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The impact of flexible resources in distribution systems on the security of electricity supply: A literature review

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ABSTRACT

The power system is transitioning from the traditional one-way system to a more integrated and complex system with more active end-users and with generation and reverse power flow at the distribution level. As a part of this transition, flexible resources such as energy storage systems, electrical vehicles and demand response are increasingly being deployed in distribution systems. Among their benefits, flexibility services are often directly or indirectly associated with a positive impact on the security of electricity supply (SoS). However, the SoS perspective is not given satisfactory attention in the existing research literature. The objective of this article is therefore to provide a structured review of methodologies for assessing the impact of flexible resources in distribution systems on SoS. Four main aspects of security of electricity supply are distinguished in this article: energy availability, power capacity, reliability of supply, and power quality. Flexibility services are classified in relation to each of these aspects, and the literature is reviewed for methods and indicators for quantifying their impact. Finally, the article discusses the need for more holistic and comprehensive assessments of SoS considering flexible resources and possible implications for managing the SoS of the power system in the future.

1. Introduction

The electric power system has been, and still is, largely hierarchical: There is a one-way power flow from centralized generation systems, through transmission systems and to the distribution systems, and the interaction between different levels of the power system has been limited. The power system is under change and the transition has started to a more decentralized and complex power system, with more distributed generation and active end-users, and it is generally acknowledged that the need for flexibility is increasing [1-6]. In this context, the concept of flexibility has been defined in a variety of ways, for instance as “the modification of generation injection and/or consumption patterns, on an individual or aggregated level, often in reaction to an external signal in order to provide a service within the energy system or maintain stable grid operation” [3, 5]. We will use the term flexibility service broadly to refer to any such service to any actor in the power system. Flexibility services can be provided by flexible resources (also referred to as flexibility resources) in distribution systems, such as distributed energy storage systems (ESS), electrical vehicles (EV) and demand response (DR). These flexible resources are believed to play an important role in the planning and operation of the power system in the future [3-8]. The main driver for flexible resources is often described to be the increase in variable renewable energy sources (VRES) that need to be integrated in the power system in general and at the distribution level in particular [1, 6, 9-17]. While the share of sustainable, renewable electric energy is increased, the security

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Abbreviations: DA, Degree of Autarky; CVaR, Conditional Value-at-Risk; DR, Demand Response; ECC, Equivalent Conventional Capacity; EENS, Expected Energy Not Supplied; EFC, Equivalent Firm Capacity; EGCS, Equivalent Generation Capacity Substituted; EIC, Expected Interruption Costs; ELCC, Effective Load Carrying Capacity; ELD-EV, Effective Load Demand of EVs; EPE, Expected Postponed Energy; EPNS, Expected Power Not Supplied; ESS, Energy Storage System; EV, Electrical Vehicle; LAA, Load-Altering Attacks; LOLE, Loss Of Load Expectation; LOLP, Loss Of Load Probability; MAIFI, Momentary Average Interruption Frequency Index; MCS, Monte Carlo Simulation; MTTR, Mean Time To Repair; PV, Photovoltaic; SAIDI, System Average Interruption Duration Index; SAIFI, System Average Interruption Frequency Index; SoS, Security of Electricity Supply; V2G, Vehicle-to-Grid; VDI, Voltage Deviation Index; VRES, Variable Renewable Energy Source

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of electricity supply[1] (SoS) must also be ensured [18, 20]. In fact, key benefits and applications reported for flexible resources also regularly include improvement of such aspects as power system reliability, security, stability, and power quality [5, 6, 12, 15, 23-25]. However, in the literature these positive impacts on the security of electricity supply are often mentioned only in passing and not substantiated by quantitative analysis. Furthermore, in recent reviews of the research literature, these benefits are given little attention relative to the benefits with respect to VRES integration. An acceptable security of supply is a fundamental requirement for the power system, and the increasingly complex and decentralized power system of the future may call for new approaches to assessing the security of supply. This motivates the present literature review focusing on assessing the impact on security of electricity supply of flexible resources in distribution systems.

1.1. Related work

There already exists a large number of literature reviews on different types of flexible resources. For instance, the literature on demand response is reviewed in [10, 26-28], the impact of electrical vehicles on the power system is reviewed in [29, 30], and applications of stationary ESS are discussed in literature reviews such as [12, 23, 31-35]. However, each review considers one type of flexible resource in isolation, and none of the reviews previously reported specifically consider applications and implications of these resources related to security of electricity supply. Notable exceptions include Ref. [23], which covers ESS deployed in distribution systems for power quality purposes; Ref. [36], which considers the impact of ESS on power system reliability; Ref. [28], which considers the impacts of demand response on power systems, including reliability; and Ref. [37], which reviews reliability analysis methods for "modern distribution networks" that incorporate demand response, energy storage, electrical vehicles, microgrids and distributed generation. Still, each of these reviews are limited to a single aspect of SoS, i.e. power quality and reliability of supply, respectively. Furthermore, they do not consider how flexible resources in distribution systems also can impact SoS in the bulk power system and that this implies interactions between different levels of the power system. The scope is much broader in [38], where a qualitative assessment of energy storage technologies is proposed from the perspective of 15 different dimensions of energy security, including non-technical aspects such as policy, culture and literacy. The North American Electric Reliability Corporation (NERC) [39] presents a qualitative assessment of the benefits of flexible resources to bulk power system SoS, focusing on frequency regulation services. Reference [40] discusses reliability impacts of "smart grid resources" including DR, ESS and EV but the review is not based on quantitative analysis or a comprehensive survey of the research literature.

Other references exist that give a good overview of the use of flexible resources for ancillary services although they do not focus on security of supply as the ultimate purpose of such services. A comprehensive review of energy system flexibility measures, including flexible resources, is provided by Ref. [11] from the perspective of VRES integration. Similarly, in [41], concepts of flexibility and their relationship to security of power systems with high VRES penetration are surveyed, focusing on reserve requirements and short-term security. Reference [9] offers another review from the same perspective, focusing on the impact of flexibility measures on the power system. The impact on SoS is not discussed specifically in [9], but the review highlights the relationship between flexibility and reliability as a research gap in the existing literature.

As indicated above and discussed in greater detail below, the security of electricity supply is a many-faceted concept comprising several interrelated aspects at different levels in the power system. In this article, security of electricity supply is used as a collective term comprising energy availability, power capacity, reliability of supply and power quality. Previous reviews of the rapidly expanding field of flexible resources either do not consider the SoS perspective at all, only discusses the perspective rather superficially, or have a limited scope considering only certain aspects of SoS and neglecting possible interrelations between different aspects.

1.2. Contributions and outline

Given that the security of supply perspective so far has received relatively limited attention in the literature on flexible resources, this article presents a review of the research literature considering the impact of flexible resources on the multiple aspects of security of supply. The main objectives of the article are to 1) provide a clearer and more comprehensive understanding of how flexible resources can impact security of supply, 2) summarize and structure the scientific state of the art on how this impact can be quantified, and 3) identify outstanding research gaps in methodologies for assessing security of electricity supply considering flexible resources. It thus aims to contribute to answering the broader question: "how should one assess the security of electricity supply in the future?", assuming that flexible resources in distribution systems will play a major role in future power systems.

Other research questions include: What methods and indicators are most appropriate for comprehensively quantifying the impact on SoS from flexible resources? What are the most important factors that determine this impact, and thus need to be taken into account in the modelling? Are there also potential negative impacts and new vulnerabilities that should be considered? Compared to related work, the main contributions of this review are putting power system flexibility in a security of supply perspective, extending the scope to cover multiple flexible resources, multiple aspects of SoS (energy availability, power capacity, reliability of supply and power quality) and considering the interrelation of these aspects. A classification of flexibility services related to SoS is also proposed.

The rest of this article is structured as follows and as illustrated in Fig. 1: Section 2 and Section 3 provide further background for the literature review: Section 2 introduces the concept of security of electricity supply and the classification of its four main aspects that is adopted for this work; Section 3 establishes the understanding of flexible resources adopted in this article and delimits the scope of the literature review to three main types of flexible resources (ESS, EV and DR). An overview of the approach followed for the literature review is presented in Section 4, including an introduction to the classification of flexibility services related to SoS. The findings on quantitative methods and indicators in the literature are presented in Section 5. In Section 6, the findings are discussed in the context of the ongoing transition of the power system and its implications on assessing SoS, before the article is concluded with suggestions for future research.

2. Security of electricity supply

The European Commission has defined security of electricity supply as "the ability of an electricity system to supply final customers with electricity" in the Directive concerning measures to safeguard security of electricity supply and infrastructure investment [42]. Two basic observations that follow from this definition is that it 1) considers security of supply from the perspective of final customers (or end-users) of the electricity system, and 2) that it describes security of supply as a

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[1] In this article, we will mostly use the term *security of electricity supply* as a collective term, with a specific definition elaborated below. A related term is *energy security*, for which alternative definitions and classifications have been proposed [18-20]. Usually, energy security is understood as a broader term than security of electricity supply [21] and may also consider other aspects than the primarily technical aspects of the power system considered in the present article. Also note that the concept of *security of electricity supply* is distinct from the concept of *power system security* [22].

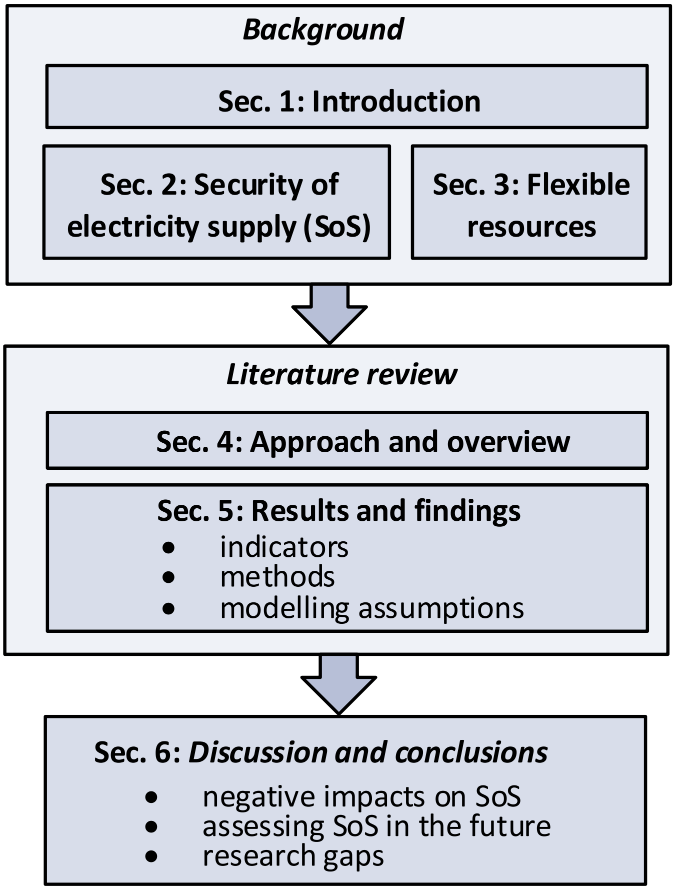

Fig. 1. Outline of the article.

property of the electricity system (or the electric power system) as a whole. The second point is underscored by a proposed amendment to this Directive [43], which argues for "taking a holistic point of view to the entire electricity system". The electric power system in this context comprise the generation system, the transmission system and distribution systems, as well as demand-side (end-user) flexibility [43]. Thus, there are several aspects that need to be considered when assessing the overall security of supply of a power system.

In a Norwegian context, security of electricity supply is defined as the ability of the electric power system to supply end-users with electricity of a certain quality on a continuous basis. Furthermore, security of electricity supply is understood as a concept that comprises four main aspects: i) Energy availability, ii) power capacity, iii) reliability of supply, and iv) power quality [44]. In this article we have chosen this holistic, four-way definition as our starting point for classifying the research literature and assessing the extent to which it addresses the relation between flexible resources and different aspects of security of supply[2].

Energy availability refers to the ability of the power system to supply the energy demand. Energy shortages, or deficits in energy security, are characterized by reduced production of electric energy due to lack of primary energy resources (water, gas, coal, etc.) [46]. Note that this aspect is related to the energy storage capacity associated with the generation system rather than the power generation capacity as such. Power capacity refers to the ability of the power system to supply the instantaneous demand. Capacity shortages, or deficits in the power capacity, are characterized by a lack of available generation and/or transmission/distribution capacity [46].

Reliability of supply is the ability of the power system to supply electric energy to end-users [45]. It is related to the frequency and duration of interruptions of power supply to end-users due to failures and forced outage occurrences in the power system (contingencies). The term reliability of supply is closely related to the classical term reliability of power systems, which is divided in power system adequacy and power system security[3] [49].

Power quality refers to the quality of the supply voltage according to given criteria [45, 50], regarding its frequency, magnitude and waveform. The aspect of power quality can be further classified in frequency quality (i.e. of the fundamental frequency of the supply voltage), the voltage magnitude (i.e. its root-mean-square value), and the voltage waveform (i.e. the lack of distortions thereof).

Fig. 2 illustrates of the concept of security of electricity supply and how it is challenged both by power quality phenomena and phenomena causing power supply interruptions. The aspects of security of electricity supply (emphasized fonts in Fig. 2) can be distinguished by the time scales of associated phenomena challenging the security of supply. Energy shortages challenge the energy availability aspect and are typically long-term phenomena with time scales of more than a month [46]. Capacity shortage is typically a phenomenon with shorter time scales than energy shortage, i.e. from a few hours to several days [46]. Relevant time scales for contingencies range from milliseconds for the initial failure event and up to hours or even days for the restoration of end-user power supply. Power quality problems range from voltage spikes developing over a few milliseconds to under-voltage problems lasting for many minutes. These differences in time scales are important to consider when assessing the potential of different measures – such as flexible resources – to improve aspects of the security of supply [19, 21, 22].

3. Flexible resources and flexibility services

The traditional electric power system is a hierarchical system with a one-way power flow: Primary energy sources are converted to electric energy by centralized generation assets, transmitted through transmission assets and supplied to the end-users through distribution assets. This view is illustrated in Fig. 3. End-users have traditionally been understood to be external to the power system as passive demand points in assessments of security of supply. With more active and responsive end-users that can provide flexibility services to the power system (DR) as well as providing to their own security of supply (e.g. through photovoltaic (PV) generation combined with ESS), this understanding may have to be revised. In addition, (distributed) generation assets are now commonly found at a distribution system level and causes reversed and two-way power flows. Furthermore, flexible resources are power system assets that can be located at end-users as well as at all levels in the power system (Fig. 3).

There exist numerous approaches and criteria that are proposed for classifying flexible resources and the services they can provide, see e.g. [5, 16, 39, 51]. Flexibility in general can be grid-side or supply/demand-side. Grid-side flexibility emanates from the technologies and the grid management system in place. Demand/supply-side flexibility, however, largely includes generation assets, loads and energy storage assets. We delimit the scope of our work by not considering the impact of distributed generation assets to security of supply, as this topic has a long and well-developed history for both conventional generation and VRES [37, 52-56]. We therefore consider three types of flexible

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[2] The definitions in this section are based on the authors' translations to English of the Norwegian definitions in [44, 45], in addition to definitions in [46] and supported by the definitions in [22, 47].

[3] Note that several different definitions exist for reliability and related terms such as adequacy and security in the context of power systems; for a review of alternative definitions we refer to [48]. Note also that the reliability of supply is dependant upon the energy availability and power capacity of the power system as well as power system component failures.

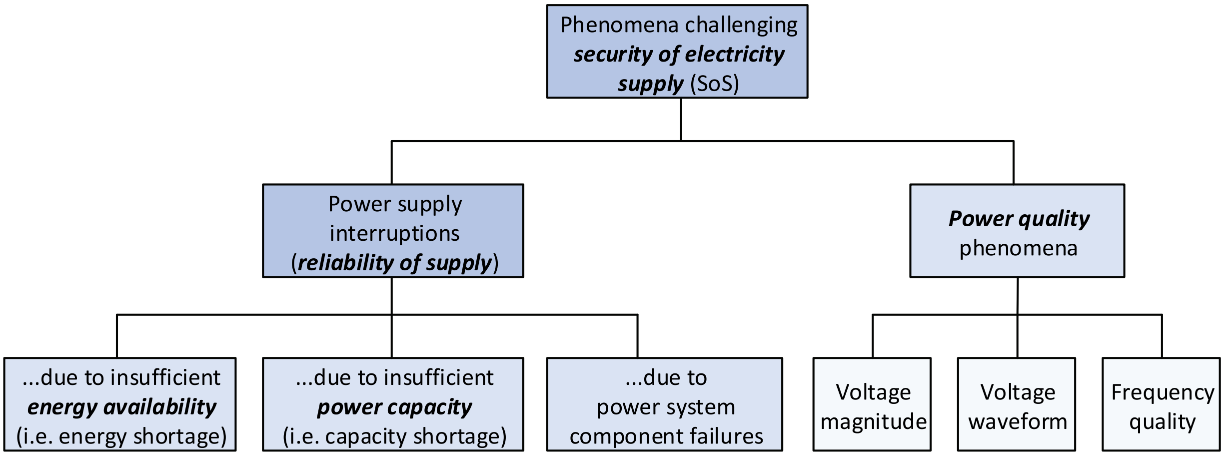

Fig. 2. Classification of phenomena challenging the security of electricity supply (SoS) and associated aspects of SoS.

resources: 1) the term DR (demand response) denotes load-based resources[4], 2) the term ESS denotes stationary energy storage systems, and 3) the term EV represents mobile energy storage systems (typically electrical vehicles).

Since this article is concerned with the impact of flexible resources on SoS we will narrow down the scope to those flexibility services that are in a sense related to SoS. This concept of a SoS-related flexibility service is related to but still distinct from the concept of ancillary services (or grid support services), defined as services “necessary for the operation of a transmission or distribution system” [58]. Reference [11] classifies ancillary services from flexible resources according to the time scale of their response or duration: very short (1 ms – 5 min; power quality and regulation); short (5 min – 1 h; spinning, non-spinning/contingency reserves and black-start), intermediate (1 h – 3 days; e.g. load levelling/following, peak shaving, transmission curtailment prevention, transmission loss reduction) and long (months; seasonal shifting). In anticipation of the classification to be proposed in Section 4.1, we note here that ancillary services with “very short” and “short” duration are most relevant for the power quality and reliability aspects, while ancillary services with “intermediate” to “long” time scales are more relevant for power capacity and energy availability, respectively. In some sense, the definition of ancillary services implies that their purpose ultimately is to ensure SoS. However, ancillary services by definition are services provided to system operators, whereas flexible resources also can provide services directly to end-users, e.g. to improve their security of supply [47, 48, 57].

We furthermore restrict this literature review to consider flexible resources located in the power system at the distribution level or at the end-user level, i.e. flexible resources that are in some sense distributed or decentralized. This excludes e.g. large-scale pumped-hydro energy storage systems that are typically associated with the bulk power system (transmission or generation level). Fig. 4 illustrates the scope of this article. As indicated by the arrows, flexible resources that are located within distribution systems or at end-users can impact the security of supply at higher levels in the power system. For instance, EVs can contribute to frequency regulation, ensuring frequency quality at a transmission system level, as well as providing grid services more locally to the distribution system operator [8, 59]. A positive impact on frequency quality also has an indirect positive impact on security of supply for individual end-users. On the other hand, an EV providing backup power to its owner has a positive impact for that particular end-user's security of supply but not necessarily on the power system at large.

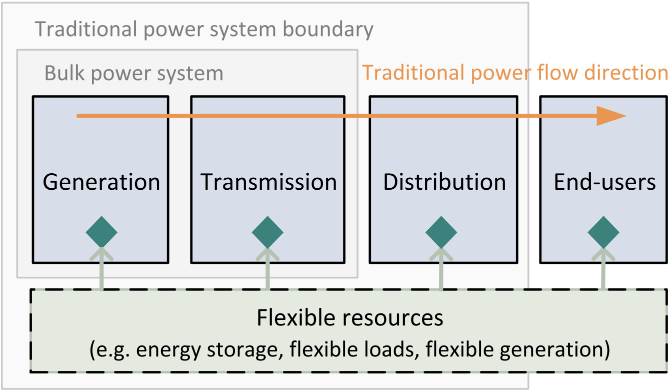

Fig. 3. Possible locations of flexible resources in the power system as shown by the traditional hierarchical and one-directional power system (generation – transmission – distribution – end-users).

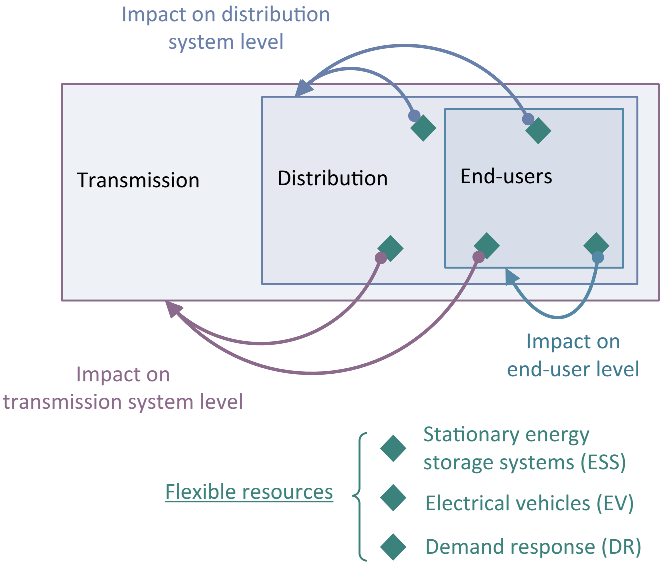

Fig. 4. The scope of the article as indicated by the arrows: Flexible resources located at the distribution system and end-user level can impact the security of supply at different levels in the power system.

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[4] DR is more formally defined as “Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized” [57]. We moreover refer to [24] for the definition of DR programs and their classification in price-based and incentive-based DR programs.

In order to limit the scope, assets providing so-called grid-side flexibility[5] [60] or grid interconnection [41] are not considered as flexible resources in this article, but the focus is on demand-side and supply-side flexibility. Furthermore, we do not include the vast literature existing on power balancing and security of supply within island energy systems or microgrids [61-64], and we do not consider the impact of microgrids on distribution system reliability [65]. On the other hand, we do consider the possibility of flexible resources allowing parts of distribution systems to operate in island mode.

4. Literature review approach

This section first gives an overview of the approach for selecting references and the classifications for assessing them (Section 4.1), after which an overview of the reviewed literature is given (Section 4.2).

4.1. Approach and classifications

The work reported in this article followed as semi-systematic literature review approach: A literature search was first carried out using search terms documented in [66]. The results were screened for references considered potentially relevant for the scope of this article. This list was supplemented by recent reviews considering flexible resources individually [10, 23, 26-28, 30, 33-36], or reliability of supply [37] in distribution systems more generally. Taking these references as a starting point, all cited and citing references were then considered. In addition, other relevant references known to the authors were also included. This resulted in a list of 424 potentially relevant references, and the full list of references is available online [66]. After surveying these references, a representative selection relevant to the scope of this article was then reviewed in more detail and categorized as described below. The selection criteria were that the references should consider (one or more aspects of) SoS directly and quantitatively and that they should cover the set of flexible resources and the aspects of SoS as widely as possible. The references were assessed considering the following primary dimensions: 1) The type of flexible resource that is considered (ESS, EV or DR); 2) what kinds of services it provides (and thus what aspects of SoS are impacted); 3) for whom it provides these services (i.e. at which level of the power system SoS is impacted); 4) where in the power system it is located.

Assessing references along dimension (2) requires a classification of flexibility services related to SoS. Existing classifications of flexibility services [5, 16, 39, 51] were found not to be suitable for this purpose. Moreover, the literature often describes the purpose of a flexibility service without labelling it according to any explicit classification. We therefore propose to classify the services considered in the literature according to which of the four main aspects of SoS (energy availability, power capacity, reliability of supply, and power quality) that the service primarily is intended to benefit. Services related to power capacity were subsequently classified as either related to generation capacity or grid capacity. Services related to power quality were classified according to the three sub-aspects frequency quality, voltage magnitude, and voltage waveform. A large fraction of the initially surveyed references consider reliability analyses, involving power system component failures and consequent power supply interruptions. All these references are here classified under the aspect “reliability of supply” in the tables below[6]. Since we found it useful to further subdivide flexibility services related to this main aspect, we propose a possible classification based on [67] and illustrated in Fig. 5: Here we distinguish between services associated with i) preventive actions taken before a potential failure of a power system component (and subsequent forced outage), ii) corrective actions taken in response to a failure to keep the power system within its operational limits, and iii) restorative actions to restore power supply to end-users after a power supply interruption. Table 1 gives an overview of flexibility services related to SoS according to this classification.

4.2. Overview of the reviewed literature

Table 2 shows an overview of the references selected for more detailed review categorized according to two of the dimensions discussed in Section 4.1, namely 1) the type of flexible resource and 2) the classification of SoS-related flexibility services. The survey identified a relatively large number of references considering flexible resources' impact on reliability of supply. Energy availability, on the other hand, was not directly considered in any of the surveyed references, so this main aspect is omitted from the overview. One can observe from Table 2 that, on the whole, previous research has considered the impact from each of these flexible resources on all of these three main aspects of SoS. However, most references consider a specific type of flexible resources and do not e.g. offer comparative analysis of available flexibility options. Moreover, almost all the references consider only a single aspect of SoS. As shown in [66], the references cover impacts on all power system levels (dimension 3), but almost no reference consider the impact on more than a single level. (Exceptions are [68], where the reliability impact on both the distribution and transmission system level is analysed, and [69], considering both the end-user and distribution system level.)

5. Methodologies for assessing the impact of flexible resources on security of supply

The following subsections reports on the main findings from reviewing the selection of references presented in the preceding section: Section 5.1 considers indicators considered to quantify the impact, Section 5.2 considers the methods for estimating the value of these indicators, and Section 5.3 considers how the flexible resources are modelled as part of these methods. Detailed tables with findings for each of the reviewed references are available online [66].

5.1. Indicators for security of supply

This section primarily concerns the indicators used to quantify reliability of supply (Section 5.1.1) and power quality (Section 5.1.2). Table 3 gives an overview of the indicators in the reviewed literature, classified according to phenomena with different time scales that challenge the security of electricity supply (cf. Fig. 2 and [23]). Very few of the references explicitly considered indicators for the power capacity aspect of security of supply, but some indicators related both to reliability of supply and power capacity are mentioned in Section 5.1.1. None of the surveyed references were classified as quantifying the energy availability aspect of security of supply. However, the authors of [122] can be regarded as considering the energy availability for an end user with a PV + ESS system. The main focus of their work is the end-user-level emergency power supply service during blackout events, but they also quantify a degree of autarky (DA) indicator, which is defined as the ratio PV energy production consumed by the end-user to the total energy consumption of the end-user.

5.1.1. Reliability of supply indicators

The impact of flexible resources on reliability of supply is in the literature generally quantified using conventional reliability indicators [123]. New reliability indicators proposed in the context of microgrids

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[5] Grid-side flexibility includes flexible grid assets such as FACTS devices, dynamic voltage restorers, phase-shifting transformers, HVDC converters and distribution transformers with on-load tap changers.

[6] Note that none of the references classified below as being only related to the reliability of supply aspect of SoS consider power supply interruptions due to capacity shortage or energy shortage. References considering power supply interruptions due to capacity shortage are classified as being related to the power capacity aspect of SoS.

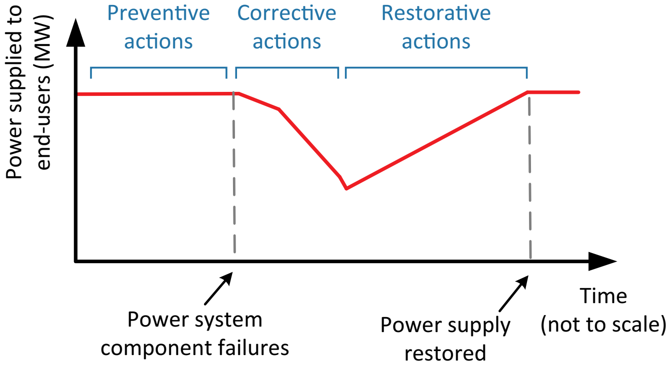

Fig. 5. Classification of services related to power system component failures and power supply interruptions by i) preventive, ii) corrective, and iii) restorative actions.

[62] have not been adopted in the reviewed literature. Reliability of supply indicators are defined in terms of power interruption events for which the supply voltages vanish (or drop below a certain limit, e.g. 5% of their nominal values [50]). Similar indicators can be used to quantify the power capacity aspect of SoS but refer to shortage or rationing events instead of interruption events [70, 72].

These indices are all probabilistic in the sense that they predict the performance of the power system using estimates of the probability of events [123]. However, the results for these indicators are in the literature predominantly reported as expected values rather than as probability distributions. Exceptions include Refs. [87, 94] which account for the uncertainty in the reliability indicators and use the Conditional Value-at-Risk (CVaR) to quantify the risk of poor reliability performance. Another limitation of using expected values for interruption duration indices, for instance, is that one is ignoring the difference between contributions from very short and very long interruption events. Flexible resources can reduce the interruption duration, but the amount of reduction depends upon the available amount of energy associated with the flexible resource. This is considered in e.g. [77, 97, 103, 122], and in Ref. [93], the MAIFI (Momentary Average Interruption Frequency Index) is used to specifically consider the contributions from very short (temporary) interruptions.

The impact on reliability of supply has also been assessed from a deterministic perspective [77, 78, 97, 100], by considering the fulfilment of deterministic N–k reliability criteria. In Ref. [78], the cost of ESS peak shaving the loading of a substation to ensure a N–1 reliability criterion for the at all times is quantified. This work is extended in [97], which estimates the impact on (probabilistic) reliability indicators of considering intermediate reliability criteria – between N–1 and N–0 – for a similar case.

When assessing the impact of DR on reliability and interruption costs one has to distinguish between load reductions due to preventive DR, corrective DR and ordinary power supply interruptions [37]. It is furthermore discussed e.g. in Refs. [64, 99, 107] how preventive or corrective activation of incentive-based DR reduce overall end-user inconvenience compared to the alternative of involuntarily controlled corrective or uncontrolled load shedding. However, this distinction is not reflected in the quantitative indicators found in the literature review. Some novel reliability indicators have nevertheless been proposed for more differentiated assessment of reliability of supply: The Expected Postponed Energy (EPE) is introduced in Ref. [107] to consider separately the interruption of responsive (flexible) loads. The authors of Ref. [100] also discriminate between “normal” end-users (with “normal”, inflexible loads) and “responsive” end-users (with flexible load) in their reliability indicators.

In Ref. [80], the Equivalent Generation Capacity Substituted (EGCS) indicator is proposed to quantify the conventional generation capacity that could be displaced by ESS or DR and keep the same level of reliability. The EGCS is applied in a power capacity (market) context in Ref. [73], where the reduction in generator investments is used to estimate the capacity value (or capacity bids) of DR resources. The potential negative impact of increasing EV penetration is considered in

Table 1
Overview of security of supply-related flexibility services.

Main aspect of SoS	Classification of SoS-related service	Exemplary descriptions of services
Energy availability	Seasonal shifting, ensuring energy self-sufficiency	
Power capacity	Generation capacity	Power injection or peak shaving in peak load hours, strategic/non-spinning reserves
	Grid capacity	Load levelling in case of insufficient transmission/distribution grid capacity
Reliability of supply	Preventive	Load reduction load prior to a potential power system component failure (e.g. in strained operating conditions) to reduce failure rates, overloads or end-user consequences
	Corrective	Load reduction to alleviate overload during contingencies, emergency demand response program, direct load control, contingency reserves
	Restorative	End-user backup power supply, emergency power to support islanding or power system restoration, black-start capability
Power quality	Voltage magnitude	Voltage regulation, mitigation of flicker, phase balancing
	Voltage waveform	Damping of harmonics, end-user voltage conditioning
	Frequency quality	Frequency regulation, frequency containment reserves, fast frequency reserves, damping of oscillations

Table 2
Classification of research on the impact of flexible resources on security of supply.

Main aspect of SoS	Classification of SoS-related service	ESS	EV	DR
Power capacity	Generation capacity	[70]	[71]	[72, 73, 70]
	Grid capacity	[74]	[75]	[74]
Reliability of supply	Preventive	[76, 77, 78, 79, 80]	[81, 82, 83]	[84, 85, 86, 87, 79, 88, 89, 80, 90, 91]
	Corrective	[77, 92, 78, 68, 93, 94, 74, 95, 96, 97]	[98, 94]	[99, 77, 100, 74]
	Restorative	[101, 68, 102, 103]	[104, 105, 106, 69]	[107]
Power quality	Voltage magnitude	[108, 109, 110, 111, 112, 113]	[114, 115, 83]	[116, 117, 118, 90]
	Voltage waveform		[115]	
	Frequency quality	[109, 119]		[120, 121, 119]

Table 3
Overview and classification of indicators for security of electricity supply in the reviewed literature.

Phenomenon	Aspect	Indicators	References
Frequency deviations	Frequency quality	Frequency deviation or frequency nadir after contingencies, time required for the system to restore nominal system frequency	[109, 121, 120]
Harmonic distortion	Voltage waveform	Total harmonic deviation index (THDI)	[115]
Flicker	Voltage magnitude	Flicker minimization index	[112]
Voltage dips	Voltage magnitude	Frequency of voltage dips, cost of voltage dips	[110]
Voltage unbalance	Voltage magnitude	Voltage unbalance factor	[111]
Overvoltage/undervoltage	Voltage magnitude	Voltage Deviation Index (VDI), voltage stability index (SI), penalty cost of energy supplied with poor voltage quality (i.e. violating voltage limits)	[83, 111, 112, 115, 114, 113]
Very short power supply interruption (due to power system component failures)	Reliability of supply	Momentary Average Interruption Frequency Index (MAIFI)	[93]
Power supply interruption (due to power system component failures)	Reliability of supply	Conventional reliability indices, e.g.: Loss Of Load Probability (LOLP), Loss Of Load Expectation (LOLE), Expected Power Not Supplied (EPNS), Expected Energy Not Supplied (EENS), Expected Interruption Costs (EIC), System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIDI)	[76, 79, 82, 83, 84, 86, 88, 91, 68, 95, 98, 100, 101, 102, 104, 105, 103, 106]
		Conventional capacity credit indicators: Effective Load Carrying Capacity (ELCC), Equivalent Firm Capacity (EFC), Equivalent Conventional Capacity (ECC)	[97, 80]
		Novel indices: Expected Postponed Energy (EPE), Effective Load Demand of EVs (ELD-EVs), Equivalent Generation Capacity Substituted	[107, 81, 80]
Capacity shortage	Power capacity	Rationing probability (LOLP), number of shortage hours, rationing volume (EENS), rationing costs	[70, 72]

Ref. [81], which proposes the Effective Load Demand of EVs (ELD-EVs) to quantify the amount of generation that needs to be added to maintain the level of reliability.

5.1.2. Power quality indicators

Power quality can be measured according to the supply voltage characteristics described in EN 50,160 standard [50]; see also e.g. [124]. These include characteristics such as power frequency (e.g. required to be within ± 0.01 p.u. for at least 99.5% of the year), voltage magnitude variations (e.g. required to be within ± 0.1 p.u. for at least 95% of the week), supply voltage dips (e.g. number of events with supply voltage below 0.6 p.u. for less than 1 s), harmonic voltages (e.g. measured by the total harmonic distortion, required to be less than 8% for at least 95% of the week).

In the reviewed references, power quality is most often quantified in terms of voltage deviation indices (VDI). These indicators measure how the voltage profiles in a distribution grid deviate from nominal voltage values or how far they are from violating specified voltage limits. The reliability analyses that include AC power flow implicitly consider voltage profiles and voltage limits (e.g. [88, 90, 95, 100, 104, 107]), but only a few of the reviewed articles assessing reliability of supply include voltage profiles amongst the outputs [83, 84, 90]. Methodologies that quantify the impact of flexible resources both as reliability of supply indices and power quality indicators were not found in the review. Voltage deviation indices and voltage profiles are typically reported as snapshots for a given hour or as worst-case values for the considered time period. Except from Ref. [110] and [113], probabilistic power quality indicators also considering how frequently or with which probability e.g. voltage deviation events occur were not found in the review. Ref. [113] proposes an indicator that measures the cost of energy supplied with poor voltage quality (i.e. violating voltage limits).

Moreover, most references consider e.g. an hourly time resolution and do not measure the duration of voltage deviation events or capture events of shorter durations. One exception is Ref. [110], which estimates how ESS may reduce the frequency of voltage dip events of different durations. The authors of [112] propose a combined power quality index considering both the impact of DR on long-term voltage deviation and short-term flicker events.

For the frequency quality aspect, the stability or instability of the power system has been used as a binary and deterministic indicator [125], but otherwise, the impact on frequency quality is not assessed quantitatively in the references considering this aspect. One possible explanation is that the power output of e.g. an individual distribution-level ESS is too small to discernibly affect the frequency in a large power system [126].

5.2. Methods for assessing the impact of flexible resources on SoS

The review of the methods revealed that they can be broadly classified into two main groups, as shown in Table 4: i) methods focusing

Table 4
Overview and classification of the main methods for assessing the impact of flexible resources on SoS in the reviewed literature.

Method	References with an assessment focus (i)	References with an optimization focus (ii)
Monte Carlo simulation (probabilistic)	[95, 105, 106, 77, 100, 81, 84, 101, 79, 76, 68, 80, 97]	[94, 113, 87]
Analytical – contingency enumeration (probabilistic)	[110, 98, 90, 107, 88]	[99, 82, 93, 96]
Analytical – other (probabilistic)	[85, 89, 102, 103]	[86]
Analytical (deterministic)		[104, 117, 92, 78]
Power flow analysis (static)	[118, 108]	[111, 114, 116]
Power flow analysis (harmonic)		[112, 115]
Power flow analysis (dynamic)	[121, 109]	
Market models	[71, 72, 73]	

on assessing aspects of security of electricity supply, and ii) optimization methods embedding SoS assessment as part of the optimization problem. The latter category typically focuses on utilizing flexible resources in the optimal planning, design, operation or control of a power system or a power system component. But there does not seem to be fundamental differences between the two categories in the actual methods used for quantifying the impact on SoS. Another finding is that most works in the literature explicitly or implicitly assume that flexible resources are operated to have a positive impact on SoS. For methods in group (ii), this assumption is explicit through the set-up of the optimization problem.

Methods for reliability analysis considering some form of DR have a long history [28] but were until recently limited to the generation system or the bulk power system. Reliability analysis methods assessing the impact of ESS or EV on the bulk power system have also been considered in the literature over the last decade. Generally, these methods estimate how the presence of flexible resources preventively modify load profiles aggregated to the generation or transmission level. A standard reliability analysis is then typically conducted to quantify how this changes the consequences of contingencies.

Table 4 classifies the reviewed reliability analysis methods in Monte Carlo simulation (MCS) methods and analytical methods. Several authors generally recommend sequential MCS methods, most importantly to capture the time-interdependencies of flexible resource operation [37, 80]. (See also Section 5.3.1.) For reliability analysis methods considering the impact on the distribution level, one also finds application of analytical reliability analysis methods based on contingency enumeration; simpler contingency enumeration approaches could be justified in radial distribution grids where single-component outages often lead to consequences for end-users. A hybrid method combining MCS with analytical expression capturing the contribution to reliability indicators from insufficient ESS power capacity and ESS outages is proposed in [97] to increase the computational efficiency. An analytical method capturing both time-dependencies and ESS outages is proposed in [103].

The research works that were found on assessing the impact on the power capacity aspect of SoS mostly use market models to identify the possible occurrence of power shortage events. For a discussion of conceptual differences and difficulties in assessing energy shortages, capacity shortages and power supply interruptions due to power system component failures, we refer to [46]. Most of these models are applicable to a bulk power system level (neglecting transmission and distribution grid modelling). Very few references were found that considered the aspect of distribution or transmission grid power capacity [74, 75].

As indicated by Table 4, the methods considered for quantifying the impact on power quality mostly are generic methods for power flow analysis: Indicators related to the long-term voltage quality problems [23] are typically derived from voltage profiles from steady-state power flow solutions; indicators related to flicker have been obtained from harmonic load flow calculations [112]; the frequency quality aspect has been assessed through dynamic power flow and electromagnetic transient simulation (e.g. in [109]).

5.3. Modelling assumptions

This section reviews modelling assumptions that may be important in assessing the SoS impact of flexible resources. An overview of relevant modelling features and factors and an outline of the following subsections is given in Fig. 6.

5.3.1. Modelling the operation of power systems with flexible resources

Flexible resources differ from transmission and distribution assets in that they in principle can be actively controlled to vary the real power injection/consumption over time. Options for activation of the flexible resources introduce additional degrees of freedom in the operation of the power system. Moreover, these degrees of freedom are coupled in time through intertemporal constraints related to the amount of energy associated with the flexible resources. In other words, modifying power injection/consumption for an ESS, EV or DR resource at one point in time has implications for the power injection/consumption that is possible at other points in time. The schedule of injection/consumption over time influences its operational benefits, such as its impact on SoS. It is therefore relevant to investigate how scheduling, aggregation [127] and activation of flexible resources is modelled in the reviewed research works. One should note, however, that the operational scenario assumed for the flexible resources often is not clearly described in the literature. Often it is presented as if the power system operator directly controls the power active power injection/consumption (here referred to as the operation of the flexible resource), and other actors such as ESS operators or DR resource aggregators are not explicitly described.

The modelling approaches for flexible resource operation can be broadly divided into statistical approaches, simulation approaches or optimization approaches. Statistical approaches assume that the consumption/injection schedule is determined by probability distributions, time series or stochastic processes. This approach has been used to model EV charging [81, 98]. In that case, it implies that EVs are viewed more as a variable load than as a flexible resource that can be directly or indirectly controlled by a power system operator to improve SoS. For DR, a common approach to quantify its impact on reliability of supply is to use data on the price elasticity and cross-elasticity of demand to model the curtailment and shifting of load [76, 88].

A simulation approach, on the other hand, typically uses heuristics to model the control strategy underlying the flexibility services that are provided. This is often found for models for corrective and restorative services related to reliability of supply, e.g. that an ESS should discharge during a contingency with as high a power output as needed to supply the loads it is serving and that it otherwise charge when possible until reaching the maximum state of charge [77, 93, 95, 97, 103, 122]. Such simple control strategies may be reasonable and straightforward to implement when the system topology is simple, such as an islanded radial of a distribution grid, a single end-user or aggregated delivery point.

The majority of research, across most groups of SoS-related flexibility services, model the operation of the flexible resource using optimization models. This is the case for market models assessing the impact of DR on power capacity [70-73] or reliability of supply [89], where market actors are modelled with an objective to maximise their profit or minimize their cost. Models for preventive reliability-related services generally implement a multi-period optimization model, typically with a 24-hour planning horizon. The objective of the model can be to minimize peak load [79] or make the load profile as even as possible [90] over the planning horizon. Alternatively, some models incorporate the calculation of reliability indicators in the objective function of the optimization model and implicitly find the modified load curve that e.g. maximizes the reliability of supply [82] or minimizes the system costs including interruption costs and DR incentive payments [86]. Corrective services are more often modelled using single-period optimization models that aim to minimize interruption costs after contingencies [68, 74, 94, 100, 101, 107].

Overall, similar modelling approaches are used for the operation of different flexible resources. ESS can both inject and consume power, DR can effectively inject power by reducing power demand from its baseline level, and EV can in principle modify its consumption schedule or also inject power in case of vehicle-to-grid (V2G). However, there are differences in how intertemporal constraints are modelled: For DR with shiftable load, one must consider the limitations in how much load can be shifted for how long [80, 90, 107]. The considerations also include the statistical information regarding the appliance use habit throughout the different hours of a day [128]. These time couplings may give rise to the rebound effect [79, 80, 100], which involves new load peaks being created from load that is shifted in time. If load shifting is modelled by a

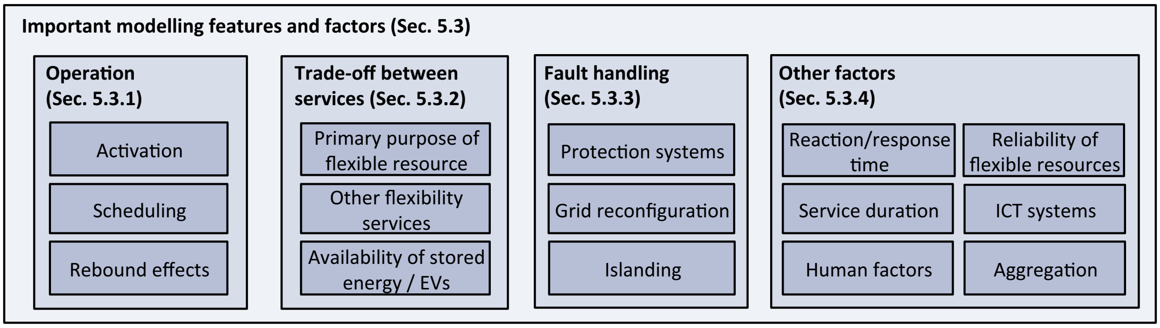

Fig. 6. Overview of important modelling features and factors in the methodologies.

multi-period optimization model, however, the schedule can avoid this by implicitly anticipating possible rebound effects. Rebound-like effects may also be present for ESSs and EVs that are modelled to have a certain state of charge at the end of the planning horizon, e.g. for EVs that are to be used for transportation purposes.

5.3.2. Modelling the trade-off between different flexibility services

That a resource in the power system is flexible implies that it can serve multiple purposes. In the case of a DR resource (a flexible load), for instance, the primary purpose of the power supply is to serve the needs of the end-user. But at the same time, the flexibility in load can both give benefits to the end-user in terms of reduced electricity costs and enable her to provide services to the power system operator to benefit the security of supply. However, the review revealed (see [66] for details) that the majority of the methods only consider provision of services related to SoS and neglect the use of the flexible resources for other purposes. This also holds for ESS, even if the general consensus is that ESS projects typically need to provide multiple services (so-called “service stacking” or “benefit stacking”) to be economically viable [12, 25, 35, 129].

A common modelling assumption is that 100% (or some fixed and pre-defined proportion) of the energy and power capacity of the flexible resources is available at the time needed for the SoS-related service [37, 92, 93, 103, 104]. For instance, for an ESS providing a corrective reliability-related services, this implies that it always is fully charged at the time of a contingency requiring it to respond. Some of the work on the impact of EVs use probabilistic models for the availability of EVs [82] and EV's state of charge [94]. Some references also consider the time development of the state of charge during “normal” (non-SoS-related) operation of the flexible resources and thus captures how this may reduce the SoS benefits [101, 122]. However, these approaches do not consider how to optimize the trade-off between SoS-related services and other services. Other models consider this trade-off and co-optimization of services explicitly [78] or implicitly [96] in the scheduling of the flexible resource. A few reviewed articles analyse and discuss separately how much of the capacity should be reserved for SoS services [92]. The use of ESS to provide preventive and corrective reliability-related services is compared in [77] and [78] but not co-optimized. How service stacking can be achieved in practice by assigning battery capacity blocks to different markets (e.g. frequency control and a fast frequency response) is discussed in [6]. Detailed modelling of the state of charge may be less important for services related to power quality that require a relatively small amount of energy to be charged/discharged.

5.3.3. Modelling fault handling in distribution systems

Methods concerned with failures in distribution systems need to account for the handling of the fault and the response in the system. These are aspects of the consequence analysis part of the reliability analysis that are not described in detail in many of the references. Methods applicable to distribution system analysis need to consider that the grid is radially operated, and it often is not clear whether or how fault handling is accounted for in the analysis. The modelling of fault handling involves assumptions about circuit breaker tripping, automatic reclosure, fault localisation, grid reconfiguration and switching times. These modelling assumptions are likely to impact the contribution from short power interruption events to the reliability of supply indices. For a more detailed review of the modelling of protection devices in distribution system reliability analysis we refer to [37]. Interactions between flexible resources and protection systems seems to be largely unaddressed in the literature.

Moreover, many of the references do not explicitly describe how controlled islanding is modelled or how one assumes the flexible resources are operated throughout the islanding transition. In some cases this has made it difficult to assess from a reference whether a flexibility resource is providing restorative or corrective services according to our classification: As an example, it is restorative if one assumes that the flexible resource provides backup power after a brief power interruption to restore operation of an isolated radial, but it is corrective if one assumes that it supports the transition of the radial to island mode operation without incurring end-user power supply interruptions. The challenges of voltage and frequency control during controlled islanding is commented on in [37, 65, 93] but largely neglected in the reviewed literature considering flexible resources. Some references consider the success or failure of islanding in a simplified fashion, e.g. by a simplified representation of droop control [95], but consideration of dynamical phenomena during contingencies is largely neglected.

5.3.4. Other modelling assumptions and important factors

In Section 2 and 3, it was explained how time scales are important to consider carefully. Firstly, the response time requirement of a service is related to the characteristic time scales for that aspect of security of supply: Fast frequency reserves (i.e. services related to frequency quality) need to have response times from milliseconds to around a second and to ramp up to full power capacity within a few seconds. Backup power for managing grid constraints during contingencies (e.g. overloads) need to respond and ramp up within 10–30 min. However, the reaction time and response time for activation and how it affects the benefits of the flexibility services is mostly neglected in the literature. The reaction time is often not negligible in practice when flexibility is activated through indirect control. Moreover, for direct control the reliability of the response is dependant on the ICT systems used to control the distributed resources [91, 130].

When the flexibility service is only required to be activated for a few seconds, e.g. as for fast frequency reserves, the service duration and the associated energy capacity of the flexible resource is not the limiting factor. For other reliability-related services, e.g. restorative or corrective backup power supply, the requirements for the service duration become more important. In [77] and [97] it is pointed out how the value of ESS for corrective reliability-related services decreases strongly with the mean time to repair (MTTR) because larger amounts of energy are needed to avoid long durations of end-user power interruptions. For power capacity services, the characteristic time scale is given by the duration of the peak load period, and a service duration of several hours or more may be required.

Furthermore, the reviewed articles generally assume that the flexible resources are perfectly reliable and available to provide flexibility services when needed. Some methods also account for outages of e.g. the ESS units [97, 103], and in Ref. [97] the SoS benefits were found to be strongly dependant on the ESS availability. Some references [10, 26] maintain that the reliability or predictability of the flexible resource on an asset level is essential for SoS-related services. For e.g. EV and DR, this lack of reliability can be due to the high uncertainty of the power and energy that will be available for flexibility services [74]. The effectiveness of DR can be hampered by the complexity and unpredictability end-user (human) behaviour [91], and the effectiveness of EV services may depend on driving patterns etc. [82]. High uncertainty and low asset-level reliability could be mitigated by more accurate forecasting and/or aggregating a larger number of distributed flexible resources. However, none of the references attempt to quantify such effects, and especially for DR, there is some disagreement in the literature over the extent to which aggregation mitigates this problem [10, 26].

6. Discussion and conclusions

The review presented in this article indicates that there is a lack of research taking a holistic view of SoS by comprehensively assessing the impact of flexible resources on multiple aspects of SoS and multiple levels of the power system. Moreover, most of the reviewed research focus exclusively on the positive impacts of flexible resources on SoS. Therefore, in Section 6.1 we first discuss possible negative impacts of flexible resources. We then address the broader topic of assessing the security of electricity supply in the future in Section 6.2. Section 6.3 concludes the article by summarizing the implications for assessment methodologies, summarizing the identified research gaps, and suggesting directions for future work.

6.1. Negative impact of flexible resources on security of supply

The literature reviewed primarily consider the SoS benefits of flexible resources, but the use of flexibility resources may also have unintended negative side effects. In particular, the rebound effect for shiftable loads may cause load peaks to be shifted to a later time and potentially become more severe than they would have been without DR. This effect may offset the benefits from preventively shifting the original load peak. Furthermore, DR activation may affect reactive power consumption/injection (and not only real power), which may lead to power quality problems. In addition, the large inrush currents consumed by some appliances may cause power quality problems if these appliances are turned on in synchronism after deactivation of the DR service [120]. In the long term, it is moreover argued that a flatter load duration curve due to flexible resources ultimately could make the system being operated closer to its limit and thus more often susceptible to failures [40].

As flexible resources become more prevalent in the operation of the power system, they also become more relevant targets for malignant (cyber) attacks threatening the security of supply. If the operation of the power system is reliant on distributed resources, these resources introduce new vulnerabilities [67], and attackers may not have to compromise transmission-level assets to impact the bulk power system. One example is static [125] or dynamic [125] load-altering attacks (LAA) that target DR. In a dynamic LAA, an attacker could for instance make direct load control act to aggravate rather than alleviate frequency instabilities in the system [125]. Vulnerability to such attacks makes it important to consider the security of ICT systems that the control of flexible resources depends upon.

Flexible resources may also negatively impact SoS in their normal operation, i.e. when providing other services than SoS-related services. For instance, it is well established how EV charging may negatively impact power quality unless appropriately controlled. Potential negative impacts mainly include voltage drops, but also harmonic distortion, voltage unbalances, congestion, grid asset overloading, increasing power losses and voltage instability [30, 59]. CIGRE WG C6.20 ([29], p. 52, p. 158) considers impacts on the bulk power system and is mostly concerned with the potential for increasing the generation power capacity and ramp rate requirements.

A general measure to mitigate negative impacts is to enable these distributed energy resources to function as flexible resources. An energy resource may be inflexible due to regulatory, market or technical limitations but can be made to be flexible with the appropriate measures. For EVs this implies implementing appropriate EV charging strategies [82, 59]. One should also note that while EVs may contribute to e.g. improving frequency quality on the level of the bulk power system, they may nevertheless have a negative impact on other aspects of security of supply on a more local (i.e. distribution) level (59, p. 60).

6.2. Assessing security of supply in the power system in the future

As outlined in Sections 1 through 3, current trends in the power system include a transition from centralized to more decentralized generation and from one-way to two-way power flow. In summary, we argue that these trends imply that 1) distribution systems become more similar to transmission systems, 2) that there will be more interaction between the different levels (transmission/distribution/etc.) of the power system, and 3) that there will be greater interplay between different aspects of the SoS.

As alluded to in Section 5.3.1, flexible resources introduce new degrees of freedom or control variables in the operation of distribution systems. These control options can be seen as analogous to control options for managing reliability of supply at a transmission level, e.g. rescheduling of generation to avoid overloading. At a transmission level, steps are taken towards more probabilistic approaches to manage reliability of supply that rely more on corrective and preventive control measures that can be taken during operation and less on grid investment measures [131]. Flexible resources thus make it more relevant to consider probabilistic approaches to manage security of supply also at a distribution level in the future. On the other hand, relying more on flexibility resources during operation may also introduce new vulnerabilities due to operational uncertainties related to the availability, activation and response of flexibility services (when needed e.g. after a failure, cf. Section 5.3), or related to cyber-attacks (e.g. of DR resources, cf. Section 6.1).

Distribution systems or parts of distribution systems may also to a greater extent be able to operate in island mode and as microgrids [63]. This presents methodological challenges as described in Section 5.2. It also presents conceptual challenges to the way of managing security of supply when distribution systems or end-users have the option to manage their own security of supply locally (schematically illustrated in Fig. 7b) rather than relying on being supplied through a centralized generation and transmission system (Fig. 7a). It may call for new SoS indicators representing such scenarios and raises the issue of more differentiated requirements on security of supply for different end-users. As mentioned in Section 5.1.1 and in [37], similar issues are also raised by the use of corrective DR services: These imply loss of load and associated costs and inconvenience for some end-users but may avoid involuntary and uncontrolled load shedding for many other end-users. Furthermore, in principle demand response should also be implemented in a more selective manner such that end-user consequences are minimized [64, 99]. Overall societal costs associated with flexibility services (including operational costs and avoided end-user costs) are not discussed or quantified in the reviewed literature [128].

Flexible resources located at a distribution and end-user level can also impact SoS at higher levels of the power system. There are also examples of more complex interplay between power system levels: If a

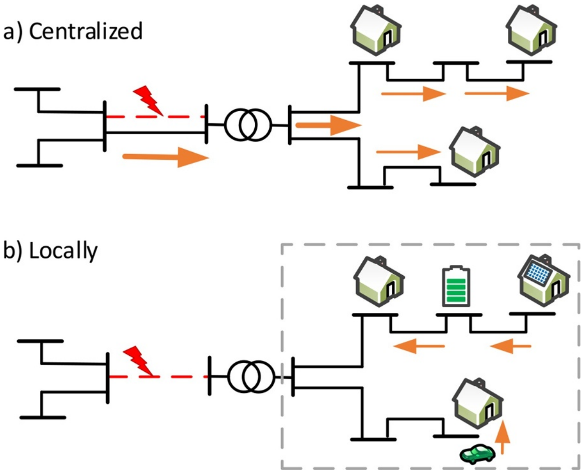

Fig. 7. Schematic comparison of a) the (traditional) centralized approach to managing security of supply (here: by redundancy of transmission or distribution assets) and b) managing security of supply locally. Orange arrows indicate power flow, red indicates a power system component fault, and flexible resources are coloured green.

flexible resource in a distribution system is used to manage SoS at the transmission level, this has implications for its availability for SoS-related services at a more local level. The emerging dilemma of managing security of supply locally (e.g. through islanded operation) or centralized (relying on supply from the transmission system) also illustrates the interplay and blurring of boundaries between different aspects of security of supply. Reliability of supply (considering power system component failures) may be less relevant as end-users or distribution systems become less reliant on centralized power supply; on the other hand, local power (generation) capacity and energy availability becomes more relevant as lower levels of the power system rely more on being self-sufficient over shorter or longer or periods [65].

Flexible resources in distribution systems may reduce the frequency of medium-term (e.g. minutes–hours) power interruption events but give less improvement for 1) longer-term and 2) shorter-term events, because: 1) the flexible resources are associated with a limited energy capacity and can thus support restoration of power supply for a limited time; 2) unless the resource can support successful transition to island mode for e.g. a distribution radial, there will still be a short interruption event. And even in case of transition to island mode without power interruptions, and thus without reliability of supply problems, there may still be voltage and frequency (i.e. power quality) problems during the transition. This illustrates how the distinction between power quality and reliability of supply may be unclear, as a there is a continuum of supply voltage problems from 100% of nominal voltage to the limit defining a power supply interruption.

6.3. Concluding remarks

Flexible resources in distribution systems can have a positive impact on several aspects of security of electricity supply: Energy storage systems, electrical vehicles and demand response can all provide services that benefit the reliability of supply, power quality and power capacity of the power system. However, flexibility services can also influence security of supply negatively. Services can be provided to different actors: ancillary services can be provided to the transmission system operator to improve SoS on a bulk power system (transmission and generation) level; ancillary services can be provided to the operator of a distribution system; or end-users can use flexible resources to improve their own reliability of supply and power quality. The benefits of flexible resources to the aspect of energy availability are not equally evident, but energy availability and reliability of supply may become more interrelated in a future with more distributed power systems (e.g. parts of distribution systems operating in island mode). Comprehensive and holistic assessment of multiple aspects of security of supply and their interrelation has not been addressed in the existing research literature, and more attention has been given to reliability of supply than to the power quality and power capacity aspects.

From the assessment of the literature, we conclude that methodologies for quantifying the SoS impact of flexible resources need to capture their operational benefits and thus need to simulate their services during the operation of the power system. More specifically, time-sequential simulation may be needed to capture the variability, time dependence, chronology and restrictions related to ESS or EV energy constraints, DR rebound effects, and restoration times, etc. Because the impact of a flexible resource depends on the duration of the event challenging security of supply (e.g. outage duration), it is important to consider the probability distribution of this duration and capture it in the SoS indicators.

The review has also identified several research gaps in the literature. First, due to the time-dependence and variability discussed above, we argue that flexible resources make it more important to consider probabilistic methodologies for quantifying security of supply. This need is clearest for the power quality aspect, and there is a need for more detailed simulation methods and probabilistic power quality indicators to quantify the benefits of power quality-related services. It is also relevant to develop indicators that capture the variability in both the duration and magnitude of the voltage deviation. In this way, one can capture the benefits of flexible resources with respect to the full continuum of voltage quality events and not only power supply interruptions.

There also appears to be a need for more research on accounting for new uncertainties introduced by flexible resources. This includes operational uncertainties related to the aggregation and activation of flexible resources and their availability and reliability to respond when needed, as rapidly as needed and for as long as needed. More work is also needed to understand potential new risks and vulnerabilities introduced by flexible resources and their dependency on ICT systems. The operational risks should be accounted for when assessing the SoS benefits of flexible resources, and risk-based approaches should be considered when developing models for the optimal activation of the flexible resources.

A related research gap lies in considering the trade-off between different services provided by flexible resources and how it affects the SoS impact. This both includes multiple SoS-related services provided by the same resource, the trade-off between benefits to different actors and end-users, and the trade-off between SoS-related services and other services or uses of the resource. The interplay between different levels of the power system will become more complex, and it will be relevant to investigate the trade-off between measures to manage security of supply locally (e.g. flexible resources to allow island operation) and traditional centralized measures to ensuring end-users' security of supply.

CRediT authorship contribution statement

Iver Bakken Sperstad: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing - original draft. **Merkebu Zenebe Degefa:** Conceptualization, Investigation, Writing - review & editing. **Gerd Kjølle:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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