in more detail.

External effects that are not part of the existing regulation

In practice, most regulatory models do not explicitly incentivize the development of new tasks and business models (value creation). As already noted above, the rationale for value-creating incentives was (unintentionally) provided in the seminal work on quality regulation by Spence (1975). Regulation works differently for cost and demand changes, as illustrated in figure 3 below.

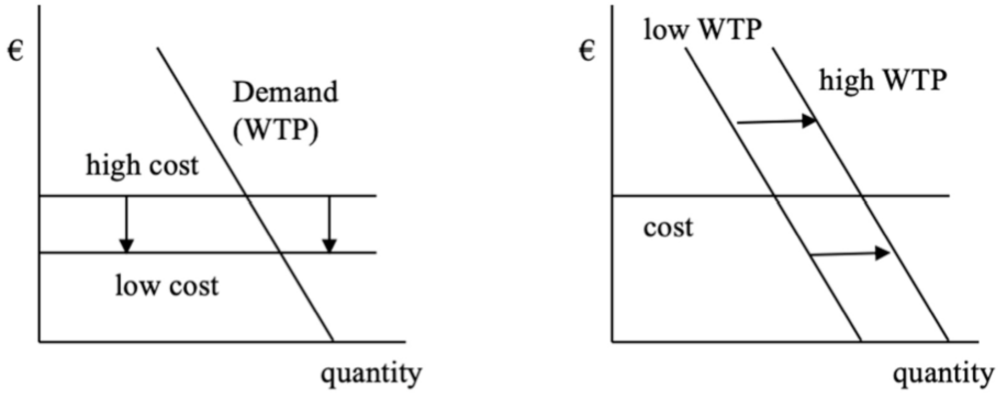

Figure 3: Shift in cost curve versus shift in demand curve
Source: Brunekreeft et al, 2020.

When improving efficiency, the cost curve shifts downwards while the demand curve remains constant. This is the goal of price- or efficiency-based approaches. The situation changes when the demand curve shifts: an innovation improves the product and increases consumers' willingness to pay (WTP). As Spence argues, price-based models, where the price is fixed, cannot handle this situation very well. When the demand curve is shifted, an additional surplus (the extra area below the demand curve) is created: value creation. Since regulation sets prices, the company cannot sufficiently absorb the additional surplus and will therefore invest inefficiently little in product improvements. This holds whether costs increase or not, but the problem gets worse when costs increase.

External effects (benefits or costs) of product improvement (here: resilience improvement) follow the same logic: they result in a shift in demand. As willingness to pay increases, additional surplus is created: ‘value creation’. Following the logic set out above, if regulation fixes the prices, the firm cannot sufficiently recoup additional surplus and will underinvest in product improvement.

A recent development in regulation tries to address this by output-oriented regulation (cf. Brunekreeft et al., 2020). Output-oriented regulation supplements efficiency-oriented price-cap or revenue-cap regulation with revenue elements that reflect the achievement of specific output targets, rather than just pursuing cost minimization. We can use this idea to improve the incentives for resilience. To the network operator, the benefits of improved resilience are largely external. Lowering the costs of restoring the system are benefits for the users, not for the network operator. Following the logic in Spence (1975) concerning quality, if such benefits are not (partly) reflected in the regulated revenues, the network operator will invest too little to improve resilience. Following the idea of output-oriented regulation, we develop an incentive mechanism in addition to the base regulation, which sets incentives for the network operator to invest in resilience.

Internal effects: cost-undercoverage and the OPEX-CAPEX-bias

The second dimension of regulatory challenges for resilience improvement focuses on cost-recovery for investments into resilience. These effects are referred to as internal, as these actions of a network operator with primarily internal effects aim to improve the *internal* efficiency of production and/or operations of the grid operator. This is the target of price- or efficiency-based regulation (e.g. price caps or revenue caps) as it is observed all over the world. Yet, practical regulation knows many hurdles to efficient behavior and biases occur a lot (cf. e.g. Brunekreeft & Rammerstorfer, 2021).

Generally speaking, such biases are due to time-related effects, in particular so-called base-year effects. Typically, regulation has two aspects: first, the regulatory lag within a regulatory period and second, the regulatory review: the base year. Figure 4 illustrates the regulation timeline.

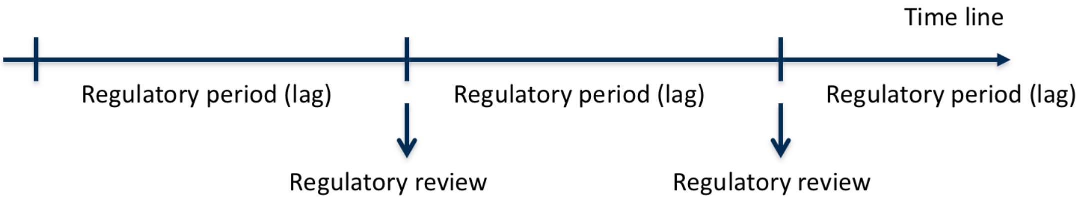

Figure 4: The regulation timeline.
Source. Own illustration

During the regulatory lag, the development of allowed revenues is exogenously set by the regulation; the development is determined by the regulatory formula. During the regulatory lag, the revenues are delinked from actual underlying costs. If the firm decreases its costs during the regulatory lag more than the decrease in regulated revenues, it will increase profits; on the other hand, if costs exceed the allowed revenues, these costs cannot be recovered and the firm suffers a loss. If expenses change during the regulatory lag, these changes cannot be passed through into revenues. The connection between revenues and underlying costs is restored at the regulatory review: the base year. The regulator adjusts the starting revenues for the next regulatory period to the firm's costs at that moment, after which the next regulatory period starts.

Expenses incurred during the base year are the determining factor of the revenue cap of the next regulatory period. However, costs may also be incurred outside the base year, with the result that they are not included at all or only at a later time in the revenue cap. Unanticipated additional expenses in the years after the base year would, therefore, lead to cost-undercoverage. The firm would not want to make these expenses or delay these to the next base year.

In order to smooth the expenses of resilience improvement and to avoid the risk of cost-undercoverage, below we will suggest a forward-looking budget approach for eligible and approved projects. The planned costs for the project-specific budget (including the timeline) are agreed with the regulator in advance.

3 Resilience regulation

With the above-mentioned distinction between internal and external effects in mind, we propose a mechanism for resilience regulation in this section. In the design, we aim for two goals. First, it should increase the incentive to improve resilience in theory and second, the design should be such that the mechanism can be implemented in practice.

Resilience regulation, which we propose here, is an addition to, not a replacement of the base regulation. Thus, overall regulation would be a base regulation for core activities (say, a base revenue cap) *plus* the resilience regulation. In the following notation, we ignore the base regulation and focus on the additional resilience regulation. The resilience regulation is specified for each year t:

$$RR_t = RIM_t + B_t \tag{1}$$

The first term on the RHS, in eq. (1) is the resilience incentive mechanism (RIM_t) for external effects of resilience improvement, i.e. it sets incentives for the network operator to minimize total outage costs of a HILF-event, as specified in eq. (2). The second term on the RHS is a budget-approach (B_t) for selected and approved resilience improving measures, as specified in eq. (6). Below we discuss these two parts in detail.

3.1 The resilience incentive mechanism (RIM)

Eq. (2) describes the resilience incentive mechanism, RIM_t:

$$RIM_t = \beta \cdot \left(\sum_h \left(VoLL \cdot ENS_{t,h}^{Sim} - CDF(d) \cdot ENS_{t,h}^{Real} \right) \right) \tag{2}$$

In this:

- β - incentive parameter, which can range between 0 and 1
- d - duration of the outage
- t - year t
- h - HILF-event causing an outage within year t
- ENS - energy not supplied (kWh)
- VoLL - static value of lost load, regardless of the duration of the outage
- CDF(d) - consumer damage function as a function of the duration of the outage

We suggest that the network operators calculate the set of CDFs before or when the mechanism is implemented, not after a HILF-event actually occurred; i.e. the CDFs should be determined ex ante (before the event), not ex post (after the event). This may be done by the network operators collectively or individually; the latter has the advantage that the CDFs can be better adjusted to specific case-sensitive network situations. The regulator will then have to approve these CDFs. The approved set of CDFs is then the base for the resilience incentive mechanism (RIM). This should guarantee that the CDFs reflect truth-telling and should avoid perverse incentives using flawed CDFs.

The incentive mechanism sets an incentive to reduce outage costs as compared to a reference value. The left part of the term in brackets in eq. (2) are the reference outage costs ($VoLL*ENS^{Sim}$). In a HILF-event, where the mechanism would be activated, the reference outage costs are simulated by the regulator for the specific event in a specific network, using a "naïve" approach. Outage costs (i.e. restoring the system, are simulated using the static duration-independent VoLL; this applies to both the simulated ENS as well as the total reference outage costs,

The second part in brackets are the real outage costs ($CDF*ENS^{Real}$); these are determined by the real ENS, using the CDFs that were approved by the regulator ex-ante. After the outage event, the network operator will restore the system by optimally starting it up using the CDFs. This delivers controllable data for ENS per user group. The outage costs are then calculated using the CDFs (per user group) as used by the network operator.

Note that the reference outage costs are exogenous from the perspective of the network operator; this number is not under the control of the network operator. Only the real outage cost, or more precisely, only the outage volume (ENS^{real}) is a variable under the control of the network operator. This is precisely the variable which needs to be optimized.

The conceptual difficulty of the resilience incentive mechanism is the determination of the reference cost. Above, we propose a "naïve" simulation as the reference for a workable approach, as it fulfills the following requirements:

- The scheme should not be a malus system only; therefore, the reference cost cannot simply be set to zero. Eq. (2) reveals that if the reference costs would simply be set to zero, the RIM would always be negative and the system would always be a malus system. Economically speaking, the incentives would still work, but it would be unreasonable and risky for the network operators, who could only lose. The higher risk would sooner or later be transferred into a higher risk-adjusted rate of return on capital, thus increasing total cost of the system.

- The reference costs cannot be set arbitrarily either, because the bonus or malus may then become unreasonably high. In fact, if the bonus would become very high, the network operator may actually have the perverse incentive to trigger an outage to activate the mechanism. Therefore, the reference costs should have a reasonable relation to real cost.
- The outage events take place very infrequently, and possibly not at all. Therefore, we cannot use the outage costs from the past (say, t-1) as a reference. This number may not exist, or may be very different from the outage costs in t.[2]
- The outage costs are case-sensitive and network-sensitive. The outage costs depend on the details of the outage event, the network area covered by the event, and on the user structure in the network area. Therefore, a yardstick approach, using something like an average of all network operators, will be problematic. The same holds for an ex-ante simulation with reference model networks: which event should be modelled?

Our “naïve” approach with the simulated outage costs as a reference based on a static VoLL addresses the issues above. Ideally, the calculation of the CDFs is a duration-dependent extension of the VoLL, in which case, we would expect that a hypothetical average of the CDFs corresponds to the underlying VoLL.[3] Moreover, we assume that the CDFs allow a more efficient restoring of the system; otherwise, it would be counterproductive to use the CDFs. Based on these assumptions in our approach, we should expect that the real outage costs are always lower than the simulated outage costs based on the VoLL.[4] Therefore, we should expect that the incentive scheme is primarily a bonus scheme.

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[2] The reader may note that this is in fact an important difference to the quality regulation.

[3] This is important. We presume a systematic internal relation in the calculation of the VoLL and the CDFs, such that a hypothetical average of the CDFs approximates the underlying VoLL.

[4] This is not necessarily always the case. The network operator may -irrationally- decide to restore the system not using the set of CDFs, but something different, resulting in higher outage costs. If the bonus is calculated using the CDFs, then the bonus might be negative. We further dismiss this case.

The direction of the incentives can readily be seen. Let ENS^{real} be a function of some variable e (for effort) to optimize ENS. Also, let C be the cost function of e. Now, profit of the resilience incentive mechanism (RIM) is defined as:

$$\pi(e) = \beta \cdot \left(VoLL \cdot ENS^{SIM} - CDF \cdot ENS^{Real}(e)\right) - C(e) \tag{3}$$

Optimizing for e (while noting that the first term in brackets is not under control of the firm):

$$\frac{\partial \pi}{\partial e} = \beta \cdot \left(-CDF \cdot \frac{\partial ENS^{Real}}{\partial e}\right) - \frac{\partial C}{\partial e} = 0 \tag{4}$$

And thus:

$$\beta \cdot \left(-CDF \cdot \frac{\partial ENS}{\partial e}\right) = \frac{\partial C}{\partial e} \tag{5}$$

Note that $\frac{\partial ENS}{\partial e} < 0$; a higher effort e leads to lower energy not supplied (ENS). This implies that the firm optimizes until its marginal benefit (avoided outage costs times the incentive parameter β) is equal to its marginal costs. This is independent of the exogenous reference costs. The incentive scheme internalizes the external benefit (the saving of outage costs for the users) to the network operator (the decision maker); without the incentive scheme, the marginal benefit for the firm would be zero, per definition. The level of β can be seen as a sharing parameter, sharing the risk and possible benefits between firm and consumer. We will discuss the concept of a sharing factor in more detail in section 3.2.

Below, we will switch the perspective from the external effects limiting regulatory efficiency of resilience measures, which can be addressed by the resilience incentive mechanism, towards the challenges arising from internal effects of resilience improvement in the next section.

3.2 The forward-looking budget approach with a sharing factor

In section 2.3, we have briefly explained that expenses may not always be fully reflected in the regulated revenues, resulting in cost-undercoverage. Clearly, if companies anticipate cost-undercoverage, they will be reluctant to make these expenses, leading to underinvestment. Depending on the details of the regulation, there can be a number of reasons to expect cost-undercoverage. If measures to improve resilience are effective, the outage may never occur, in which case the bonus system from section 3.1 will never be activated and we would need another way to recover the costs of the resilience improving measure. Moreover, in section 2.3, we mentioned the base-year effect: expenses in the base year inflate the regulated revenue base (but may be unlikely to be approved), and additional expenses beyond the base year lead to cost-undercoverage. To address this problem, we suggest a forward-looking budget approach with a sharing factor, which we will present and discuss below.

In a forward-looking budget approach, the firm requests an ex-ante budget for a predefined project. The budget must be checked and approved by the regulator. The budget is specified for each year t in the overall period of the budget. Importantly, the budget starts whenever the project starts. This is a key advantage of the budget approach, as it cancels out the base-year effect: the project start *is* the base year.

To strike a balance between risks and incentives of ex-post cost-overruns or -underruns for the network operator and the customers sharing factors may be used that determine the allocation of cost differences ex ante. We define a high sharing factor in such a way that the firm bears a large share of the cost difference between planned and actual costs and the customers a small share (cf. e.g. BMWi, 2020). And accordingly: a low sharing factor means that the grid operator passes on a large share of the cost difference and the grid customers carry most of it.

Formally, the budget approach (B) with a sharing factor can be formulated as follows:

$$B_t = RC_t^{real} + \alpha\left(RC_t^{bud} - RC_t^{real}\right) \tag{6}$$

With:

- α sharing factor, which can range between 0 and 1
- RC^{bud} regulatory costs according to the budget
- RC^{real} real expenses
- t period t

To illustrate, it can readily be seen that with a high sharing factor (say, $\alpha = 1$), the system is a pure budget approach. The firm bears all risk for cost over- und underruns. With a low sharing parameter (say, $\alpha = 0$), the system has become a pure cost-pass-through approach, and the term budget approach becomes meaningless. The idea of sharing factors is, of course, to find a reasonable balance between these extremes, to set a balance between incentives and risk.

Although a budget approach has strong advantages, there are also two significant challenges associated with it. Firstly, calculating and getting approval for the appropriate budget is costly. In order to limit the workload, the budget approach presented here is intended for a limited number of larger projects. Secondly, a budget approach may contain strategic incentives to overestimate the submitted budget. If the sharing factors are high, a budget overrun may lead to inflated profits. It is up to the regulator to evaluate if the submitted budget is appropriate, which can be a difficult task due to the informational disadvantage compared to the firm.

The budget approach is an addition to the resilience incentive mechanism, implying that we should avoid double counting so that the firm is not paid twice for the same expense. The resilience incentive scheme in section 3.1 focusses on optimizing running up the system, given the network and given the user structure. However, the optimum itself can be improved by targeted measures in the network or for users; e.g. installing a back-up system in a demarcated user-area. We should avoid that the network operator is paid twice for such measures: once as these expenses are passed through in the budget approach, and a second time, as it would increase the bonus in the resilience incentive scheme (provided that an outage event occurs). The possible way out seems straightforward: if a resilience-improving measure is part of the budget approach, it should be approved (and checked for usefulness) by the regulator, and the measure can then enter the data to calculate the simulated reference ENS. In that case, the measure would be neutralized in the resilience incentive mechanism. On the other hand, if the measure is not part of the budget approach, the measure will not be reflected in the data for the simulated reference ENS and thus will be reflected (if it is effective at all) in the resilience incentive mechanism when an outage event occurs as the real ENS will be lower than the reference ENS by the effect of the measure.[5]

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[5] As a side-remark, including expenses in the budget approach can set positive counter incentives. Spending under the budget avoids perverse incentives to cause an outage to make artificial profits with the incentive scheme.

4 Concluding remarks

This paper presents an approach for resilience regulation of electricity network operators. Most regulatory models have a quality element, but not a resilience element. Quality regulation is, however, not well equipped to deal with long and large disturbances related to extreme situations. It also does not aim at restoring the system after a breakdown occurs. For these reasons we think that quality regulation does not cover resilience, which requires an additional term.

We define resilience of an electric power system as the ability of the power system to deal quickly and efficiently with *large-scale* and *long-lasting* power interruptions. These are described in the literature as being caused by high-impact, low-frequency (HILF) events. Resilience comprises two related aspects. First, resilience means minimizing the damage caused by a HILF-event and restoring the system optimally. Second, resilience means increasing the robustness of the system, such that HILF-events are unlikely to occur (if man-made or technical) or to cause damage in the first place.

The design of the resilience regulation proposed in this paper has been set up such that the incentives improve economic efficiency in theory, and at the same time, that the scheme can readily be implemented in practice.

In our approach for resilience regulation, we distinguish between external effects and internal effects. Internal means that costs and benefits of an action are primarily incurred by the decision-maker. External means that costs and/or benefits are (partly) incurred by third parties and not by the decision-maker. Our approach for resilience regulation contains two complementary parts. First, a resilience incentive mechanism, which aims at the external effects, and second, a budget approach with a sharing factor targeting the internal effects. Importantly, in practical application, it should be checked that resilience measures are not incentivized twice.

If resilience improves, it is the network users who benefit directly; this is an external effect for the network operator. Therefore, the proposed resilience incentive mechanism aims to internalize this external effect. It is designed as a classical incentive mechanism, where a bonus or malus depends on the difference of the target value compared to some reference value. In a HILF-event, where the mechanism would be activated, the reference outage costs are simulated by the regulator for the specific event in a specific network, using a "naïve" approach: outage costs (i.e. restoring the system) are simulated using the static duration-independent VoLL. The targeted real outage costs are determined by the real outage quantity (Energy Not Supplied), using the duration-dependent CDFs.

Depending on the details of the regulation, expenses may lead to the risk of cost-undercoverage. HILF-events hardly happen, such that the bonus-mechanism may never be activated. The so-called base-year-problem is a renowned example. Thus, there may exist internal hurdles to efficient spending, here triggered by details in the regulation. Our approach of a forward-looking budget approach aims to address such internal effects. In a forward-looking budget approach, the firm requests an ex-ante budget for a predefined project. The budget must be checked and approved by the regulator. The budget is specified for each year t in the overall period of the budget. Importantly, the budget starts whenever the project starts. This is a key advantage of the budget approach, as it cancels out the base-year effect: the project start *is* the base year. It is common to add a sharing factor to a budget approach, to strike a balance between risk and incentives.

As an issue for further research, we note that the calculation of the CDFs is a challenge. They differ for user groups and regions and calculations can thus quickly get out of control. Some aggregation seems to be required. Moreover, for our approach the internal relation between VoLL and the CDFs is quite critical. The precise relation between duration-independent VoLL and duration-dependent CDFs is not well understood both theoretically and practically.

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