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A Framework to Evaluate Security of Supply in the Electricity Sector

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Abstract

Security of Electricity Supply (SoES) has become a major concern for regulators and policymakers over the last decade. However, most work focusses either more generally on energy security or on a single fuel. We develop a comprehensive but flexible framework to assess the SoES for a single jurisdiction, taking into the account the specificities of electricity. This framework has two aims: (i) provide a snapshot of the situation to understand current weaknesses and determine what actions are required; (ii) capture the evolution over time to evaluate progress and identify potential problems before they materialise. The framework, based on an extensive literature review, consists of twelve dimensions that are critical for SoES. We develop metrics that capture the state and evolution of each dimension. This framework is intended to be a management information tool for all stakeholders, aimed at organising data and structuring its analysis, to enable monitoring the evolution of the SoES, while also functioning as an early-warning system by flagging potential future problems.

Keywords:

Security of supply, electricity, energy security, framework

1. INTRODUCTION

Energy security (ES) has been a concern for regulators and policymakers since the oil crisis in the seventies [1]. However, security of electricity supply (SoES) has only recently become a major issue. Over the last two decades many countries around the world have developed competitive electricity markets [2], and regional markets are emerging [3], implying an increase in cross-border transmission and trade. Research has thus focussed on the consequences of the deregulation [4] and privatisation of the electricity sector [5], including market design [6,7], market regulation, and providing the right incentives [8].

Over the last few years electricity markets have undergone major changes: decisions to close down nuclear capacity, a shift to renewable energies, insufficient new investments in thermal generation, and the decreasing profitability of utility companies. This has resulted in security of supply becoming a central issue for all the actors of the electricity industry, from consumers, through utility companies to regulators and policymakers; several national regulators have expressed concerns about long-term SoES, e.g., in the UK [9] and in Belgium [10].

The particularities of electricity systems, the changes in the market structure, and the pressure resulting from environmentally driven policies, together with technological innovations over the last thirty years, have also led to a notable change in the technologies used for electricity generation. The significant shift towards gas-fired turbines as the main technology for newly installed conventional generation capacity [8] has, among others, made the European electricity market increasingly dependent on gas imports [11]. Recently, renewable energy technologies have reached a significant share of new installed capacity [12,13]. Regional issues further complicate the situation. For instance, a significant share of Europe's existing generation capacity will soon become obsolete, and thus needs to be replaced [14]. Several countries intend to phase-out nuclear plants, which often represent a non-trivial share of their generation; this will affect future capacity adequacy [15].

These issues need to be understood in the context of environmental factors. For instance, while a move from old generation plants to new gas fired plants typically reduces emissions, the opposite is true when gas fired plants replace nuclear ones [16]. This raises the question of the degree to which renewables can play a role in this replacement. Furthermore, in many countries the grid is more fragile than anticipated, as illustrated by several large blackouts in Europe and the USA [17]. Finally, there is the question of whether consumers are able to understand these issues, and will accept to pay what might be significantly higher tariffs to ensure SoES, generally considered a “non-issue” until blackouts start occurring [18,19]. The magnitude of the economic impact of such events is huge. For instance, the blackout in the U.S.A in 2003 costed between 4 and 10 billion U.S. dollars [20], and according to a study of the Swiss Federal Office of Energy, the cost of a blackout in Switzerland varies between 8 and 30 million CHF per minute [21]. Such estimates do not include less tangible consequences, such as loss of reputation.

Finally, there is the question of time horizon. Investment planning in the electricity system is a long-term process: building new thermal capacity requires at least three years, large hydro might take up to ten years, and the expected lifetime of investments ranges from twenty to more than fifty years. While disruptions to the electricity supply are often attributed to sudden, short term, events (e.g., grid failure, unscheduled plant outage, unexpected demand peak), the true underlying cause is a lack of long-term planning. These disruptions force the regulators to become reactive rather than proactive, preventing them from taking a long-term perspective.

In this paper we develop a framework to assess the level of security of supply of the electricity sector, and its evolution over time, for a single jurisdiction. The term framework refers to a set of principles, ideas, etc., used to form a judgement and reach a decision. Our aim is to provide a framework for regulators, policy makers, utilities and other stakeholders to understand, asses and act on the state of the security of supply of an electricity system.

In legal terms, a jurisdiction is formally defined as "the limits or territory within which authority may be exercised" [22]. In our context, the electricity sector, this refers to a geographical area under the authority of a single regulator, governed by a common set of rules. A jurisdiction may or may not coincide with national borders or with the area under the control of a single system operator. For instance, despite being divided into different areas, each with its own system operator, Germany is considered as a single jurisdiction, because the legislation of its market is determined at the national level [23]. On the contrary, while in the USA the Federal Energy Regulatory Commission (FERC) provides general guidelines and directives to the regional markets, there are well-established, autonomous, regional markets (e.g., PJM, NYISO and ERCOT), each with its own independent system operator and public utilities commission, resulting in very different regulatory frameworks; we therefore consider these regional markets to be jurisdictions. We thus use the term jurisdiction to refer to an area under the control of a single regulator or policy maker.

The paper is organised as follows: first we review the existing literature and outline our framework. Then we develop our framework and the metrics necessary for its evaluation. Next we elaborate on how this framework can be used, and conclude with a more general discussion, including the limitations of the proposed framework.

2. LITERATURE REVIEW

Jewell *et al*. [24] define energy security as low vulnerability of vital energy systems. More concretely, according to the IEA [25], energy security refers to the uninterrupted availability of energy sources at an affordable price. The IEA [26] emphasises the importance of the time-frame: while in the short-term energy security focuses on the ability of the energy system to react promptly to sudden changes within the supply-demand balance, in the long-term it mainly deals with timely investments to supply energy in line with economic developments and sustainable environmental needs. A similar definition is provided by Chester [27], who suggests that the concept is based on ‘reliability’ and ‘adequacy’ at ‘reasonable’ market-determined energy prices. Likewise, Sovacool *et al*. [28] define energy security as “how to equitably provide available, affordable, reliable, efficient, environmentally benign, proactively governed and socially acceptable energy services to end-users” (p. 5846). An extensive review of energy security definitions is presented in Winzer [29]. These definitions illustrate that SoES is a complex concept, with a very broad scope.

Previous work has focused on the conceptualisation of the multiple factors affecting ES, using different approaches depending on the specific fuels analysed, the geographic dimension and the time-horizon under consideration. Other work has focused on specific energy sectors or primary energy sources, (mainly oil, and to a lesser degree gas). Examples include [30–33]. Studies regarding security of oil supply tend to take a global view, while those concerning the gas industry, due to the network aspects, take a regional view [34].

One of the most widely used frameworks, proposed by the APERC [35], defines ES using the four A's: availability, accessibility, affordability and acceptability. Several authors have built on this framework. For instance, Jonsson *et al*. [36] base their work on the first three A's, focusing on whether energy systems are exposed to insecurity (e.g., infrastructural disturbances), or whether they create insecurity, (e.g., energy used as a "weapon" in geopolitics). Cherp and Jewell [37] build on this definition by discussing whether the four A's deal with the fundamentals of security in the broadest sense. Likewise, Gracceva and Zeniewski [38] propose five properties, strongly related to the four A's, that energy systems should have to ensure supply: stability, flexibility, resilience, market adequacy and robustness. They also identify potential threats to those properties and classify them according to the time-horizon of their impact and the segment of the supply chain that they affect.

Other authors focus on defining the different dimensions of ES, and indicators to assess these, rather than on conceptualising a definition for ES. For instance, Von Hippel *et al*. [39] propose four major elements that should be included in a definition of energy security: the environment, technology, demand-side management and domestic socio-cultural and political factors. Cherp *et al*. [40] insist on the need to include environmental factors given the tangible impact of climate change on energy systems. Vivoda [41] adds three further dimensions: human security, international issues and policy aspects. This work [39,41] is closely related to that based on the APERC's four A's [35]. For instance, an environmentally friendly electricity system will gain acceptability from society. Likewise, Kruyt *et al*. [42] argue that their four dimensions of ES (globalisation, regionalisation, economic efficiency and environmental acceptability) are strongly linked to the four A's. For instance, political embargoes (regionalisation dimension) endanger the accessibility (property) of energy resources.

Several authors focus on evaluating the multiple dimensions of ES. Kruyt *et al.* [42] provide a review of the available indicators to assess ES in the long-term, while Löschel *et al.* [43] elaborate on two indicators proposed by the IEA for evaluating the risk of price disturbances and physical availability of fossil fuels. Others develop a single metric for ES by aggregating the indicators used to measure the different dimensions. For instance, Sovaccol [28] and Vivoda [41] both calculate a global index to assess the level of energy security in the Asia-Pacific region. The very different nature of the dimensions of ES casts doubts on the usefulness of aggregate indicators: a good performance on one dimension will not necessarily compensate a poor performance on another one; worse, a reasonable overall performance could hide critical situation on one dimension. Several authors, including [38], are very critical towards the use of indicators due to the simplifications required for their calculation.

Two of the more comprehensive ES frameworks found in the literature are the Model of Short-term Energy Security (MOSES) [44] and the General Energy Assessment (GEA) [40]. The main difference between these two studies is the time frame. While the former focusses on issues affecting ES in the short-term, the latter considers the short- to medium-term. The former considers how an energy system's resilience could mitigate the risks of energy disruptions related to domestic and foreign external factors. The latter proposes three main perspectives (robustness, sovereignty and resilience) to classify threats and mitigation strategies. Thus, while these studies incorporate some aspects of the electricity system, we consider the level of detail insufficient to evaluate the security of electricity supply.

Although the electricity sector and the generation technologies (e.g., hydropower and nuclear power) are included as one element of the ES frameworks previously mentioned [40,44], there is relatively little work focusing specifically on the SoES. In particular, while the Cherp *et al.*

framework [40] includes a wide range of potential threats to energy systems, it only provides a very narrow set of indicators for electricity systems. Furthermore, the impact of renewable energies, which are leading the electricity markets' transition and reshaping their dynamics, is not analysed in detail. Overall, studies analysing the SoES focus on the supply-side view of the problem, dismissing the increasingly active role of demand.

Several frameworks focused on the electricity sector have been developed [45,46]. In both papers, the frameworks are tailored to national specificities. Consequently, they ignore important dimensions, such as the environmental impact and the profitability of peak generators, which hinders their adaptability to other regions. The framework developed by Nepal and Jamasb [20] focusses on the network risks, and proposes an aggregated risk measure.

Finally, there is a significant amount of work on estimating the value of SoES. For instance, de Nooij *et al*. [47] compute estimates for different economic sectors in the Netherlands, based on the opportunity cost resulting from an interruption of the electricity supply. A similar analysis has been performed for Spain [48].

We can thus conclude that, although most studies acknowledge the multidimensional nature of security of supply, they focus on energy systems as a whole. The few studies that specifically analyse SoES, do not attempt to provide a comprehensive and general framework; they are context-dependant, tailored to the particular features of a country or adapted to specific scenarios [38,45]. Assessing the SoES of a jurisdiction requires a sound understanding of its particularities, and the conclusions and policy implications are necessarily context dependant. Still, we believe that an appropriate framework should be comprehensive and sufficiently flexible to be adaptable to the electricity sector of any jurisdiction.

3. FRAMEWORK DEVELOPMENT: OBJECTIVE AND BOUNDARIES

Electricity markets deserve particular attention due to their specific characteristics. These include non-storability of electricity (thus requiring real-time balancing of demand and supply), long construction delays and life-times for generation and transmission infrastructure, low demand elasticity, rigidity of the transport infrastructure and the regional nature of markets [49]. These elements differentiate electricity from other energy markets, such as oil or gas, which can be stored and transported over long distances. Also, oil and gas are traded in global markets, with a global price, while electricity is priced locally; several prices can co-exist inside a single country, e.g., in Norway [50]. Furthermore, the infrastructure and the regulation differ significantly from most other energy forms. Therefore there is a need for a framework designed specifically for electricity.

We develop a framework focused on the electricity sector of a single jurisdiction. This framework is comprehensive enough to ensure that the central elements determining SoES are taken into account, while being sufficiently flexible to be adaptable to the specificities of most jurisdictions. Our framework enables the various stakeholders to monitor the changes in the industry. We do not make any attempt to prioritise the different dimensions, as this would induce users to focus on a (small) subset of measures. We believe all are important and need to be monitored, allowing policy makers and regulators to act on the appropriate parts of the system to ensure SoES.

Our framework differs from previous work in the area of energy security in the following respects:

- Given its specificities, we consider only the electricity sector, not the energy sector as a whole.
- We aim to develop a set of measures that can be used to evaluate the current state of SoES, using a multi-dimensional view; we do not try to aggregate these measures into one single indicator.
- We aim to develop a framework that will allow decision makers to follow the development of SoES over time, enabling them to observe the changes that take place in the different dimensions.
- We focus on a single jurisdiction, because the ability of regulators and policy makers to act on signals indicating potential problems is limited to their jurisdiction.
- The framework is not intended to compare jurisdictions; we do not prioritise the dimensions, nor do we provide a single measure that would enable such a comparison. The framework could be used to make comparisons between jurisdictions but, given the specificities of each jurisdiction, we do not believe that this would provide any useful insights for a regulator attempting to solve problems in the jurisdiction he is in charge of. Furthermore, the disaggregated nature of the framework makes a comparison across jurisdictions difficult.

Based on an extensive literature review of work analysing security of supply in energy systems, we have identified twelve dimensions that influence the performance of an electricity system. This review included a wide variety of approaches, ranging from quantitative frameworks to policy papers. It covered different aspects such as the primary energy sources and potential energy-uses. We considered studies that took a disaggregated, as well as an aggregated approach to evaluating security of supply.

For each dimension we either suggest an existing metric or develop a new one. The metrics we propose can be calculated using data that is (usually) publicly available, as this enables a wider use. While more accurate measures exist, their calculation requires more sophisticated tools, e.g., operational models of electricity systems. These cases will be discussed in detail in the next section.

Another important aspect of the framework is its longitudinal nature. Drawing a comparison with accounting, numbers for a single year are not particular useful to understand the development of a company. Similarly, to valuate an electricity system, it is necessary to monitor the evolution of the indicators over several years, focussing on those that worsen, and taking action when an indicator points to a potential threat to SoES in the near- or medium-term. Given the long investment delays in this sector, the framework should function as an early-warning system, aimed at preventing future SoES problems.

In this paper we have chosen to focus on a detailed motivation of the framework, its dimensions, and their measures, at the expense of providing a numerical example or a case study. Indeed, applying our framework to a specific jurisdiction is a major undertaking; the outcome of such an endeavour would be a 100-page policy report.

4. DIMENSIONS OF THE FRAMEWORK

In this section we discuss the twelve key dimensions policymakers should considered when assessing security of supply in an electricity market. For each dimension we develop one or more indicators to evaluate the current state of the system.

4.1 Generation adequacy

This dimension refers to a jurisdiction's capability to meet domestic demand in the short- and medium-term with its own generation capacity. SoES has mostly been approached as a capacity adequacy problem [49,51–53], which is appropriate as demand has to be matched in real-time; capacity should thus be available in the right amount at the right time. Capacity adequacy has traditionally been measured by the reserve margin, the ratio between installed capacity and peak-demand. The increasing role of renewable intermittent resources makes the reserve margin less informative: while their long-term average production level is known, their actual availability at a given point in time is difficult to predict. This has led to an increasing use of the de-rated capacity margin to measure a system’s capacity to meet annual peak-demand [54,55].

Rather than considering peak-demand, we suggest focussing on the hour that exhibits the lowest de-rated margin within a year. For systems with, for instance, a significant share of hydro and annual peak-demand occurring during summer afternoons, this measure may be more representative as the tightest margin does not necessarily occur when demand peaks. One example is California, where in 2009 the de-rated margin was lower in winter (10%) than in summer (14%), when demand peaked [56].

Still, this measure could overestimate capacity adequacy in countries with a significant share of hydro-storage generation, as this technology's de-rating factor is generally assumed to exceed 80%, ignoring the constraint created by a limited water supply. In such a situation the energy margin, which estimates the ratio between the surplus (or lack of) energy and demand, might be more appropriate [57]. Depending on the generation mix of a country, we thus propose the de-rated capacity margin or the energy margin as indicator of generation capacity adequacy.

4.2 Resilience

This concept is defined as “the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event” [58]. While capacity adequacy captures energy availability under normal conditions, resilience refers to the capacity of electricity systems to maintain an uninterrupted electricity supply in the face of sudden changes in resource availability.

Causes of disruption can be environmental, technological or political factors, human error or deliberate actions. One example of an environmental factor is the ENSO phenomenon in South American countries, which can result in reservoir inflows being 30% lower than normal for periods lasting from 6 months to over a year. The consequences can be devastating as illustrated by the programmed blackouts in Colombia in the 1990s [4]. Turning to political factors, a country without gas reserves, relying mainly on CCGT generation (e.g., Ukraine) might be seriously affected by a disruption in the gas supply [59]. This dimension is thus about ensuring that available capacity can actually be used, so the jurisdiction is able to meet demand in the short-term under changing supply availability.

Measuring the intrinsic ability of a country to adapt to sudden change is quite abstract; running “real” experiments to establish this capability is inconceivable, and simulation experiments only provide limited insights. This makes it necessary to rely on proxies to track the evolution of resilience. It has been argued that geographical expansion through the interconnection of electricity markets reduces vulnerability, as a larger entity is more likely to be able to absorb short-term disruptions [60]. However, there is no clear empirical evidence yet for how strong these effects are [61].

Dependence on one or a few technologies endangers resilience as the system becomes more vulnerable to changes in the availability of the resource used by that technology (e.g., sudden gas cuts in a country highly dependent on CCGT). A more diversified country will be in a better position to prevent shortages resulting from external events. Resilience can thus be measured as the concentration of generation technologies, using an approach similar to the Herfindahl - Hirschman index (HHI): the higher the value of this index, the higher the dependency on a limited number of technologies.

4.3 Reliability

This concept is related to the quality of the service, i.e., electricity supply. Since electricity is a non-differentiated product, quality refers exclusively to being uninterrupted. While the metrics used above to assess capacity adequacy and resilience show a trend in SoES, they are not as such a measure of the risk of interruption. Nor do they provide any information on how large an outage event may be. Reliability thus refers to the capability of the system to provide an uninterrupted supply. The most commonly used metric is the System Average Interruption Duration Index (SAIDI), i.e., the ratio between the total annual customer-minutes without service and the total number of customers in the system [20]. This data is typically provided by the Transmission system operator (TSO), based on information from the utilities, and is used as a benchmark in reliability improvement programmes.

4.4 Supply flexibility

Electricity systems must be able to deal with sudden imbalances, whether due to inaccurate demand forecasts, technical problems or, more recently the inherent variability of intermittent renewable generation sources. Events like a solar eclipse or an unexpected thunderstorm suddenly become of major concern when photovoltaic plays a significant part in the production [62]. Generators with fast response times, e.g., hydro-storage plants and CCGT, can meet sudden fluctuations in demand or help compensate for the loss of other power supply options [63].

While variable renewable energies (VRES), i.e., wind and solar (PV), create short-term problems, countries with a large share of hydro, but limited reservoirs, face medium-term problems as they also need sufficient non-hydro capacity to withstand longer periods of drought caused by local weather systems [4]. As metric for flexibility, we use the ratio between, on the one hand, the available flexible load (hydro-storage and CCGT) and, on the other hand, the maximal load supplied by VRES over the last year.

4.5 Condition of the grid

This dimension refers to grid performance and adequacy. The degree to which both transport capacity adequacy and grid ageing affect the reliability of the system depends on grid topology, which in turn depends on the geographical distribution of the demand/supply nodes. The locational constraints of PV and wind lead to a much more decentralised generation system, which increases topological complexity. In the presence of congested power-lines, the reorganisation of electricity flows in a highly decentralised system, following either an ageing failure or a power loss, becomes increasingly complicated and might lead to disruption [64]. Older systems operating close to their saturation level are more likely to suffer cascade events, as occurred in the USA in 2003 and in Europe in 2003 and 2006 [17,65].

Grid capacity adequacy

While capacity adequacy assessments tend to focus exclusively on the generation segment, the adequacy of power-grid capacity also deserves attention, as transportation of electricity depends on the transmission and distribution grid. Some work has focused on the impact of different congestion management mechanisms on investments in cross-border interconnectors [66,67] and on the TSO costs within a jurisdiction.

Grid congestion leads to deterioration of service quality due to frequent power outages [20]. It can also lead to higher prices and to an inefficient allocation of resources, highlighted by significant price differences among pricing zones within a single market. For instance, in 2012 average prices in Norway differed by more than 8% across regions [50]. In Germany, curtailment of wind power plants due to network congestion has increased in recent years [68].There are several mechanisms to deal with congestion management within a market; the two most widely used are market splitting and redispatch. In the former a market is split into different zones, leading to zonal prices. This mechanism is used among others in Nordpool and Italy. In the latter some generators, whose power contributes to congestion, are asked to produce less while others are requested to increase production. This mechanism is used for instance in Germany and some markets in the USA. Kumar *et al*. [69] provide a detailed review of the different mechanisms. According to the type of mechanism, Alomoush [70] proposes different indicators to measure congestion and its severity. With zonal prices, he proposes an “index of locational marginal prices” as measure of the differences between zonal prices and the unconstrained marginal price. The unconstrained marginal price might be difficult to calculate, or not publicly available; one could instead use the weighted average of zonal prices. When there is redispatching, [70] proposes the “Index of Total Congestion Charge”, which is the ratio between the total congestion charge (TCC) and the total system generation. TCC expresses the difference between what consumers pay (strictly for the electricity, i.e., excluding any other fees) and what generators are paid. Since TCC data can be unavailable, an alternative could be the number of hours with redispatching, such as reported for Germany [71]. Alternatively, congestion might be measured in just a single critical power line. This can be done using the power transfer distribution factor, which is the physical flow on the transmission line in question as a fraction of the flow between the two points connected by the power line.

Grid ageing

A significant share of grid infrastructure in western countries was developed after the Second World War. For instance, two thirds of Swiss transmission capacity was built in the 1950s and the 1960s [72] and 70% of the transmission lines and power transformers of the USA's grid are now over 25 years old [73]. Unplanned interruptions due to system breakdowns and increased planned outages due to maintenance and upgrades are more frequent in old and/or poorly maintained networks [20]. The share of ageing failures grows significantly when components age [74]. Operating conditions such as bad weather may also increase a component’s failure rate, particularly in the presence of ageing components [75]. As a result, the age of the grid’s components contributes to the incidence of weather-related power outages.

Investments in transmission should aim not only at relieving congestion by adding transmission capacity, but also at modernising and increasing the resilience of the grid. The amounts invested, while a useful indicator of the state of the network, are not a satisfactory measure as a component is not restored to an as good as new condition from a reliability perspective [76]. The age of the grid seems a more appropriate indicator of current performance and potential problems. In particular, it provides an indication of the investments that will be required in the medium- to long-term to maintain reliable transmission.

4.6 Demand management

Security of supply can also be improved by influencing demand, referred to as demand side management (DSM); this includes demand conservation, consumer efficiency, and load-shifting.

Conservation

Conservation is the reduction in energy demand resulting from users foregoing certain services. This can be achieved, among others, by direct load control, demand bidding and industrial/commercial programmes, such as interruptible contracts [77]. Conservation usually provides only a temporary demand reduction in response to either higher prices or other external pressures [78]. We do not propose a specific metric for this aspect as it can be measured by subtracting interruptible demand from peak demand when calculating the de-rated margin. For instance, the California ISO accounts for demand response and interruptible load programmes when assessing capacity adequacy [79].

Efficiency

Consumer efficiency is the ratio of energy service to the energy required to deliver that service. Improving consumer efficiency decreases demand [78], leading to higher margins of available capacity and a higher level of SoES. This dimension thus focuses on the impact of energy efficiency measures, e.g., white certificates, energy efficiency obligations, and electricity savings trusts [80]. A successful demand side management programme focussing on efficiency gains (e.g., electricity saving light bulbs or improved insulation) will also reduce electricity intensity. To measure efficiency we use electricity intensity (adapted from Sovacool [28]), which represents the economic activity of a country (GDP) per unit of electricity consumed. This metric is preferable to the electricity consumption to avoid interpreting a decrease in consumption due to an economic recession as improved efficiency [81,82].

Demand flexibility

Unlike conservation and efficiency measures, load-shifting does not imply a demand reduction, but it relieves the stress on the electricity systems during demand spikes, or more generally, when demand/supply imbalances occur. The more flexible the demand, the more load can be shifted when needed. Consequently, increasing demand flexibility also contributes to the SoES. A TSO might be interested in “load shifting” or “load shaping” to fill a load valley, allowing for more efficient energy scheduling. This can be done either to increase demand when there is excess production, e.g., wind at night, or to dampen demand when prices are high [83]. Demand flexibility is thus strongly linked to capacity adequacy: for a given energy margin, SoES is higher when demand is more flexible.

As metric, we use estimates of flexible demand relative to total demand. As explained above, shifted load is not necessarily peak-demand but rather demand that can be ‘allocated’ in a more efficient way to match the generation profile, which usually leads to a more cost-effective allocation of resources. As meeting annual peak-demand tends to remains the main challenge of electricity system planners, load shifts generally lead to flatter load curves. On the positive side, these flatter load curves avoid price spikes and decrease generators' uncertainty regarding their operating hours. On the negative side, they may result in the highest cost producers no longer being profitable and withdrawing from the market, thus creating an availability problem [84]. Therefore, the long-term effects of such measures need to be monitored carefully, as the benefit in terms of SoES from a higher de-rated margin resulting from a flatter load curve could be more than off-set by the closure of a peak unit due to decreased profitability.

4.7 Regulatory efficiency

Regulation should aim at ensuring well-functioning electricity markets; this includes sending the right signals to investors at the right time, without need for repeated regulatory interventions. Here we focus specifically on market performance and the need to provide incentives to conventional generators; environmental regulations are included in the sustainability dimension. There is also a link with the socio-cultural dimension, e.g., the main barriers to building new high-voltage lines in the U.S.A and optimizing the grid are not so much technical or economic, as bureaucratic [85].

Market performance

This dimension focuses mainly on the prevention of market power, which could lead to market distortions, such as artificially high prices [86]. For instance, reform failures in the 90s in Norway and California, leading to uncertainty, created transmission congestion and a capacity shortage. This resulted in market power, leading to high prices [87]. Market power is generally more likely when there are fewer companies, i.e., competition is positively correlated with the number of competitors [88]. Regulation aimed at preventing market concentration has been one of the main issues for regulators after market liberalisation. For instance, it is recognised by most experts that there were too few companies in the England and Wales market in the early nineties, resulting in relatively high prices, until the regulator intervened [89]. Concentration is often measured by the HHI, using the market share of the five largest companies in the sector [90]. A high value indicates a high concentration, which is likely to lead to higher prices, thus decreasing affordability.

Incentives for conventional generators

Environmental pressures, combined with the current uncompetitive cost-level of VRES, have induced policy-makers to provide incentives for these technologies. However, this support leads to a lower residual demand for thermal generators, who become economically unviable. Still, thermal units are required for balancing and as backup during adverse weather conditions, when output from renewables is low, leading to regulatory concerns [84]. This has resulted in the implementation of different forms of support for thermal generation, such as capacity markets, capacity payments and strategic reserves [91,92]. While supporting VRES can be considered a long-term investment, aimed at allowing the technology to mature and achieve grid parity, supporting conventional generators indicates a market failure. The percentage of the tariff allocated to supporting conventional generators, i.e., hydro, nuclear and thermal generators, measures the support needed to keep these technologies online.

4.8 Sustainability

In the literature, the term "sustainability" is usually found to refer solely to the environmental implications of energy use: a sustainable system is unlikely to damage the environment. This aspect increasingly dominates current energy policy decisions at national and EU levels [93]. Furthermore, environmental commitments are acknowledged to have a considerable impact on security of supply because of the significant transformations and investments required to reduce the environmental impact of energy systems.

However, the concept of sustainability goes beyond the environmental aspect: it includes longer-term economic viability as well as the long-term physical availability of resources. While most studies addressing the economic aspect of sustainability focus on the fact that energy should be affordable for consumers, little attention has been given to the supply-side: energy production should be profitable so as to ensure the availability of facilities to produce and transport energy.

Finally, energy availability is one of the dimensions receiving major attention in studies concerning energy security. This dimension refers mainly to the existence of resources, which is particularly important in fossil fuel markets. Still, fossil fuels are used not only to generate electricity, but also for, among others, transportation and heating. Therefore their availability specifically for electricity generation is hard to quantify. However, given the exhaustible character of fossil fuels, relying on these to generate electricity endangers the future availability of electricity. We next discuss in more depth these four aspects of sustainability: environmental sustainability, affordability, profitability, and fossil fuel dependency.

Environmental sustainability

Discussion persists on whether environmental sustainability should be considered as one of the dimensions of SoES; for instance [93] and [38] implicitly split environmental sustainability and energy security. However, environmental consequences of energy production and consumption affect energy systems; e.g., climate change has an effect on water patterns and availability [40]. According to van Vliet *et al*. [94] over two thirds of hydropower plants will face a reduction in their capacity due to reduced inflows and increased sedimentation. Thermoelectric plants will also be affected as they use large amount of water for their cooling systems. Given that 98% of world generation comes from the two sources, this impact cannot be ignored [94]. Climate change is also expected to affect the demand-side; for instance, Eskeland and Mideksa [95] show that in Europe an increase in temperature will result in significantly higher demand.

Given the complexity of measuring to what extent electricity-related environmental impacts affect the electricity sector, we focus on the driver of climate change, emissions, a directly measurable environmental aspect. We propose the annual carbon emissions per unit of production, e.g., TWh. Depending on a country's characteristics, other emissions, such as sulphur, particles or NO_x, may need to be considered.

Affordability

There exist many approaches to measuring affordability. Some authors address the issue of high costs in energy markets by considering fuel prices as a metric [28,42,43]. Other metrics depend on very detailed information that is not always available, e.g., energy systems' internal costs [96]. However, these metrics do not take into account the purchasing power of consumers. A suitable metric should thus relate costs and income, e.g., by calculating the ratio between fuel costs and GDP [41] or fuel expenses as a share of household revenues [97]. A measure for the affordability of electricity tariffs should specifically incorporate consumers' income [27]; we therefore adapt the approach of [97] and define the metric as the ratio between the average cost of electricity cost per household and the median household wage.

The validity of this measure depends on the electricity grid coverage. Developing countries often have high income inequality and/or low coverage. Therefore, comparing the cost of electricity to the median income in a country with high income inequality might provide a misleading view of affordability, as the indicator hides the real cost of electricity for the poorest part of the population. Likewise, a high level of affordability in a country with low coverage is a poor indicator as it does not capture access to electricity. Furthermore, in some situations there can be a trade-off between electricity tariffs and the electricity coverage policy, when the income from high tariffs is dedicated to improving coverage. If countries have differentiated tariffs depending on household income (e.g., the Ontario Electricity Support Program [98]), this should be taken into account when evaluating this measure.

Profitability

On the supply side, a measure of the economic sustainability of the system should reflect the adequacy of generators' revenues. A price decrease does not necessarily reduce generators' profitability as it can result from technological progress, such as a more efficient use of fuel [89]. Similarly, a price increase resulting from changing oil and gas prices or exchange rates does not necessarily affect the generators’ profitability.

We focus on generators because the transmission and retail segments usually have regulated tariffs that ensure their economic viability. This is not the case of the generators, who are increasingly facing very difficult market conditions due to the larger penetration of subsidised VRES [99]. Consequently, not only are prices decreasing, but so is the residual load.

It is important to distinguish between base-load and peak-load generators. Base-load generators are likely to be profitable as the price mostly exceeds their marginal costs. Marginal producers, i.e., peak units, have relatively short production hours and may at times only recover their marginal costs, leaving them without a margin to cover their fixed costs. The profitability of these generators, who are the most affected by large VRES penetration, is important: prolonged periods of insufficient profitability result in few or no investments in new capacity, and may even cause mothballing or early closures, leading to a shortage.

Data about individual plants' profitability is rarely publicly available, and mostly unknown even to TSOs; we thus suggest as alternative metric the load factor of conventional and peak generators. A significant decrease of their load factor should act as an early-warning, signalling potential future problems. For instance, the Belgian gas-power plant Drogenbos used to operate on average 8,000 hours/year, but in the first quarter of 2014 it only operated 100 hours [100]; likewise, the German plants Irsching 4 and 5 supplied no merchant power at all in 2014 and were only dispatched when they were needed to stabilize the network [101]. The resulting lack of profitability is endangering their availability; these and other plants are being mothballed across Europe [102].

Fossil fuel dependency

Although dependency on fossil-fuels is included by [41] in the measurement of the environmental impact, the explicit inclusion in our framework is not redundant. This is indeed tightly related to the economic and environmental aspects: fossil-fuels are expected to become more expensive not only because of the environmental commitments, but also because of their depletion.

The finite nature of fossil fuels will require the eventual replacement of fossil-based generation. While this can partly be achieved through a decrease in demand, a shift to renewable generation technologies, existing or new, will be necessary in the long-term. This might be possible with technological progress in electricity generation and storage [103], but future technological breakthroughs are difficult to predict. As a measure we propose the ratio between current fossil-based generation and the expansion potential of generation by renewable sources.

4.9 Geopolitics

Yergin [104] recognises that energy security is affected by international relations. Import dependency has attracted major attention, in particular in the oil and gas markets, as noncompetitive pricing could result from the exercise of market-power by fuel exporters, with adverse socio-economic implications for consumers [31]. Furthermore, import dependency is seen as a threat because of some suppliers' political instability [27,41]. There are numerous examples of countries using gas as a political instrument; examples include Russia [105] and Bolivia [106]. Dependency on imported gas for electricity is recognised as a threat to SoES.

While the increased interconnection of electricity markets has been seen as a major achievement of foreign policy to promote SoES, this exposes the system to threats of cascade failures [20]. Furthermore, reliance on imported electricity might decrease investment incentives in the long-term [52]. The degree to which a country is vulnerable depends on the concentration of imports. We distinguish two main sub-dimensions: dependency and vulnerability. The metrics we propose for these dimensions are adapted from Constantini *et al*. [107] to be applicable to single jurisdictions.

Dependency

This dimension captures to what extent imports are necessary to meet local demand. Imports include direct electricity imports, as well as imports of primary fuels used for electricity generation, e.g., gas, coal and oil. The higher the percentage, the more dependent the country is; particular attention should be given to the evolution over time. An analysis of the stability of the countries of origin, the relationships with exporters and the balance of trade are also essential. For instance, the EU is developing an integrated electricity market, and can be considered as politically stable, implying that significant exchanges between EU countries should not be seen as a threat from a geopolitical point of view. However, sudden shortages due to extreme weather conditions or significant price changes could threaten SoES in countries which are net importers, e.g., Italy.

Vulnerability

This dimension focuses on the concentration of imports, which depends on volumes imported and the number of jurisdictions where imports come from. As was the case for resilience of generation capacity, the aim is to highlight the risk of relying on a limited number of fuels, or on electricity from a few jurisdictions. The SoES in the importing jurisdiction could be seriously endangered in case of political problems or extreme weather conditions in the exporting jurisdictions. This was observed for instance during the Californian crisis in 2000 and 2001, which was caused among others by an excessive dependence on imports from the Northwest of the USA [108]. We suggest two metrics, similar to the HHI, to measure the concentration of import jurisdictions and of electricity and primary fuels respectively. In their analysis of oil trade, Cohen *et al*. [30] propose to adjust the metric for political risk. Their arguments also apply to electricity markets, as political factors in the exporting jurisdiction could lead to sudden disruptions. We thus propose the use of the “Government effectiveness” index, provided by the Global Risk Service and included in the Worldwide Governance Indicators – WGI [109], which measures how confident businesses can be of the continuity of economic policy.

4.10 Socio-cultural factors

Opposition caused by environmental concerns may result in investments in new transmission or generation capacity being delayed, suspended or even cancelled. For instance, a heated debate about wind energy and hydropower is taking place in Switzerland. Opponents of wind energy projects criticise the construction of wind farms, because of their impact on the landscape, birds, etc. These debates have led to the cancellation of several projects [110]. Likewise, hydropower expansion potential is severely limited because opponents criticise the impact of these projects on water flows and ecosystems [111]. The installation of new high-voltage transmission lines is often objected to by people living close-by. Recent examples include projects in Switzerland [112], Germany [113] and the USA [85]. Furthermore, several wind projects in the north of Germany have been suspended due to the resistance to a new north-south “super-grid” [114].

Opposition is not limited to new technologies. For instance, nuclear energy has faced political and grassroot pressure for many decades: a moratorium on new plants was launched in California in the 70s [115]. More recently, following the 2011 Fukushima accident, Germany closed several plants [116] and Switzerland plans to close at least a third of its nuclear capacity between 2019 and 2032 [117]. In these decisions, political arguments and fear often outweigh technical, economic and security arguments [118]. These decisions will have a significant influence on the capacity adequacy issue discussed above, and there is evidence that prices might increase as a result of nuclear plant shutdowns [119].

Although socio-cultural factors are rather subjective, they could be approximated by estimates of the total time required to implement a project (including the time for consultations and delays due to appeals). For instance, installing a new high voltage grid in Switzerland takes between 9 and 12 years [120], a multiple of the actual construction time.

4.11 Access

For many developing countries it is furthermore necessary to keep track of the share of the population who have the physical possibility of connecting to the grid and receive electricity, i.e., energy access; this can in some countries be less than half the population [121]. Indeed, there could be a trade-off between increasing the share of the population connected to the grid, and the degree of SoES for those who do have access. It is important to keep track of how this fraction evolves over time, yielding as metric the percentage of the population having access to the grid.

4.12 Terrorism

High voltage transmission systems, in particular overhead transmission lines, are vulnerable to sabotage. Simultaneous attacks at several places in an electricity system, including cyber-attacks, could leave a region without electricity for an extended period of time [122]. While the economic impact of such power outages would be significant, the long-term consequences are limited [63]. Since the costs of damages due to terrorist attacks in the electricity sector might not be publicly available, we propose using one of the measures of the World Economic Forum (WEF) Report: the business cost of terrorism.

5. THE FRAMEWORK AS A POLICY TOOL

Our aim in this section is to outline how our framework can help stakeholders understand the opportunities and threats that will shape the future of the electricity industry. This framework will not provide a “silver bullet” for SoES; rather, it is a decision support tool aimed at helping to organise and present data, and structure the analysis. By providing an overview of the state of SoES, it will highlight potential future problems and help decision makers understand the challenges they face, putting them in a better position to optimally allocate their limited resources. The objective of the framework is to understand where, when and how to intervene to maintain the desired level of SoES. In this sense, the framework also works as a form of “early-warning system”. By drawing attention to changes in the values of the different metrics while there is still time to intervene, decision-makers can take the necessary steps to prevent potential problems from materialising.

Each jurisdiction should aim to establish appropriate critical values for the various metrics. A metric approaching its critical value signals that this dimension could endanger SoES in the near future. It is also crucial to keep in mind a metric's time-scale when comparing its current and critical values. When a metric reaches its critical value, it is too late to react: there thus is a need for “lag-adjusted critical values”. An indicator getting close to its lag-adjusted critical value signals to decision makers that this is their last opportunity to act before the SoES becomes endangered.

While a simple graphical representation of the metrics' time-series is a useful way to visualise their evolution, other, more sophisticated charts, may be more informative. For instance, spider-web diagrams showing the evolution of (a subset of) the metrics over a number of years could provide an overview of the “dynamics” of SoES, identifying which metrics have improved and which have deteriorated.

As mentioned previously, we do not propose one single aggregate metric representing SoES, as such a metric would not provide insights for investors, regulators or policy makers to act on. Rather, the focus should be on the evolution over time of the metrics, as long time-scales are one of the key characteristics of the industry. Consequently, observing the evolution of the metrics over time is critical, as reversing a trend can take years, even decades. One should particularly be aware of the fact that each measure has its own time-frame. For instance, reversing a decreasing trend in the de-rated margin takes years due to construction delays, while strengthening the high-voltage grid requires decades.

6. CONCLUSION AND POLICY IMPLICATIONS

Ensuring the security of electricity supply is currently a matter of concern for regulators and policy makers. There is a need for a comprehensive framework that clearly maps out the dimensions of SoES in a way that allows decision makers to monitor the system's evolution and act before problems arise. Most of the previously proposed frameworks either address the entire energy sector or focus on selected fossil fuels. The few frameworks developed for the electricity sector are too specific to be generalised. This paper has developed a framework to evaluate security of supply in the electricity industry, acknowledging its multidimensional and inter-temporal nature, and the need for one or more accompanying metrics to assess each dimension.

Our framework enables regulators and policymakers to act timely as it offers the following advantages: (i) an exclusive focus on the electricity sector; (ii) a disaggregation of SoES into a series of key indicators that allow identification of specific potential problem areas; (iii) a temporal dimension that enables tracking the evolution of these indicators over time, highlighting emerging trends; (iv) a focus on a single jurisdiction within the decision makers remit and responsibility; (v) a reliance on publicly available data for most indicators.

The debate on SoES has often been very one-dimensional, focussing on the most critical issue at a given point in time, rather than on the bigger picture. Examples include the European dependence on Russian gas [123–125] and insufficient investments in the electricity sector [92,126,127]. Our framework aims to broaden the debate, by pointing to the need to focus not on one, but on a multitude of dimensions simultaneously, to achieve a true understanding of SoES. Focusing on one dimension removes attention for what might be the next issue, leading to a situation of constant firefighting: problems which could have been resolved easily and cheaply if addressed at an early stage become major issues. The framework developed here should induce stakeholders to keep the bigger picture in mind when analysing the situation, thus contributing to the quality and pertinence of the public debate about the priorities in the electricity industry.

This framework has a number of limitations one needs to be aware of. While it is comprehensive and covers the most important aspects of the electricity industry, it may require adaptation for use in jurisdictions with very atypical characteristics; some of the proposed dimensions or metrics may be irrelevant, while others may need to be added. For instance, for Norway, which is close to 100% hydro-based, CO_2 is clearly not an issue, but climate change is an essential dimension.

A further complexity that we have not dealt with explicitly is the increasing interdependency of the many factors that determine security of supply, i.e., addressing problems in isolation is difficult as any action will have knock-on effects: an action might improve one dimension while adversely affecting others. Understanding these interdependencies, and their consequences across the whole electricity sector, is essential if we are to achieve a real understanding of the security of electricity supply. Although defining such interdependencies is beyond the scope of this paper, our work does point out some of these, increasing policy makers' awareness of the consequences and potential side effects of policy modifications. For instance, while regulators may tolerate a reasonable tariff increase to subsidise renewable energies, there is a limit to how much tariffs can rise before affecting the standard of living of the general population or industrial competitiveness.

Finally, one of the main obstacles to a successful implementation of this framework is data availability: while we have privileged measures requiring only publicly available data, required data may be unreliable (e.g., socio-cultural factors) or simply non-existent (e.g., congestion costs). A successful use of the framework will only be possible with the collaboration of all parties involved.

Future work will include the mapping of the interdependencies between the different dimensions, as well as the development of a number of cases for specific jurisdictions to illustrate the applicability of the framework.

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