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**Short Communication**



# Market signals as adequacy indicators for future flexible power systems

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## Abstract

Existing indicators of electricity system adequacy need to be supplemented with economic performance indicators. As power systems are decarbonized, energy storage technologies are being developed and demand is becoming more flexible. Reliability standards need to reflect the price elasticity of these sources of flexibility. During scarcity situations, this increased demand flexibility may prevent outages, but still lead to high electricity prices. If the average electricity price is well above the average cost of power supply, this can be an indication that the system is not adequate, even if the outage rate does not exceed the current reliability standards.

**Keywords:** electricity markets, renewable energy, adequacy assessment, system adequacy

## INTRODUCTION

Existing indicators of electricity system adequacy are not fit-for-purpose for the future power system. The current European resource adequacy assessment methodology uses reliability standards that underestimate the impact of energy storage and flexibility provided by demand response. In this publication, we refer to flexibility as the ability of the system to maintain system stability through changes in generation and demand. (Definition extended from [11].) In a system with a high degree of flexibility, a generation shortage may not necessarily lead to outages but manifest itself through high electricity prices. Demand flexibility increases reliability, but may cost consumers in terms of convenience or, in case of commercial consumers, lost productivity.

Adequacy is the long-term ability of the power system to meet load, in expected and in unexpected conditions [7]. Conventionally, the focus of adequacy assessment has been on the ability of the electricity generation stock to meet demand under all conditions—the term that was used was generation adequacy. The increase in demand flexibility and the introduction of electricity storage technologies means that they can contribute to the energy balance in the system. Therefore, the focus needs to shift from generation adequacy to system adequacy. This also requires a reconsideration of how we measure adequacy.

## EUROPEAN ADEQUACY ASSESSMENT REGULATION

Conventionally, power system planners aimed for a certain capacity margin in excess of expected demand to secure enough generation during peak load moments. This was defined as the available generation capacity over peak demand [17]. As the power system is being decarbonized and increasingly relies on variable renewable energy, it is no longer possible to assume that generation capacity is relatively constant. For this reason, in recent years, the methodologies for estimating adequacy have evolved from a deterministic to a probabilistic approach.

In Europe, a new methodology called the European Resource Adequacy Assessment (ERAA) was introduced in accordance with Article 23 of the Regulation (EUR) 2019/943 of the European Parliament and of the council on the internal market for electricity [13]. This replaces the Mid-term Adequacy Forecast (MAF), which does not meet the requirements of the Clean Energy Package. The regulation specifies that resource adequacy assessments should contain scenarios with different likelihoods, such as extreme weather scenarios due to climate change. In addition, interconnection targets, energy efficiency, sector integration and carbon price developments should be considered in the scenarios [6]. The ERAA specifies that the reliability standard should be expressed either in

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terms of Loss of Load Expectation (LOLE) or of Expected Energy Not Served (EENS) [1]. The LOLE is the expected number of hours per year (h/y) during which load needs to be shed. This is a common reliability standard; the accepted values are normally between 3 and 8 hours per year [14]. The EENS is the expected volume of energy (GWh/y) that the system will not be able to supply [7].

The ERAA also requires the likelihood of changes in the capacity mix to be considered through an economic viability assessment (EVA). The EVA has two steps. In the first step, the least-cost generation portfolio is established through a Monte Carlo probabilistic analysis. The second step is an iterative process in which the results from the previous step are validated by identifying which assets would be likely to be invested in and which ones would be decommissioned [2, 6].

## THE ROLE OF FLEXIBILITY IN FUTURE ELECTRICITY MARKETS

Flexibility has been widely recognized as a key enabler for the integration of a high share of variable renewable energy sources. Currently, system flexibility is mainly provided by fossil fuel plants. They can be replaced in part by other thermal plants, for instance, that are fueled by biomass or hydrogen, but these will be much more expensive. Energy storage units will also contribute to flexibility, but storage units that provide back-up power and therefore do not charge and discharge frequently will have high costs per cycle. Moreover, demand response will contribute to system adequacy by shifting demand from shortage periods to other times. Demand response can be enhanced by sector coupling, e.g. electrification of transport, industry and space heating.

As the system becomes more flexible, the dynamics of the electricity market will change. At times of abundant variable renewable energy supply, storage units and price-responsive demand will increase their consumption, avoiding the near-to-zero or even negative prices. This situation will lead to a longer demand curve with a gentle slope (see Fig 1a). When supply is scarce and the electricity price is set by the high cost of flexible generation, consumers will bid up against each other. Consumers with a lower willingness to pay—facilitated by smart appliances and digitalization—may choose to reduce their consumption or shift it to another moment. At the times when the price is high enough, storage units will also start to produce electricity (see Fig 1b). Both demand response and storage will dampen the prices. A generation shortage may not necessarily lead to outages, but manifest itself through price spikes.

As the power mix becomes decarbonized, the technologies, the regulation, the players in the market and the resulting electricity prices will evolve continuously. Currently, very high prices near the value of lost load (VOLL) are rarely, if ever, seen in the European electricity markets [3, 8]. As the increase of variable renewable energy sources gradually reduces the operating hours of thermal plants, these units will become increasingly dependent on such high price spikes to recover their fixed costs. Similarly, the business cases of low-carbon generation and of energy storage units, which operate less frequently than on a day–night schedule, will also rely on price spikes. On the other hand, the demand for these expensive resources can be reduced by consumers' willingness to shift load.

The current European reliability standards are calculated with a single VOLL. Ovaere et al. [10] suggest differentiating the VOLL per consumer group, interruption time and other aspects. They demonstrate that prioritizing the reliability of supply based on a differentiated VOLL, instead of a single one, can reduce operational cost by 2–18% in a 118-node network. However, in a consumer-centric power system, price responsive demand is likely to increase. Consumers ideally would indicate their willingness to pay themselves and reduce or shift load if the price is too high. As a result, we share with Swinand et al. [15] the conclusion that the VOLL will become less relevant in future energy systems.

## SHORTCOMINGS OF CURRENT ADEQUACY INDICATORS FOR FUTURE POWER SYSTEMS

Demand flexibility comes at a cost in terms of convenience to household consumers and in lost productivity in case of commercial consumers. Thus, a trade-off will need to be made between investing in flexible generation and storage on the one hand and demand elasticity on the other. Welfare maximization entails optimizing this trade-off; it is the objective of market design to let the market provide the correct signals to all market participants. Although the EVA considers economic aspects in its adequacy assessment, it states that the optimal capacity volume can be estimated through a cost minimization analysis. This approach was valid in a situation without demand response, but it falls short in the presence of consumer price elasticity. In the presence of demand response, the objective is no longer to minimize the cost of power supply, but to maximize overall welfare, taking into account the cost of flexibility to consumers.

Despite consumer demand elasticity, the cost of dispatchable generation and backup storage facilities may be so high that peak prices may be inevitable for recovering their costs. Hence, a certain volume of high prices will be normal. Consequently, the future power system will be characterized by volatile electricity prices, despite the increase in flexibility. In these new price dynamics, a lack of system adequacy—a shortage of dispatchable generation and storage, considering the available demand elasticity—may not necessarily lead to power interruptions. Instead, a lack of adequacy could manifest itself in prolonged periods of high prices, which would cause excess demand reductions, more than the optimal level from a socio-economic perspective. If average prices rise well above the average cost of power supply, this may indicate a lack of investments in the power system, even

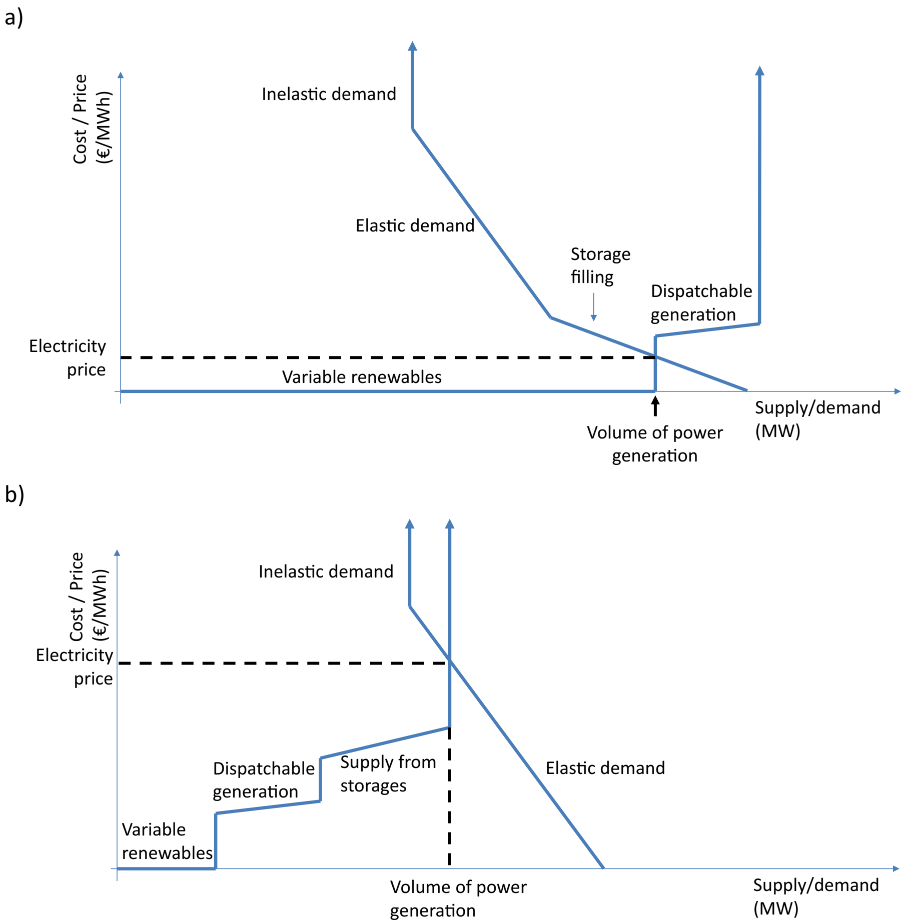


**Figure 1.** Future supply and demand curves with increased flexibility at times of (**a**) abundant variable renewable energy and (**b**) limited variable renewable energy.

if the market demand can be covered by supply. In this case, the current indicators of system adequacy no longer suffice, as they only measure physical shortages.

A second respect in which the ERAA needs to be made future-proof is in the way in which weather uncertainty is handled. While the method considers the general effects of climate change in its scenarios, the real stress test of a future power system will arise during a prolonged combination of adverse weather conditions. For instance in northern climates, a cloudy, cold and windless weather period, with low energy supply and high demand, will be the main challenge. There will be a range of such events, with the larger (more adverse) ones being less likely. But society will become more reliant on electricity and may still want to protect itself against these events, even if they occur not more than once in 20 years. This raises questions of how adequacy will be provided during rare, extreme weather events and how to measure the ability of the energy system to withstand such events in the future.

## MARKET SIGNALS AS ADDITIONAL ADEQUACY INDICATORS

In the Texas blackout of 2021, electricity prices were allowed to rise to 9000 $/MWh; total electricity bills for the shortage period added up to an estimated $47 billion [4]. Although the Texas blackout was not due to a lack of installed capacity, this illustrates how blackouts are not only a matter of unserved energy, but may also produce large income transfers.

If average electricity prices are above the average cost of power supply, this would imply windfall profits to generation companies. The opposite case could imply that there might not be enough incentives to invest and that the security of supply is in danger. The EVA recognized that it is essential to consider the cost recovery of investments, remarking that the revenues should be equal to the costs. In this sense, the EVA accepts that the cost recovery level is an indicator of system adequacy, but its focus is on revenue sufficiency. However, the other side, excess revenues, should also be considered. Perez-Arriaga et al. [12] argued that in systems with significant elasticity of demand, prolonged or frequent periods of high electricity prices can be a supplementary indicator of system stress, in addition to the traditional measures of outage risk.

Flexibility will be an intrinsic aspect of system adequacy in the future; price volatility is an indicator of it, in the sense that high volatility indicates low flexibility [5]. Price volatility implicitly includes many effects; for instance, negative power prices suggest limited ramp-down capabilities, while price spikes indicate shortages. Dozens of technical parameters influence a system's flexibility, and some have countervailing effects on price volatility. Price volatility indicates their net effect on the system. A concern is, however, that market signals in the form of high price spikes might be less socially acceptable than a certain volume of outages, and might therefore lead to regulatory intervention [9]. Moreover, volatile prices increase investment risk and therefore capital cost. Hence, price volatility may also be considered as an indicator of system performance and an early signal of stress in the system.

Future market design should provide a reasonable level of cost recovery at a reasonable risk to investors. Otherwise, underinvestment may lead to average electricity prices well in excess of the average cost of power supply, if not to periods of outages. Price volatility should be dampened with economically efficient flexibility measures, but should not be suppressed, as short-term prices provide a key operational signal to all market parties. Changes in market design such as implementing a capacity market or capacity subscription may dampen price volatility and improve adequacy, even in a low-carbon electricity system [16]. To effectively judge the (expected) performance of new market designs, cost recovery and price volatility need to be added to the set of adequacy indicators.

## CONCLUSION

Adequacy indicators were developed at a time when demand response was limited. Historically, their purpose was to signal whether supply could meet demand. Current adequacy indicators are still based on outage rates and the value of lost load. In a future power system, in which consumers exhibit significant flexibility and thereby avoid (a large share of) physical shortages, these standards are insufficient as indicators of the level of stress in the system. System stress can also be expressed through higher price volatility and excessive prices without physical outages. We propose to add market signals based on the degree of cost recovery and price volatility as indicators of system adequacy.

## SUPPLEMENTARY DATA

Supplementary data are available at *Oxford Open Energy* online.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## AUTHORS' CONTRIBUTIONS

L.V. and I.S.J. both worked on the conceptualization, investigation, writing of the original draft and reviewing and editing of the final draft.

## DATA AVAILABILITY STATEMENT

There are no new data associated with this article.

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