
Sustainable and Resilient Infrastructure

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tsri20

# A review on resilience assessment of energy systems

**Patrick Gasser, Peter Lustenberger, Marco Cinelli, Wansub Kim, Matteo Spada, Peter Burgherr, Stefan Hirschberg, Božidar Stojadinovic & Tian Yin Sun**

SUSTAINABLE AND RESILIENT INFRASTRUCTURE
2021, VOL. 6, NO. 5, 273–299
https://doi.org/10.1080/23789689.2019.1610600

REVIEW ARTICLE

OPEN ACCESS Check for updates

# A review on resilience assessment of energy systems

Patrick Gasser[†a], Peter Lustenberger[†a], Marco Cinelli[a], Wansub Kim[a], Matteo Spada[b], Peter Burgherr[b], Stefan Hirschberg[b], Božidar Stojadinovic[c] and Tian Yin Sun[a]

[a]Future Resilient Systems (FRS), Singapore-ETH Centre (SEC), Swiss Federal Institute of Technology (ETH) Zürich, Singapore; [b]The Energy Division, Laboratory for Energy Systems Analysis (LEA), Paul Scherrer Institut (PSI), Villigen, Switzerland; [c]Institute of Structural Engineering, Swiss Federal Institute of Technology (ETH) Zürich, Zurich, Switzerland

**ABSTRACT**

Energy systems are regularly subject to major disruptions affecting economic activities, operation of infrastructure and the society as a whole. Resilience assessment comprises the pre-event oriented classical risk assessment as a central element, but it goes beyond that because it also includes and evaluates post-event strategies to improve the functioning of the system during its future operation. First, an overview of resilience definitions used across various scientific disciplines is presented, followed by an in-depth analysis of resilience assessment and quantification for energy systems. The relevant literature is classified by approach and according to four key functions of resilience: resist, restabilize, rebuild, and reconfigure. Findings show that irrespective of the research field, a resilient system always operates with an aim to minimize the potential consequences resulting from a disruptive event and to efficiently recover from a potential system performance loss.

**ARTICLE HISTORY**
Received 19 October 2018
Accepted 19 April 2019

**KEYWORDS**
Resilience; energy systems; review; swoosh resilience curve; biophysical resilience functions

## 1. Introduction

Traditionally, the performance of critical infrastructure (e.g., power grid, telecommunication or water supply systems) has been analysed by classical risk assessment methods for their safe and reliable design and operation (Linkov et al., 2014). This approach allows responding adequately to known and credible hazards and threats. However, more recently it has become apparent that additional efforts and considerations are needed beyond the well-established state-of-the-art to ensure efficient recovery from low-probability high-impact disruptive events (Panteli & Mancarella, 2015). As a consequence, increased attention is given worldwide to the resilience of infrastructure systems, which is considered a key property to adequately deal with disruptions, i.e., natural and man-made disasters (i.e., technical, human and organizational factors and intentional attacks) (Jackson, 2015). This view is strongly supported by the notion that not all hazards and threats can be averted (Cimellaro, 2016), as major disasters repeatedly demonstrated in the past decades (Garrick, 2008; Zio & Aven, 2013). Well-known examples include the September 11 terrorist attacks in 2001, hurricane Katrina in 2005, the blackouts in North America (2003) (Andersson et al., 2005), India (2012) (Tang et al., 2012), and Turkey (2015) (European Network of Transmission System Operators for Electricity, 2015), the 2007 cyber-attack on the Estonian government (Herzog, 2011), the global financial crisis in 2008 (Taylor, 2009), or the Fukushima Daiichi nuclear disaster in 2011 (International Atomic Energy Agency, 2015). These events stress the necessity to be prepared for a disaster and its consequences and to be able to recover in a reasonable and timely manner from sudden, unexpected changes that pose a risk to the proper functioning of critical infrastructures and associated services upon which modern society relies. Furthermore, the types of risks are constantly evolving, and the numbers and value of assets at stake have dramatically increased over time, which is why current approaches may no longer be fully sufficient. Finally, critical infrastructures (i.e., infrastructure essential for the functioning of a society and economy) are becoming more and more interdependent, increasing their complexity and criticality (Ouyang, 2014). As a consequence, a paradigm shift is needed ‘to complement the existing knowledge-base of risk analysis and management by further developing frameworks and models enabling system- and network-wide *resilience* analysis, engineering and management’ (Linkov et al., 2014).

**CONTACT** Patrick Gasser patrick.gasser@frs.ethz.ch; Peter Lustenberger lustenberger@frs.ethz.ch

[†]These authors contributed equally to this work.
This article has been republished with minor changes. These changes do not impact the academic content of the article.
Supplemental data for this article can be accessed here.

To distinguish between risk and resilience assessment and management, the former is considered a pre-event analysis, i.e., risk assessment links hazard identification with exposure and consequence assessment to provide a characterization of the potential risk of disruptive events (Hans Rudolf Heinimann, 2016). This usually results in preventive measures to minimize the frequency and consequences of disruptions. In contrast, resilience assessment includes not only the analysis of potential disruptive events but also post-event analysis (e.g., recovery) covering the whole life-cycle of a system. Starting from the seminal work by Holling (1973) that introduced resilience in the field of ecology, it has been continuously popularized and applied to socio-technical systems (Folke, 2006; The Rockefeller Foundation, 2013; Walker et al., 2002). Despite the application of the concept of resilience in a large number of fields and at different temporal and spatial scales, a clear approach to manage resilience is still lacking (Couzin-Frankel, 2018; Redman, 2014). Nevertheless, we identified a number of common features, including critical functions (e.g., services), thresholds, recovery through interactions across scales (e.g., space and time), and memory and adaptive management (e.g., adjusting response strategies in advance to disruptive events) (Connelly et al., 2017). In this sense, the common features are in line with various definitions of resilience (Hosseini et al., 2016b), resilience functions (e.g., system functions (Heinimann & Hatfield, 2017)) and their assessment. Consequently, resilience comprises several functions, such as the absorption of a shock, the adaptation to new conditions and the speed of recovery (Park et al., 2011). Furthermore, it takes into account the growing complexity of the systems resulting from increasing connectivity as well as the increase of ambiguous and unexpected events (Murray et al., 2013).

Critical infrastructures are often interconnected and interdependent (Buldyrev et al., 2010; Rinaldi et al., 2001). The energy system (e.g., infrastructure systems throughout the energy supply chains) is considered one of the most complex and important critical infrastructure systems. It forms the backbone of modern societies by providing essential services of reliable energy supply, which facilitates productivity, trade and economic growth. Disruptions and breakdowns of the energy supply may cause serious economic damage and affect large segments of the population (Willis & Loa, 2015). This indicates the importance of building a more resilient energy system to better cope with impacts from natural disasters, technical failures and man-made accidents. To proactively improve the resilience of energy infrastructure (i.e., infrastructure used to maintain energy flows), it is key to define it in such a way that it can be operationalized and subsequently analysed using quantitative measures (Chuang et al., 2018). In the past years, numerous frameworks to quantify resilience have been proposed (Hosseini et al., 2016b). Although these studies looked at different types of infrastructure (e.g., energy systems, transportation, information and communications technology, communities, etc.), they can also be considered relevant for resilience analysis of energy infrastructure with regard to theoretical and conceptual developments as well as to specific methodological aspects.

Nevertheless, a systematic overview on resilience assessment specifically for energy systems and related infrastructure is still missing. For example, there are extensive reviews addressing the resilience of complex systems (Fraccascia et al., 2018; Hosseini et al., 2016b; Wang et al., 2017) in general or urban resilience (Cerè et al., 2017; Rus et al., 2018; Sanchez et al., 2018; Sharifi & Yamagata, 2016) in particular. In those reviews, the energy infrastructure is only addressed as one of many sectors. Consequently, there is a clear need to compare how different studies address energy system resilience in a comprehensive manner. In particular, a review with focus on selected aspects, and how the various resilience components are measured and possibly aggregated to evaluate the resilience of energy infrastructures against the impacts from different types of hazards and threats is missing. To this end, we focus on single and rather instantaneous disruptive events (i.e., natural disaster, technical failures or malicious attacks). The inclusion of multiple successive disruptions (i.e., earthquake aftershocks) as well as persistent changes of stress on a system (i.e., climate change) go beyond the scope of this review.

Based on this premise, the purpose and major contributions of this review are threefold. Section 2 presents a general conceptualization of resilience, including the description of its components and temporal dimension, followed by an overview of specific resilience definitions and applications across various fields. Section 3 compares selected resilience assessment methodologies used to assess resilience within the wider field of infrastructure management, which are also applicable to the energy sector. Section 4 details the methodology adopted to select and analyse relevant energy-related resilience studies. Section 5 discusses the studies and employed methods, considering four resilience functions adopted from (H. R. Heinimann & Hatfield, 2017): (1) resist, (2) restabilize, (3) rebuild, and (4) reconfigure. These functions form the core of physical resilience engineering that focuses on a system's behaviour throughout a disruption (H. R. Heinimann & Hatfield, 2017). By applying this resilience framework, the current state-of-the-art is characterized, and major gaps and potential research areas for future advancements are identified. Section 6.produces and analyses a keyword co-occurrence network.

## 2. Resilience definitions and fields of application

First uses of resilience could be traced to materials science as early as the nineteenth century (Tredgold, 1818). However, the word itself comes from Latin *resilire* and means 'bounce back' (Alexander, 2013). A conceptualization of resilience is shown in Figure 1. It can be seen as a representation of both the amount and type of 'draw-down' and 'draw-up' behaviour of a system, reflecting the temporal effect of an adverse event it is exposed to. In the case of a system analysis, the measure (y-axis in Figure 1) is often a representation of the system performance. The definition of the system performance itself depends on the service provided by the system (unit representation of system-specific function or normalized) as well as, for example, the scope and type of the analysis.

Modern understanding of resilience is that of a process that the observed system undergoes in response to a disruption quantified in terms of a measure of system performance and its evolution during the system response time after an event. As we illustrate in Figure 1, the occurrence of a disruptive event results in a 'draw-down' or loss of the system's performance, which is then followed by a bounce back or 'draw-up' phase, reflecting the recovery behaviour of the system. Both 'draw-down' and 'draw-up' can have various shapes, with the former ranging from an immediate to a rather gradual measure drop (Ayyub, 2013). The use of this kind of 'swoosh' shaped resilience curve (involving a possible 'draw-down' and 'draw-up' shape) provides a conceptually sound representation of the various resilience functions of the system under study that can then be analysed by means of quantitative performance indicators. According to the extent of 'draw-down' and the subsequent 'draw-up', four typical recovery behaviours can be distinguished (Gasser et al., 2017; Singapore-ETH Centre, 2015):

- Robust behaviour: the system returns to its initial state before the disruptive event (Bruneau et al., 2003)
- Adaptive behaviour: the system compensates the loss in its performance, and even reaches an improved state compared to the initial state, reflecting not just a simple recovery, but a (partial) reconfiguration (Ayyub, 2013)
- Ductile behaviour: the system comes back to a certain level, but its functionality is not completely restored (Decò et al., 2013)
- Collapsing behaviour: the system is not able to recover and completely loses its functionality (Nan & Sansavini, 2017)

The resilience curve itself, however, is dependent, for example, on robust, adaptive or recovery behaviours. In addition, these four generic resilience curve patterns do not represent all the possible shapes of the resilience curve, but aim to capture some key outcomes and bounding cases. Hence, there still may be substantial variation in a specific case study application for both the steepness and extent of the 'draw-down', and the duration and level of recovery of the 'draw-up'. It is also often argued that the smaller the performance loss ('draw-down') and the faster the bounce back ('draw-up') of a system after a disruption, the higher is its resilience (Bruneau et al., 2003; Ganin et al.,

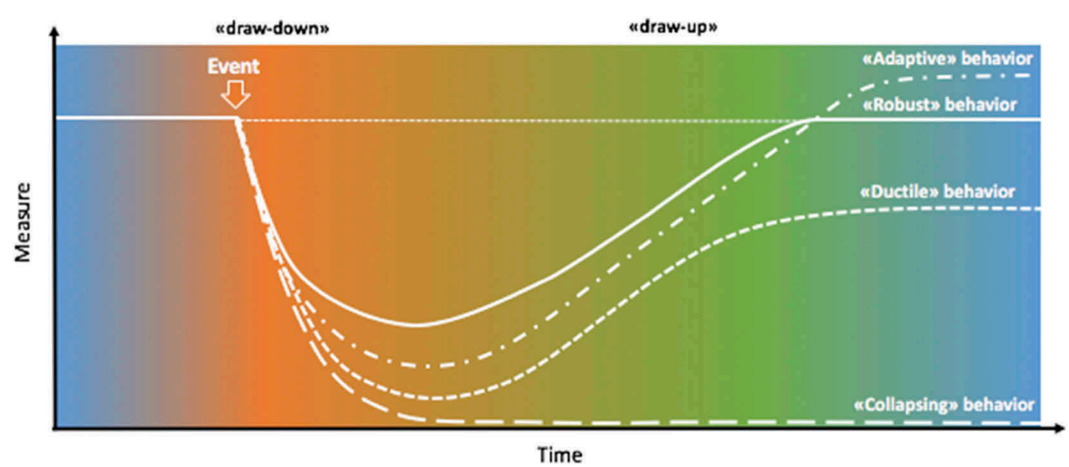


Figure 1. Typical understanding of the 'swoosh' resilience curve over time, with a reduction ('draw-down') and bounce back ('draw-up'). The possible outcomes illustrate the different resilience behaviours that the resilience curve can take (modified from (Singapore-ETH Centre, 2015)).

2016). For example, robust and adaptive behaviours are more resilient than ductile or collapsing behaviours. It follows that a more resilient system could be achieved with investments either to avoid performance loss ('draw-down') or to boost the bounce back ('draw-up') as, for instance, demonstrated in Kyriakidis et al. (2018b).

Furthermore, depending on the scope and objectives of a system resilience assessment, it may not always be appropriate to measure the overall resilience of a system with a single, aggregated system performance indicator. Instead, a portfolio of indicators is used to shed light onto different phases of the resilience process and different system behaviours and assess the resilience of a system by aggregating different indicators (Gasser et al., 2017; Jovanović et al., 2016). Another approach is to separate the supply and demand aspects of the system performance and to observe the resilience of a system (or, more precisely, the lack of resilience) as the difference between the supply and demand 'swoosh' curves (Didier et al., 2017).

As we discussed above in the context of Figure 1, resilience is a promising concept to achieve a more comprehensive understanding of how a system is affected by a disruptive event and how its recovery takes place over time. Furthermore, the resilience-focused assessment and management complements the traditional risk assessment and management by explicitly focusing on the 'draw-down' and 'draw-up' post-disruption process (Hans Rudolf Heinimann, 2016).

Due to the recently increased popularity of resilience in various research disciplines (H. R. Heinimann & Hatfield, 2017; Hosseini et al., 2016a; McAslan, 2010; Molyneaux et al., 2016; Norris et al., 2008; Xu & Kajikawa, 2017), numerous definitions, conceptualizations, and approaches for quantification have been proposed. Table 1 provides an overview of resilience definitions in different research fields, their key characteristics, and examples of applications. Following Ayyub (2013)'s definition of explicit and implicit quality of resilience, we characterize each resilience definition in Table 1 with respect to its explicit quality of resilience, and provide example(s) of its implicit quality of resilience. The explicit quality of resilience (i.e., 'resilience of what?') addresses the system under investigation (e.g., infrastructure, organism, community, etc.), but does not explain against which types of events the system should be resilient (e.g., earthquake, wind storm, etc.). For example, the statement that 'a transportation system should be resilient' refers to the infrastructure system as such, but it does not include information about the disruptive events to which the system should be resilient. In contrast, the implicit quality of resilience (i.e., 'resilience to what?') focuses on the event, but it does not explicitly mention the system that should be resilient to a particular event. For example, the statement that 'flood resilience should be achieved' just describes the type of event, but not the systems as such (e.g., natural gas pipeline network). To give a comprehensive picture, we list in Table 1 examples of the explicit and implicit qualities of resilience for each research field, and we also mention possible performance indicators and published case study examples. Moreover, some studies give information about both explicit and implicit characteristics of resilience, such as, for instance, storm (implicit) resilience of power grids (explicit) (Ji et al., 2016).

Table 1 clearly demonstrates that the definition of resilience strongly depends on the research field, whereas the application area and considered disruption event type(s) affect the choice of a suitable performance indicator. On the one hand, a systematic comparison of the different resilience concepts and applications can also help to facilitate exchange across research fields and to avoid potential misunderstandings. On the other hand, the comparative overview given in Table 1 also suggests that irrespective of the research field and application, resilience describes a response to a disruption and the evolution during the response time with the ultimate goal to minimizing the potential consequences resulting from a disruptive event.

Finally, the strongly increased general interest in resilience, both within basic and applied research as well as actual infrastructure management, clearly indicates that resilience is considered a promising concept to better understand and improve the performance of complex and highly inter-connected infrastructures that are indispensable for the functioning of our modern society and the products and services it depends on. Furthermore, there is a continuous increase of (1) infrastructure density per unit of area, (2) the flows of goods, services, information and people, (3) the system's complexity, and (4) the values at risk. This continues to increase calls for a methodological approach that in a consistent and comprehensive manner can contribute to successfully master future challenges (H. R. Heinimann & Hatfield, 2017). We present a review of different resilience assessment methodologies with a focus on energy systems below.

## 3. Resilience functions applicable to energy systems

Energy systems play a central role in modern societies. Various concepts to describe and assess the resilience of energy systems emerged among scholars within the wider field of infrastructure and engineered systems. Resilience

**Table 1.** Overview of resilience definitions, explicit and implicit characteristics of resilience ('resilience of what?', 'resilience to what?'), dimensions (i.e., measure characteristics of the y-axis in Figure 1), performance indicators and case study examples in different research fields.

| | Explicit quality of resilience | | | Implicit quality of resilience | | |
|---|---|---|---|---|---|---|
| Research field | Definition example | Application example | Dimension | Event example(s) | Measure over time example(s) | Reference example |
| Material science | Resisting a body in motion.<br>Ability to spring back into shape; elasticity (Oxford Dictionaries, 2018a) | Timber<br>… | Physical | Stressor<br>… | Load<br>Stress<br>Charge | Tredgold (1818), Campbell (Campbell, 2008) |
| Psychology (human) | Ability of positive adaptation to adversity (Fletcher & Sarkar, 2013) | Individual (psychological perspective)<br>… | Psychological | War<br>Terror<br>Stress<br>… | Well-being<br>… | Fletcher and Sarkar (2013); Luthar et al. (2000); Masten et al. (1990), Coutu (2002) |
| Ecology | Ability to absorb changes of states and still exist (Holling, 1973) | Aquatic (e.g., lake)<br>Terrestrial (e.g.,, forest)<br>… | Ecological | Eutrophication<br>Acidification<br>… | Population<br>Diversity<br>… | Holling (1973) |
| Sociology | Ability to cope with, adapt to and transform as a result of social, political and environmental change (Keck & Sakdapolrak, 2013) | Individual (social perspective)<br>Organization (social perspective)<br>Communities (social perspective)<br>… | Social | Globalization<br>Automatization<br>Natural catastrophes<br>… | … | Adger (2000); Keck and Sakdapolrak (2013) |
| Organizational science | Ability to bounce back from disruptions by building in redundancy and flexibility (Sheffi, 2005) | Supply chain<br>Firms/companies/enterprises<br>… | Organizational | Natural catastrophes<br>Intentional attacks<br>Technical accidents<br>Management failures<br>… | Sales<br>Production level<br>Profits<br>Customer service<br>… | Sheffi (2005); Vogus and Sutcliffe (2007) |
| Economics | Inherent and adaptive responses to disasters that enable individuals and communities to avoid some potential losses (A. Rose, 2004) | Households<br>Firms/companies/enterprises<br>Industries<br>Technologies<br>Institutions<br>Regions<br>Financial<br>… | Economic | Natural catastrophes<br>Intentional attacks<br>Technical accidents<br>… | Regional economic output<br>… | Martin (2012); Rose (2007) |
| Infrastructure/engineered systems science | Ability to withstand within acceptable degradation parameters and to recover within an acceptable time and costs (Haimes et al., 2008) | Energy systems<br>Railway systems<br>Road transport systems<br>Water distribution systems<br>… | Technical<br>Physical | Natural catastrophes<br>Intentional attacks<br>Technical accidents<br>… | Performance measure of the corresponding infrastructure system, e.g.,, power load | Haimes et al. (2008), Hollnagel and Woods (2006),<br>O'Brien and Hope (2010), Nan and Sansavini (2017), P Bocchini et al. (2012); Cimellaro et al. (2010); Decò et al. (2013); Filippini and Silva (2011); Jia et al. (2017); Sharma et al. (2018) |

(*Continued*)

**Table 1.** (Continued).

| | Explicit quality of resilience | | | Implicit quality of resilience | | |
|---|---|---|---|---|---|---|
| Research field | Definition example | Application example | Dimension | Event example(s) | Measure over time example(s) | Reference example |
| Community science | Ability to mitigate, contain the effects and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future events Bruneau et al. (2003) | City<br>Urban<br>Area<br>Village<br>… | Social<br>Organizational<br>Economic<br>Technical | Natural catastrophes<br>Intentional attacks<br>Technical accidents<br>… | Performance measure, e.g.,, population/ demographic, environmental/ ecosystem, social-cultural capital, economic development, lifestyle and community competence, physical infrastructures, organized governmental services | Bruneau et al. (2003); Norris et al. (2008),<br>Bruneau and Reinhorn (2007); Burby et al. (2000); Chang and Shinozuka (2004); Cimellaro (2016); Olshansky et al. (2012) |

concepts often consider certain dynamics over time, but lack general methodologies to operationalize and measure resilience as such (Häring et al., 2017). For example, all resilience concepts applicable to energy systems describe the 'draw-down' and 'draw-up' phases (resilience curve), but they differ with respect to the extent of consideration of the pre-event and post-event phases. The resilience curve is commonly divided into sets of enabling functions (H. R. Heinimann & Hatfield, 2017; Jackson & Ferris, 2013), properties (Bruneau et al., 2003), capacities (Francis & Bekera, 2014; Vugrin et al., 2010) or abilities (Cutter et al., 2013; Haimes et al., 2008; National Academy of Sciences, 2012; National Infrastructure Advisory Council, 2009) along the time axis, generally referred to as resilience functions in this review to avoid excessive use of terms. Furthermore, most definitions also recognize that resilience is not the sum (or average) of the resilience of its components, which further complicates its actual measurement and operationalization (Hosseini et al., 2016b). To capture its full complexity and transform resilience into a measurable concept, many frameworks suggest to describe and measure the classical resilience curve using different functions of time as the basic variable (H. R. Heinimann & Hatfield, 2017).

The diversity of concepts and definitions of resilience is high. For instance, many national and international institutions proposed their own definitions as a result of the calls for public policy improvements considering critical infrastructure protection (CIPedia, 2018). In this study, we analysed the peer-reviewed literature on resilience of critical infrastructure considering the systems behaviour over time and identified the 'functions' (i.e., describing essential functionalities or behaviour of resilient systems (Heinimann & Hatfield, 2017)) of each resilience assessment method (Figure 2). We select the resilience functions considered in a recent comprehensive review by Hosseini et al. (2016b) and we complement it by those advanced in a timely global workshop on resilience and risk (Linkov & Palma-Oliveira, 2017).

The resilience functions listed in Figure 2 can be classified according to the phase and the gradient of the resilience process. While the phases ('draw-down'; 'draw-up') provide a relatively coarse description of the resilience curve, the gradients (e.g., stable, increasing, and decreasing) describe more precisely the temporal evolution of the observed system after a disruptive event. Some concepts consider the pre-event (ex-ante) phase functions such as 'prepare/plan' (i.e., 'for hazards and risks' (National Academy of Sciences, 2012)), 'avoid' (i.e., 'to eliminate contact between the system and the threat and to suffer no damage or disruption of functionality from the threat' (Jackson & Ferris, 2013)) or 'anticipate' (i.e., 'to better anticipate risks' (National Infrastructure Advisory Council, 2009)). The pre-event phase is widely investigated and well-understood for many systems and resilience research fields using mainly the established risk assessment and management methods. The same methods cover, to some extent, the 'draw-down' phase of the resilience process. In contrast, the research is less structured for the 'draw-up' phase, where the existing functions are quite diverse and scattered along the time axis (see Figure 2). This indicates that there is a need for better and more comprehensive resilience assessment approaches.

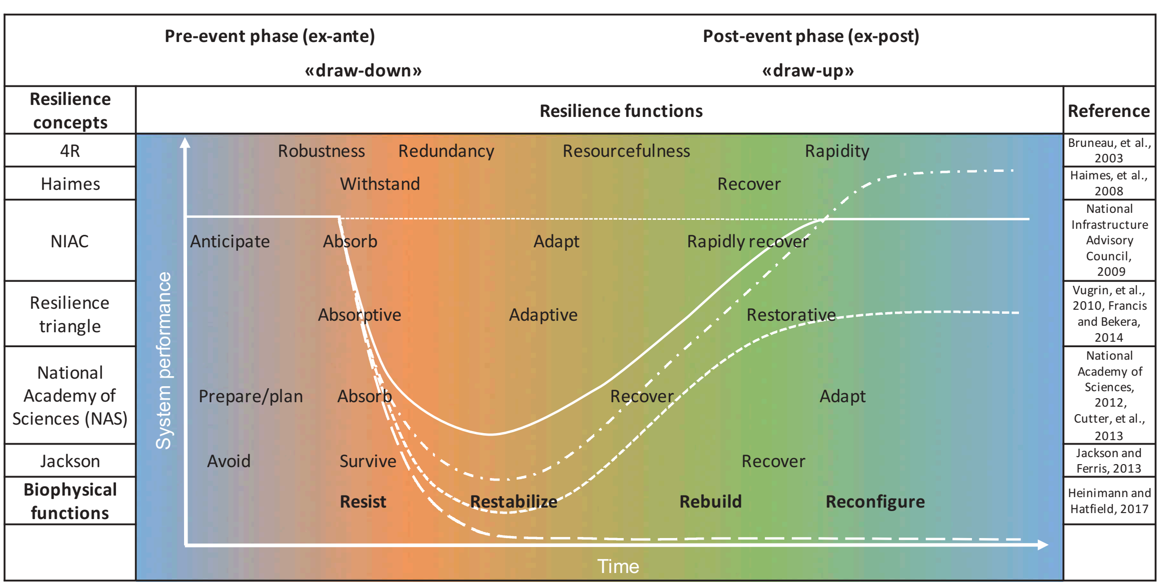


Figure 2. Selected resilience functions located along the time (roughly) and system performance axes to indicate where they come to play in the resilience process. The reddish area represents the 'draw-down' phase and the greenish area the 'draw-up' phase.

The extent and severity of a disruptive event represent the 'draw-down' of the resilience curve. It can be assessed using several resilience functions such as:

- 'robustness' (i.e., to withstand a given level of stress or demand without suffering degradation or loss of function (Bruneau et al., 2003)),
- 'withstand' (i.e., 'within acceptable degradation parameters' (Haimes et al., 2008)),
- 'absorptive' and 'absorb' (i.e., 'degree to which a system can absorb the impacts of system perturbations and minimize consequences with little effort' (Francis & Bekera, 2014; National Academy of Sciences, 2012; National Infrastructure Advisory Council, 2009; Vugrin et al., 2010)),
- 'survival' (i.e., 'survival after the encounter with a threat' (Jackson & Ferris, 2013)),
- or 'resist' (i.e., 'critical systems stay within an acceptable range of functionality' (Heinimann & Hatfield, 2017)) behaviour.

These functions represent the 'draw-down' of the considered system with its ability to handle the corresponding event. The lower parts of the resilience curve, including the lowest point of the 'draw-down' are often described using resilience functions such as:

- 'redundancy' (i.e., the extent to which elements, systems, or other units of analysis exist that are substitutable, meaning that they are capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality (Bruneau et al., 2003)),
- 'resourcefulness' (i.e., the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis (Bruneau et al., 2003)),
- 'adaptive/adapt' (i.e., 'the ability of a system to adjust to undesirable situations by undergoing some change's (Francis & Bekera, 2014; National Infrastructure Advisory Council, 2009; Vugrin et al., 2010)),
- or 'restabilize' (i.e., 'ensures critical system functionality survives' (H. R. Heinimann & Hatfield, 2017)).

Recovery behaviours, in the 'draw-up' phase of the resilience curve, are assessed using resilience functions such as:

- 'recover' i.e., 'system to recover quickly- and at low cost- from potentially disruptive events' (Haimes et al., 2008; Jackson & Ferris, 2013; National Academy of Sciences, 2012; National Infrastructure Advisory Council, 2009),
- 'rapidity' (i.e., 'the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption' (Bruneau et al., 2003)),
- 'rebuild' (i.e., 'rebuild all the functions and to re-establish normalcy' (Heinimann & Hatfield, 2017)),
- 'reconfigure' (i.e., 'adapt and change systemic properties by introducing or deleting interdependencies, or introducing or deleting components' (Heinimann & Hatfield, 2017)),
- and 'adapt' (i.e., 'to new conditions' (National Academy of Sciences, 2012)).

Whereas in some cases 'recover' is applied to describe the entire 'draw-up' phase, in most cases a more detailed distinction of resilience functions is used. Some resilience assessment methods consider 'adaptation' before the 'recovery' function (i.e., 'ability of a system to adjust to undesirable situations by undergoing some changes' (Francis & Bekera, 2014)) and others after (i.e., 'adapt to new conditions' (The National Academies of Sciences, 2012) (National Academy of Sciences, 2012)). This is a result of giving the same word different meanings. The difference is that some scholars consider 'adaptation' as a push of the system's performance to a higher level of performance after 'recovery' (National Academy of Sciences, 2012), which could also be regarded as the 'reconfigure' resilience function. In contrast, other resilience assessment methods consider the 'adapt' resilience function as 'the ability of a system to adapt to a shock to normal operating conditions' (i.e., 'ability of the grid to adapt quickly to regional power losses') (National Infrastructure Advisory Council, 2009), which could also be regarded as a 'restabilization' function.

We give in Figure 2 various resilience concepts, including functions, and illustrate that all the given concepts are meaningful and describe in a similar way aspects of a system experiencing a disruptive event throughout time. A comprehensive definition of resilience functions, inspired by biophysical systems and aimed at integrating the multitude of the above-mentioned resilience functions, was proposed recently (H. R. Heinimann & Hatfield, 2017). The terms resist, restabilize, rebuild and reconfigure are used to answer the following questions:

- Resist: 'What is a system's ability to withstand disruptions or resist within acceptable degradation limits?' Resist makes sure that the critical system stays within an acceptable range of functionality. It corresponds, for example, to the elasticity threshold limit in materials science and is very similar to the concept of reliability.

- Restabilize: 'How can we best re-establish key functionalities or restabilize a system's behaviour?' This is about better absorbing disruptions once a system's performance is decreasing. Robustness and absorptivity are related to this function.
- Rebuild: 'How can we best rebuild a system's performance up to normalcy?' After restabilization, the rebuild function describes the recovery or ability to come back to a normal state. It comprises the shape of the recovery curve and recovery speed.
- Reconfigure: 'How can we best change the biophysical architecture/topology of the system to make it more fault-tolerant?' This corresponds to the ability to adapt to new environments/conditions. A system can be reconfigured to achieve better performances than before the disruption.

Those questions, and the corresponding resilience functions are broadly covering all the important features of resilience from a critical energy infrastructure perspective. Consequently, this review uses these biophysical resilience functions to consistently classify and analyse the compiled set of energy infrastructure resilience studies with respect to how they consider the resilience curve.

## 4. Literature screening and assessment methodology

The literature on resilience assessment of energy systems is multidisciplinary and covers a broad range of concepts, approaches, methods and case study applications. As presented in Section 3, the variety of resilience concepts results in many resilience functions that are partially overlapping or used to designate different aspects of the resilience process. This further complicates a direct comparison between studies analysing the resilience of energy systems. To overcome this obstacle, we adopted the structured paper selection, assessment and classification methodology illustrated in Figure 3.

First, we analysed five recently published review studies including their references, namely Hosseini et al. (2016b), Cimellaro (2016), Willis and Loa (2015), Jackson (2015) and Francis and Bekera (2014). We assumed that the publications collected from these studies provide a good starting point for our analysis. In a second step, we searched Web of Science (Clarivate Analytics, 2018) and Google Scholar (Google, 2018) for publications up to December 2018, using specific combinations of keywords. A non-exhaustive list of the keywords used is: resilience, energy, power network, power system, electricity, gas, infrastructure, interdependencies, quantification, risk, complex networks, resist, reliability, robustness, restabilize, rebuild, recovery, and reconfigurability. Afterwards, we conducted a relevance judgement and refinement process to remove studies that were not related to the energy sector. For this purpose, we used a two-tier approach: (1) solely on the abstract and (2) on the full paper content. Hence, if after reading the abstract it was still unclear whether the paper was relevant for the present study, we based our final decision on the full paper content. This selection process resulted in a final set of 100 energy-related resilience studies.

Subsequently, we further assessed and classified each item. First, it was assigned to one of two assessment approaches, i.e., qualitative or quantitative. Qualitative approaches assess resilience without using numerical values, formulas or models. Quantitative studies were then further differentiated into semi-quantitative, deterministic and probabilistic (stochastic) approaches. Quantitative studies rely on numerical data, employ mathematical models to describe relationships, or use indicators measured with interval or ratio scales. Second, we identified the modelling approach used (complex networks, agent-based modelling, fuzzy logic, etc.). Third, for each study, we identified the resilience functions according to Section 3. (resist, restabilize, rebuild and reconfigure). These four functions cover resilience comprehensively, i.e., pre- and post-event phases as well as the 'draw-down' and 'draw-up' (see Figure 2). Hence, they are useful to establish a harmonized resilience function classification of all studies because not all of them employ the same set of resilience functions. Fourth, we assigned the disruptive events considered in each study to the following broad categories: natural disasters, technical failures, malicious attacks, geopolitical or generic disruptions, etc. Fifth, we identified the system analysed, such as electric power system (fictive or real case study), components of the electric power system, types of power plants, natural gas networks, etc. Sixth, as most of the energy-related resilience studies handle either the electric power system or the oil and gas sector, we categorized each paper into either (1) the electric power sector, (2) the oil and gas sector, or (3) other energy-related sectors. Seventh, if the topic of sustainability was addressed in the paper, we established the relations with resilience and analysed how both concepts were framed.

The complete list of energy-related resilience studies that was compiled and subsequently categorized

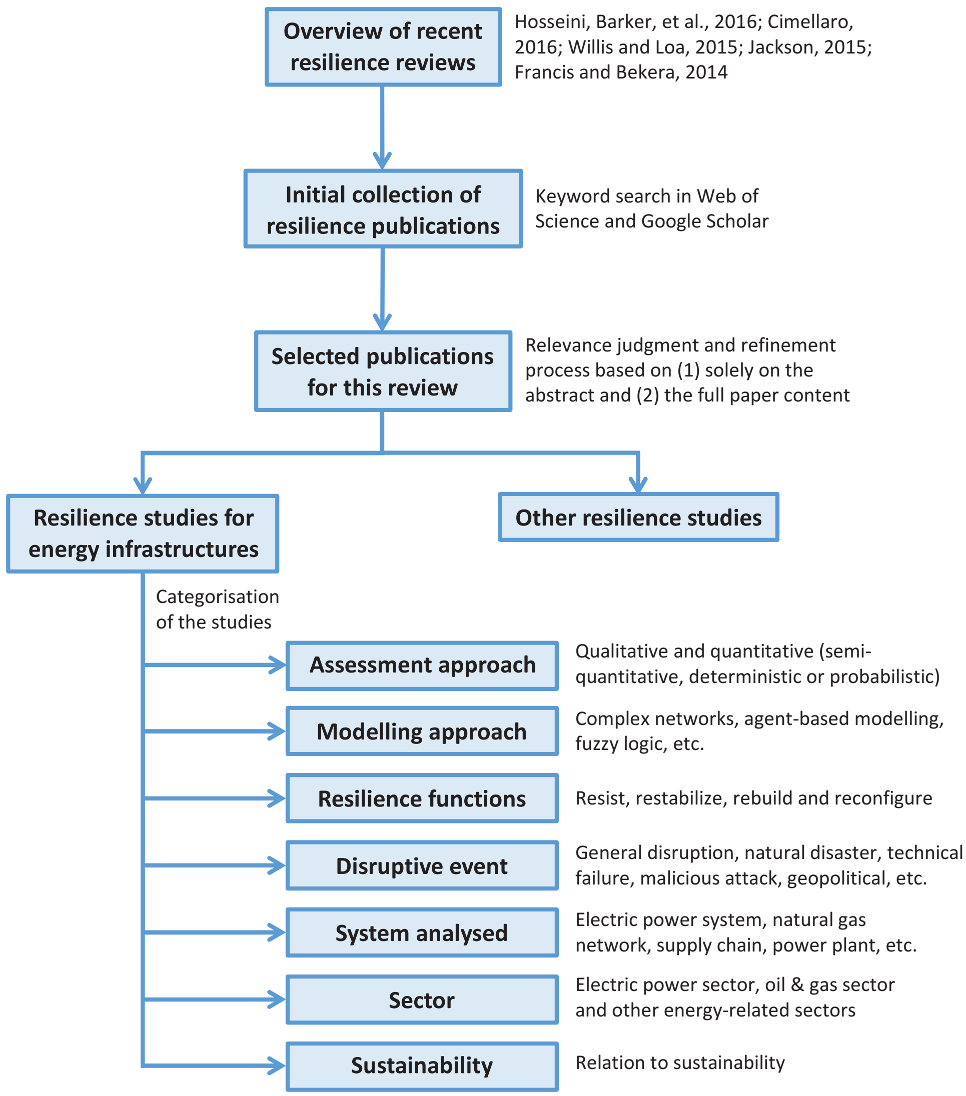


**Figure 3.** Flowchart of the literature screening methodology used in this review.

is shown in Table S1. This list was used to produce Figure 4 and 5. The results of Figure 4 have been built using the R's *SuperExactTest* package developed by M. Wang et al. (2015), which is suitable for statistical testing and visualization of multi-set intersections. This package calculates the frequencies of each possible intersection and their statistical significances in terms of p-values. Compared to the original package, which uses a Markov-Chains Monte Carlo framework for computing the exact statistical distributions of multi-set intersections, the p-values are not displayed. In fact, the present dataset consisting of 100 references is too small for the algorithm to converge. To deal with all the possible intersections in the dataset under interest, we applied the *SuperExactTest* function, which is able to deal with $2^m$-$1$ intersections for $m$ sets automatically. We removed the intersections considering simultaneously both qualitative and quantitative assessment approaches from Figure 4. In fact, as soon as a research article included a quantitative analysis, it was classified as 'quantitative', regardless if it also included qualitative statements. Hence, these intersections are empty.

Figure 5 shows the keyword co-occurrence network made with VOSviewer, an open-source software tool for constructing and visualizing bibliometric networks (van Eck & Waltman, 2014). To create such a figure, it is necessary to download the full record and cited references of the literature of interest. This can be obtained via Web of Science, where most of the literature cited was found. For the literature not available on Web of Science, we extracted the keywords manually from the Portable Document Format (PDF) files. Out of the 100 references that constitute this figure, 10 did not have keywords. For each of these references, we selected 3–5 keywords based on the

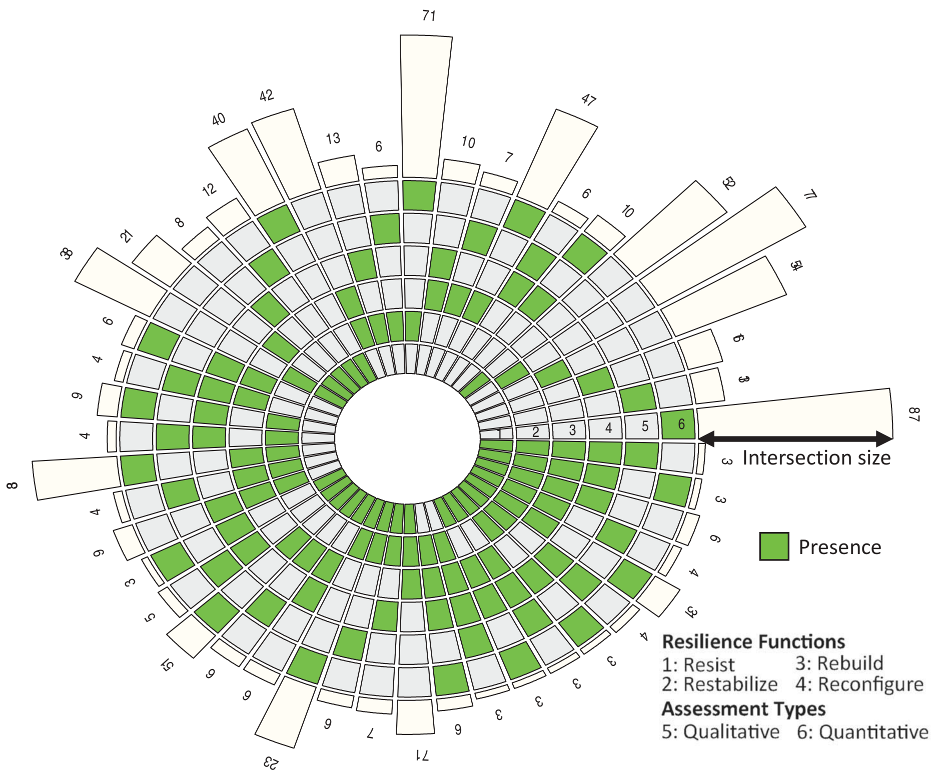


**Figure 4.** Circular plot showing all possible intersections and the corresponding numbers of studies (intersections). Tracks 1–6 represent the four biophysical resilience functions and the two main assessment approaches (qualitative and quantitative), with individual blocks showing 'presence' (green). The height of the bars in the outer layer refers to the intersection size.

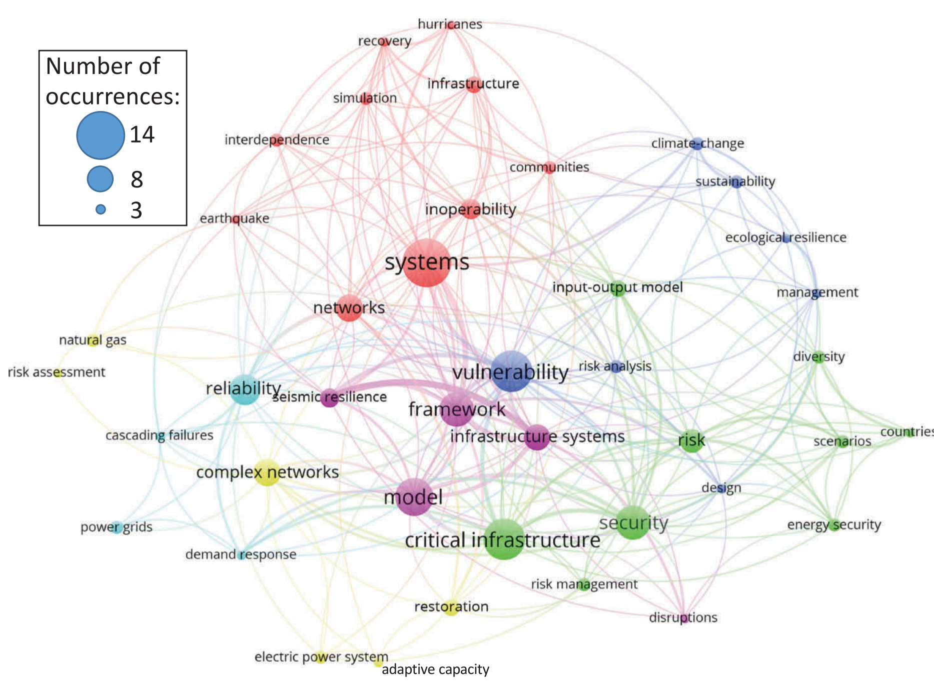


**Figure 5.** Keyword co-occurrence network. The size of the nodes are proportional to the number of occurrences of the keywords. The colours represent the clusters, which were calculated based on a maximization of the association strengths between nodes.

disruptive event, system and sector analysed, the assessment approach considered and the resilience functions studied (see Table S2). The clusters were calculated through the modularity function which is based on the association strength between nodes (for details see Waltman et al. (2010)). Hence, clustering is an optimization problem where the connection strengths between nodes are maximized. Regarding mapping, it also is an optimization problem, but it consists in minimizing the compromise between the connection strength between nodes and their distance.

## 5. Energy systems resilience assessment approaches

Figure 4 summarizes the numbers of each possible intersection for the four biophysical functions and two types of assessment approaches in the final set of studies as described in Table S1. Among the total number of studies collected (100), 52 assess the 'resist', 77 the 'restabilize', 54 the 'rebuild' and only 16 the 'reconfigure' function. The cumulated number of intersections is about 1.5 times higher for the studies addressing the 'resist' or 'restabilize' functions, compared to those looking at the 'rebuild' or 'reconfigure' functions. The more frequent consideration of the 'resist' and 'restabilize' functions indicates that the 'draw-down' (including pre-event) phase is more often analysed and possibly better understood. In contrast, the 'rebuild' and particularly the 'reconfigure' functions have been much less investigated, although they are crucial to extend risk assessment towards a more comprehensive resilience assessment. The most frequent combinations of functions and approaches include 'restabilize/quantitative' (71), 'rebuild/quantitative' (47), 'restabilize/rebuild' (41) and 'resist/quantitative' (40). This confirms that resilience assessment has to build upon quantifiable measures and indicators, similar to risk assessment. Furthermore, as the combination 'reconfigure/quantitative' only appears 10 times, the challenge to quantitatively assess the 'reconfigure' function of the resilience curve is highlighted.

On the one hand, almost all of the quantitative studies that analyse the 'resist' function (40) simultaneously analyse the 'restabilize' function (32), which shows a close link between these two functions. In fact, if the system in question fails to 'resist' properly, it tries to 'restabilize' the performance drop. On the other hand, only about half of the research articles quantifying 'restabilize' (71) simultaneously quantify 'resist' (32). The reason is that many resilience studies only consider the situation where a disruptive event leads to a performance drop, without considering the likelihood of occurrences of such events or the probability of failure if such an event occurs. Overall, it can be concluded that 'resist' and 'restabilize' are commonly assessed jointly, but only few studies also include the 'rebuild' and even fewer the 'reconfigure' functions.

Finally, 17 studies assess the first three biophysical functions of the resilience curve together, and only 6 studies analyse all four resilience functions (Forssén et al., 2017; Gong & Liang, 2017; Kim et al., 2017; Nan & Sansavini, 2017; Ouyang et al., 2012; Urciuoli et al., 2014), of which only three used a quantitative approach. This emphasizes the difficulty to comprehensively quantify resilience, and the need to specifically focus on the 'reconfigure' function.

In the remainder of this section, the two assessment approaches used with respect to each biophysical function are discussed in more detail. The motivation is to use the four functions, which makes a comparison between studies feasible and represents a novel contribution.

Qualitative approaches assess resilience without using numerical values, formulas or models. They are especially useful to determine the underlying drivers of a problem, its causes, critical areas and motivations for further development. A qualitative assessment can be the starting point to understand a situation before moving towards a quantitative analysis. For example, expert elicitation offers a convenient way to foster discussions and to identify areas for resilience improvement (Berkeley III and Wallace, 2010; Forssén et al., 2017; Gong & Liang, 2017; Labaka et al., 2015; Urciuoli et al., 2014). Expert elicitation processes are conducted using well-defined procedures (e.g., SSHAC Guidelines for seismic hazard assessment of nuclear power plants (Budnitz et al., 1997)). They can include surveys, interviews or workshops. The focus can either be on the operation of a single critical infrastructure including responsible operators, managers and regulators only (Gong & Liang, 2017; Urciuoli et al., 2014), or in a broader context that requires the participation of many different stakeholder groups, for example, when the whole electric power sector is considered (Erker et al., 2017; Keogh & Cody, 2013). Exercises involving humans in a real-world setting can reveal the reactions of people and systems in response to diverse emergency scenarios, which in turn help developing simple and efficient emergency procedures that operators should follow (Furniss et al., 2011; Labaka et al., 2015). Finally, reviews and meta-analyses of existing qualitative studies can also generate new insights and identify research gaps (Erker et al., 2017; Furniss et al., 2011; Givens et al., 2018; Keogh & Cody, 2013; McLellan et al., 2012; McNally et al., 2009; Mu et al., 2011; Park et al., 2011). Overall, the methodologies used in the energy sector to conduct qualitative studies are threefold:

- In-depth interviews: Interviews to elicit knowledge from experts
- Focus groups: Workshops in which experts discuss the topic of interest
- Review: Analysis of the available literature, documents and reports in order to understand the essence of the studied topic or develop frameworks

The classification of the energy-related studies into these methodologies is provided in Table S1.

Quantitative approaches generate numerical data, and they can be further categorized as semi-quantitative, deterministic and probabilistic approaches. A semi-quantitative approach is one that relies not only on quantitative indicators (i.e., measured with interval or ratio scales), but partially also on qualitative indicators (i.e., measured with ordinal or nominal scales). These qualitative scales can be comparative scores between alternatives or indicators quantified through stakeholders' surveys (Fisher et al., 2010; McCarthy et al., 2007; Shirali et al., 2012; Thorisson et al., 2017). Thus, an indicator's performance is measured through expert judgement. In this context, fuzzy logic methods are increasingly applied because they are appropriate when data are unavailable or uncertain and they are powerful in integrating experts' knowledge in view of sometimes uncertain subjective judgements (Azadeh et al., 2014a; Guo et al., 2016). Fuzzy logic allows quantifying indicators and their weights are determined by expert judgement, resulting in the construction of composite resilience scores.

Deterministic approaches differ from semi-quantitative ones in the sense that they do not include nominal or ordinal scales. They have a single solution for given sets of inputs and the outcomes are precisely determined. In contrast, introduction of uncertainties as probabilities requires probabilistic approaches. Overall, among the 87 quantitative studies, 48 are probabilistic. Many deterministic and probabilistic methods have been applied to quantify the resilience curve, including complex networks theory (Afgan & Cvetinovic, 2013; Akhavein & Fotuhi Firuzabad, 2011; Anghel et al., 2007; Bagchi et al., 2013; Bilal et al., 2016; Bompard et al., 2010; Carvalho et al., 2014; Cavalieri et al., 2014; Cimellaro et al., 2012; Cong et al., 2018; Ellison et al., 2013; Esposito et al., 2013; Fang & Sansavini, 2018; Hernandez-Fajardo & Dueñas-Osorio, 2013; Hines et al., 2010; Holmgren, 2007; Kim et al., 2017; Kyriakidis et al., 2018a; Layton, 2004; Li et al., 2017; 2016; Lustenberger et al., 2017; Martinez-Anido et al., 2012; Montoya, 2010; Moslehi & Reddy, 2018; Nadeau, 2007; Nan et al., 2013; Nezamoddini et al., 2017; Ouyang & Dueñas-Osorio, 2014; Ouyang et al., 2012, 2009; Panteli et al., 2017; Poljansek et al., 2010; Rocchetta et al., 2018; Schiel et al., 2017; Shinozuka et al., 2004; Su et al., 2017, 2018; Veeramany et al., 2017; Xu et al., 2007), agent-based modelling (Nan et al., 2013; Nan & Sansavini, 2017; Sun et al., 2015; Vugrin et al., 2011), input-output models (Anderson et al., 2007; Baghersad & Zobel, 2015; He et al., 2017; Leung & Hsu, 1984; MacKenzie & Barker, 2012; Cameron A. MacKenzie et al., 2014; Pant et al., 2014; Reed et al., 2009; Rose et al., 1997; Sato et al., 2017; Tan, 2011), composite indices not relying on nominal or ordinal scales (Binder et al., 2017; Bompard et al., 2017; Gnansounou, 2008; Molyneaux et al., 2012), computational general equilibriums (A. Rose et al., 2007), hazard and operability study (Karimi et al., 2016), high-level architecture (Nan et al., 2013), Bayesian networks (Bilal et al., 2016) and statistical models that do not include any of the previously mentioned methods (N Afgan & Cvetinovic, 2010; Amirat et al., 2006; Barker & Baroud, 2014; Beheshtian et al., 2018a; Blume & Sansavini, 2017; Feofilovs & Romagnoli, 2017; Liévanos & Horne, 2017; Cameron A MacKenzie & Barker, 2012; Morshedlou, 2018; Rose et al., 2012).

The 'resist' function of resilience describes the ability of a system to withstand disturbances with no or only small fluctuations in its performance. In the case of electric power systems, suitable performance measures include the number of people without power (Sun et al., 2015), the loss of load (Ouyang & Dueñas-Osorio, 2014; Ouyang et al., 2012), the generation capacity available (Sun et al., 2015), and reliability indices such as the System Average Interruption Duration Index (SAIDI) (Layton, 2004). In the oil and gas sector, the deterministic or probabilistic flow through the distribution network is a well-established indicator (Carvalho et al., 2014; Lustenberger et al., 2017; Nadeau, 2007). More than half of the studies use complex networks theory to model the studied infrastructure in order to quantify the 'resist' function of resilience (Akhavein & Fotuhi Firuzabad, 2011; Bilal et al., 2016; Bompard et al., 2010; Carvalho et al., 2014; Cimellaro et al., 2012; Cong et al., 2018; Holmgren, 2007; Kim et al., 2017; Kyriakidis et al., 2018a; Layton, 2004; Li et al., 2017, 2016; Lustenberger et al., 2017; Martinez-Anido et al., 2012; Nadeau, 2007; Nezamoddini et al., 2017; Ouyang & Dueñas-Osorio, 2014; Ouyang et al., 2012; Rocchetta et al., 2018; Shinozuka et al., 2004; Su et al., 2017, 2018; Veeramany et al., 2017). Generally, energy system networks are considered 'complex' because of their non-trivial topological features, and because their elements (i.e., nodes and links) are neither purely random nor regular. For these reasons, the complex network approach is particularly suitable. Other approaches considered are fuzzy logic (A. Azadeh, et al., 2014a; Bilal et al., 2016; Guo et al., 2016; Makarov & Moharari, 1999), composite indexes (Fisher et al., 2010; Gnansounou, 2008; Molyneaux et al., 2012), agent-based modelling (Nan &

Sansavini, 2017), hazard and operability studies (Karimi et al., 2016), multi-attribute utility theory (McCarthy et al., 2007), economic interdependence models (Bing Li et al., 2017) and statistical models (Amirat et al., 2006; Beheshtian et al., 2018a; Feofilovs & Romagnoli, 2017; S. Rose et al., 2012). It is important to note that the concept of reliability is widespread in studies assessing the 'resist' function of resilience.

Concerning the 'restabilize' function of resilience, it characterizes the ability of a system to re-establish key functionalities in order to better absorb disruptions once a system's performance is decreasing. For energy systems, central elements include aspects of diversity, fuel reserves, and control of cascading effects. Diversity indices are often used because a more diverse energy supply allows for more flexibility during unforeseen supply shortages, including short, medium- and long-term time horizons (Molyneaux et al., 2012), leading to a better overall resilience performance. In contrast, fuel reserves are a preferred option to cope with short-term supply shortages, and thus many countries have minimal local storage requirements (Fisher et al., 2010; Gnansounou, 2008; Molyneaux et al., 2012; Mu et al., 2011). While diversity and fuel reserves can usually be addressed by deterministic approaches, cascading effects are typically analysed using probabilistic approaches in combination with complex networks theory for infrastructure modelling (Anghel et al., 2007; Bagchi et al., 2013; Cavalieri et al., 2014; Cimellaro et al., 2012; Esposito et al., 2013; Hernandez-Fajardo & Dueñas-Osorio, 2013; Hines et al., 2010; Holmgren, 2007; Li et al., 2017, 2016; Lustenberger et al., 2017; Nezamoddini et al., 2017; Ouyang & Dueñas-Osorio, 2014; Ouyang et al., 2012, 2009; Panteli et al., 2017; Poljansek et al., 2010; Schiel et al., 2017; Su et al., 2017; Veeramany et al., 2017). This combination allows estimating probabilistically if an initial failure will propagate through the entire network, and result in a collapsing behaviour, which is one of the possible shapes of the resilience curve (see Figure 1). Therefore, it is not surprising that all the quantitative studies analysing cascading failures (14 out of 87) include the 'restabilize' function of resilience (Anghel et al., 2007; Bagchi et al., 2013; Baghersad & Zobel, 2015; Cavalieri et al., 2014; Hernandez-Fajardo & Dueñas-Osorio, 2013; Kim et al., 2017; Li et al., 2017; Makarov & Moharari, 1999; Montoya, 2010; Nan et al., 2013; Nan & Sansavini, 2017; Ouyang et al., 2012; Panteli et al., 2017; Veeramany et al., 2017).

After restabilization, the ability of a system to come back to its normal state, i.e., the shape of the recovery curve and recovery speed, represents the 'rebuilt' function of resilience. Studies on this function only emerged in the context of energy systems' infrastructure in the 2000s, and their numbers have significantly increased in the first half of the 2010s (Hosseini et al., 2016b). There are a number of studies identifying qualitative measures to improve recovery processes, such as emergency preparedness and protocols (Gong & Liang, 2017; Park et al., 2011; Urciuoli et al., 2014), availability of skilled repair personnel and spare parts (Urciuoli et al., 2014), and system governance (Berkeley & Wallace, 2010). All these studies involve interviews with experts and operators of critical infrastructures. Similarly, to the 'resist' and 'restabilize' functions, the 'rebuild' function is also mainly quantified through complex networks theory (Naim Afgan & Cvetinovic, 2013; Anghel et al., 2007; Cimellaro et al., 2012; Esposito et al., 2013; Fang & Sansavini, 2018; Kim et al., 2017; Kyriakidis et al., 2018a; Li et al., 2017, 2016; Martinez-Anido et al., 2012; Montoya, 2010; Moslehi & Reddy, 2018; Ouyang & Dueñas-Osorio, 2014; Ouyang et al., 2012; Panteli et al., 2017; Poljansek et al., 2010; Rocchetta et al., 2018; Shinozuka et al., 2004; Veeramany et al., 2017; Xu et al., 2007). There, the probability for a system's component recovery can be determined stochastically (Afgan & Cvetinovic, 2013; Anghel et al., 2007; Cimellaro et al., 2012), based on historical data (Esposito et al., 2013; Kim et al., 2017; Martinez-Anido et al., 2012; Montoya, 2010; Panteli et al., 2017; Shen & Tang, 2015) or resulting from analytical frameworks (Hughes et al., 2016; Poljansek et al., 2010) (Montoya, 2010). Some studies also use complex networks to compare different recovery strategies (Anghel et al., 2007; Cimellaro et al., 2012; Fang & Sansavini, 2018; Kyriakidis et al., 2018a; Moslehi & Reddy, 2018; Ouyang & Dueñas-Osorio, 2014; Panteli et al., 2017; Veeramany et al., 2017; Xu et al., 2007). For example, in a network, it could represent different sequences in which nodes and links are being repaired (Kyriakidis et al., 2018a). Another particularly suitable and powerful method is agent-based modelling because it simulates the (inter-)actions of autonomous agents (Nan & Sansavini, 2017; Sun et al., 2015; Vugrin et al., 2011). For example, parameters, such as the speed of travel and the repair success rate, can be assigned to the agents. Finally, some studies directly try to approximate the recovery process of the resilience curve through case studies (Afgan & Veziroglu, 2012; Francis & Bekera, 2014; Rochas et al., 2015; Shen & Tang, 2015). The recovery times and costs are either based on assumptions (Francis & Bekera, 2014; Rochas et al., 2015) or historical data (Afgan & Veziroglu, 2012; Shen & Tang, 2015). These quantitative recovery studies indicate also the scarcity of historical recovery data describing recovery time and/or recovery costs.

Finally, the 'reconfigure' function of resilience is about the topology of a system in order to make it more fault-tolerant. The aim is that after reconfiguration, resilience towards future disruptions is increased. The 'reconfigure' function is the most difficult one to assess, which is also reflected by the fact that about half of the studies considering reconfigurability are qualitative or semi-quantitative (Forssén et al., 2017; Furniss et al., 2011; Gong & Liang, 2017; Labaka et al., 2015; Park et al., 2011; Shirali et al., 2012; Urciuoli et al., 2014). On the one hand, these studies discuss the risks along energy supply chains, and possibilities to redirect the related supply routes (Urciuoli et al., 2014). On the other hand, they evaluate aspects of organizational resilience within a plant or facility (Furniss et al., 2011; Gong & Liang, 2017; Labaka et al., 2015; Shirali et al., 2012). Available quantitative studies use again complex network theory to compare different network topologies (Anghel et al., 2007; Ellison et al., 2013; Hines et al., 2010; Kim et al., 2017; Nan et al., 2013; Ouyang et al., 2012), and to analyse the effects of randomly removed links or nodes on the flows (Anghel et al., 2007; Hines et al., 2010; Kim et al., 2017). The idea is to reconfigure the network's topology to increase its performance. As for the rebuild function, agent-based modelling is a useful and practical method to model human performances for the 'reconfigure' function (Nan et al., 2013; Nan & Sansavini, 2017).

Based on these 100 studies, similarities between the concepts of sustainability and resilience emerge. There exist four general perspectives about how the two can be related. First, sustainability defined as 'the ability to … maintain[] [an objective or system] at a certain rate or level' (Oxford Dictionaries, 2018b) is indeed closely related to resilience. In fact, according to this definition, sustainability could actually also be visualized through the same 'swoosh' resilience curve (cf. Figure 1). For example, the larger the disruption, the less sustainable the system becomes, exactly as for resilience (Marchese et al., 2017). In this sense, sustainability and resilience can be used interchangeably. Second, as stated previously, many resilience studies particularly emphasize the post-event strategies, which correspond to the 'rebuild' and 'reconfigure' biophysical functions. On the contrary, sustainability could rather be seen as representing the two first functions of resilience ('resist' and 'restabilize'). In fact, if an event leads to a performance drop, then the system was not able to maintain a certain performance level indicating that it is unsustainable. This view integrates sustainability into the broader concept of resilience. Third, some studies provide an opposite perspective, where resilience is a component of the concept of sustainability (Marchese et al., 2017). Fiksel (2003) argues that including a resilience perspective aimed at coping with external impacts, i.e., beyond the boundaries that one controls, enables to become more sustainable (Fiksel, 2006). Furthermore, Moslehi and Reddy (2018) state that 'improving infrastructure systems resilience … [is] a crucial attribute of sustainable systems'. In the same line of thoughts, Givens et al. (2018) and (Summers et al., 2017) see resilience towards change as being part of broader sustainability aims. Following such frameworks, resilience can be one among several dimensions of sustainability. Fourth, there are approaches, which account for sustainability on the one hand and resilience on the other. For example, sustainability is assessing the impact on the infrastructure and its service states under normal operational conditions, whereas resilience assesses the impact after exceptional events (Paolo Bocchini et al., 2013). Therefore, they should be combined into a global impact assessment by weighting with the probabilities of occurrence of the events. Similarly, McLellan et al. (2012) argues that sustainability considers normal operations and resilience unusual conditions. Furthermore, in the Enhanced Energy Trilemma framework, sustainability represents one dimension and resilience is a component of another dimension on energy security (Pliousis et al., 2019). This shows that resilience and sustainability can be viewed as complementary.

As these four views are divergent, it is of utmost importance to define what is meant by sustainability or resilience when they are used in a study. Furthermore, sustainability usually considers long-term effects and persistent pressures on a system under normal operating conditions, whereas resilience tends to describe short-term and immediate disruptions, although long-term aspects have been recently proposed, e.g., for transport infrastructure (Beheshtian et al., 2018b). Extending on this, the concept 'sustainable resilience' came to prominence (Gillespie-Marthaler et al., 2018). It represents the ability to maintain desired levels of system performance by adapting in response to expected and unexpected events over time. Therefore, sustainable resilience considers all kinds of disturbances in a long-term view (Sanchez et al., 2017, 2016).

Regarding indicator-based approaches, Afgan and Veziroglu (2012) defined the sustainability index as the weighted linear aggregation of indicators representing the concept to be measured. The resilience index is the integral over time of the sustainability index, which represents the 'swoosh' curve. Hence, sustainability is measured for single time steps, whereas resilience is the aggregated measure over time.

While sustainability is usually divided into three pillars (environmental, social and economic) (Drexhage & Murphy, 2010), resilience does not have such a distinct and broadly accepted categorization yet. Nonetheless, most of the resilience studies touch at least one of the three sustainability pillars. In the present set of 100 studies, 20 investigate aspects related to the environmental pillar of sustainability (Berkeley & Wallace, 2010; Binder et al., 2017; Erker et al., 2017; Forssén et al., 2017; Francis & Bekera, 2014; Givens et al., 2018; Gnansounou, 2008; Harto et al., 2012; Hughes et al., 2016; Karimi et al., 2016; Liévanos & Horne, 2017; McCarthy et al., 2007; McLellan et al., 2012; McNally et al., 2009; Molyneaux et al., 2012; Mu et al., 2011; Poljansek et al., 2010; Thorisson et al., 2017; Urciuoli et al., 2014) and 18 to the social pillar (Azadeh et al., 2014b; Berkeley & Wallace, 2010; Binder et al., 2017; Erker et al., 2017; Forssén et al., 2017; Francis & Bekera, 2014; Givens et al., 2018; Gong & Liang, 2017; Labaka et al., 2015; Li et al., 2016; Liévanos & Horne, 2017; McCarthy et al., 2007; McLellan et al., 2012; McNally et al., 2009; Mu et al., 2011; Ouyang & Dueñas-Osorio, 2014; Poljansek et al., 2010; Thorisson et al., 2017). The economic pillar is the most commonly examined one with 42 related studies (N Afgan & Cvetinovic, 2010; Anderson et al., 2007; Anghel et al., 2007; Baghersad & Zobel, 2015; Berkeley & Wallace, 2010; Bompard et al., 2017; Carvalho et al., 2014; Cimellaro et al., 2012; Erker et al., 2017; Esposito et al., 2013; Feofilovs & Romagnoli, 2017; Forssén et al., 2017; Francis & Bekera, 2014; Givens et al., 2018; Hauser et al., 2017; He et al., 2017; Hughes et al., 2016; Keogh & Cody, 2013; Leung & Hsu, 1984; Li et al., 2017, 2016; Liévanos & Horne, 2017; MacKenzie & Barker, 2012; MacKenzie et al., 2014; McCarthy et al., 2007; McLellan et al., 2012; McNally et al., 2009; Montoya, 2010; Moslehi & Reddy, 2018; Mu et al., 2011; Nadeau, 2007; Nezamoddini et al., 2017; Ouyang & Dueñas-Osorio, 2014; Ouyang et al., 2012, 2009; Rochas et al., 2015; Rose et al., 1997, 2007; Thorisson et al., 2017; Tsang et al., 2002; Urciuoli et al., 2014; Vugrin et al., 2011). This is due to the fact that monetary losses are easier to quantify compared to social or environmental consequences, especially in the short term. Therefore, the general approach consists in quantifying the costs of implementing resilience-enhancing strategies versus the resilience gains due to less likely and less costly disruptions. This assumes that there exists a single optimal point between the investment costs and the resilience gains obtained (Li et al., 2016).

## 6. Clusters in energy systems resilience research

In Section 5, we categorized and analysed the compiled set of energy system studies according to the considered resilience functions and assessment approaches. In this section, we analyse the same selection of studies with respect to potential relationships, based on the keywords provided in each study.

Figure 5 shows the keyword co-occurrence network for the 100 energy system resilience studies analysed. In parenthesis, the keywords' number of occurrences and categorization are given. There are five categories: (i) 'modelling approach' used (e.g., complex networks, input-output model), (ii) 'function' as it relates to resilience functions (e.g., recovery, reliability, adaptive capacity), (iii) 'disruptive event' (e.g., hurricanes, earthquake), (iv) 'system analysed' (e.g., power grids), and (v) 'concepts' that define general terms (e.g., sustainability, security). The colours of the nodes correspond to the cluster membership of the respective keywords and keyword combinations. It should be noted that resilience, as the most common keyword, was not considered because all the studies are related to this keyword. Only the keywords cited at least 3 times are shown. In fact, showing keywords with fewer occurrences does not allow identifying trends. Furthermore, setting the threshold higher than 3 occurrences would have resulted in too few keywords appearing in the figure. Hence, the trade-off of at least 3 occurrences has been considered the most appropriate.

In total, the 100 studies have a cumulative number of 520 keywords. The most common keywords are 'systems' (14 occurrences), 'vulnerability' and 'critical infrastructure' (12 occurrences each), 'model' (11 occurrences), 'framework' and 'security' (10 occurrences each), 'reliability' (9 occurrences), 'complex networks' and 'networks' (8 occurrences each), and 'risk' and 'infrastructure systems' (7 occurrences each). This confirms that the two resilience functions of 'resist' characterized through 'reliability', and 'restabilize' characterized through 'vulnerability', are the most studied ones, supporting the findings of Section 5. It is interesting to note that vulnerability (i.e., the risk and the degree that the system can be affected (Aven et al., 2015)) is not expressed as function of resilience (see Figure 2), since it could cover many aspects of the resilience curve (Zio, 2016). According to the given definition, however, it emerges that vulnerability would be rather assigned to the 'draw-down' phase of the resilience curve. Furthermore, the keywords 'systems', 'complex networks' and 'networks' illustrate the topological aspects of energy systems. Finally, the frequent occurrences of ‘framework’ and ‘model’ reaffirms the attempts to define, conceptualize and quantitatively measure resilience. Regarding methodological approaches, ‘complex networks’ theory (8 occurrences) is most often mentioned, followed by ‘input-output model’ (5 occurrences), which shows the popularity of these approaches. The sectors mostly studied are the electric power grid (4 occurrences each for ‘power grids’ and ‘electric power system’), followed by the natural gas system (4 occurrences for ‘natural gas’). The most frequent natural hazard analysed is earthquakes (3 occurrences), with ‘seismic resilience’ (5 occurrences), due to its potentially high destructive impact on civil infrastructure.

Based on a maximization of the association strengths between keywords calculated through the modularity function (Waltman et al., 2010), keyword clusters can be identified (see the electronic supplementary information for further details about the methodology). Figure 5 and Table 2 present the 6 clusters calculated by VOSviewer (van Eck & Waltman, 2014). The first cluster is a broad one that focuses on the resilience of the interdependent infrastructure systems and networks of communities towards natural hazards. The second cluster is about energy security risk management of countries’ critical infrastructures. A popular modelling approach to do so is input-output models. Furthermore, climate-change, sustainability and ecological resilience are assigned to the third cluster. Complex networks theory is used in the fourth cluster to perform risk assessment, quantify restoration and analyse the adaptive capacity of highly topological systems such as the electric power system and the natural gas system. The fifth cluster covers modelling disruptions and creating frameworks for assessing infrastructure systems resilience. Finally, the sixth cluster measures the reliability and demand response with respect to cascading failures of power grids.

## 7. Conclusions and outlook

The increasing number of publications related to resilience reflects the broad consensus aimed at designing resilient infrastructures, which are essential for the functioning of our society (Hosseini et al., 2016b). As a consequence, a plethora of resilience definitions and frameworks have been proposed in different disciplines and applied in a variety of case studies worldwide. Based on the well-known and widely adopted ‘swoosh’ resilience curve concept, the two main facets of resilience can be combined, i.e., the amount and type of ‘draw-down’ and ‘draw-up’ behaviour. Therefore, irrespective of the research field, resilience assessment always aims to minimize the potential consequences resulting from a disruptive event and to efficiently recover from a potential system performance loss. Additionally, the resilience curve can be further divided into different segments, representing specific resilience functions. It is important to consider functions along the time axis involving both disruptive and recovery components to describe the resilience curve to its full extent. Furthermore, most of the studies consider that the performance level after recovery from a disruptive event is the same as before the event, assuming a robust behaviour. However, resilience is also about improving a system’s performance (adaptive behaviour) due to, for example, learning processes or synergies during reconstruction. Additionally, systems might not always fully recover and enter partially functioning states (ductile behaviour) or, in the worst case, even collapse (collapsing behaviour). Finally, the scope and objectives of a resilience study should be defined by describing specific characteristics relating to the event and the system under study, i.e., implicit (the event) and explicit (the system) factors, respectively. For example, resilience of a community (system) against seismic hazard (event), resilience of the electric power grid (system) against hurricanes (event) or resilience of the natural gas network (system) against intentional attacks (event), etc.

The findings about resilience in general presented in the previous paragraph are also valid for the energy sector, which is a critical infrastructure in the majority of countries since it is of crucial importance for the well functioning of society. This review indicates that the considerable amount of resilience research and case studies carried out in the energy sector have produced many important insights and achievements, in particular for the electric power or natural gas grids, which are both complex networks with a distinct topology. Network dynamics are often studied using complex networks theory because it allows highlighting important topological aspects. Two other promising approaches are agent-based modelling to model the (inter-)actions of autonomous agents (managers, operators, regulators, etc.), and indicator-based approaches to model multidimensional problems. Almost all of the selected studies consider components related to reliability, vulnerability or robustness, indicating that the two resilience functions of ‘resist’ and ‘restabilize’ are much more developed than ‘rebuild’ and ‘reconfigure’. This is likely due to a more pronounced lack of awareness for the functions attributable to the ‘draw-up’ phase of resilience. Additionally, quantitative data for recovery processes and the ability to reconfigure a system are often not publicly available or simply missing.

**Table 2.** Keyword clusters as calculated by VOSviewer. The cluster colours refer to Figure 5. The keywords' number of occurrences is given in parenthesis, as well as its categorization. There are five categories: (i) 'modelling approach' used (e.g., complex networks, agent-based modelling), (ii) 'function' as it relates to resilience functions (e.g., reliability, adaptive capacity), (iii) 'disruptive event' (e.g., hurricane, earthquake), (iv) 'system analysed' (e.g., power grids), and (v) 'concepts' that define general terms (e.g., sustainability, security).

| Category | Cluster 1 (red): Community resilience towards natural hazards | Cluster 2 (green): Energy security risk management of countries' critical infrastructures | Cluster 3 (blue): Climate-change, sustainability and ecological resilience | Cluster 4 (yellow): Complex networks theory for topological systems | Cluster 5 (purple): Frameworks and disruption modelling of infrastructure systems | Cluster 6 (arctic blue): Reliability and demand response of cascading failures of power grids |
|---|---|---|---|---|---|---|
| Modelling approach | Simulation (4) | Input-output model (5)<br>Risk management (4) | Risk analysis (4) | Complex networks (8)<br>Risk assessment (3) | Framework (10)<br>Model (11) | |
| Function | Recovery (3) | | Vulnerability (12) | Adaptive capacity (3)<br>Restoration (5) | | Reliability (9) |
| Disruptive event | Earthquake (3)<br>Hurricanes (3) | | | | Disruptions (3)<br>Seismic resilience (5) | Cascading failures (3) |
| System analysed | Communities (4)<br>Infrastructure (5)<br>Networks (8)<br>Systems (14) | Countries (3)<br>Critical infrastructure (12) | | Electric power system (4)<br>Natural gas (4) | Infrastructure systems (7) | Power grids (4) |
| Concepts | Inoperability (6)<br>Interdependence (4) | Diversity (4)<br>Energy security (4)<br>Risk (7)<br>Scenarios (4)<br>Security (10) | Climate-change (4)<br>Design (3)<br>Ecological resilience (3)<br>Management (3)<br>Sustainability (4) | | | Demand response (3) |

### 7.1. Outlook and future research directions

Although the quantification of disaster recovery processes in certain fields (e.g., construction management, roads and railroads) has been investigated for decades, only few studies have attempted to comprehensively quantify them for natural disasters (e.g., earthquakes). Three promising approaches are competing, namely (1) model fitting using empirical data, (2) development of theoretical models that do not rely on empirical data, and (3) evaluation of suitable recovery strategies. For example, recovery strategies can represent different recovery sequences of network elements, as well as their recovery probabilities. Considering the limited availability of quantitative information describing the reconfigure function of energy system resilience, it is not surprising that this function is the least studied. Therefore, future research should clearly focus on the quantification of recovery processes (including the collection and sharing of data and information) that minimize performance losses and/or reinforce the 'draw-up' phase. For example, the ability to reroute supply chains and energy flows affects (1) the ability to incorporate technical change and innovation, (2) the diversity of the energy system under consideration, and (3) the ability to adapt to new operating conditions. Furthermore, robust resilience assessment of large-scale systems, e.g., on national levels, should include not only technical elements but also organizational, geopolitical and managerial measures (Gasser et al., 2017). Ultimately, our infrastructures are complex, socio-technical systems, which is why a comprehensive resilience assessment should not just evaluate the biophysical functions, but also consider enabling and cognitive functions. These functions deal with staying aware, remembering and learning from past disruptions, and being able to cope with them (H. R. Heinimann & Hatfield, 2017). Last but not least, there are attempts to standardize resilience engineering and implement it into practice on different levels (such as international standards for the industry (International Organization for Standardization, 2017) and governmental institutions (Fraunhofer Institute, 2018; Jovanović et al., 2016; UN General Assembly, 2015)), but there is a clear need for intensified cooperation between operators, authorities, and researchers to ensure that resilience assessment is operationalized according to current state-of-the-art methodological developments. This will also allow for more realistic scenarios in emergency preparedness exercises, and enable better simulations of disruptive events and their potential large-scale consequences and cascading effects on other critical infrastructure and the communities they underpin (Sircar et al., 2013).

## Article highlights

- All resilience approaches have the ultimate goal of minimizing adverse consequences
- Resilience assessment includes functions covering the draw-down and draw-up phases
- Abilities to resist/restabilize are better understood than recovery/reconfigurability
- Modelling the topology of energy systems with complex network approaches is promising
- Indicator-based approaches are suitable to reflect the behaviour of complex systems

## Acknowledgments

The research was conducted at the Future Resilient Systems (FRS) at the Singapore-ETH Centre (SEC), which was established collaboratively between ETH Zürich and Singapore's National Research Foundation (FI 370074011) under its Campus for Research Excellence And Technological Enterprise (CREATE) programme.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

This work was supported by the National Research Foundation Singapore [FI 370074011].

## Notes on contributors

*Patrick Gasser* is a PhD researcher at ETH Zurich's Future Resilient Systems (FRS) program in Singapore. His research topic focuses on adopting Multi-Criteria Decision Analysis (MCDA) methods to build indicator-based country rankings with respect to their electricity supply resilience. Patrick Gasser holds a Master's Degree in Energy Science and Technology from ETH Zurich and a Bachelor's Degree in Mechanical Engineering from the Ecole Polytechnique Fédérale de Lausanne (EPFL). Furthermore, besides experience in energy consulting, Patrick Gasser held positions at Swissgrid, the owner and operator of the Swiss high-voltage electricity transmission grid, in the promotion of renewable energy technologies and developing markets for ancillary services.

*Peter Lustenberger* joined the Future Resilient Systems programme at the Singapore-ETH Centre in December 2015. Prior to that, he was working for the Swiss Agency for Development and Cooperation at the Embassy of Switzerland in Beijing, P.R. China. His duties involved scientific consulting with respect to planning, monitoring and developing of Sino-Swiss cooperation projects in general and in particular in the field of air quality. Peter has also conducted research in water quality and groundwater modelling, both as visiting student at Tsinghua University (Beijing, P.R. China) supported by a Zeno Karl Schindler

Foundation Scholarship, and as research intern at the Centre for Hydrogeology and Environmental Geology Survey (CHEGS, Baoding, P.R China), which is affiliated to the China Geological Survey (CGS).

*Marco Cinelli* (Ph.D. Engineering, University of Warwick, UK, 2016) is a Marie Skłodowska-Curie Global Fellow at the National Risk Management Research Laboratory (NRMRL) of the U.S. Environmental Protection Agency in Cincinnati, USA (current location) and Institute of Computing Science at Poznan University of Technology, Poland. Between April 2017 and August 2018, he was a postdoctoral researcher at the Future Resilient Systems (FRS) Programme of Singapore-ETH Centre in Singapore. Prior to this, he was an early career fellow at the Institute of Advanced Study. He also held, between May 2016 and February 2017, a visiting scientist position at the Joint Research Centre of the European Commission in Ispra (VA), Italy.

*Wansub Kim* holds MSc in Geoinformation and Disaster Risk Management from ITC, University of Twente, Netherlands. Kim has been working for both industries (Yahoo Japan, Mizuho, SK) and academia (ETH) across several countries such as Korea, Japan, Netherlands and Singapore. Kim has expertise on GIS including geospatial database, mobile mapping, AR, remote sensing, cloud computing, car navigation, and natural hazards.

*Matteo Spada* is a risk analyst at the Technology Assessment group in the Laboratory for Energy Systems Analysis at the Paul Scherrer Institute. Since 2014, he participates as Co-PI at the activities of the risk group on "Assessing and Measuring Energy Systems Resilience" within the Future Resilient Systems program of the Singapore ETH Centre. His personal research interests focused on the comparative risk assessment in the energy sector, the risk of rare accidents related to production and consumption of energy and in complex decision-making tools such as Multi-Criteria Decision Analysis (MCDA). Matteo is also one of the responsible for the update and extensions of the world largest database on accidents in the energy sector ENSAD (Energy-Related Severe Accident Database).

*Peter Burgherr* leads the inter-disciplinary Technology Assessment group of the Laboratory for Energy Systems Analysis at the Paul Scherrer Institut (PSI). The group carries out integrated assessments of current and future energy technologies to support the complex decision-making processes towards a low-carbon, sustainable energy system. His personal research interests focus (1) on comparative risk assessment in the energy sector and its relevance in the broader context of sustainability, resilience, energy security and critical infrastructure protection, and (2) the use of MCDA methods to identify trade-offs and robust solutions. Furthermore, he is also the primary responsible for PSI's database ENSAD (Energy-Related Severe Accident Database), which is the world's most authoritative database on severe accidents in the energy sector.

*Stefan Hirschberg* is the Senior Advisor in Energy Divisions at the Paul Scherrer Institute (PSI), Switzerland. Until May 2017 he was the Head of the Interdepartmental Laboratory for Energy Systems Analysis at PSI. He has managed a large number of projects on energy and mobility for regulators, for electrical utilities and vendors, and within international programs. He is individual member of the Swiss Academy of Engineering Sciences. Before joining PSI in 1992 he was responsible for Risk and Reliability Assessment within ABB, Sweden. Between 1974 and 1982 he was researcher in the Department of Reactor Physics at Chalmers University of Technology, Gothenburg, Sweden. He has a M.Sc. degree in engineering physics and Ph.D. degree in reactor physics from Chalmers.

*Božidar Stojadinovic* is the Chair of Structural Dynamics and Earthquake Engineering at the Swiss Federal Institute of Technology (ETH) Zürich and a member of the ETH Risk Center. His degrees are in Civil Engineering: PhD from the University of California, Berkeley in 1995, MS from Carnegie-Mellon University in 1990 and BS (Dipl.Ing.) from the University of Belgrade, Serbia in 1988. His main research is in the field of community disaster resilience. In this area, he specializes in performance-based probabilistic resilience evaluation and design of civil infrastructure systems, buildings and bridges. Professor Stojadinović is also working on earthquake response modification techniques and onhybrid simulation methods to investigate the response of structures to dynamic loads.

*Tian Yin Sun* was a Postdoctoral researcher at the Future Resilient System Program of ETH Zurich while conducting this research. He is now a senior research fellow at the Research Center for Green Finance Development of Tsinghua University. His primary research interests concern physical damage and monetary loss of physical properties caused by weather and climate related events, monetary loss due to business interruptions induced by weather and climate related disasters, and the application of probabilistic methods in engineering.

## ORCID

Patrick Gasser http://orcid.org/0000-0002-1054-7558
Peter Lustenberger http://orcid.org/0000-0003-4055-5265
Marco Cinelli http://orcid.org/0000-0001-5822-3627
Matteo Spada http://orcid.org/0000-0001-9265-9491
Peter Burgherr http://orcid.org/0000-0001-6150-5035
Božidar Stojadinovic http://orcid.org/0000-0002-1713-1977

## References

Adger, W. N. (2000). Social and ecological resilience: Are they related? *Progress in Human Geography*, *24*(3), 347–364. doi:10.1191/030913200701540465

Afgan, N., & Cvetinovic, D. (2010). Wind power plant resilience. *Thermal Science*, *14*(2), 533–540.

Afgan, N., & Cvetinovic, D. (2013). Resilience evaluation of the South East European Natural Gas Routes system catastrophe. *International Journal of Engineering and Innovative Technology (IJEIT)*, 3(5), 175–180.

Afgan, N., & Veziroglu, A. (2012). Sustainable resilience of hydrogen energy system. *International Journal of Hydrogen Energy*, *37*(7), 5461–5467. doi:10.1016/j.ijhydene.2011.04.201

Akhavein, A., & Fotuhi Firuzabad, M. (2011). A heuristic-based approach for reliability importance assessment of energy producers. *Energy Policy*, *39*(3), 1562–1568. doi:10.1016/j.enpol.2010.12.030

Alexander, D. E. (2013). Resilience and disaster risk reduction: An etymological journey. *Natural Hazards and Earth System Sciences*, *13*(11), 2707–2716.

Amirat, A., Mohamed-Chateauneuf, A., & Chaoui, K. (2006). Reliability assessment of underground pipelines under the combined effect of active corrosion and residual stress. *International Journal of Pressure Vessels and Piping*, *83* (2), 107–117.

Anderson, C. W., Santos, J. R., & Haimes, Y. Y. (2007). A risk-based input–output methodology for measuring the effects of the August 2003 Northeast Blackout. *Economic Systems Research*, *19*(2), 183–204. doi:10.1080/09535310701330233

Andersson, G., Donalek, P., Farmer, R., Hatziargyriou, N., Kamwa, I., Kundur, P., … Sanchez-Gasca, J. (2005). Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance. *IEEE Transactions on Power Systems*, *20*(4), 1922–1928.

Anghel, M., Werley, K. A., & Motter, A. E. (2007). Stochastic model for power grid dynamics. *2007 40th Annual Hawaii International Conference on System Sciences*: HICSS 2007, Waikoloa, Big Island.

Aven, T., Ben-Haim, Y., Andersen, H. B., Cox, T., Droguett, E. L., Greenberg, M., … Thompson, K. M. (2015). SRA glossary. *The Society For Risk Analysis*

Ayyub, B. (2013). Systems resilience for multihazard environments: Definition, metrics, and valuation for decision making. *Risk Analysis*. doi:10.1111/risa.12093

Azadeh, A., Salehi, V., Arvan, M., & Dolatkhah, M. (2014a). Assessment of resilience engineering factors in high-risk environments by fuzzy cognitive maps: A petrochemical plant. *Safety Science*, *68*, 99–107. Retrieved from http://www.sciencedirect.com/science/article/pii/S092575351400071X

Azadeh, A., Salehi, V., Ashjari, B., & Saberi, M. (2014b). Performance evaluation of integrated resilience engineering factors by data envelopment analysis: The case of a petrochemical plant. *Process Safety and Environmental Protection*, *92*(3), 231–241.

Bagchi, A., Sprintson, A., & Singh, C. (2013). Modeling the impact of fire spread on an electrical distribution network. *Electric Power Systems Research*, *100*, 15–24.

Baghersad, M., & Zobel, C. W. (2015). Economic impact of production bottlenecks caused by disasters impacting interdependent industry sectors. *International Journal of Production Economics*, *168*, 71–80. doi:10.1016/j.ijpe.2015.06.011

Barker, K., & Baroud, H. (2014). Proportional hazards models of infrastructure system recovery. *Reliability Engineering & System Safety*, *124*, 201–206. Retrieved from http://www.sciencedirect.com/science/article/pii/S0951832013003256

Beheshtian, A., Donaghy, K. P., Gao, H. O., Safaie, S., & Geddes, R. (2018a). Impacts and implications of climatic extremes for resilience planning of transportation energy: A case study of New York city. *Journal of Cleaner Production*, *174*, 1299–1313. doi:10.1016/j.jclepro.2017.11.039

Beheshtian, A., Donaghy, K. P., Richard Geddes, R., & Oliver Gao, H. (2018b). Climate-adaptive planning for the long-term resilience of transportation energy infrastructure. *Transportation Research Part E: Logistics and Transportation Review*, *113*, 99–122. doi:10.1016/j.tre.2018.02.009

Berkeley, A., III, & Wallace, M. (2010). A framework for establishing critical infrastructure resilience goals: Final report and recommendations: *National Infrastructure Advisory Council (NIAC).*

Bilal, Z., Mohammed, K., & Brahim, H. (2016). Bayesian network and bow tie to analyze the risk of fire and explosion of pipelines. *Process Safety Progress*. *36*(2), 202–212.

Binder, C., Mühlemeier, S., & Wyss, R. (2017). An indicator-based approach for analyzing the resilience of transitions for energy regions. Part I: theoretical and conceptual considerations. *Energies*, 10(12). doi:10.3390/en10010036

Blume, S. O. P., & Sansavini, G. (2017). Effects of stressor characteristics on early warning signs of critical transitions and "critical coupling" in complex dynamical systems. *Chaos*, *27*(12), 121101. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/29289044

Bocchini, P., Decò, A., & Frangopol, D. (2012). Probabilistic functionality recovery model for resilience analysis. In Fabio Biondini, Dan M. Frangopol (Eds.), *Bridge maintenance, safety, management, resilience and sustainability* (pp. 1920–1927). UK: CRC Press, Taylor and Francis.

Bocchini, P., Frangopol, D. M., Ummenhofer, T., & Zinke, T. (2013). Resilience and sustainability of civil infrastructure: Toward a unified approach. *Journal of Infrastructure Systems*, *20*(2), 04014004.

Bompard, E., Carpignano, A., Erriquez, M., Grosso, D., Pession, M., & Profumo, F. (2017). National energy security assessment in a geopolitical perspective. *Energy*, *130*, 144–154. Retrieved from http://www.sciencedirect.com/science/article/pii/S0360544217306746

Bompard, E., Napoli, R., & Xue, F. (2010). Extended topological approach for the assessment of structural vulnerability in transmission networks. *IET Generation, Transmission & Distribution*, *4*(6), 716–724.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., … von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, *19*(4), 733–752.

Bruneau, M., & Reinhorn, A. (2007). Exploring the concept of seismic resilience for acute care facilities. *Earthquake Spectra*, *23*(1), 41–62. Retrieved from http://www.earthquakespectra.org/doi/abs/10.1193/1.2431396

Budnitz, R. J., Apostolakis, G., & Boore, D. M. (1997). *Recommendations for probabilistic seismic hazard analysis: Guidance on uncertainty and use of experts,*USA: Nuclear Regulatory Commission.

Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E., & Havlin, S. (2010). Catastrophic cascade of failures in interdependent networks. *Nature*, *464*(7291), 1025–1028. Retrieved from http://www.nature.com/nature/journal/v464/n7291/suppinfo/nature08932_S1.html

Burby, R. J., Deyle, R. E., Godschalk, D. R., & Olshansky, R. B. (2000). Creating hazard resilient communities through land-use planning. *Natural Hazards Review*, *1*(2), 99–106. Retrieved from https://ascelibrary org/doi/abs/10.1061/%28ASCE%291527-6988%282000%291%3A2%2899% %X29The Second National Assessment on Natural and Related Technological Hazards calls land-use planning the single most promising approach for bringing about sustainable hazard mitigation. This article describes the essential elements of land-use planning for hazard mitigation. It highlights important choices involved in formulating planning processes, undertaking hazard assessments, and crafting programs to manage urban development so that it is more resilient to natural hazards. Research conducted over the past two decades suggests that if local governments make the right choices in crafting land-use-planning programs, communities will be less likely to suffer severe losses of lives and property in natural disasters.

Campbell, F. C. (2008). *Elements of metallurgy and engineering alloys*. Materials Park, Ohio: ASM International.

Carvalho, R., Buzna, L., Bono, F., Masera, M., Arrowsmith, D. K., & Helbing, D. (2014). Resilience of natural gas networks during conflicts, crises and disruptions. *PloS one*, *9*(3), e90265. doi:10.1371/journal.pone.0090265

Cavalieri, F., Franchin, P., Buriticá Cortés, J. A. M., & Tesfamariam, S. (2014). Models for seismic vulnerability analysis of power networks: comparative assessment. *Computer-Aided Civil and Infrastructure Engineering*, *29* (8), 590–607. doi:10.1111/mice.12064

Cerè, G., Rezgui, Y., & Zhao, W. (2017). Critical review of existing built environment resilience frameworks: Directions for future research. *International Journal of Disaster Risk Reductiondoi*, *25*, 173–189. Retrieved from http://www.sciencedirect.com/science/article/pii/S2212420917302388

Chang, S. E., & Shinozuka, M. (2004). Measuring improvements in the disaster resilience of communities. *Earthquake Spectra*, *20*(3), 739–755.

Chuang, W. C., Garmestani, A., Eason, T. N., Spanbauer, T. L., Fried-Petersen, H. B., Roberts, C. P., . . . Allen, C. R. (2018). Enhancing quantitative approaches for assessing community resilience. *Journal of Environmental Management*, *213*, 353–362. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/29502020

Cimellaro, G. P. (2016). *Urban resilience for emergency response and recovery*. Switzerland: Springer.

Cimellaro, G. P., Reinhorn, A. M., & Bruneau, M. (2010). Framework for analytical quantification of disaster resilience. *Engineering Structures*, *32*(11), 3639–3649.

Cimellaro, G. P., Villa, O., Reinhorn, A. M., Bruneau, M., & Kim, H. U. (2012) Resilience-based design of natural gas pipelines. *Paper presented at the 15 WCEE*, Lisboa.

CIPedia. (2018). Resilience. Retrieved fromhttp://www.cipedia.eu.

Clarivate Analytics. (2018). Web of science. Retrieved from https://webofknowledge.com.

Cong, H., He, Y., Wang, X., & Jiang, C. (2018). Robust optimization for improving resilience of integrated energy systems with electricity and natural gas infrastructures. *Journal of Modern Power Systems and Clean Energy*, *6*(5), 1066–1078. doi:10.1007/s40565-018-0377-5

Connelly, E. B., Allen, C. R., Hatfield, K., Palma-Oliveira, J. M., Woods, D. D., & Linkov, I. (2017). Features of resilience. *Environment Systems and Decisions*, *37*(1), 46–50. doi:10.1007/s10669-017-9634-9

Coutu, D. L. (2002). How resilience works. *Harvard Business Review*, *80*(5), 46–56.

Couzin-Frankel, J. (2018). The roots of resilience: American Association for the Advancement of Science.

Cutter, S. L., Ahearn, J. A., Amadei, B., Crawford, P., Eide, E. A., Galloway, G. E., . . . Zoback, M. L. (2013). Disaster resilience: A national imperative. *Environment: Science and Policy for Sustainable Development*, *55*(2), 25–29.

Decò, A., Bocchini, P., & Frangopol, D. M. (2013). A probabilistic approach for the prediction of seismic resilience of bridges. *Earthquake Engineering & Structural Dynamics*, *42*(10), 1469–1487. Retrieved from https://onlinelibrary.wiley.com/doi/abs/10.1002/eqe.2282

Didier, M., Broccardo, M., Esposito, S., & Stojadinovic, B. (2017). A compositional demand/supply framework to quantify the resilience of civil infrastructure systems (Re-Codes). *Sustainable and Resilient Infrastructures* 3(2), 286–102.

Drexhage, J., & Murphy, D. (2010). Sustainable development: From Brundtland to Rio 2012. *Background paper prepared for consideration by the High Level Panel on Global Sustainability at its first meeting* 19 September 2010, New York: United Nations Headquarters.

Ellison, J. F., Corbet, T. F., & Brooks, R. E. (2013). *Natural gas network resiliency to a "ShakeOut scenario" earthquake,* Sandia National Laboratories, USA.

Erker, S., Stangl, R., & Stoeglehner, G. (2017). Resilience in the light of energy crises – Part I: A framework to conceptualise regional energy resilience. *Journal of Cleaner Production*, *164*, 420–433. doi:10.1016/j.jclepro.2017.06.163

Esposito, S., Giovinazzi, S., Elefante, L., & Iervolino, I. (2013). Performance of the L'Aquila (central Italy) gas distribution network in the 2009 (Mw 6.3) earthquake. *Bulletin of Earthquake Engineering*, *11*(6), 2447–2466.

European Network of Transmission System Operators for Electricity. (2015). *Report on Blackout in Turkey on 31st March 2015*. Retrieved from https://www.entsoe.eu/Documents/SOC%20documents/Regional_Groups_Continental_Europe/20150921_Black_Out_Report_v10_w.pdf

Fang, Y.-P., & Sansavini, G. (2018). Optimum post-disruption restoration under uncertainty for enhancing critical infrastructure resilience. *Reliability Engineering & System Safety*, *185*, 1–11. doi:10.1016/j.ress.2018.12.002

Feofilovs, M., & Romagnoli, F. (2017). Resilience of critical infrastructures: Probabilistic case study of a district heating pipeline network in municipality of Latvia. *Energy Procedia*, *128*, 17–23.

Fiksel, J. (2003). Designing resilient, sustainable systems. *Environmental Science & Technology*, *37*(23), 5330–5339.

Fiksel, J. (2006). Sustainability and resilience: Toward a systems approach. *Sustainability: Science, Practice, & Policy*, *2*(2), 14–21.

Filippini, R., & Silva, A. (2011). A modelling language for the resilience assessment of networked systems of systems. In Bérenguer, C., Grall, A., Guedes Soares, C. (Eds.), *Advances in Safety, Reliability and Risk Management: ESREL 2011*, London, UK: CRC Press, Taylor & Francis Group, 401.

Fisher, R., Bassett, G., Buehring, W., Collins, M., Dickinson, D., Eaton, L., … Lawlor, M. (2010). *Constructing a resilience index for the enhanced critical infrastructure protection program,*Argonne National Laboratory, USA.

Fletcher, D., & Sarkar, M. (2013). Psychological resilience. *European Psychologist*, *18*, 12–23.

Folke, C. (2006). Resilience: The emergence of a perspective for social–Ecological systems analyses. *Global Environmental Change*, *16*(3), 253–267. doi:10.1016/j.gloenvcha.2006.04.002

Forssén, K., Mäki, K., Räikkönen, M., & Molarius, R. (2017). Resilience of electricity distribution networks against extreme weather conditions. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering*, *3*(2), 021005–021009.

Fraccascia, L., Giannoccaro, I., & Albino, V (2018). Resilience of complex systems: State of the art and directions for future research. Complexity. doi:10.1155/2018/3421529

Francis, R., & Bekera, B. (2014). A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering & System Safety*, *121*, 90–103. Retrieved from http://www.sciencedirect.com/science/article/pii/S0951832013002147

Fraunhofer Institute. (2018). Resilience. Retrieved from https://publicwiki-01.fraunhofer.de/CIPedia/index.php/Resilience.

Furniss, D., Back, J., Blandford, A., Hildebrandt, M., & Broberg, H. (2011). A resilience markers framework for small teams. *Reliability Engineering & System Safety*, *96*(1), 2–10. doi:10.1016/j.ress.2010.06.025

Ganin, A. A., Massaro, E., Gutfraind, A., Steen, N., Keisler, J. M., Kott, A., … Linkov, I. (2016). Operational resilience: Concepts, design and analysis. *Scientific Reports*, *6*, 19540.

Garrick, B. J. (2008). *Quantifying and controlling catastrophic risks*. Academic Press.

Gasser, P., Lustenberger, P., Sun, T., Kim, W. Spada, M., Burgherr, P., Hirschberg, S., Stojadinović, B. (2017) Security of electricity supply indicators in a resilience context. IN: Cepin, M., Bris, R. (Eds.) Safety and Reliability - Theory and Applications. London, UK, CRC Press, Taylor & Francis Group. doi:10.1201/9781315210469 –130

Gillespie-Marthaler, L., Nelson, K. S., Baroud, H., Kosson, D. S., & Abkowitz, M. (2018). An integrative approach to conceptualizing sustainable resilience. *Sustainable and Resilient Infrastructure*, 1–16. doi:10.1080/23789689.2018.1497880

Givens, J. E., Padowski, J., Guzman, C. D., Malek, K., Witinok-Huber, R., Cosens, B., … Adam, J. (2018). Incorporating social system dynamics in the columbia river basin: Food-energy-water resilience and sustainability modeling in the Yakima River Basin. *Frontiers in Environmental Science 6*. doi:10.3389/fenvs.2018.00104

Gnansounou, E. (2008). Assessing the energy vulnerability: Case of industrialised countries. *Energy Policy*, *36*(10), 3734–3744.

Gong, Z., & Liang, D. (2017). A resilience framework for safety management of fossil fuel power plant. *Natural Hazards*, *89*(3), 1081–1095. doi:10.1007/s11069-017-3009-x

Google. (2018). Google Scholar. Retrieved from https://scholar.google.com.sg.

Guo, Y., Meng, X., Wang, D., Meng, T., Liu, S., & He, R. (2016). Comprehensive risk evaluation of long-distance oil and gas transportation pipelines using a fuzzy Petri net model. *Journal of Natural Gas Science and Engineering*, *33*, 18–29.

Haimes, Y. Y., Crowther, K., & Horowitz, B. M. (2008). Homeland security preparedness: Balancing protection with resilience in emergent systems. *Systems Engineering*, *11*(4), 287–308.

Häring, I., Sansavini, G., Bellini, E., Martyn, N., Kovalenko, T., Kitsak, M., … Barker, K. (2017). Towards a generic resilience management, quantification and development process: general definitions, requirements, methods, techniques and measures, and case studies. In *Resilience and risk* (pp. 21–80). Dordrecht: Springer.

Harto, C., Yan, Y., Demissie, Y., Elcock, D., Tidwell, V., Hallett, K., … Tesfa, T. (2012). *Analysis of drought impacts on electricity production in the Western and Texas interconnections of the United States,*Argonne National Laboratory, USA.

Hauser, P., Hobbie, H., & Möst, D. (2017). Resilience in the German natural gas network: Modelling approach for a high-resolution natural gas system. *2017 14th International Conference on the European Energy Market (EEM),*Dresden, Gemany.

He, P., Ng, T. S., & Su, B. (2017). Energy-economic recovery resilience with Input-Output linear programming models. *Energy Economics*, *68*, 177–191. doi:10.1016/j.eneco.2017.10.005

Heinimann, H. R. (2016). *A generic framework for resilience assessment resource guide on resilience*. Lausanne, Switzerland: EPFL International Risk Governance Center.

Heinimann, H. R., & Hatfield, K. (2017). Infrastructure resilience assessment, management and governance–state and perspectives. In *Resilience and risk* (pp. 147–187). Dordrecht: Springer.

Hernandez-Fajardo, I., & Dueñas-Osorio, L. (2013). Probabilistic study of cascading failures in complex interdependent lifeline systems. *Reliability Engineering & System Safety*, *111*, 260–272. Retrieved from http://www.sciencedirect.com/science/article/pii/S0951832012002153

Herzog, S. (2011). Revisiting the Estonian cyber attacks: Digital threats and multinational responses. *Journal of Strategic Security*, *4*, 49–60.

Hines, P., Blumsack, S., Sanchez, E. C., & Barrows, C. (2010). The topological and electrical structure of power grids. *2010 43rd Hawaii International Conference on System Sciences (HICSS),*Koloa, Kauai, Hawaii, USA.

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, *4*, 1–23.

Hollnagel, E., & Woods, D. D. (Eds.) . (2006). Epilogue: Resilience engineering precepts. In *Resilience engineering–concepts and precepts, ashgate, aldershot* (pp. 347–358), London: CRC Press. Retrieved from: https://doi.org/10.1201/9781315605685

Holmgren, Å. J. (2007). A framework for vulnerability assessment of electric power systems. In A. T. Murray and T. H.

Grubesic (Eds.), *Critical Infrastructure* (pp. 31–55). Springer.

Hosseini, S., Al Khaled, A., & Sarder, M. D. (2016a). A general framework for assessing system resilience using Bayesian networks: A case study of sulfuric acid manufacturer. *Journal of Manufacturing Systems*, *41*, 211–227. doi:10.1016/j.jmsy.2016.09.006

Hosseini, S., Barker, K., & Ramirez-Marquez, J. E. (2016b). A review of definitions and measures of system resilience. *Reliability Engineering & System Safety*, *145*, 47–61. Retrieved from http://www.sciencedirect.com/science/article/pii/S0951832015002483

Hughes, L., de Jong, M., & Wang, X. Q. (2016). A generic method for analyzing the risks to energy systems. *Applied Energy*, *180*, 895–908.

International Atomic Energy Agency. (2015). *The Fukushima Daiichi Accident,*Vienna, Austria: International Atomic Energy Agency.

International Organization for Standardization. (2017). Security and resilience – Organizational resilience – Principles and attributes.

Jackson, S. (2015). Overview of resilience and theme issue on the resilience of systems. *Insight*, *18*(1), 7–9. doi:http://dx.doi.org/10.1002/inst.12001

Jackson, S., & Ferris, T. L. (2013). Resilience principles for engineered systems. *Systems Engineering*, *16*(2), 152–164.

Ji, C., Wei, Y., Mei, H., Calzada, J., Carey, M., Church, S., … Wilcox, R. (2016). Large-scale data analysis of power grid resilience across multiple US service regions. *Nature Energy*, 1(5). doi:10.1038/nenergy.2016.52

Jia, G., Tabandeh, A., & Gardoni, P. (2017). Life-cycle analysis of engineering systems: Modeling deterioration, instantaneous reliability, and resilience. In *Risk and reliability analysis: Theory and applications* (pp. 465–494). Cham: Springer.

Jovanović, A., Klimek, P., Choudhary, A., Schmid, N., Linkov, I., Øien, K., … Székely, Z. (2016). Analysis of existing assessment resilience approaches, indicators and data sources.

Karimi, S., Shoushtar, R. S. Z., Balist, J., & Bigdeli, S. M. (2016). Pipeline risk assessment by using hazard risk assessment,(HAZOP) method (Case study: Gas transmission pipeline of savadkooh, Iran). *Environmental Science: An Indian Journal*, *12*(3), 104–111.

Keck, M., & Sakdapolrak, P. (2013). What is social resilience? Lessons learned and ways forward. *Erdkunde*, *67*, 5–19.

Keogh, M., & Cody, C. (2013). Resilience in regulated utilities. In *The national association of regulatory utility commissioners (NARUC)(November 2013)* (pp. 1–17), USA: The National Association of Regulatory Utility Commissioners.

Kim, D. H., Eisenberg, D. A., Chun, Y. H., & Park, J. (2017). Network topology and resilience analysis of South Korean power grid. *Physica A: Statistical Mechanics and Its Applications*, *465*, 13–24. doi:10.1016/j.physa.2016.08.002

Kyriakidis, M., Lustenberger, P., Burgherr, P., Dang, V. N., & Hirschberg, S. (2018a). Quantifying energy systems resilience - A simulation approach to assess recovery. *Energy Technology*, *6*, 1700–1706. doi:10.1002/ente.201700841

Kyriakidis, M., Lustenberger, P., Burgherr, P., Dang, V. N., & Hirschberg, S. (2018b). Quantifying energy systems resilience—A simulation approach to assess recovery. *Energy Technology*, *6*, 1700–1706. Retrieved from https://onlinelibrary.wiley.com/doi/abs/10.1002/ente.201700841

Labaka, L., Hernantes, J., & Sarriegi, J. M. (2015). Resilience framework for critical infrastructures: An empirical study in a nuclear plant. *Reliability Engineering & System Safety*, *141*, 92–105. Retrieved from http://www.sciencedirect.com/science/article/pii/S0951832015000678

Layton, L. (2004). Electric system reliability indices. *Retrieved May*, *11*, 2015.

Leung, P., & Hsu, G. J. (1984). An integrated energy planning model for Hawaii. *Energy Economics*, *6*(2), 117–121.

Li, B., Barker, K., & Sansavini, G. (2017). Measuring community and multi-industry impacts of cascading failures in power systems. *IEEE Systems Journal*, 1–12. doi:10.1109/jsyst.2017.2768603

Li, B., Roche, R., & Miraoui, A. (2016). System resilience improvement using multiple energy supply systems under natural disasters. *IECON 2016-42nd Annual Conference of the IEEE, Industrial Electronics Society*, Florence, Italy.

Liévanos, R. S., & Horne, C. (2017). Unequal resilience: The duration of electricity outages. *Energy Policy*, *108*, 201–211. doi:10.1016/j.enpol.2017.05.058

Linkov, I., Bridges, T., Creutzig, F., Decker, J., Fox-Lent, C., Kroger, W., … Thiel-Clemen, T. (2014). Changing the resilience paradigm. *Nature Climate Change*, *4*(6), 407–409. [Commentary]. doi:10.1038/nclimate2227

Linkov, I., & Palma-Oliveira, J. M. (2017). *Resilience and risk: Methods and application in environment, cyber and social domains*. Dordrecht, The Netherlands: Springer.

Lustenberger, P., Sun, T., Gasser, P., Kim, W., Spada, M., Burgherr, P., … Stojadinović, B. (2017) Potential impacts of selected natural hazards and technical failures on the natural gas transmission network in Europe. *Paper presented at the European Safety and Reliability Conference*, Portorož, Slovenia.

Luthar, S. S., Cicchetti, D., & Becker, B. (2000). The construct of resilience: A critical evaluation and guidelines for future work. *Child Development*, *71*(3), 543–562. doi:10.1111/1467-8624.00164

MacKenzie, C. A., & Barker, K. (2012). Empirical data and regression analysis for estimation of infrastructure resilience with application to electric power outages. *Journal of Infrastructure Systems*, *19*(1), 25–35.

MacKenzie, C. A., Baroud, H., & Barker, K. (2014). Static and dynamic resource allocation models for recovery of interdependent systems: Application to the Deepwater Horizon oil spill. *Annals of Operations Research*, *236*(1), 103–129. doi:10.1007/s10479-014-1696-1

Makarov, Y., & Moharari, N. (1999). *A generalized power system reliability and security index. IEEE Power Tech. Conference*, Budapest.

Marchese, D., Reynolds, E., Bates, M. E., Morgan, H., Clark, S. S., & Linkov, I. (2017). Resilience and sustainability: Similarities and differences in environmental management applications. *The Science of the Total Environment*, *613–614*, 1275–1283. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/28962075

Martin, R. (2012). Regional economic resilience, hysteresis and recessionary shocks. *Journal of Economic Geography*, *12*(1), 1–32.

Martinez-Anido, C. B., Bolado, R., De Vries, L., Fulli, G., Vandenbergh, M., & Masera, M. (2012). European power grid reliability indicators, what do they really tell? *Electric Power Systems Research*, *90*, 79–84.

Masten, A. S., Best, K. M., & Garmezy, N. (1990). Resilience and development: Contributions from the study of children who overcome adversity. *Development and Psychopathology*, *2*(04), 425–444.

McAslan, A. (2010). *The concept of resilience: Understanding its origins, meaning and utility*. Adelaide: Torrens Resilience Institute.

McCarthy, R. W., Ogden, J. M., & Sperling, D. (2007). Assessing reliability in energy supply systems. *Energy Policy*, *35*(4), 2151–2162.

McLellan, B., Zhang, Q., Farzaneh, H., Utama, N. A., & Ishihara, K. N. (2012). Resilience, sustainability and risk management: A focus on energy. *Challenges*, *3*(2), 153–182. doi:10.3390/challe3020153

McNally, A., Magee, D., & Wolf, A. T. (2009). Hydropower and sustainability: Resilience and vulnerability in China's powersheds. *Journal of Environmental Management*, *90* (Suppl 3), S286–293. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/19013007

Molyneaux, L., Brown, C., Wagner, L., & Foster, J. (2016). Measuring resilience in energy systems: Insights from a range of disciplines. *Renewable and Sustainable Energy Reviews*, *59*, 1068–1079. doi:10.1016/j.rser.2016.01.063

Molyneaux, L., Wagner, L., Froome, C., & Foster, J. (2012). Resilience and electricity systems: A comparative analysis. *Energy Policy*, *47*, 188–201.

Montoya, G. A. (2010). *Assessing resilience in power grids as a particular case of supply chain management,*USA: Department of the Air Force Air University.

Morshedlou, N. (2018). *Adaptive and restorative capacity planning for complex infrastructure networks: Optimization algorithms and applications* PhD Thesis. Univesity of Oklahoma.

Moslehi, S., & Reddy, T. A. (2018). Sustainability of integrated energy systems: A performance-based resilience assessment methodology. *Applied Energy*, *228*, 487–498. doi:10.1016/j.apenergy.2018.06.075

Mu, D., Seager, T. P., Rao, P. S. C., Park, J., & Zhao, F. (2011). A resilience perspective on biofuel production. *Integrated Environmental Assessment and Management*, *7* (3), 348–359.

Murray, R. M., Day, J. C., Ingham, M. D., Reder, L. J., & Williams, B. C. (2013). *Engineering resilient space systems*. Pasadena, CA. http://www.kiss.caltech.edu/study/systems/

Nadeau, J. (2007). *Improving the resiliency of the natural gas supply and distribution network*. USA: DTIC Document.

Nan, C., Eusgeld, I., & Kröger, W. (2013). Analyzing vulnerabilities between SCADA system and SUC due to interdependencies. *Reliability Engineering & System Safety*, *113*, 76–93. Retrieved from http://www.sciencedirect.com/science/article/pii/S0951832013000033

Nan, C., & Sansavini, G. (2017). A quantitative method for assessing resilience of interdependent infrastructures. *Reliability Engineering & System Safetydoi*, *157*, 35–53. Retrieved from http://www.sciencedirect.com/science/article/pii/S095183201630374X

National Academy of Sciences. (2012). *Disaster resilience: A national imperative*. Washington, D.C.: The National Acadamies Press.

National Infrastructure Advisory Council. (2009). Critical infrastructure resilience: Final report and recommendations: *National Infrastructure Advisory Council.*

Nezamoddini, N., Mousavian, S., & Erol-Kantarci, M. (2017). A risk optimization model for enhanced power grid resilience against physical attacks. *Electric Power Systems Research*, *143*, 329–338. Retrieved from http://www.sciencedirect.com/science/article/pii/S0378779616303546

Norris, F. H., Stevens, S. P., Pfefferbaum, B., Wyche, K. F., & Pfefferbaum, R. L. (2008). Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. *American Journal of Community Psychology*, *41* (1), 127–150. doi:10.1007/s10464-007-9156-6

O'Brien, G., & Hope, A. (2010). Localism and energy: Negotiating approaches to embedding resilience in energy systems. *Energy Policy*, *38*(12), 7550–7558. Retrieved from http://www.sciencedirect.com/science/article/pii/S0301421510001965

Olshansky, R. B., Hopkins, L. D., & Johnson, L. A. (2012). Disaster and recovery: Processes compressed in time. *Natural Hazards Review*, *13*(3), 173–178. Retrieved from https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29NH.1527-6996.0000077

Ouyang, M. (2014). Review on modeling and simulation of interdependent critical infrastructure systems. *Reliability Engineering & System Safety*, *121*, 43–60.

Ouyang, M., & Dueñas-Osorio, L. (2014). Multi-dimensional hurricane resilience assessment of electric power systems. *Structural Safety*, *48*, 15–24. doi:10.1016/j.strusafe.2014.01.001

Ouyang, M., Dueñas-Osorio, L., & Min, X. (2012). A three-stage resilience analysis framework for urban infrastructure systems. *Structural Safety*, *36*, 23–31.

Ouyang, M., Hong, L., Mao, Z.-J., Yu, M.-H., & Qi, F. (2009). A methodological approach to analyze vulnerability of interdependent infrastructures. *Simulation Modelling Practice and Theory*, *17*(5), 817–828. Retrieved from http://www.sciencedirect.com/science/article/pii/S1569190X0900015X

Oxford Dictionaries. (2018a). Resilience. Retrieved from https://en.oxforddictionaries.com/definition/resilience.

Oxford Dictionaries. (2018b). Sustainability. Retrieved from https://en.oxforddictionaries.com/definition/sustainability.

Pant, R., Barker, K., Ramirez-Marquez, J. E., & Rocco, C. M. (2014). Stochastic measures of resilience and their application to container terminals. *Computers & Industrial Engineering*, *70*, 183–194.

Panteli, M., & Mancarella, P. (2015). The grid: Stronger, bigger, smarter?: Presenting a conceptual framework of power system resilience. *IEEE Power and Energy Magazine*, *13*(3), 58–66.

Panteli, M., Mancarella, P., Trakas, D., Kyriakides, E., & Hatziargyriou, N. (2017). Metrics and quantification of operational and infrastructure resilience in power systems. *IEEE Transactions on Power Systems*, *32*(6), 4732–4742.

Park, J., Seager, T. P., & Rao, P. S. C. (2011). Lessons in risk-versus resilience-based design and management.

*Integrated Environmental Assessment and Management*, *7*(3), 396–399.

Pliousis, A., Andriosopoulos, K., Doumpos, M., & Galariotis, E. (2019). A multicriteria assessment approach to the energy trilemma. *The Energy Journal*, *40*(01). doi:10.5547/01956574.40.SI1.apli

Poljansek, K., Bono, F., & Gutiérrez, E. (2010). *GIS-based method to assess seismic vulnerability of interconnected infrastructure: A case of EU gas and electricity networks*. Publications Office of the European Union JRC No. JRC57064, Italy.

Redman, C. L. (2014). Should sustainability and resilience be combined or remain distinct pursuits? *Ecology and Society*, *19*(2). doi:10.5751/es-06390-190237

Reed, D. A., Kapur, K. C., & Christie, R. D. (2009). Methodology for assessing the resilience of networked infrastructure. *IEEE Systems Journal*, *3*(2), 174–180. doi:10.1109/JSYST.2009.2017396

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine*, pp. 11–25.

Rocchetta, R., Zio, E., & Patelli, E. (2018). A power-flow emulator approach for resilience assessment of repairable power grids subject to weather-induced failures and data deficiency. *Applied Energy*, *210*, 339–350. doi:10.1016/j.apenergy.2017.10.126

Rochas, C., Kuzņecova, T., & Romagnoli, F. (2015). The concept of the system resilience within the infrastructure dimension: Application to a Latvian case. *Journal of Cleaner Production*, *88*, 358–368. doi:10.1016/j.jclepro.2014.04.081

Rose, A. (2004). Defining and measuring economic resilience to disasters. *Disaster Prevention and Management: an International Journal*, *13*(4), 307–314.

Rose, A. (2007). Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions. *Environmental Hazards*, *7*(4), 383–398.

Rose, A., Benavides, J., Chang, S. E., Szczesniak, P., & Lim, D. (1997). The regional economic impact of an earthquake: Direct and indirect effects of electricity lifeline disruptions. *Journal of Regional Science*, *37*(3), 437–458.

Rose, A., Oladosu, G., & Liao, S. Y. (2007). Business interruption impacts of a terrorist attack on the electric power system of Los Angeles: Customer resilience to a total blackout. *Risk Analysis*, *27*(3), 513–531.

Rose, S., Jaramillo, P., Small, M. J., Grossmann, I., & Apt, J. (2012). Quantifying the hurricane risk to offshore wind turbines. *Proceedings of the National Academy of Sciences*, *109*(9), 3247–3252.

Rus, K., Kilar, V., & Koren, D. (2018). Resilience assessment of complex urban systems to natural disasters: A new literature review. *International Journal of Disaster Risk Reduction*, *31*, 311–330. doi:10.1016/j.ijdrr.2018.05.015

Sanchez, A. X., Osmond, P., & van der Heijden, J. (2017). Are some forms of resilience more sustainable than others? *Procedia Engineering*, *180*, 881–889. doi:10.1016/j.proeng.2017.04.249

Sanchez, A. X., van der Heijden, J., Osmond, P., & Prasad, D. (2016). Urban sustainable resilience values: Driving resilience policy that endures. *Creating Built Environments of New Opportunities*, *1*, 53.

Sanchez, X. A., van der Heijden, J., & Osmond, P. (2018). The city politics of an urban age: Urban resilience conceptualisations and policies. *Palgrave Communications*, *4*(1), p 25. doi:10.1057/s41599-018-0074-z

Sato, M., Kharrazi, A., Nakayama, H., Kraines, S., & Yarime, M. (2017). Quantifying the supplier-portfolio diversity of embodied energy: Strategic implications for strengthening energy resilience. *Energy Policy*, *105*, 41–52. doi:10.1016/j.enpol.2017.02.024

Schiel, C., Lind, P. G., & Maass, P. (2017). Resilience of electricity grids against transmission line overloads under wind power injection at different nodes. *Scientific Reports*, *7*(1), 11562. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/28912454

Sharifi, A., & Yamagata, Y. (2016). Principles and criteria for assessing urban energy resilience: A literature review. *Renewable and Sustainable Energy Reviews*, *60*, 1654–1677. doi:10.1016/j.rser.2016.03.028

Sharma, N., Tabandeh, A., & Gardoni, P. (2018). Resilience analysis: A mathematical formulation to model resilience of engineering systems. *Sustainable and Resilient Infrastructure*, *3*(2), 49–67.

Sheffi, Yossi. (2005). *The Resilient Enterprise: Overcoming vulnerability for competitive advantage*. MIT Press Books, edition 1, volume 1, number 0262693496, January..

Shen, L., & Tang, L. (2015). *A resilience assessment framework for critical infrastructure systems. First International Conference on Reliability Systems Engineering (ICRSE)*, Beijing, China *2015*.

Shinozuka, M., Chang, S. E., Cheng, T.-C., Feng, M., O'rourke, T. D., Saadeghvaziri, M. A., … Shi, P. (2004). Resilience of integrated power and water systems. In Jane E. Stoyle (Ed.). *Research Progress and Accomplishments 2003–2004* (pp. 65–86).

Shirali, G., Mohammadfam, I., Motamedzade, M., Ebrahimipour, V., & Moghimbeigi, A. (2012). Assessing resilience engineering based on safety culture and managerial factors. *Process Safety Progress*, *31*(1), 17–18.

Singapore-ETH Centre. (2015). *Future Resilient Systems (FRS) booklet* (2nd ed.), Singapore: Singapore-ETH Centre.

Sircar, I., Sage, D., Goodier, C., Fussey, P., & Dainty, A. (2013). Constructing Resilient Futures: Integrating UK multi-stakeholder transport and energy resilience for 2050. *Futures*, *49*, 49–63. doi:10.1016/j.futures.2013.04.003

Su, H., Zhang, J., Zio, E., Yang, N., Li, X., & Zhang, Z. (2017). An integrated systemic method for supply reliability assessment of natural gas pipeline networks. *Applied Energy*. doi:10.1016/j.apenergy.2017.10.108

Su, H., Zio, E., Zhang, J., & Li, X. (2018). A systematic framework of vulnerability analysis of a natural gas pipeline network. *Reliability Engineering & System Safety*, *175*, 79–91. doi:10.1016/j.ress.2018.03.006

Summers, J. K., Smith, L. M., Harwell, L. C., & Buck, K. D. (2017). Conceptualizing holistic community resilience to climate events: Foundation for a climate resilience screening index. *Geohealth*, *1*(4), 151–164. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/30148246

Sun, L., Didier, M., & Stojadinovic, B. (2015) *Study of seismic recovery and resilience of electric power supply system. Paper presented at the Safety and Reliability of Complex Engineered Systems*. doi:10.1201/b19094-576

Tan, R. R. (2011). A general source-sink model with inoperability constraints for robust energy sector planning. *Applied Energy*, *88*(11), 3759–3764. doi:10.1016/j.apenergy.2011.04.016

Tang, Yong, & . (2012). "Analysis and lessons of the blackout in indian power grid on July 30 and 31, 2012". Zhongguo Dianji Gongcheng Xuebao (Proceedings of the Chinese Society of Electrical Engineering). Vol. *32*. No. 25. Chinese Society for Electrical Engineering.

Taylor, J. B. (2009). *The financial crisis and the policy responses: An empirical analysis of what went wrong*, Canada: Bank of Canada.

The Rockefeller Foundation. (2013). *Rebound: Building a more resilient world,*USA: The Rockefeller Foundation.

Thorisson, H., Lambert, J. H., Cardenas, J. J., & Linkov, I. (2017). Resilience analytics with application to power grid of a developing region. *Risk Analysis : an Official Publication of the Society for Risk Analysis*, *37*(7), 1268–1286. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/27689783

Tredgold, T. (1818). *On the transverse strength and resilience of timber*. The Philosophical Magazine, 51:239, 214–216, doi:10.1080/14786441808637536.

Tsang, J. L., Lambert, J. H., & Patev, R. C. (2002). Extreme event scenarios for planning of infrastructure projects. *Journal of Infrastructure Systems*, *8*(2), 42–48.

UN General Assembly. (2015). The sendai framework for disaster risk reduction 2015–2030.

Urciuoli, L., Mohanty, S., Hintsa, J., & Gerine Boekesteijn, E. (2014). The resilience of energy supply chains: A multiple case study approach on oil and gas supply chains to Europe. *Supply Chain Management: An International Journal*, *19*(1), 46–63. doi:10.1108/scm-09-2012-0307

van Eck, N. J., & Waltman, L. (2014). Visualizing bibliometric networks. In *Measuring scholarly impact* (pp. 285–320). Cham: Springer.

Veeramany, A., Coles, G. A., Unwin, S. D., Nguyen, T. B., & Dagle, J. E. (2017). Trial implementation of a multihazard risk assessment framework for high-impact low-frequency power grid events. *IEEE Systems Journal*, 1–9. doi:10.1109/jsyst.2017.2737993

Vogus, T. J., & Sutcliffe, K. M. 2007, 7–10 Oct. *Organizational resilience: Towards a theory and research agenda. 2007 IEEE International Conference on Systems, Man and Cybernetics,*Montréal, Canada.

Vugrin, E. D., Warren, D. E., & Ehlen, M. A. (2011). A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane. *Process Safety Progress*, *30*(3), 280–290.

Vugrin, E. D., Warren, D. E., Ehlen, M. A., & Camphouse, R. C. (2010). A framework for assessing the resilience of infrastructure and economic systems. In *Sustainable and resilient critical infrastructure systems* (pp. 77–116). Berlin, Heidelberg: Springer.

Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., … Pritchard, R. (2002). Resilience management in social-ecological systems: A working hypothesis for a participatory approach. *Conservation Ecology*, *6*(1). Retrieved from http://www.consecol.org/vol6/iss1/art14

Waltman, L., van Eck, N. J., & Noyons, E. C. M. (2010). A unified approach to mapping and clustering of bibliometric networks. *Journal of Informetrics*, *4*(4), 629–635. doi:10.1016/j.joi.2010.07.002

Wang, M., Zhao, Y., & Zhang, B. (2015). Efficient test and visualization of multi-set intersections. *Scientific Reports*, *5*, 16923.

Wang, Z., Nistor, M. S., & Pickl, S. W. (2017). Analysis of the definitions of resilience. *IFAC-PapersOnLine*, *50*(1), 10649–10657.

Willis, H. H., & Loa, K. (2015). *Measuring the resilience of energy distribution systems*. Santa Monica: RAND Corporation.

Xu, L., & Kajikawa, Y. (2017). An integrated framework for resilience research: A systematic review based on citation network analysis. *Sciencedoi Sustainability*. doi:10.1007/s11625-017-0487-4

Xu, N., Guikema, S. D., Davidson, R. A., Nozick, L. K., Çağnan, Z., & Vaziri, K. (2007). Optimizing scheduling of post-earthquake electric power restoration tasks. *Earthquake Engineering & Structural Dynamics*, *36*(2), 265–284.

Zio, E. (2016). Critical infrastructures vulnerability and risk analysis. *European Journal for Security Research*, *1*(2), 97–114. doi:10.1007/s41125-016-0004-2

Zio, E., & Aven, T. (2013). Industrial disasters: Extreme events, extremely rare. Some reflections on the treatment of uncertainties in the assessment of the associated risks. *Process Safety and Environmental Protection*, *91* (1–2), 31–45. Retrieved from http://www.sciencedirect.com/science/article/pii/S0957582012000055