Chapter 11
Indicators for the Resilience Monitoring of Energy Systems

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Abstract Indicators are crucial for any management as they allow for monitoring, reviewing and adapting strategies towards a previously planned objective. The key challenge for fulfilling this task is to identify and define indicators that enable the assessment of the system under consideration. Regarding energy systems, if understood as complex socio-technical systems, a multitude of indicators for resilience assessments have been proposed, which vary according to the different systems analysed as well as indicators and stakeholder requirements. Hence, it seems that universal indicator frameworks are not applicable for resilience assessments and thus specific indicators are needed. However, a crucial step towards developing a general resilience assessment and monitoring framework is to understand on which aspects indicators depend, what "good" indicators can cover and what the limits of these indicators are. Therefore, this chapter gives an insight into the general characteristics of indicators. Then, it describes the indicator requirements particularly with respect to the resilience (monitoring) for energy systems. Furthermore, the chapter will address some specifics for the resilience assessment and management of energy systems based on some exemplary indicators.

Keywords Indicators · Assessment · Energy system · Resilience · Reliability · Indicator selection · Monitoring

11.1 Introduction

Indicators have become crucial elements for any management related processes and were initially introduced by economics and management disciplines (Linser 1999; Merry 2011). Since then, the use of indicators spread into other disciplines such as governance and politics, medicine and engineering, as well as sustainability related

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aspects. Indicators facilitate the monitoring and evaluation of systems, tasks or objectives. Further, they allow the comparison of different systems, technologies or products regarding their performance and the effectiveness of implemented measures (ILO 2015). For example, based on previously defined indicators, situations can be analysed regarding the performance and if indicators surpass certain thresholds potential counter measures can be initiated in time. Consequently, indicators are relevant for any assessment and evaluation, however, potential users should consider certain relevant aspects of indicators and their selection. Therefore, this chapter not only focuses on the overview of key indicator characteristics, but also give indicator examples for the resilience monitoring of energy systems.

11.2 General Aspects of Indicators and Their Requirements

Although a general unified theory of indicators does not yet exist, indicators share common aspects throughout various disciplines. If the sole meaning of the term is considered, it can be traced back to the latin verb *indicō*, which means to point out or to show at/to/on something. The German dictionary "Duden" defines indicators as *"something (fact, feature), which relates to a (statistically applicable) sign/evidence for a certain progress or a condition entered*" (Duden 2023, translated by the authors). Hence, indicators describe certain aspects of the object in question and thus they should be related to the overall purpose of the analysis.

Before indicators can be defined, several steps of abstraction have to be done. The term "indicator" is often synonymously used for different levels of the data pyramid with data, information, indicators and indices as shown in Fig. 11.1 with an increasing degree of abstraction used during indicator definitions. Firstly, the initial point is the real-world object that can be either analysed by experiments (e.g. lab-scale) or computational models. Secondly, from these tools, data can be obtained focusing on the model/experiment purpose. Thirdly, data are processed (interpreted) and thereby transformed into information. Fourthly, the indicators are defined according to a specific purpose and can be aggregated at process information level. Fifthly, indices can aggregate and weight several indicators, which are also named composite indicators.

When analysing systems, the measuring point and basis for indicators can be assigned to different stages of the system model ranging from inputs, processes (throughput), outputs, outcomes and impacts, which are shown in Fig. 11.2. At each of these metering points data, information, indicators and indices can be ascertained following different purposes of the indicators obtaining data and information. Whilst, the input and output can refer to the efficiency and quality of the system service (i.e. purpose), respectively, the process of the system is mostly related to the system behaviour and its state during an observation period. The system outputs directly contribute to the results causing additional outcomes in mid-term and at higher

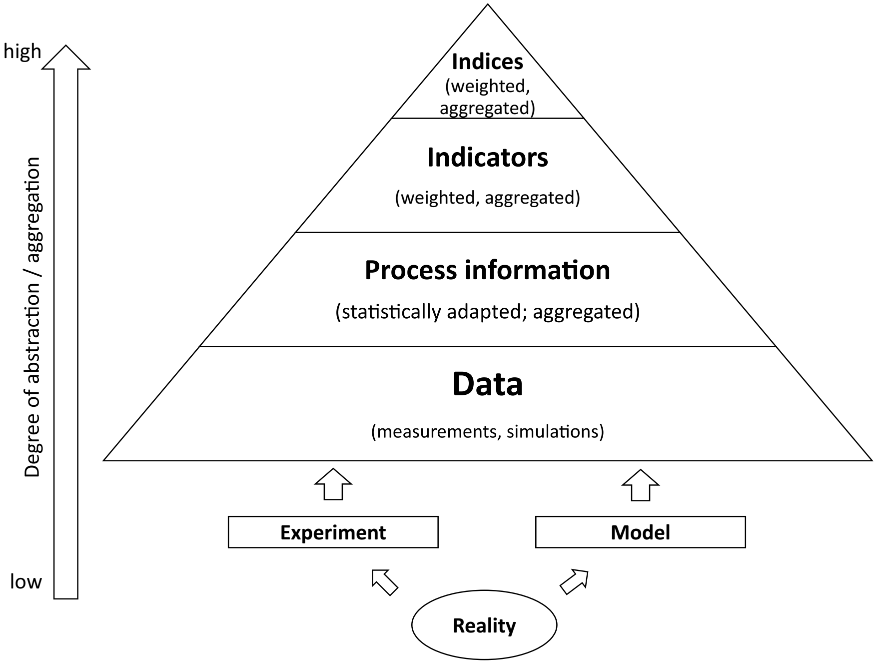

Fig. 11.1 Abstractions steps considered in modeling and evaluation processes for indicator and indices definitions. (adapted and extensively extended from Adriaanse (1995) cited in Linser (1999))

geographical scale (e.g. nationally and not only local). In contrast, outcomes and their impacts are less tangible because they are not directly traceable from system outputs and results (Zwart 2017). For example, if the output of a system (or a certain management measure) creates higher productive employment, the outcome of this system output would be the increase of the national state's welfare. Nevertheless, the global impact might be also positive in the mid- or long-term, but it is often challenging to identify direct linkages of outcomes and impacts. Depending on study objective, the indicator definition has to consider this differentiation since particularly the outcomes and impacts as reference points for the success of a management action often are not related to the direct system output and thus may have to include other aspects avoiding misinterpretations.

11.2.1 Types of Indicators

Due to the wide range of indicator applications, it is worthwhile to examine various indicator classifications addressing different aspects. The most common distinction is between **quantitative or qualitative** indicators. Presumably, the former is preferred over the latter, as numbers (often in cardinal scales) enable an easier comparison

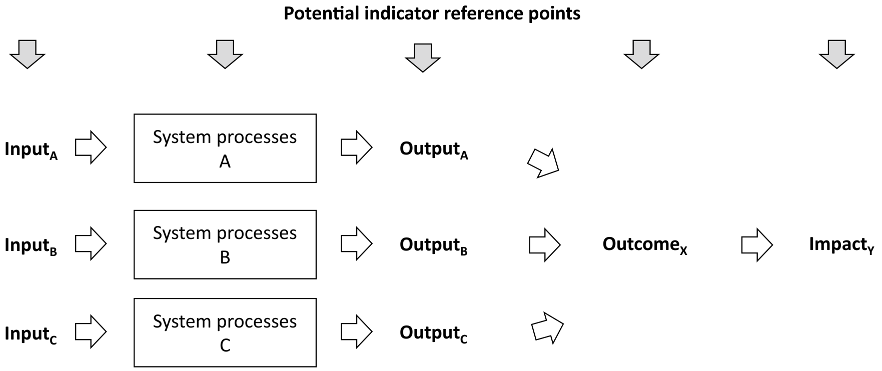

Fig. 11.2 Potential reference points for indicators for system inputs, processes, outputs, outcomes to impacts for the assessment of systems (own illustration based on Zwart 2017)

and understanding. Therefore, qualitative indicators are often converted into semi-quantitative numbers by using ordinal scales (Merry 2011).

The subcategory **direct and indirect (i.e. proxy)** indicators is another relevant differentiation. Direct indicators directly measure the phenomenon of interest. Proxy indicators are used when direct measurements are not possible, which often applies for complex systems. For instance, in medical contexts, the high or low blood pressure can indicate some severe problems related to the heart itself or blood vessels, without measuring directly the phenomenon and the actual cause (e.g. heart activity).

From a management perspective, indicators can be used not only for **descriptive** but also for **normative** purposes. Whilst, the former neutrally depicts the system state and behaviour as well as impacts, the latter focuses on either the **evaluative** or **prescriptive** (management) aspects by comparing to strictly set goals. A special type of indicator are **composite indicators**, also called indices, that are used to aggregate several indicators to describe the intended purpose. By doing so, complex issues can be easier communicated. Furthermore, the temporal perspective with the focus on past, present or future developments is a relevant characteristic of indicator to consider for differentiations.

11.2.2 Pros and Cons of Indicators

The use of indicators has benefits and detriments about which a vast amount of literature is available. Thus, only a brief overview will be given in this subsection.

Indicators have the advantage of facilitating the communication of complex issues to both non-experts and decision-makers (Meadows 1998; Mair et al. 2018). Hence, indicators should be appropriately aligned to the decision objectives (i.e. the purpose). As it is shown in Fig. 11.2, indicators generally generate knowledge at an abstract level and thereby, when applied to comparable objects, enable the scoring, ranking, comparing as well as monitoring and evaluating of the objects in question. By doing so, indicators support the decision-making for experts and non-experts.

Although the “simplification” of complex matters appears to be appealing for communication and decision purposes, every abstraction and aggregation process involves the loss of information. In the abstraction process, the relevant aspects for the specific purpose have to be identified and accordingly considered in the indicator definition. Hence, the abstraction process and with that the indicator definition strongly depends on the individual’s expertise and experience who develops the indicator. Consequently, indicators are not an objective description of the research object (Mair et al. 2018) and thus are value-laden (Bossel 1996; Turnhout et al. 2007).

Another critical aspect of indicators is their interpretation. Even though indicators ease the evaluation and communication of complex matters, it is of high relevance to report the actual indicator purpose and to consider the corresponding limitations for the interpretation. This is particularly relevant when indicators are used in different contexts in which the original purpose does not fit to the decision context (Copeland et al. 2020). Furthermore, the often-desired quantitative illustration of indicators can be misleading. The crucial point of criticism is that those indicators may suggest a wrong precision, because particularly quantitative indicators are associated to the claim of (mathematical) correctness (Porter 1995). Consequently, the limits of indicators are discussed in different disciplines, and it is generally recommended to illustrate the uncertainty enabling the transparent interpretation of the results.

Furthermore, it has to be noted that cause and effect relations of specific measures cannot necessarily be traced back, because particularly in complex systems nonlinear relationships may dominate and hamper to the identification of cause-effect-chains with the risk of oversimplifications (Mair et al. 2018; Merry 2011).

11.2.3 Quality Criteria for Selecting Indicators

In order to avoid or minimize the disadvantages mentioned in the previous subsection, it is important to ensure a transparent indicator selection. The process of developing and selecting indicators should be well documented and methodologically guided, particularly when stakeholders and experts are involved in the decision preparation. Thus far, a multitude of assessment frameworks were proposed to guide through the process of the decision preparation for various contexts (e.g. sustainability, environmental protection, etc.) (Guo et al. 2021; Nguyen and Akerkar 2020; Bill et al. 2020).

The need for transparency even becomes more crucial when multiple indicators have to be considered in the assessment, because the indicators have not only to be defined and distinct but also have to be weighed against each other. For this, the method of multi-criteria decision analysis (MCDA) is established as a transparent approach to guide through complex decision situations. Baumann et al. (2019)

summarised the MCDA approach in the following steps: goal and problem definition, selection of alternatives for comparison, identification of criteria (i.e. indicators), choice of suitable MCDA method, aggregation and weighing of criteria/ indicators, interpretation of the results, if possible with stakeholder involvement. In the following subsection steps of goal and scope together with the indicator selection will be discussed in more detail due to their relevance for the indicator setup.

11.2.3.1 Indicator Selection

In the first step, the goal and scope of the study have to be determined, if possible by the decision-makers who have information on the decision situation and object. Once the goal and purpose are defined, indicators can be collected and defined that are fitting to the agreed decision objectives. Basically, two major approaches exist to identify indicators for any assessment that usually complement each other (Mangoyana et al. 2013). Firstly, the top-down strategy attempts to identify already existing official indicator frameworks (e.g. sustainable development goals), reports or other published scientific literature that deal with the objective intended. Secondly, the bottom-up strategy accesses the knowledge of experts and other stakeholders that are familiar with the decision context or are affected by the decisions, respectively (Quinlan et al. 2016). This knowledge and indicator needs can be obtained by conducting workshops, interviews or questionnaires, for instance. The top-down strategy is more often applied due to time and resources constraints, although stakeholder and expert workshops give a practical insight into ranking and selection of indicators due to the perceived relevance. This additionally support the trust into the indicators and the acceptance by decision-makers. The actual indicator selection is often not explicitly documented in the literature, which hamper the transparency and potential support of decision-makers for the selected indicators.

11.2.3.2 Criteria for Selecting Indicators

So far, there is no consensus in scientific literature on which quality criteria should be fulfilled by indicators and thus each study has to define their criteria, as no universally accepted indicator set can be defined. The main reason is that the decision objective and participating stakeholders finally determine the indicator selection in bottom-up studies. However, Hirschberg et al. (2008) summarized several criteria that can be applied to select indicators, which are depicted in Table 11.1. The different criteria for indicator selection are assigned to the characteristics scientific, pragmatic and functional aspects determining the decision situation. It has to be noted that some of these criteria cannot undoubtedly be assigned to one category, because several characteristics can be attributed to one criterion. The following Table 11.1 is mainly based on Hirschberg et al. (2008).

The selection of indicators is particularly challenging for the assessment of complex systems, because such systems own features such as being dynamic, having

Table 11.1 Summary of potential criteria for selecting indicators sorted by scientific, pragmatic and functional characteristics. (based on Hirschberg et al. (2008))

Scientific	Pragmatic	Functional
Measurable	***Manageable***[1]	***Relevant***[+]
Qualitatively and quantitatively	Adequate number of indicators	For most stakeholders involved
Meaningful[*+]	***Understandable***[*]	***Compelling***
Reflects the users' needs	Possible to comprehend	Interesting and suggestive for actions
Clear in value[*]	***Feasible***	***Leading***
Clear positive or negative denotation	Possible to collect within time and cost constraints	Basis for the decision about actions
Clear in content[*]	***Timely***	***Influenceable***
Understandable units	Easy and quick to calculate	Indicators are able to influence actions
Appropriate in scale[#1]	***Coverage of the intended aspects***[#*+]	***Comparable***
Suitable dis-/aggregation scale	Purpose is covered	If applied in different systems, the comparison should be possible
No redundancy		***Comprehensive***[+]
Avoid double counting		Describes the relevant aspects of the system under study
Robust / reproducible		
Transparent and sound indicator calculation method		
Sensitive / specific		
Sensitive to changes during the time scale considered		
Verifiable		
Verifiable by third persons		
Hierarchical[*]		
Adjustable levels of detail		

[*], [+],[1] and [#] marked criteria that are linked to other criteria of different characteristics

non-linear or emergent properties that aggravate the identification of suitable indicators. Consequently, it is generally recommended to involve experts and stakeholders to gather in-depth knowledge, which is required for the assessments. Stakeholders and experts can contribute to both the identification of the long list (i.e. all potential indicators) and the final short-listed indicators which can be selected based on the reasons mentioned in Table 11.1.

11.2.3.3 Selection of Indicator Sets

When selecting indicators for monitoring systems, the question automatically arises how many indicators are needed for a sound assessment and monitoring process. There generally is no definite answer to the correct number of indicators or indices as it depends on the study purpose, system complexity and stakeholder needs. For example, when analysing systems with a low complexity, simple data points (cf. Fig. 11.2) can be sufficient describing the necessary systemic aspects that allow for the assessment. In contrast, for complex systems it can be challenging to identify and select suitable indicators (Quinlan et al. 2016) and thus more pragmatic aspects have to be considered for the selection of indicators. Describing complex phenomena with the help of a single indicator or indices (i.e. aggregated indicators) is in general critically discussed (Martišauskas et al. 2022), since information is lost because of omitting indicators or by the indicator aggregation, respectively. However, when defining indicators sets with non-aggregated indicators, different indicator sets can cover the same study purpose, because the system behaviour originates from different system characteristics and depending on the stakeholder and expert perspectives can lead to different selections. Therefore, it is recommended to include stakeholder and experts in the participatory definition and selection process to gain the trust of decision-makers as final users. Furthermore, the weighing of different indicator domains in the sustainability assessments should be targeted to avoid any biases favouring either the economic, environmental and social dimension, for instance (Gillespie-Marthaler et al. 2019).

11.3 Challenges for Resilience Assessment and Monitoring Frameworks for Energy Systems

The subsection will focus on resilience and its challenges regarding indicator definition as well as give a short overview on frameworks and exemplary indicators for resilience assessments. The assessment and monitoring of energy systems regarding their resilience is a multidimensional challenge due to several reasons. Firstly, energy infrastructures are considered as complex systems, which are characterized by their spatially and temporally dependent parameters that aggravate the resilience assessment and monitoring (Kaloti and Chowdhury 2023). Secondly, energy systems cover large geographical areas with diverse system states depending on time and location that need to be considered for the assessments. Thirdly, resilience depends on the stress cases with their various stressors (i.e. resilience against what) and also on the stakeholders (i.e. resilience for whom) who can be affected by the loss of energy supply (Wied et al. 2020). Fourthly, resilience is an emergent system property and thus it is not directly measurable (Cains and Henshel 2021). Resilience depends not only on the stress case, but also on system design (e.g. redundancy, diversity), recovery, mitigation and adaptation strategies that determine the system capacity and capability to (re)act resilient (Watson et al. 2022). Consequently, resilience assessments usually have to establish several proxy indicators for determining or monitoring the energy system's resilience (Martišauskas et al. 2022).

These combined challenges aggravate the selection of indicators and development of frameworks applicable for energy systems. For example, when assessing a specific part of the energy system, potential stress cases will affect the physical infrastructure and its operation at different geographical areas. In such cases, indicators and indices at low geographical resolution (i.e. high aggregation) may show a positive resilience performance, indicators and indices at higher temporal and spatial resolution can point to the opposite. The main reason is that the adaptive capacity, which reduces the system vulnerability, has to be available and accessible at the affected region to cope with the local stress case impacts. Even if the energy system may have high adaptive capacities in general, it is crucial to consider if these can be accessed at the right point of time during the stress case to minimise or even mitigate the stressor impacts. Thus, the potential disruptive events (and failures) as well as the available capacity and capability to react and recover are always context-dependent (Watson et al. 2022). This challenge will become even more severe when the resilience assessment is conducted as permanent monitoring. Resilience monitoring is understood as the continuous observation of the system state (Mentges et al. 2023), the aforementioned challenges have to be considered for the interpretation and/or when used for performance checks, the indicators should be selected only for the agreed objectives. By doing so, monitoring processes can address both real-time (i.e. operational) and strategical aspects and allow the identification of necessary adaptation strategies. Also, in the context of resilience monitoring, the decision makers are interested in how potential resilience measures may affect the resilience level of the system so that already taken decisions can be revised or a priori defined mitigation strategies initiated, if necessary.

11.3.1 Resilience Assessment Frameworks

Numerous resilience assessment frameworks were developed in recent years that differ in purposes and covered aspects (Guo et al. 2021; Nguyen and Akerkar 2020; Bill et al. 2020). Likewise, the considered types and number of indicators vary among the studies (Mujjuni et al. 2021; Gillespie-Marthaler et al. 2019) and thus aggravates their comparison and the identification of standard indicator sets (Martišauskas et al. 2022). Resilience assessment frameworks can employ quantitative, semi-quantitative, qualitative or combinations of these indicator types. Resilience assessments are usually not limited to one domain, but cover several domains as for example technical, organizational/management, social, safety, security and sustainability (Osei-Kyei et al. 2023; Ahmadi et al. 2021). Each of these domains comes with its own set of requirements not only regarding the indicator definitions and purposes, but also the data required for the assessment, setting a cumbersome task

(Cantelmi et al. 2021). Although the comprehensive view on all domains is becoming more relevant (Poulin and Kane 2021), the main focal point for energy systems was laid on the technical domain, so far.

The technical domain is most often considered quantitatively by applying the resilience curve approach, therefore focusing on the system performance (Gasser et al. 2020; Poulin and Kane 2021; Bill et al. 2020). The resilience curve, or also named bath tube curve, shows the development of the system performance depending on time, where the former is impacted by disruptive events decreasing the performance.

Generally, the resilience curve can be distinguished by the temporal stages of the event. This includes the system performance before, during and after event (Resilens 2016; Bill et al. 2020). During each of these stages different actions can be established to improve the resilience and with that the system performance. The *pre-event stage* is characterized by proactive strategies such as to prepare, prevent and protect the system against potential stressors. It thus focuses on questions about system design and/or on decreasing potential exposures to the stressors. The *during event* stage includes mitigation, absorption and mobilisation of adaptive capacities (in short-term) for buffering or minimizing potential impacts on energy infrastructures (Resilens 2016). The *post-event stage* represents the respond, recovery and learning capabilities (Resilens 2016). Similarly, to the event-related differentiation, the *pre-, during* and *post-event stage* can be differentiated according to the main actions that a system should perform. In these stages, the system should resist, re-stabilize, rebuild and reconfigure to deal with the impacts of the stressors (Gasser et al. 2021). Likewise, for each of these four stages different indicators can be defined. Consequently, for each domain and stage of the resilience curve, several indicators are required to describe complex socio-technical systems (Jovanović et al. 2020; Martišauskas et al. 2022),

The described multidimensionality of resilience assessments and monitoring is also reflected in the various frameworks that have been developed so far. This is also reflected by several reviews on frameworks, metrics, models and general assessment methods that were published in the last years (Hosseini et al. 2016; Kaloti and Chowdhury 2023; Cassottana et al. 2023; Wang et al. 2022; Wied et al. 2020; Stanković et al. 2023). Moreover, professional associations such as the Institute of Electrical and Electronical Engineers (IEEE) worked out a specific resilience assessment framework applicable for power systems (Bill et al. 2020). This IEEE framework considers potential hazards of any kind and their impacts on the power system with five focus areas. Several technical and operational metrics were defined to assess critical energy infrastructures and prioritize investment decisions (Bill et al. 2020). Besides the technical domain, other researchers emphasized the need also to include other resilience curve stages such as recovery/repair (Kottmann et al. 2021) as well as other domains such as social-economic aspects (Ottenburger et al. 2020; Quinlan et al. 2016; Meerow and Newell 2019; Copeland et al. 2020). Since it is not the aim of this chapter to provide a comprehensive overview on all potential indicators and frameworks (cf. e.g. Martišauskas et al. 2022), the following sections will provide some examples of commonly used indicators.

Table 11.2 Overview of the exemplary indicators presented in this subsection

Indicator name	Structural/Performance
Loss of Load Probability (LOLP)	Performance
Loss of Load Expectation (LOLE)	Performance
Storage capacity	Structural
Diversity—Primary fuels/energy carrier	Structural
Diversity—Installed capacity	Structural
Share of renewable energy in generation	Structural
Import dependency	Structural
Change of network connection of the system	Structural

11.3.2 Indicators for the Resilience Assessment and Monitoring of Energy Systems

The assessment and monitoring of energy systems has a long tradition as it was always the main objective to provide energy to different stakeholders at highest quality with minimized interruptions. For this reason, various tools and indicators are already well-established for determining the status of power systems, which are related to reliability and robustness. Although the boundaries of reliability and resilience are inconclusive, both share common aspects so that they can be used complementarily (Gasser et al. 2020).

In the following subsections some exemplary indicators are described, which can be used for the monitoring of the energy system during disruptive events. An overview of the discussed indicators is available in Table 11.2. It has to be noted that this list does not aim for comprehensiveness. The indicators were selected as relevant examples since they can be used in most of the assessments or are quantifiable with power system models used in the ReMoDigital project. It also has to be emphasized that these indicators mainly cover the technical aspects of power system and does not include additional aspects such as sustainability perspective which should be included in future assessments (Netz et al. 2023).

Before the indicators are briefly discussed, firstly the distinction of reliability and resilience in the context of performance indicators is described and some selected reliability indicators are introduced. Secondly, the difference between structural and performance indicators is given. Thirdly, exemplary structural indicators will be introduced, which will be integrated in the resilience curve.

11.3.2.1 Reliability Indicators for the Performance Assessment of Energy Systems

In long term planning of energy systems, reliability of the generation system plays a key role for the expansion of installed capacities to meet the future demand (Nikzad et al. 2012). Reliability is defined as the **ability to meet customers energy demand** needs despite unexpected equipment breakdowns reducing the supply of energy (Felder and Petitet 2022). On the other hand, the ability to **quickly bounce back** from an undesirable situation was described as resilience. Thus, reliability focuses on certain aspects of resilience, but resilience includes additional aspects regarding the adaptation and recovery capabilities (Chi et al. 2018). Consequently, a higher reliability can increase the resilience and vice versa, but there can be certain situations in which this does not pertain (Kaloti and Chowdhury 2023).

During the planning process, reliability indicators aid to take decisions on investment opportunities of forthcoming installed capacities (Nikzad et al. 2012). The reliability of the energy system can be evaluated by following standard indicators such as 'Loss of Load Probability (LOLP)' and 'Loss of Load Expectation (LOLE)', which usually depicts the interruptions of the annual average. The definitions of these indicators are:

- **Loss of Load Probability (LOLP):** It refers to probability of an occurrence of event where loss of one generation unit '*i*' causing risk of the power supply (Ferro Ferdinant et al. 2020).

  $$LOLP = \sum_{i=1}^{n} p_i \times t_i$$

  where, n is the number of units that supply energy to the system, p_i is the probability of loss of capacity, and t_i is the duration of loss of capacity
- **Loss of Load Expectation (LOLE):** It refers to the expected number of hours per year where the occurrence of an outage might possibly occur in an energy system (Ferro Ferdinant et al. 2020).

  $$LOLE = \sum_{i=1}^{n} p_i \times t_i$$

  where, n is the number of outages in a year, p_i is the probability of loss of capacity, and t_i is the duration of loss of capacity.

Especially the LOLE is a useful indicator for performance measurement, as energy systems are usually benchmarked by their outage hours for end-users. Methodologically, these indicators need to be distinguished from structural indicators.

11.3.2.2 Structural Indicators for the Resilience Assessment of Energy Systems

Indicators in quantitative resilience frameworks are helpful for comparing the degrees of resilience in various systems or for assessing the efficacy of certain resilience strategies (Bill et al. 2020). When following the standard resilience curve approach, indicators are often based on quantifications for performance assessment in a technical meaning. However, regarding resilience assessments of energy systems, indicators can be categorized in three different categories: performance-, structure- and hybrid-based approaches (Hosseini et al. 2016; Wied et al. 2020; Martišauskas et al. 2022; Biringer et al. 2013).

Performance-based indicators focus on the benefits (i.e. services) that a system provides for stakeholders as the main concern of resilience (Wied et al. 2020; Jasiūnas et al. 2021). However, the sole focus on performance indicators cannot contribute to an understanding why certain system designs perform better than others against disruptive events. Hence, it is crucial to consider also the system's structure, even though relevant system characteristics can be difficult to identify (Biringer et al. 2013). Thus, structural indicators are required for assessing how the internal characteristics (i.e. architecture and design) of a system affect the system's resilience. Those characteristics are attributes that can decrease or increase the energy system's resilience depending on the stress case, such as the availability of redundant power lines in the grid (Martišauskas et al. 2022). Structural resilience indicators have the disadvantage, though, to be complex, more time-consuming to obtain and require a high level of expertise, as the system's inner structure needs to be modelled (Hosseini et al. 2016; Mottahedi et al. 2021). On the other hand, performance indicators are more validated, but as all systems have certain dynamics, it can be difficult to determine what the base performance of a system was before an event, and when exactly that event started. This may lead to uncertainty when the base performance is compared to the performance within an adverse event (Biringer et al. 2013; Wied et al. 2020).

In a hybrid-based approach, that employs both structural and performance indicators, the structural indicators provide potential explanations for the system behaviour that are measured and evaluated with performance indicators. In the best case, the relationship between structural (i.e. system design) changes and the performance can be explained (Biringer et al. 2013; Martišauskas et al. 2022). This knowledge can be used for improving the system's resilience, because resilience assessment and monitoring is a continuous process.

11.3.2.3 Structural Indicators: Examples for the Energy Sector

The structural indicators for the energy sector try to measure properties of a power system related to resilience enhancing system characteristics such as redundancy or diversity. In the following an exemplary overview about structural indicators is given, which addresses some system characteristics. It has to be noted that these structural indicators are not comprehensive but are relevant in most frameworks.

Storage Capacity ($\mathbf{I_{SCA}}$):

This indicator $\mathbf{I_{SCA}}$ represents the amount of available reserves that can be used for the energy supply. Higher storage capacities can show the potential characteristics of stronger resilience. However, the impact of an uncertain event on storage capacity relies on the available and accessible reserves at the time of disruption.

The advantages of the storage capacity indicator are that the indicator itself and the principle behind it is approachable and easy to assess for most systems. In some cases, with higher demand of stored energy it has to be considered that storage systems can only discharge to certain power system specific limits and there not the capacity, but the power output of the system is the limiting factor.

Inputs needed to evaluate the storage capacity includes capacity of storage/reserves, used generation capacity, available generation capacity, and usable stored energy.

$$I_{SCA} = \frac{SC}{EP}$$

where SC is the capacity of storage/reserves in MWh and EP is the total energy consumption in MWh (Martišauskas et al. 2022).

Diversity—Primary fuels/energy carrier ($\mathbf{I_{PF}}$):

The indicator $\mathbf{I_{PF}}$ demonstrates the diversification of installed capacity through various fuel sources. A diversified energy system with multiple fuels or energy carriers for energy production can result in higher resilience during the disruption than less diversified systems, because energy carriers can be differently affected by the same disruptive event. Moreover, domestic and imported fuels can be combined in this indicator to consider the diversified sourcing strategies, which points at the supply chain of energy carriers. Thereby, this indicator gives insights into the dependence on single energy carriers, this is especially relevant for fossil fuels that are imported from abroad, as these resources can be easier restricted for political reasons than nationally sourced energy carriers. A strong dependency on one renewable energy carrier can be especially relevant for abnormal climate patterns, for example, droughts can limit the supply of hydroelectric energy. (Martišauskas et al. 2022; Gasser et al. 2020).

The following equation is based on the Herfindahl–Hirschman index (HHI) and Shannon–Wiener index (SWI) that applies to different types, shares and number of primary fuels.

$$I_{PF} = -\sum\nolimits_{i=1}^{N} p_i * \ln(p_i)$$

where $\boldsymbol{p_i}$ is the share of single energy carrier ‘i’, **N** is the number of primary fuels in energy supply (Martišauskas et al. 2022).

Diversity—Installed generation capacity ($\mathbf{I_{IGC}}$):

The indicator $\mathbf{I_{IGC}}$ represents the diversified installed capacity for energy production through various energy carriers. Whilst, the previous I_{PF} indicator only represents the supply-side of specific energy carriers, the I_{IGC} indicator focuses on the capacity to make use of these energy carriers. A restricted generation capacity because of a disruptive event would endanger the system’s resilience, for instance, even if energy carriers are available and accessible. Thus, a diversified installed capacity for energy production can increase the resilience in face of disruptive events. This will always allow one type of the installed capacities to compensate the damaged one. Like the primary fuel indicator, this indicator gives guidance for overdependence. However, the diversity of the installed generation capacity focuses on constraints in energy production facilities, not only the fuel supply as the diversity of primary fuel/energy carrier indicator. A good example for overdependence on one type of energy production facility is the French nuclear power fleet. The reactors were mostly built in the same period and therefore needed repair and renovation works at a similar point in time, which lead to concerns about the security of electricity supply in France (Müller-Lancé 2022).

Inputs needed to evaluate the installed capacity include types of energy production technologies, shares of energy production technologies, number of energy production technologies. The following equation reflects the diversity of generation capacities,

$$I_{IC} = -\sum\nolimits_{i=1}^{N} s_i * \ln(s_i)$$

where $\boldsymbol{s_i}$ is the share of individual installed capacity, **N** is the number of energy production technologies 'i' (Martišauskas et al. 2022; Jewell et al. 2014).

Share of renewable energy in generation ($\mathbf{I_{RES}}$):

The indicator I_{RES} can evaluate the share of the renewable power generation over the total generation. Renewable power with independent generation from primary fuels has a capability to influence the system's resilience. However, renewable power generation is completely dependent on the weather and day/night patterns. This indicator is similar to the diversity indicators but gives a special insight about the renewable energy sources and the constraints and risks that may be associated with them. Further, is this indicator relevant for sustainability assessment.

Inputs such as total generation, and renewable power generation are needed to evaluate the indicator.

$$I_{RES} = \frac{TG}{RPG} * 100\%$$

where **TG** is the total generation in MWh and **RPG** is the total renewable power generation in MWh (Martišauskas et al. 2022).

Import dependency ($\mathbf{I_{ID}}$):

This indicator represents the share of energy and electricity import in the total energy and electricity demand. This indicator can be difficult to interpret, because supply risk may vary widely between the regions of origin and are dependent on unpredictable events in the future. A higher value indicates the higher dependency on energy imports and thus reflects the capability of energy system with less resilience. For example, the energy system can export energy if the value of indicator is less than 1 (energy production is higher than consumption) and further indicates that the energy system is robust and resilient. On the other hand, the energy system could depend on energy imports if the value of indicator is more than 1 (energy consumption dominates the production). This makes the energy system less robust and more susceptible to interruptions (Martišauskas et al. 2022).

Inputs needed to evaluate the indicator include electricity demand, used generation capacity, imported electricity, type of primary fuels, and imported primary fuels.

$$I_{ID} = (1 - \frac{PE}{DE}) * 100\%$$

where **PE** is the amount of produced energy regardless of imports, **DE** is the amount of energy demand (Martišauskas et al. 2022)**.**

Change of network connections ($\mathbf{I_{CNC}}$):

Connectedness and redundancy are important aspects of resilience (Zhang et al. 2015). To analyse the interconnectedness and redundancy of the network, the method developed by Omer et al. (2014) can be used. The method was originally used to show the resilience of communication networks, but has been also considered in engineering contexts (Patriarca et al. 2021). It is based on the graph theory describing a network with nodes and edges. Similarly, the nodes represent the technical components (i.e. generators, transformers, households etc.) and the links represent the power lines in the power system. The indicator "closeness to centrality" is used as a measure of structural resilience, which considers the fact that the more connections a network node has, the more redundancies exist if the edges are impacted by disruptive events. Consequently, a higher resilience can be reached. This indicator is especially important to include, as it is the only one that measures the graphical structure of the system. Since the indicator is measured as the closeness to centrality before and after the disruptive event, it is thus named as change of network connections. For all nodes n the equation is defined as (Omer et al. 2014):

$$Changeofnetworkconnections = \frac{\sum_{i=1}^{n} C_C(v)_{before\_event}}{\sum_{i=1}^{n} C_C(v)_{after\_\text{event}}}$$

Therefore, the change of network connection is a measure of the structural resilience for a node. The closeness of a single node v to all other nodes is defined as $C_C(v)$. The highest value is 1, the lowest 0. To allow for the inclusion of disconnected nodes, the following alternative formulas are used. In case all nodes are reachable, the closeness is described with the nodes of the network V, where A_v is the number of reachable nodes (Mathworks 2023):

$$C_c(v) = \left(\frac{A_v}{n-1}\right)^2 \frac{1}{\sum^{n}_{\substack{s \in V \\ s \neq v}} d_G(v, s)}$$

11.3.2.4 Structural and Performance Indicators for the Resilience Assessment and Monitoring

The resilience monitoring of energy systems can pursue different objectives, which are centred at the resilience curve stages system (design) planning (i.e. *before* disruptive events), system operations *during* disruptive events and feedback loops *after* disruptive events, which corresponds to the well-established resilience curve approach (Poulin and Kane 2021). Thereby, the resilience monitoring process can either focus on the operational status (Mentges et al. 2023) or on assessing the effectiveness of initiated measures by comparing planned and actual results (ILO 2015).

The former aims for continuously monitoring the system status in order to identify any deviations from the operational defaults. If the status does not match the required parameter range, predefined or improvised fallback and recovery strategies can be initiated for stabilizing the system performance. For this purpose, performance indicators are used, because they cover the system performance with an optional temporal resolution that can be relevant for monitoring purposes.

The latter aspect focuses on the success or failure of designed system capability/ capacities in face of disruptive events. If predefined measures (e.g. redundant generators, transformers) are not effective during disruptive events, these measures have to be reviewed in the continuous resilience management process to derive recommendations for future improvements. Consequently, the focus on performance indicators only cannot provide explanations for a certain system behaviour and hence structural aspects also become relevant for the decision preparation regarding the system's resilience. In each stage of the resilience curve, structural and performance indicators can be different significant and thus are relevant to consider for certain decision situations (Jackson and Ferris 2013).

Structural indicators can be allocated to different stages of the resilience curve, which consists of plan & prepare, absorb & recover as well as adapt to the performance loss. For instance, on the one hand, the storage capacity, which provides insights about buffer and storage of electricity, heat as well as gas storage systems, aids to the preparedness before an uncertain event. Although the storage capacity is basically determined in the plan & prepare stage, the resilience measure will be only effective once the system is exposed to the disruptive event, which is why this indicator would also be representative for the absorb and recover stage. Similarly, diversity indicators related to the installed capacity, primary fuels and share of renewables with diversified nature of production and transmission, enables to absorb and recover from disruptive events (Brand et al. 2017), but can also affect the plan & prepare stage.

Hence, the quest for linking structural system characteristics with their performance has been difficult (Watson et al. 2022). The reasons are that the system performance depends not only on the system structure at a given location, but also on the (type of) disruptive event, failure duration and recovery strategy (Watson et al. 2022) as well as temporal progress of the disruptive event and its impacts. Moreover, various terms are used for resilience design principles in the literature, which is why a commonly accepted framework would contribute to the progress towards proactively designing energy systems more resilient (Specking et al. 2022). However, this kind of feedback would be required from the continuous resilience assessment and monitoring to recommend successful design for improving of the system's resilience. According to Poulin and Kane (2021), analysts, operators, designers and stakeholders should carefully choose indicators metrics. Based on the situation which should be evaluated, different metrics can yield significantly different recommendations.

11.4 Conclusion

Indicator theory is a commonly applied concept in any management contexts, which was successfully used throughout the last decades in several research disciplines. Indicators have the advantage to enable the communication of complex matters to informed or uninformed decision-makers by abstraction. Resilience (i.e. the continuous supply of a service) became a relevant aspect to consider in systemic decision situations, particularly in the context of critical infrastructures such as energy systems. This book chapter described the different types of indicators used for resilience assessment together with the pros and cons of with each indicator definition is accompanied. Thereby, it was emphasized that the indicator purpose crucially is to be defined together with experts and stakeholders to gain the trust of the users particularly in resilience monitoring applications, where different perspectives unite in the assessment of complex socio-technical systems. Thus, a comprehensive criteria list was proposed to guide the indicator selection. Furthermore, the book chapter shed light on the complexity to assess and monitor the resilience of energy systems. Thereby, several exemplary indicators were briefly introduced, which are relevant and easily obtained in most assessments. Finally, the relation of structural and performance indicators was discussed. It was emphasized that both indicator types are required to be considered in resilience monitoring processes to derive successful resilience design principles for future system designs.

References

Adriaanse, A.: In search of balance. A conceptual framework for sustainable development indicators. In: MacGillivray, A. (ed.) Accounting for Change: Papers from An International Seminar, pp. 3–10. Toynbee Hall, London (1995)

Ahmadi, S., Saboohi, Y., Vakili, A.: Frameworks, quantitative indicators, characters, and modeling approaches to analysis of energy system resilience: a review. Renew. Sustain. Energy Rev. **144**, 110988 (2021). https://doi.org/10.1016/j.rser.2021.110988

Baumann, M., Weil, M., Peters, J.F., Chibeles-Martins, N., Moniz, A.B.: A review of multi-criteria decision making approaches for evaluating energy storage systems for grid applications. Renew. Sustain. Energy Rev. **107**, 516–534 (2019). https://doi.org/10.1016/j.rser.2019.02.016

Bill, C., Bose, A., Brown, S., Chalamala, B., Immermann, D., Khodaei, A., et al.: Resilience framework, methods, and metrics for the electricity sector. The Institute of Electrical and Electronic Engineers - Power & Energy Society (2020). https://opcom.velco.com/library/document/download/7134/DOE-IEEE_Resilience%20Paper_10-30-2020%20for%20publication%20%28002%29.pdf. Accessed 17th Jan 2024

Biringer, B., Vugrin, E., Warren, D. (eds.): Critical Infrastructure System Security and Resiliency, 1st edn. CRC Press, Boca Raton (2013)

Bossel, H.: Deriving indicators of sustainable development. Environ. Model. Assess. **1**, 193–218 (1996)

Brand, U., Giese, B., von Gleich, A., Heinbach, K., Petschow, U.: Resilient design of energy systems: "RE-methane-system" and "regional self-supply" as options for transformation. University of Bremen. Bremen, Germany (Executive Summary of the final report of the project RESYSTRA) (2017). http://www.resystra.de/files/publikationen/resystra-executive-summary-final.master.pdf, Accessed 31 Aug 2023

Cains, M.G., Henshel, D.: Parameterization framework and quantification approach for integrated risk and resilience assessments. Integr. Environ. Assess. Manag. **17**(1), 131–146 (2021). https://doi.org/10.1002/ieam.4331

Cantelmi, R., Di Gravio, G., Patriarca, R.: Reviewing qualitative research approaches in the context of critical infrastructure resilience. Environ. Syst. Decis. **41**(3), 341–376 (2021). https://doi.org/10.1007/s10669-020-09795-8

Cassottana, B., Roomi, M.M., Mashima, D., Sansavini, G.: Resilience analysis of cyber-physical systems: a review of models and methods. Risk Anal. **43**, 2359–2379 (2023)

Chi, Y., Xu, Y., Hu, C., & Feng, S. (eds.): A state-of-the-art literature survey of power distribution system resilience assessment, 5–10 August 2018. Institute of Electrical and Electronics Engineers; IEEE Power & Energy Society. IEEE, Piscataway, NJ (2018). http://ieeexplore.ieee.org/servlet/opac?punumber=8540807

Copeland, S., Comes, T., Bach, S., Nagenborg, M., Schulte, Y., Doorn, N.: Measuring social resilience: trade-offs, challenges and opportunities for indicator models in trans-forming societies. Int. J. Disaster Risk Reduct. **51**, 101799 (2020). https://doi.org/10.1016/j.ijdrr.2020.101799

Duden: Keyword "Indikator" (2023). https://www.duden.de/rechtschreibung/Indikator. Accessed 31 Aug 2023

Felder, F.A., Petitet, M.: Extending the reliability framework for electric power systems to include resiliency and adaptability. Electr. J. **35**(8), 107186 (2022). https://doi.org/10.1016/j.tej.2022.107186

Ferdinant, P.F., Nurdiana, L., Irman, A.: Evaluation of power plant reliability using index loss of load in the Suralaya power plant. IOP Conf. Ser. Mater. Sci. Eng. **909**(1), 12070 (2020). https://doi.org/10.1088/1757-899X/909/1/012070

Gasser, P., Lustenberger, P., Cinelli, M., Kim, W., Spada, M., Burgherr, P., et al.: A review on resilience assessment of energy systems. Sustain. Resilient Infrastruct. **6**(5), 273–299 (2021). https://doi.org/10.1080/23789689.2019.1610600

Gasser, P., Suter, J., Cinelli, M., Spada, M., Burgherr, P., Hirschberg, S., et al.: Comprehensive resilience assessment of electricity supply security for 140 countries. Ecol. Indic. **110**, 105731 (2020). https://doi.org/10.1016/j.ecolind.2019.105731

Gillespie-Marthaler, L., Nelson, K., Baroud, H., Abkowitz, M.: Selecting indicators for assessing community sustainable resilience. Risk Anal. off. Publ. Soc. Risk Anal. **39**(11), 2479–2498 (2019). https://doi.org/10.1111/risa.13344

Guo, D., Shan, M., Owusu, E.: Resilience assessment frameworks of critical infrastructures: state-of-the-art review. Buildings **11**(10), 464 (2021). https://doi.org/10.3390/buildings11100464

Hirschberg, S., Bauer, C., Burgherr, P., Dones, R., Simons, A., et al.: Deliverable D3.2 – RS 2b "Final set of sustainability criteria and indicators for assessment of electricity supply options". Brussel, Belgium (2008)

Hosseini, S., Barker, K., Ramirez-Marquez, J.E.: A review of definitions and measures of system resilience. Reliab. Eng. Syst. Saf. **145**, 47–61 (2016). https://doi.org/10.1016/j.ress.2015.08.006

ILO: Basic principles of monitoring and evaluation. International Labour Organization. Geneve, Switzerland (2015)

Jackson, S., Ferris, T.L.J.: Resilience principles for engineered systems. Syst. Eng. **16**(2), 152–164 (2013). https://doi.org/10.1002/sys

Jasiūnas, J., Lund, P.D., Mikkola, J.: Energy system resilience – a review. Renew. Sustain. Energy Rev. **150**, 111476 (2021). https://doi.org/10.1016/j.rser.2021.111476

Jewell, J., Cherp, A., Riahi, K.: Energy security under de-carbonization scenarios: an assessment framework and evaluation under different technology and policy choices. Energy Policy **65**, 743–760 (2014). https://doi.org/10.1016/j.enpol.2013.10.051

Jovanović, A., Klimek, P., Renn, O., Schneider, R., Øien, K., Brown, J., et al.: Assessing resilience of healthcare infrastructure exposed to COVID-19: emerging risks, resilience indicators, interdependencies and international standards. Environ. Syst. Decis. **40**(2), 252–286 (2020). https://doi.org/10.1007/s10669-020-09779-8

Kaloti, S.A., Chowdhury, B.H.: Toward reaching a consensus on the concept of power system resilience: definitions, assessment frameworks, and metrics. IEEE Access **11**, 81401–81418 (2023). https://doi.org/10.1109/ACCESS.2023.3300292

Kottmann, F., Kyriakidis, M., Dang, V.N., Sansavini, G.: Enhancing infrastructure resilience by using dynamically updated damage estimates in optimal repair planning: the power grid case. J. Risk Uncertainty Eng. Syst. Part A Civ. Eng. **7**(4), 4021048 (2021)

Linser, S.: Theoretical background of indicators and indicator system for the assessment of sustainable development. In: Niskanen, A., Väyrynen, J. (eds.) Regional Forest Programmes: A Participatory Approach to Support Forest Based Regional Development. EFI Proceedings, vol. 32, pp. 205–221 (1999)

Mair, S., Jones, A., Ward, J., Christie, I., Druckman, A., Lyon, F.: A critical review of the role of indicators in implementing the sustainable development goals. In: Filho, W.L. (ed.) Handbook of Sustainability Science and Research. World Sustainability Series, pp. 41–56. Springer International Publishing, Cham(2018)

Mangoyana, R.B., Smith, T.F., Simpson, R.: A systems approach to evaluating sustainability of biofuel systems. Renew. Sustain. Energy Rev. **25**, 371–380 (2013). https://doi.org/10.1016/j.rser.2013.05.003

Martišauskas, L., Augutis, J., Krikštolaitis, R., Urbonas, R., Šarūnienė, I., Kopustinskas, V.: A framework to assess the resilience of energy systems based on quantitative indicators. Energies **15**(11), 4040 (2022). https://doi.org/10.3390/en15114040

Mathworks: Centrality. Measure node importance. MathWorks, Inc. Natick, MA, U.S. (2023). https://de.mathworks.com/help/matlab/ref/graph.centrality.html. Accessed 31 Aug 2023

Meadows, D.: Indicators and information systems for sustainable development. The Sustainability Institute. Hartland four corners VT, USA (1998)

Meerow, S., Newell, J.P.: Urban resilience for whom, what, when, where, and why? Urban Geogr. **40**(3), 309–329 (2019). https://doi.org/10.1080/02723638.2016.1206395

Mentges, A., Halekotte, L., Schneider, M., Demmer, T., Lichte, D.: A resilience glossary shaped by context: reviewing resilience-related terms for critical infrastructures. Int. J. Disaster Risk Reduct. **96**, 103893 (2023). https://doi.org/10.1016/j.ijdrr.2023.103893

Merry, S.E.: Measuring the world: indicators, human rights, and global. Governance **52**(3), S83–S95 (2011)

Mottahedi, A., Sereshki, F., Ataei, M., Nouri Qarahasanlou, A., Barabadi, A.: The resilience of critical infrastructure systems: a systematic literature review. Energies **14**(6), 1571 (2021). https://doi.org/10.3390/en14061571

Mujjuni, F., Betts, T., To, L.S., Blanchard, R.E.: Resilience a means to development: a resilience assessment framework and a catalogue of indicators. Renew. Sustain. Energy Rev. **152**, 111684 (2021). https://doi.org/10.1016/j.rser.2021.111684

Müller-Lancé, K.: Energiekrise: Wieso die Atomenergie in Frankreich zum Sorgenkind wird. (engl. Energy crisis: Energy crisis: Why nuclear energy is becoming a problem child in France. In Sueddeutsche Zeitung GmbH, 10/15/2022 (2022). https://www.sueddeutsche.de/politik/frankreich-kernkraft-macron-1.5656779. Accessed 23 Jan 2024

Netz, H., Schönwandt, I., Wigger, H., Brand-Daniels, U., Lichte, D., Vogt, T.: Integrating sustainability and resilience aspects into power system technology assessments. In: 2023 IEEE PES Innovative Smart Grid Technologies Europe (ISGT EUROPE), Grenoble, France, pp. 1–5 (2023). https://doi.org/10.1109/ISGTEUROPE56780.2023.10407277.

Nguyen, H.L., Akerkar, R.: Modelling, measuring, and visualising community resilience: a systematic review. Sustainability **12**(19), 7896 (2020). https://doi.org/10.3390/su12197896

Nikzad, M., Farahani, S.S.S., Tabar, M.B., Tourang, H., Yousefpour, B.: Calculation of generation system reliability index: loss of load expectation. Life Sci. J. **9**, 3595–3599 (2012)

Omer, M., Mostashari, A., Lindemann, U.: Resilience analysis of soft infrastructure systems. Procedia Comput. Sci. **28**, 565–574 (2014). https://doi.org/10.1016/j.procs.2014.03.069

Osei-Kyei, R., Almeida, L.M., Ampratwum, G., Tam, V.: Systematic review of critical infrastructure resilience indicators. Constr. Innov. **23**(5), 1210–1231 (2023). https://doi.org/10.1108/CI-03-2021-0047

Ottenburger, S.S., Çakmak, H.K., Jakob, W., Blattmann, A., Trybushnyi, D., Raskob, W., et al.: A novel optimization method for urban resilient and fair power distribution preventing critical network states. Int. J. Crit. Infrastruct. Prot. **29**, 100354 (2020). https://doi.org/10.1016/j.ijcip.2020.100354

Patriarca, R., de Paolis, A., Costantino, F., Di Gravio, G.: Simulation model for simple yet robust resilience assessment metrics for engineered systems. Reliab. Eng. Syst. Saf. **209**, 107467 (2021). https://doi.org/10.1016/j.ress.2021.107467

Porter, T.M.: Trust in numbers. The pursuit of objectivity in science and public life. Princeton University Press, Princeton N.J. (1995)

Poulin, C., Kane, M.B.: Infrastructure resilience curves: performance measures and summary metrics. Reliab. Eng. Syst. Saf. **216**, 107926 (2021). https://doi.org/10.1016/j.ress.2021.107926

Quinlan, A.E., Berbés-Blázquez, M., Haider, L.J., Peterson, G.D.: Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. J. Appl. Ecol. **53**(3), 677–687 (2016). https://doi.org/10.1111/1365-2664.12550

Resilens: Deliverable D2.2: qualitative, semi-quantitative and quantitative methods and measures for resilience assessment and enhancement. Brussel, Belgium (2016)

Specking, E., Parnell, G.S., Pohl, E., Buchanan, R.: Engineering resilient systems: achieving stakeholder value through design principles and system operations. IEEE Trans. Eng. Manag. **69**(6), 3982–3993 (2022). https://doi.org/10.1109/TEM.2021.3056934

Stanković, A.M., Tomsovic, K.L., de Caro, F., Braun, M., Chow, J.H., Čukalevski, N., et al.: Methods for analysis and quantification of power system resilience. IEEE Trans. Power Syst. **38**(5), 4774–4787 (2023). https://doi.org/10.1109/TPWRS.2022.3212688

Turnhout, E., Hisschemöller, M., Eijsackers, H.: Ecological indicators: between the two fires of science and policy. Ecol. Indic. **7**(2), 215–228 (2007). https://doi.org/10.1016/j.ecolind.2005.12.003

Wang, C., Ju, P., Wu, F., Pan, X., Wang, Z.: A systematic review on power system resilience from the perspective of generation, network, and load. Renew. Sustain. Energy Rev. **167**, 112567 (2022). https://doi.org/10.1016/j.rser.2022.112567

Watson, B.C., Chowdhry, A., Weissburg, M.J., Bras, B.: A new resilience metric to compare system of systems architecture. IEEE Syst. J. **16**(2), 2056–2067 (2022). https://doi.org/10.1109/JSYST.2021.3062444

Wied, M., Oehmen, J., Welo, T.: Conceptualizing resilience in engineering systems: an analysis of the literature. Syst. Eng. **23**(1), 3–13 (2020). https://doi.org/10.1002/sys.21491

Zhang, X., Miller-Hooks, E., Denny, K.: Assessing the role of network topology in transportation network resilience. J. Transp. Geogr. **46**, 35–45 (2015). https://doi.org/10.1016/j.jtrangeo.2015.05.006

Zwart, R.: Strengthening the results chain: synthesis of case studies of results-based management by providers. OECD (OECD development policy papers, No.7) (2017)