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Adapting the theory of resilience to energy systems: a review and outlook

Bernhard-Johannes Jesse*, Heidi Ursula Heinrichs and Wilhelm Kuckshinrichs

Abstract

Sustainable systems must maintain their function even in the event of disruptions in order to be considered truly sustainable. The theory of resilience concerns the behavior of systems during and aftershocks. Initially, modern understanding of resilience focused on ecological systems; however, the theory was extended to include the ecological aspects and the also social aspects of a system. As a result of climate change, increased efforts have been made to ensure energy systems are more sustainable. The issue of resilience has therefore significantly gained importance of late to energy systems. In the future, modern energy systems will be increasingly exposed to disruptions, whether due to climate change, terrorism, or variable power supply from renewable energy sources. Protecting energy systems from all these threats is only possible at great cost, but it is much more sensible to design resilient systems that can quickly resume their system function after a disturbance. This review looks at research into the resilience and its application to energy systems and identifies similarities and differences. Starting with Holling's contribution to resilience, the development of the theory is examined and the different definitions are compared. The differences between engineering and ecological resilience are also discussed. Additionally, the review examines, on the one hand, criticism of the theory of resilience and, on the other hand, remaining questions in relation to the application of resilience, such as the system's state after the disruption. The paper subsequently examines the application of the theory of resilience to different energy systems. The review concludes with an outlook on the possibility of operationalizing resilience for energy systems.

Keywords: Resilience, Energy system, Transformability, Adaptability, Vulnerability, Transition

Introduction

The Earth's climate is strongly influenced by greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, which are increasingly being emitted as a result of human activities [1]. The higher concentration corresponds to an increase in the global temperature. Climate scenarios predict a significant change to the climate, severe consequences for the Earth's ecosystem and new challenges for mankind [1]. To date, 178 of the 197 parties have ratified the Paris Agreement [2], in which they agreed to keep the global temperature rise below 2° C above pre-industrial levels [3]. The European Union wants to reduce greenhouse gas emissions in the short-term by 40% and in the long-term (the year 2050) by 80–95% [4, 5]. To achieve these targets, a complex and long-term transition towards an energy system based on renewable energy and high energy efficiency seems necessary [6]. However, this transition is one of the major challenges of the twenty-first century [7]. In order to ensure a successful transformation, the continuous function of energy systems along the transition path is crucial [8]. In other words, the system must be resistant to disruptions throughout the transformation. However, it does not seem reasonable to plan an energy system that can withstand any kind of disturbance [9], because, in the future, the number of sources of possible disturbances is likely to increase. Rather, it makes sense to plan a system which can quickly restore its function after a disturbance. Therefore, resilience becomes more important for modern energy systems. The theory of resilience is one way of describing a system's ability to cope with changing circumstances or disruptions. The theory helps to provide an understanding of whether a system can return to an equilibrium state after disruption or how a system must be transformed into a new desirable system if the change is irreversible. The notion of resilience in systems analysis can be traced back to Holling's

* Correspondence: b.jesse@fz-juelich.de
Institute of Energy and Climate Research - Systems Analysis and Technology Evaluation (IEK-STE), Forschungszentrum Jülich, Wilhelm-Johnen-Straße, 52425 Jülich, Germany

paper "Resilience and stability of ecological systems" in 1973 [10]. Today, the theory can be found in many different fields, especially psychology, ecology, and social sciences, and is being applied to the analysis of energy systems. Despite the common usage of the concept of resilience for different system types, there is no universally accepted definition of resilience.

An initial indicator of the increasing popularity of resilience in a wide range of different research fields is the number of published papers concerning resilience. Figure 1 reveals the total number of papers concerning resilience and the number of papers in relation to the total number of papers published per year. This was analyzed within the scientific databases "Web of Science" [11] and "ScienceDirect" [12] for papers containing the word "resilience" in the title, keywords, or abstract.

This rise in popularity can be explained by looking at the advantages of the theory of resilience. According to Cascio [13], resilience theory "[…] accepts that change is inevitable and in many cases out of our hands, focusing instead on the need to be able to withstand the unexpected." The theory acknowledges vulnerability and aims to produce crisis-proof systems rather than of invincible systems [9]. Another reason for the widespread use of the resilience theory is that it is concerned with systems and shocks to the system, a combination that can be found in a wide range of disciplines [14]. Furthermore, the relatively intuitive meaning of resilience allows it to be used by people from different research backgrounds [15]. However, this can also have a negative effect on quantitative model-based analyses.

This paper reviews the notion of resilience in the past few decades and presents some differences and similarities in the terms of the various applications of the resilience theory. Resilience is particularly suitable for energy systems and their transformation, since they are in a state of constant change and often have to cope with external influences. To the authors' knowledge, there are no review yet on the application of the theory of resilience in energy systems. The aim of this paper is to provide an overview of the different types of resilience and how they have been used so far. This should help researchers, who are new to the topic of resilience, to apply the theory in their work by ascertaining whether resilience is suitable for their research and, if so, which type of resilience should be selected. In addition, this paper provides researchers already using the theory of resilience with the opportunity to compare their work with other uses of the theory.

The paper starts with a description of the methods used for the literature review (cf. the "Review method" section). The "Brief summary on the history of resilience" section recaps the development of the theory of resilience to help in understanding its origin. The "Introduction to the modern theory of resilience" section continues with a brief introduction of the theory of resilience in systems analysis and an overview off different definitions and multiple ways of classifying various applications of the resilience theory. The "Criticism of the theory of resilience and unanswered questions" section begins with a critical focus on the theory and concludes with questions regarding resilience theory that have yet to be conclusively answered. While the previous chapters focus on resilience in a generalized context, the "Resilience for energy systems" section discusses how the theory of resilience can be used for energy systems.

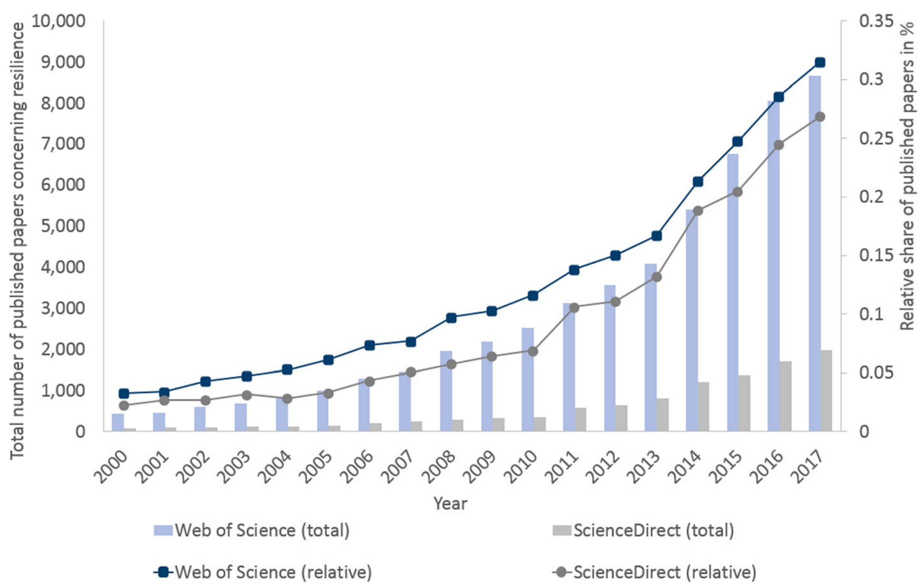

Fig. 1 Number of publications on resilience

The sections "Engineering resilience for energy systems" to "Other uses of resilience for energy systems" section discuss examples of different types of resilience. The "Unanswered questions to the resilience of energy systems" section deals with criticism and questions concerning the theory for energy systems. The paper ends with a conclusion and outlook, looking at how the resilience theory can be operationalized in the analysis of energy systems.

Review method

This section discusses the framework used to identify resilience-related literature. The review-process followed two different approaches: (i) a qualitative review of research based on Holling's paper "Resilience and stability of ecological systems" and (ii) an online database searching.

For the first approach, Holling's fundamental work was examined. Based on his paper "Resilience and stability of ecological systems" and his observation that living systems have multiple stable states, referred to as a "basin of attractions" [10], resilience thinking emerged and has since developed into an approach for understanding complex adaptive systems (CASs) [16]. Complex adaptive systems are characterized by critical thresholds, multiple drivers of change, and reciprocal feedbacks between social and ecological actors [17]. Since there is general agreement that Holling's interpretation of resilience has had a significant influence on the modern understanding of resilience [18], his other work was examined for this review as part of the first approach. Holling continued to publish work on resilience while also helping to found the Resilience Network, a program dedicated to engaging resilience thinkers that was responsible for a lot of work on resilience [19]. In 1999, the Resilience Network became the Resilience Alliance [19], with the latter seeing itself as an international science network and think tank for resilience and social-ecological systems [20]. The organization is also responsible for the journal "Ecology and Society", which has published an impressive number of papers on resilience and the development of resilience thinking. The journal thus forms part of the first research method and serves as a source for some important reviewed papers, such as the paper on the relationship between resilience, adaptability, and transformability written by Walker et al. [21], which is one of the most cited papers in "Ecology and Society" [22].

As a second source for scientific works on resilience, different online database were searched, mainly "Web of Science" [11] and "ScienceDirect" [12]. The list of keywords used and their link to the term resilience can be found in Table 1. The numbers shown in the table originate from a search of the respective keyword in combination with the term resilience. In contrast to the numbers from Fig. 1, the values here are not restricted to a specific year but include all entries from the database regardless of year. The large discrepancy between the exclusive search for the term resilience and the search for the combinations is due to the fact that the keywords primarily refer to ecological resilience. However, resilience is also used differently in other scientific areas.

Table 1 Keywords for research

Keyword	Link to resilience	No. of papers found on [11]
Resilience		57,629
Transformability	Part of the resilience theory	181
Transition	Addition to transformability	2325
Adaptability	Part of the resilience theory	823
Vulnerability	Possible opposite	6291
Resilience assessment	Possible ways of assessing resilience	4926
Resilience index	Possible way of quantifying resilience	2864
Social-ecological system	Original type of systems used with resilience	1938
Socio-technical system	Subject of interest	102
Energy system	Subject of interest	1392

There was an initial focus on basic information regarding the term resilience itself and in which scientific domains it was used. After an initial analysis of the available papers, the focus shifted to papers that used resilience to analyze systems. Furthermore, using the abovementioned keywords, the search was refined to include the papers most relevant to energy systems and energy infrastructure. This approach was applied to papers published since 2000 in order to focus primarily on recent efforts. The number of available publication was thus reduced significantly by these restrictions. In total, about 100 papers, articles, reports, and book chapters, concerning the resilience theory for energy systems, all of which had been published since 2000, were collected and reviewed.

The development of the theory of resilience

This section begins with a brief outline of the history of resilience, followed by a short introduction to the theory of resilience after Holling. This aims to help in providing an understanding as to why many different interpretations of resilience exist in the papers studied. The second half of the section shows which methods can be used to classify these applications of resilience. The "Resilience as a concept or quantity" section discusses whether the papers looked at the use of resilience as an ambiguous concept or as a measurable quantity.

Brief summary on the history of resilience

The term resilience originates from the Latin word *resilire*, which translates as "to spring back" [23] or "to bounce back" [24], and can be found in a multitude of different research areas. On the one hand, the term resilience is used in materials science, where it is defined as "[…] the ability of a metal to absorb energy when elastically deformed and then to return it when it is unloaded [25]." The deformation must be elastic, meaning that the metal returns to its initial state. In contrast to resilience, toughness describes the ability of a metal to absorb energy in the plastic range [25]. Resilience is unique in its ability to return to the initial state. Mentions of resilience in materials science date back as far as the nineteenth century (cf. [26]).

On the other hand, the term resilience was picked up on by psychologists in the 1950s [27]. In psychology, resilience describes the capacity of individuals to withstand crises and to strengthen personal resistance through adaption [28]. Unlike the understanding of resilience in materials science, this understanding does not require the subject of interest to return to its initial state, but instead focuses on adaption and an increase in resistance. However, both definitions concern some kind of deflection to the initial state of the subject of interest.

In 1973, Holling made a major contribution to the notion of resilience in social-ecological science. On the basis of observations, he discovered that social-ecological systems can have more than one equilibrium state, a discovery that was published in his paper entitled "Resilience and Stability of Ecological Systems" [10]. His proposal that there might be more than one steady state was revolutionary, since the prevailing understanding at this time was that there was only one stable state for social-ecological systems and that the system would always return to this state [19].

Since then, the theory of resilience has been further developed and adapted by a wide variety of different research areas. Today, the resilience theory can be found in various scientific communities such as urban planning, where it can be used to safeguard traditional districts against future threats of climate change (cf. [29]). Other examples of the theory of resilience can be found for technical systems (cf. [30]), computational networks (cf. [31]), economics (cf. [32]), or disaster management (cf. [33]). This versatile nature of the theory can be seen as an advantage, since it can be used in a wide variety of disciplines. However, there is also an argument that the increased usage has led to a certain loss of meaning for the term resilience, due to its unspecific use in political discourse and the media [34].

Introduction to the modern theory of resilience

An early definition of resilience for systems can be found in Holling's paper "Resilience and stability of ecological systems" [10]: "Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist."

Holling's research on resilience helped him become one of the founding fathers of the modern understanding of resilience for social-ecological systems [19]. He used a stability landscape to illustrate his discovery that social-ecological systems have more than one equilibrium state. Not all of these states are stable and the system does not usually remain in one position, but rather orbits around a stable state. Holling refers to the domain close to a steady state, which is still favorable, as a "basin of attractions" [10].

A good graphical representation of the stability landscape and its basin of attraction was produced by Walker et al. [35]. They use a ball to represent the system, while the stability landscape is illustrated by a plane and the basin of attractions by sinks in the plane. However, this simplified image only visualizes the concept and is not used quantitatively. Figure 2 presents an example of a system in a stability landscape with multiple basins of attraction. This illustration helps in providing a better understanding of resilience for a system with multiple basins of attractions.

Since the theory of resilience after Holling assumes a dynamic equilibrium, a stable system does not rest at the lowest point of a basin of attraction. Instead, the system is in motion and is considered stable as long as it does not leave the basin of attraction. If the system moves in a direction from which it cannot return to the basin of attraction, it is considered unstable. Due to the constant movement, the theory does not define labile equilibrium.

Holling differentiates between two different types of resilience to take the existing understating of resilience into account. The first type is based on the understanding of resilience in materials science and is called "engineering resilience". Engineering resilience describes the ability of a system, close to a stable point, to return quickly to this stable point after a shock [36]. The main focus of engineering resilience is on the state of balance to which it will return after having recovered from a

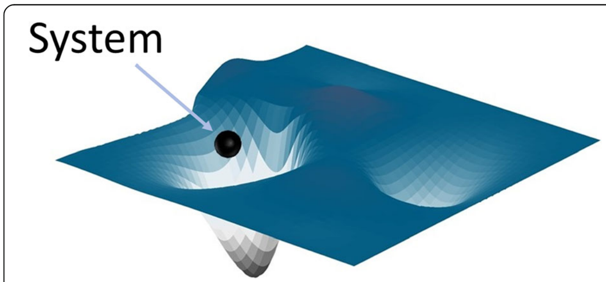

Fig. 2 Example of a system and the stability landscape (based on [35])

shock [34]. It can also be interpreted as the system's robustness or resistance [37]. Molyneaux et al. [38] define engineering resilience as the time a system needs to return to a steady state within a stable domain after a deviation. It is usually observed in systems that function locally around small perturbations. In the stability landscape, engineering resilience is typically illustrated by only one valley and the system is located close to the single equilibrium [39]. Engineering resilience usually focuses on efficiency and consistency and is used to describe systems whose behavior is predictable [40]. This kind of resilience and its properties stand in contrast to Holling's definition, in which he refers to a second type of resilience.

The second type of resilience is known as "ecological resilience" and describes the resilience of complex adaptive systems (CASs) [41]. CASs are systems with a large number of components or agents, which are able to learn or adapt [42]. Ecological resilience accepts the unpredictability of systems and emphasizes its ability to absorb disturbances to the function of the system as the focus of resilience [37]. Unlike engineering resilience, in the ecological resilience approach, the system returns to one of the multiple possible equilibrium states [37]. Ecological resilience also assumes that the system is dynamical, which is illustrated by the changing position of the ball in the basin of attraction in the stability landscape. The simple image of the stability landscape is misleading, since it does not take account of the fact that boundary conditions can change [39]. In reality, the landscape and the lowest point of the basin changes, which makes the system move around in the basin of attraction. For Molyneaux et al. [38], ecological resilience even concludes the ability of the system to reorganize through unstable domains to a new equilibrium state.

Besides these two different types of resilience, some authors refer to a third understanding of resilience, the so-called adaptive resilience (cf. [34, 37, 43]). For them, adaptive resilience is about how a system adapts to stress [44]. Adaptive resilience accepts the unpredictability and dynamics of a system such as CAS, and its focus lies on the system's ability to learn and self-organize [37]. A system with adaptive resilience does not return to its "normal" state but rather changes to an adjusted stable state [43]. Table 2 sums up the differences between engineering resilience, ecological resilience, and adaptive resilience.

Holling's work is considered to be the origin of the modern understanding of resilience for systems and their ability to change. According to Walker et al. [35], there are two ways in which a system can react to such changes. The system either adapts to the new circumstances or, if the current system is no longer sustainable and cannot adapt, it has to transform. The way in which a system reacts depends on its *adaptability* and *transformability*. Walker et al. [35] define adaptability as "[…] the capacity of actors in a system to influence resilience." In other words, a system with a high adaptability is able to cope with changes and adapt to new circumstances. Transformability is defined by them as "[…] the capacity to create a fundamentally new system when ecological, economic, or social (including political) conditions make the existing system untenable [35]." Systems with high adaptability focus on adjusting the system while preserving its basic characteristics, whereas systems with high transformability will change function and systemic logic by creating new mechanisms to respond to a disruption [18]. For example, in an energy system, actions based on adaptability could change individual energy sources, while the transition from a central fossil-based energy system to a decentralized renewable-based energy system requires high transformability [18]. The definitions of adaptability and transformability and their interconnections are as vague as the definition of resilience itself [18], as they do not define any measuring methods or concrete actions. Some refer to the adaptability of a system as adaptive capacity and to transformability as transformative capacity (cf. [9, 15]).

Hanisch [9] adds the coping capacity to the concept of the adaptive and transformative capacity in order to describe the ability of a system to resist disturbances without much alteration to the system, if adaptive capacity is not necessary. The same division into the three dimensions of adaptive capacity, transformative capacity, and coping capacity is made by Keck and Sakdapolrak [45].

In addition to these three capacity types, Walker et al. [35] present latitude, resistance, precariousness, and panarchy as four different parameters to describe the resilience of a system. Figure 3 shows a graphical representation of latitude (L), resistance (R), and precariousness (Pr).

According to Walker et al. [35], the latitude (L) describes the maximum amount the system can be changed before losing its ability to recover to a favorable state and is represented by the width of the basin of attraction. Resistance (R) is the ease or difficulty of changing the system, which is illustrated by the depth of the basin. Latitude and resistance are defined by the properties of the basin, whereas precariousness (Pr) is based on the current trajectory of the system and corresponds to the distance between the system and the threshold, which is the edge of the basin. However, since these values refer to a dynamic system, the values only present a snapshot of the current state. Finally, panarchy (Pa) defines how the three aspects above are influenced by systems at scales above or subsystems below the scale of interest [35]. Unlike adaptability and transformability, which can be found in various literature concerning resilience (cf. [9, 16, 18, 29, 38, 46–52]), the four

Table 2 Overview of engineering and ecological resilience

Type of resilience	Type of capacity	System's behavior	In stability landscape	Type of system
Engineering resilience		Close to stable point	Quick return to stable point	Predictable quasi-stationary system
Ecological resilience		Moves out of basin of attraction	Returns to one of multiple equilibrium states	Complex adaptive system
	Adaptive capacity/ adaptability	Adjusts the system	Towards new equilibrium state	
	Transformative capacity/ transformability	Transforms the system	New system and state	
	Coping capacity	Resists disturbance w/o much alteration of the system	Return to old equilibrium state	
Adaptive resilience		System learns and self-organizes	Adjustment to a new stable state	Complex adaptive system

aspects introduced by Walker et al. are less common in resilience research.

Since Holling first described ecological resilience in 1973, the theory of resilience attracted a great deal of attention (cf. Fig. 1) and developed over time, yet it does not have a universally accepted definition. One definition of resilience is given by Walker et al. [21], who explain resilience as "[…] the capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity." Unlike the definition given by Holling, which concentrates on the changes that occur, this definition focuses more on the things that stay the same. Unfortunately, Walker et al. do not provide further explanation of the terms function, structure, identity, and feedback. Allenby and Fink [53] share a similar understanding, defining resilience as the "[…] capacity of a system to maintain its functions and structure in the face of internal and external changes and to degrade gracefully when it must." Similar to Walker's definition, Allenby and Fink focus on function and structures as the consistent parts, but also include the possibility of transformation if the current state of the system is not maintainable. Both definitions claim that systems possess a main function or structure that they aim to preserve. Another definition for resilience is given by Folke [19], who writes, that resilience "[…] is about how periods of gradual changes interact with abrupt changes, and the capacity of people, communities, societies, cultures to adapt or even transform into new development pathways in the face of dynamic changes." Here, the focus is on who has the ability to adapt or transform in light of different types of changes. While all definitions cover the issue of change, Folke's definition also acknowledges that there can be slow and constant changes as well as sudden disturbances. These definitions form only a small part of existing definitions, but they clearly show that due to its ambiguity, the theory of resilience can be applied in many different disciplines, with various authors each providing a different emphasis.

Categorization of resilience

While there are efforts to conceptualize the theory of resilience by adding new components and details, there appears to be more than one understanding of the term resilience when analyzing systems. In order to deal with any potential confusion, different methods have been developed to categorize the various approaches.

Böschen et al. [14] classify the subject examined with resilience into four different models to explain why the application of the theory differs so much. In their research on how resilience is used, they found that the

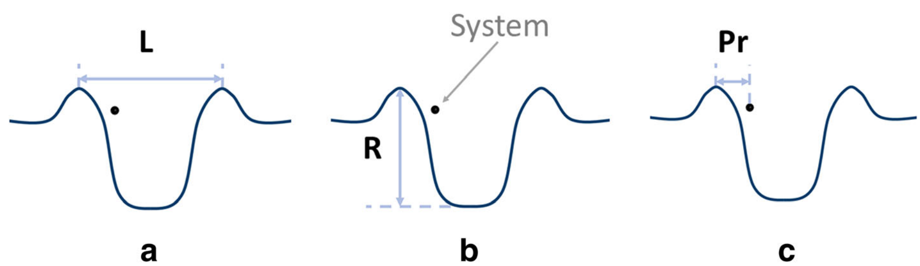

Fig. 3 Graphical representation of **a** latitude, **b** resistance and **c** precariousness (redrawn from [35])

context of the system and the theoretical concept of resilience can be used to categorize different applications of the theory of resilience. For the theory of resilience and the conceptual perspective, it is important that a distinction is made between the applications regarding structural or process analysis. For structural analysis, there is a focus on the system itself and its functions. For process analysis, however, the focus lies more on the transition and change of the system. The other category suggested by Böschen et al. [14] classifies the application of resilience in terms of its context. They distinguish between first-order resilience (closed context), which is more concerned with the resilience of a system, and second-order resilience (open context), which looks at resilience with respect to the environment of the system being viewed. Table 3 presents the differentiation used by Böschen et al. and the model types resulting from this.

Stability models focus on the resilience of the system's structure and examine the resilience of the system itself. Research into such models concentrates more on the stability and the preservation of the system [14].

Resilience in expansion models is used with a focus on a transformative process and studies the reaction of the system through change. Attention is paid to the resilience of the system and not its environment, which corresponds with first-order resilience [14].

Interference models concentrate on structure analysis, focusing not only on the resilience of the system but rather looking at the system in relation to its environment. Research into such models usually focuses on how to maintain system functions throughout a transformation of the system environment [14].

Furthermore, a transformation model uses process analysis to research the resilience of a system transformation in relation to its environment [14]. Projects using these kinds of models focus more on the transformation process and its effect on the system environment.

Erker et al. [18] use another categorization, differentiating between adaptive resilience and transformative resilience. A system focused on adaptive resilience is concentrated on maintaining its basic characteristics through adjustments within the system. In comparison, transformative resilience is characterized by a high degree of change as the system rebuilds basic structures or functions [18]. Therefore, adaptive resilience corresponds with the structure concept and transformative resilience with the process concept, without differentiating between the relations to the context of the systems.

Table 3 Distinction of application of resilience (based on [14])

		Concept	
		Structure	Process
Context	Closed	Stability model	Expansion model
	Open	Interference model	Transformation model

Resilience as a concept or quantity

The work by Böschen et al. shows that there is no uniform application of the resilience theory. Some researchers use resilience as a qualitative guiding concept, while others seek to quantify resilience as a system property. Haimes [54] sees a problem in the quantitative measurement of resilience, arguing that resilience can only be measured in terms of a specific threat. An example of the qualitative use of resilience is given by Cantatore et al. [29], studying traditional urban districts in Italy and analyzing how to increase the resilience of these districts against the effects of climate change. However, the authors only use the notion of resilience as a guiding concept and do not quantify the extent to which resilience can be increased by different measurements. On the other hand, Molyneaux et al. [55] developed a resilience index for national power systems and compared the power systems of different countries. Table 4 shows a collection of papers that were selected as part of the resilience review, while also allowing for a clear categorization of whether resilience is interpreted quantitatively or qualitatively in the papers. In addition, the majority of the papers listed have an energy system as an object of interest.

While it appears that the distribution between the quantitative and qualitative interpretation of energy systems is almost equally divided, it cannot be assumed that this is universally valid. The scope and focus of this review do not touch on the distribution for other disciplines. In addition, methods for the quantitative measurement of resilience vary substantially in the papers examined here. Afgan and Veziroglu [70] use an indicator, which they refer to as the resilience index. It is the integral of their sustainability index between the time of a disruption and the time when the sustainability index returns to its initial steady state value [70]. Their sustainability index is composed of economic, environmental, technological and social aspects [82]. Another quantified resilience value is given by Molyneaux et al. [55]. In their work, they compare the resilience of energy systems from different countries. Their index is defined as the geometric mean of seven normalized indices [55]. The normalized indices have either a technical or economical origin. Other authors quantify resilience indirectly, using auxiliary parameters. Mühlemeier et al. [78] quantify the diversity and connectivity of energy systems. They measured the variety, balance, and disparity as indicators of diversity and average path length, as well as degree centrality and modularity as indicators of connectivity, and used their observations to assess the resilience of the transition to an energy system based on renewable energy sources [78].

Table 4 Literature categorized by concept or measured value

Quantitative/ qualitative	Application	Reference
Concept	Housing for senior citizens as an example of a UK for energy system	[8]
Concept	Traditional urban districts in Italy	[29]
Concept	Framework for urban energy resilience	[37]
Concept	Energy and mobility system	[47]
Concept	Using microgrids to achieve climate change adaption and mitigation goals	[50]
Concept	Coalfields of Hunter Valley in Australia	[51]
Concept	Model for system resilience	[52]
Concept	Implementation of low-exergy technologies in northwest Germany	[56]
Concept	Region in northwest Germany to the context of climate change	[57]
Concept	Cyber threats in the energy sector	[58]
Concept	Energy systems research	[59]
Concept	Integrated energy systems	[60]
Concept	Disaster management	[61]
Concept	Microgrids to enhance energy security	[62]
Concept	Municipalities in Cambodia	[63]
Concept	Urban resilience and transformation	[64]
Concept	Earth as a system with respect to climate change	[65]
Concept	German energy transition	[66]
Concept	Sociotechnical systems such as urban development	[67]
Concept	Impact of climate change on the electricity sector in Austria and Germany	[68]
Concept	Solar-assisted carbon capture and storage	[69]
Measured value	Transformation from a fossil-based energy system to a system based on renewables	[6]
Measured value	Computer networks	[31]
Measured value	Energy system and energy security	[48]
Measured value	Austrian municipalities in to the context of climate change	[49]
Measured value	Electricity systems	[55]
Measured value	Hydrogen-based energy system	[70]
Measured value	Renewable energy hybrid system for buildings in New York City	[71]
Measured value	Aquatic trophic networks in the southern Gulf of Mexico	[72]
Measured value	Organizational resilience of critical infrastructure providers in New Zealand	[73]
Measured value	UK energy system	[74]
Measured value	Low-carbon technologies at a local level	[75]
Measured value	Energy systems of Finnish municipalities	[76]
Measured value	Assessment of energy systems in Indonesia	[77]
Measured value	Energy transition in Bavaria, Germany	[78]
Measured value	Cities and urban development	[79]
Measured value	Transition of the German energy system	[80]
Measured value	Assessment of performance-based system resilience	[81]

Furthermore, the papers can be divided according to their understanding of energy systems. A distinction can be made between a techno-economic understanding and a socio-technical interpretation. The former focuses on the process chain of primary energy and its extraction right up to the final use of energy [83]. Most of the solutions focus on cost-benefit, cost-effectiveness, and techno-physical integrity. In contrast, in socio-technical energy systems, technologies, institutions, actors, and cultures are interdependent and influence the general, social, and economic development of the system. They also cannot be considered independently [84].

Both interpretations can be found in the literature on the resilience of energy systems. Table 5 makes a distinction between the contributions from Table 4 according to their understanding of the energy system and resilience for papers that can be clearly assigned to one of the four different categories.

The division between techno-economic and socio-technical energy systems is relatively balanced. However, it is particularly striking that in the techno-economic interpretation of the energy system, the understanding of resilience more frequently corresponds to that of engineering resilience. In contrast, ecological resilience is more prominent in papers that understand the energy system as a socio-technical system. Furthermore, it is apparent that the quantitative approaches are mainly found in studies with techno-economic energy systems and

Table 5 Literature categorized by understanding of energy system and resilience

	Techno-economic energy system	Socio-technical energy system
Engineering resilience	[37, 52, 58, 60, 62, 68–71, 74, 76, 77, 81]	[29, 73, 80]
Ecological resilience	[48]	[6, 8, 47, 49, 56, 57, 59, 64–67, 75, 78]

that research which considers resilience in a quantitative manner usually interprets the energy system as a socio-technical system.

Criticism of the theory of resilience and unanswered questions

Although the theory of resilience has attracted a great deal of attention and is increasingly found in different scientific fields, it has not been immune to criticism. In addition to criticism of the general concept of resilience, there are also a number of unanswered questions about parts of the theory. The following list of criticisms and unanswered questions consists of issues that have arisen over the course of this review.

Vagueness

The most common criticism of resilience in the papers reviewed is the vague definition of resilience and how its understanding depends on the scales and context of the system [57]. There are many different definitions of resilience (cf. [10, 19, 21]), with no universally accepted definition. This prevents the development of a clear and uniform understanding of resilience. Although resilience might require a vague definition, since the understanding of resilience is at least partly subjective, it is also dependent on the answer to the question: "resilience to what?" [85]. This vagueness can be seen as an advantage. Definitions such as the one given by Holling ensure that resilience can be used in many different scientific disciplines, as a lot of research fields deal with systems exposed to disturbances [14]. However, the conceptual vagueness, the significant expansions of the theory, and its ambiguous use can endanger the practical relevance and conceptual clarity of the theory of resilience [86]. For example, in a study on resilience for marine regions by Hughes et al. [87], the theory of resilience ranges to encompass as much as international aid and leadership as well as ecological diversity, thus diluting the meaning of resilience [86]. Nevertheless, also means that the theory of the resilience can be used for many different problems and systems. However, the theory must then be specified for use in a specific discipline depending on the research question.

Positive perception

Another point of criticism, which was brought up in the early days of ecological resilience, is that an overwhelming number of research papers consider resilience as something positive [46]. While it may be true that many researchers understand resilience as a desirable feature of a system, resilience is neutral in theory and can be used to describe positive as well as negative systems [15]. For example, Phelan et al. [65] study the resilience of the fossil energy industry to change the energy system to a sustainable system. An example of a positive understanding of resilience is shown by Marschke and Berkes [63], who examined the resilience of fishermen in Cambodia to disaster and change to their environment. In conclusion, resilience does not have to be a good thing [16] and is, instead, depending on whether the system is desired or not. However, this represents an external evaluation. For the survival of a system, resilience can be considered a rather positive attribute.

Balance of power

Furthermore, the resilience approach does not provide an adequate representation of power structures in a system [15]. The theory lacks a way of describing how actors with power can influence the system or the development of the system [65]. The inclusion of power structures is necessary if different actors influence the resilience of the system in different directions. One way of considering relationships between actors and the system is to couple the theory of resilience with political-economic analytical insight [65]. While the resilience approach focuses on the overall state of the system, political economy concentrates on the different interests of actors in a system [65]. In their work on resilience, Phelan et al. use the theory of resilience to explain the Earth system with respect to climate change, while using political economy to explain the fossil-based industry's grip on humanity [65].

System structure and functions

Based on the definition given by Walker et al. (cf. the "Introduction to the modern theory of resilience" section), Smith and Sterling [30] question whether the objective of resilience is to maintain structures or functions. They argue that for a technical system, maintaining structures and functions can be mutually exclusive and that a resilient structure can undermine the functions of the system [88], since in technological systems, structures often have an adverse effect on function [30]. For example, the structure of an energy system based on fossil fuels might have to change due to new conditions in order to retain its functions of delivering energy services. Fichter et al. [57] made a similar observation while applying the theory of resilience to German energy systems. They conclude that while for an energy system, economic reasons often necessitate a conservative handling of system structure, the function of the system, which is to provide energy services, should be the focus of a resilient energy system [57]. In other words, resilience means that the core function of a system remains the same, while other aspects change [52].

Time of actions

In addition, there appears to be no agreement on whether the theory of resilience only focus on the system after an adverse event or if the theory includes components before and after the shock [89]. Carlson et al. [89] proposed four categories—preparedness, mitigation, response, and recovery—for a better understanding of resilience. Figure 4 illustrates which category is assigned to which point in time.

Preparedness refers to the activities of the system or entity in anticipation of shocks. Actions to reduce the consequence of a shock, such as resistance and absorption, belong to the mitigation category. Immediate and ongoing efforts to manage the effects fall under the response category. Finally, activities and programs designed to return the system to a stable state are part of the recovery category [89]. While the National Infrastructure Advisory Council also sees preparedness, and response activity as essential to the definition of resilience [90], other authors such as Adger [91] or Allenby and Fink [53] only define resilience as post-shock activities.

Stress or shocks

Change and reaction to change form an essential part of the theory, and there is no clear definition as to whether the resilience theory is concerned with abrupt or continuous alteration [9]. In the literature, abrupt change is often referred to as "shock" and continuous alteration as "stress" [88]. Typical shocks might include the sudden introduction of a fundamental new technology or a natural disaster. Folke [19] addresses this issue and postulates: "Resilience reflects the ability of people, communities, societies and cultures to live and develop with change, with ever-changing environments." He acknowledges that both abrupt and continuous disturbances are part of all complex adaptive systems, but adds that resilience is specifically about sudden change in a constantly changing environment. Kelly-Pitou et al. [50] cite climate change as an example for the relationship between stress, shock, and resilience. They believe that resilience measures should protect communities against the immediate damages of climate change as well as helping to mitigate the long-term impact of climate change [50].

State of the system after disturbance

While it is clear that a resilient system can overcome change, the theory does not provide clarification on the state of the system after the disruptive event [9]. When looking at a traditional definition of resilience, such as engineering resilience, the system returns to the same state it held before the disruption occurred. For ecological resilience, however, this assumption might not be true. Thoma [23] listed four different states that a system can have after a disturbance; Fig. 5 illustrates these four possibilities.

Either the system returns to the state it was before the event, or it could return to a state in which the system has a higher or lower system performance. If the system is not resilient enough and fails to return to the stable state, it will collapse, which is the last possible state.

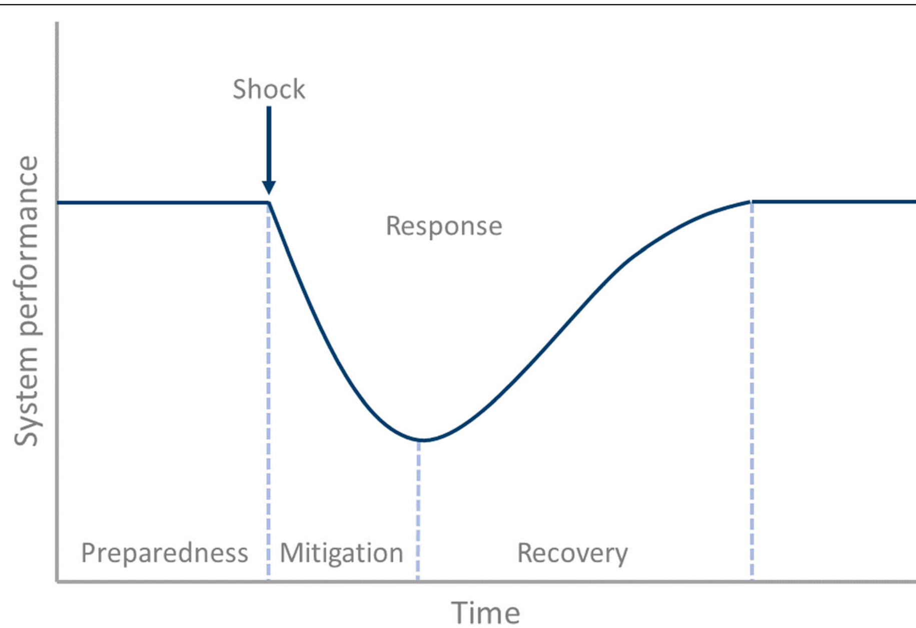

Fig. 4 Point of time for the categories (redrawn from [89])

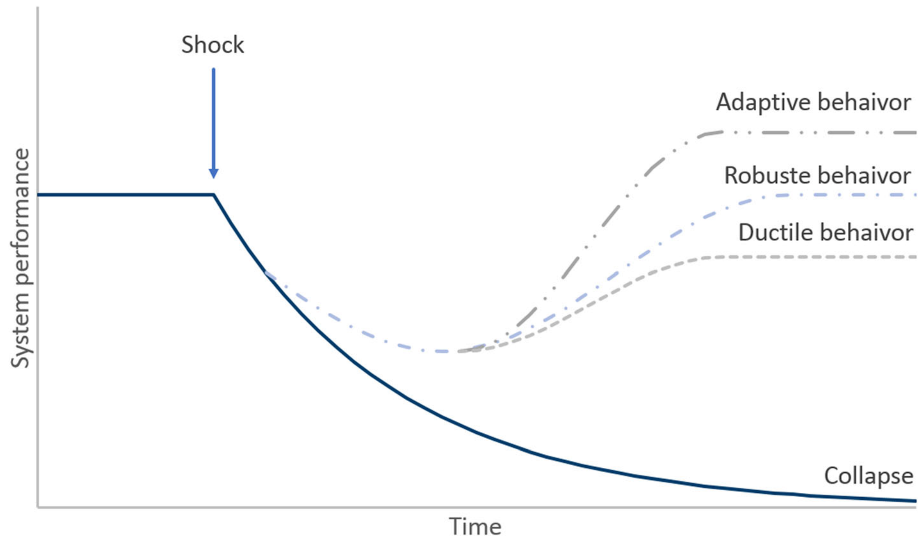

Fig. 5 Possible responses of system to a shock (redrawn from [23])

Vulnerability and sustainability

The term resilience is often used in conjunction with other terms such as vulnerability or sustainability. Some researchers argue that resilience and vulnerability are antonyms [41]. For example, Martin-Been and Anderies [41] argue that a comparison of resilience and vulnerability only makes sense after answering the question: "resilience against what?". They go on to cite the example of poverty to argue that resilience is the opposite of vulnerability. However, Gallopín [92] argues that resilience and vulnerability are not antonyms, since they differ in terms of context. While resilience is defined by actions between basins of attraction, vulnerability is concerned with system structures [92]. Fichter et al. [57] found that resilience and vulnerability describe different aspects of systems, with an increase in resilience leading to a reduction in vulnerability, while the opposite is not always the case [23]. Haimes [54] claims that vulnerability differs from resilience, as it does not provide information about the system's ability to recover.

The difference between sustainability and resilience is that sustainability is a normative concept of justice in and between generations, while resilience describes the dynamic characteristics of a system [93]. Sustainability is also a broader concept, which usually refers to the preservation of a desirable function or structure [41]. Sustainability is focused on the quality of life for present and future generations with respect to social, economic, and environmental factors [94]. In contrast, resilience is focused on the response of a system to persistent stress [19] or extreme disturbances [95]. The temporal scale is another important difference between sustainability and resilience, whereby sustainability is seen on a longer time scale [96]. Resilience, meanwhile, is applied to more immediate temporal scales [97]. If it accepted that shocks are inevitable, then sustainability over time requires resilience at all time [23]. In addition, shocks may be necessary to overcome the resilience of non-sustainable systems, such as the fossil-based energy system, and to transform it into a sustainable system (cf. [65]). A different view is put forward by Sharifi and Yamagata [37], who see resilience as an umbrella concept for sustainability rather than a synonym for sustainability.

In conclusion, resilience is neither the antonym for vulnerability nor a synonym for sustainability [23].

Resilience for energy systems

The application of the resilience theory for systems analyses started with ecological systems, but it was also used soon thereafter to study social-ecological systems. These are highly integrated networks of processes that interact with each other to provide services, with the same attributes being found in socio-technical systems [55]. Both types of systems exhibit adaptive, complex, dynamic, and multiscale properties [88]. It also seems reasonable to apply the theory of resilience to socio-technical systems.

Smith and Sterling [88] looked at how the resilience theory can be applied to socio-technical systems, concluding that the resilience of a socio-technical system is formally congruent with the resilience of a social-ecological system [88]. However, they also emphasize the importance of translating ideas carefully between the two areas of study [88]. Resilience is increasingly being used for energy systems, but the method applied is not the same in every case. On the basis of selected examples from the review, different approaches are presented and compared to evaluate the resilience of energy systems. The papers described below were selected because they reflect the range of different interpretations of resilience.

Engineering resilience for energy systems

An example of the application of the theory of resilience for energy systems can be derived from the analysis of critical infrastructure such as the electricity grid. It is often based on an understanding of resilience that corresponds to that of engineering resilience. Resilience of power infrastructures can be found in connection with the N-1 criteria. For example, Lou et al. consider the resilience of critical infrastructures designed according to these criteria [98]. However, for them, the resilience concept includes among other things robustness and redundancy. These characteristics are usually associated with preventing disruptions which contradicts the concept of resilience aimed at describing the system behavior during and after disruptions. An example of the use of engineering resilience for energy systems is given by Afgan and Veziroglu, who investigate the vulnerability of a hydrogen-based energy system [70]. They define resilience as the ability of a system to provide and maintain an accepted level of service even in the event of failure [70]. To determine the resilience, they calculate a sustainability index for each time step, which consists of the weighted sum of economic, ecological, technical, and social factors. In their example, resilience is the integral of the sustainability index over time, between a disruption and the point in time at which the index has returned to its stable state. This understanding is strongly based on engineering resilience, since it focuses on the vulnerability of the system and assumes that there is a stable state to which the system returns after disruption.

Another example of this kind of understanding is given by Hughes [99], who investigates the resilience and adaptability of energy systems. Hughes says that an energy system must meet three criteria: accessibility, affordability, and acceptance [99]. He models the system as energy and material flows, with each node having at least one demand and one supply. In the event that the system is no longer able to meet one of the three criteria, it experiences stress [99]. The system reacts to such a disturbance and strives for a stable state [99]. If the system returns to the same state as before the disruption, Hughes refers to this as resilience. In the case that the system assumes a new stable state, he calls this adaptability. Hughes believes that resilience can be measured by the time a system takes to recover from a stressful event [99]. This interpretation of resilience is also based on that of engineering resilience, in which there is a stable condition, to which the system returns after the disturbance. In contrast to the approach of Afgan and Veziroglu, however, Hughes also considers the possibility that the system can assume a new stable state.

The two examples are just two of many and both show an understanding of resilience that corresponds to that of engineering resilience. A great advantage of this type of resilience is in its relatively simple way of quantifying resilience. This allows for a comparison of different system configurations and various kinds of disturbances, although the disturbances and the system's resulting reaction must be well-known. This kind of approach is helpful when examining the technical aspects of socio-technical systems [100]. However, such approaches are very static, as they assume a quasi-stationary system. Hughes extends this approach to include adaptability, but neglects effects such as changing boundary conditions. Moreover, this type of approach often does not properly represent social aspects, such as social relationships and structures [100].

Ecological resilience for energy systems

In addition, resilience is also used in the sense of ecological resilience for energy systems. Such applications regard the technical domain and the social domain as equally important. An example of this kind of understanding is the approach to the conceptualization of energy resilience by Erker et al. [18]. In their work, they first develop a deeper understanding of resilience. In their view, resilience not only encompasses post-disaster recovery but also pre-disaster preparations, adaptation, and transformation. In order to take the later three aspects into account, they distinguish between three levels of resilience, namely "preserve", "re-stabilize" and "adapt and/or transform". According to Erker et al., the behavior of the system differs according to the temporal and spatial context of the crisis, as well as the degree of vulnerability and the adaptive capacity of the system. An overview of the possible reactions can be seen in Fig. 6. The light upper lines represent the course and the amplitude of the disturbance, while the dark lines reflect the system behavior. The dotted lines show the range of possible future states that the system can achieve due to adaptation or transformation.

According to Erker et al., long-lasting disruptions cause a greater deviation of the system's state than short-term disruptions [18]. This is reflected by the shift of the dark lines in the lower part of the graphic. Regarding the spatial context, the small influence of small scale disturbances is illustrated by the small deflections. However, the authors clearly point out that there are exceptions to this rule, like a nuclear disaster [18]. Further operationalization is only possible by a contextualizing the aspect of the system and the disturbance [18]. However, according to Erker et al. [18], a strict computation

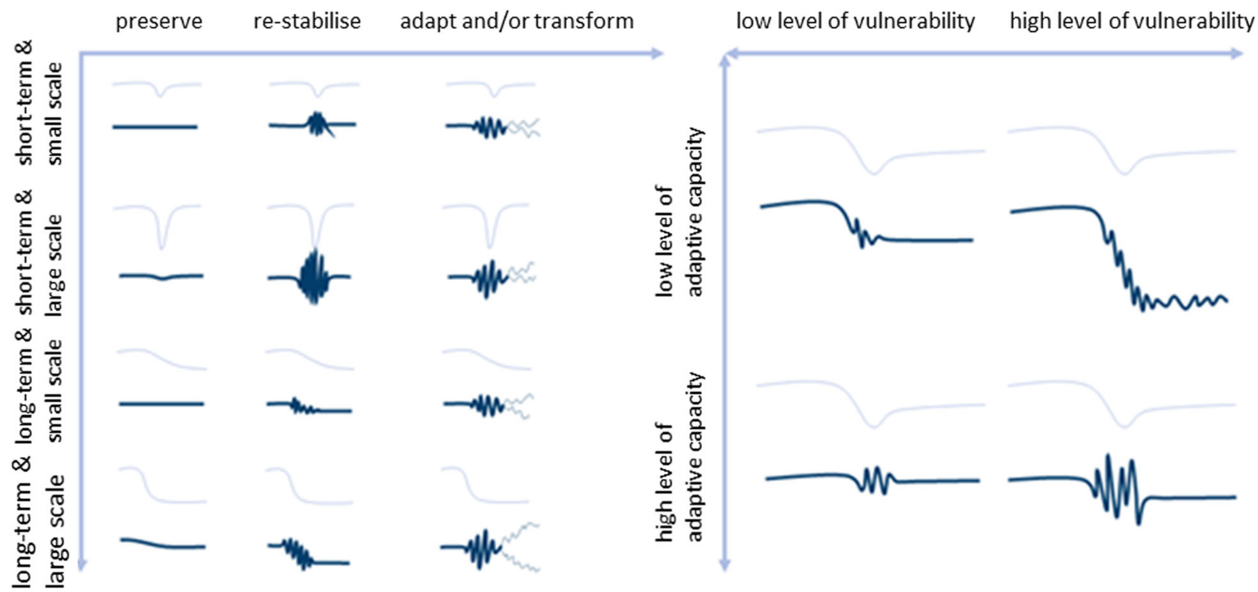

Fig. 6 Reaction of system to shock (redrawn from [18])

of energy resilience is not possible due to the complex changes and uncertainties. For their approach, resilience is examined on two levels: the factual level (FL) and the value level (VL). The FL represents the reality in an objective way and is based on characteristic values, for example, generation and distribution of energy, composition of energy sources, and energy demand. The VL, on the other hand, describes the subjective perception and is determined by value, beliefs, and attitudes, etc. According to Erker et al., resilience itself can be divided into four principles. These principles can be categorized according to process-related principles, such as ability to learn and social strength, as well as substantial principles, such as physical strength and the combination of exposure, efficiency, diversity, and redundancy. In order to determine and change the energy resilience of a region, Erker et al. developed a multistage process. The first step is to select a suitable region with heterogeneous energy production and consumption, socio-structural interactions, and coherences. In the next step, data must be determined to assess the factual level and the value level, with the issue of "resilience of what against what" being considered. The indicators and responses to their resilience performance must then be evaluated and the compatibility of facts and values assessed. Finally, policy suggestions can be identified to influence the resilience of the region. One challenge related to the presented assessment tool lies in the fact that the question to be examined must be formulated according to its available data, information, and social values, and there must also be a uniform understanding of the problem [101]. Otherwise, inconsistent signals and mixed messages might arise with respect to planning decisions and policies. If all this is taken into account, the approach offers the possibility of integrating both quantitative and qualitative data. However, there may be deviations between the values of the FL and the perception of the VL. This might be due to a lack of expert knowledge of the respondents or an incomplete or incorrect evaluation of the FL [101].

Another example of an approach to determine resilience, which involves both technical and social components, is given by Binder et al. [6]. In their work, they aim to conceptualize the role of resilience for an energy system in transition. They divide the energy system into social and technical spheres. Based on [102, 103], Binder et al. conclude that resilience is a function of diversity and connectivity [6]. In order to analyze the social sphere, Binder et al. divide it into social arenas and investigate social connectivity by means of exchange patterns between actors, regarding diversity as the functional qualitative differences between arenas. The technical sphere is operationalized by technologies, whereby the transmission infrastructure is used for connectivity and in which different forms of technologies were used as an indicator for determining diversity. On the one hand, Binder et al. use variety, balance, and disparity as indicators for evaluating diversity. On the other hand, average path length, degree centrality, and modularity are used as indicators for connectivity. According to Binder et al., when evaluating the resilience of a system in transition, it is not sufficient to exclusively consider the social or technical sphere or one of either diversity or connectivity as attributes. For all these indicators, a formula is indicated by the authors, although the indicators are partially qualitative in their application. For the evaluation of resilience, Binder et al. differentiate between the attributes connectivity and diversity in expression of weak and strong. Here, high connectivity and diversity correspond to the ideal-typical case of a resilient transition. In contrast with low connectivity and diversity, it likely leads to a failure of the transition of the system. In the two remaining cases, the outcome is not always certain. A challenge that arises when using this method is the availability and quality of data for the individual spheres [100]. Furthermore, the question of balance is heavily dependent on the indicator chosen, and the two proposed indicators are sensitive to the definition of group composition [100]. One advantage of the proposed method is that there is no need for an exact description of the disturbance, although the result is only of a qualitative nature.

The two presented approaches serve as good examples of the fact that for ecological resilience, both the technical and social aspects must be examined. Binder et al. point out that exclusive consideration of one aspect is not sufficient for evaluating ecological resilience. The advantage of this kind of approach is that it, in part, allows the resilience of a system to be evaluated, independent of the disturbance and the resulting system behavior. In addition, ecological resilience not only considers the technical components, but also the actors and allows for a consideration of adaptive capacity and learning. However, such an evaluation requires more data and expenditure in order to determine the resilience. In addition, the results of the two methods presented here are of a qualitative nature.

Other uses of resilience for energy systems

A further application of the resilience of energy systems, which appears in the literature, understands resilience as an extension of energy security. In their report entitled "Building A Resilient UK-Energy System", Chaudry et al. use indicators for vulnerability of primary energy supply, energy infrastructure, and energy usage to assess the resilience of energy systems [74]. Final energy demand, primary energy supply, and the electricity generation mix were identified as suitable macro-level indicators. A decreasing energy demand indicates low vulnerability to physical, geopolitical, or price uncertainties [74]. The other two indicators relate to the security of supply aspect of energy security, since the UK covers a large portion of its primary energy demand through imports. These indicators are determined on the basis of the maximum market share. The report then calculates four different scenarios and assesses them on the basis of these criteria. In order to assess the resilience of the systems, their behavior during external shocks, based on data from past shocks, was also examined. This understanding of resilience permits relatively intuitive indicators that are straightforward to calculate. However, the resulting systems can only be examined on the basis of explicit disturbances to their resilience. A causality between resilience and the indicators is not proven.

This understanding of resilience allows the use of intuitive indicators and ties in with the theory of energy security. However, the theory concerning energy security is not uniformly defined and includes different areas, depending on the understanding [104]. Moreover, such resilience is not found as often in the review as the other types.

Unanswered questions to the resilience of energy systems

The above examples show how versatile the application of resilience is for energy systems. In addition, the various applications have provided different answers to the unresolved questions and criticisms. In order to apply of the theory of resilience, the question of "resilience of what against what" must first be answered, since the system and the disturbance have an influence on whether engineering resilience or ecological resilience is suitable. In addition, the type of assessment desired must be clarified, whether it be quantitative or qualitative. Figure 7 shows a possible categorization according to Hosseini et al. [24].

According to the classification shown in the figure, the two examples of ecological resilience can be assigned to the qualitative assessment category and from there to the semi-quantitative indices class, while the examples from the "Engineering resilience for energy systems" section can be attributed to the quantitative assessment category. The choice of methodology and the type of understanding help to substantiate the notion of resilience and make it applicable. When describing the system, the objective function must be clarified as well as which characteristic should be retained. On the one hand, this might be the system structure. Engineering resilience is thus frequently used for questions relating to the resilience of infrastructure. On the other hand, the function of the system can be the target function, in which there are different functions of the energy system. On a technical level, it can be seen as simply the supply of energy or energy service (cf. [74]), while on a more holistic level, it can be seen as the quality of the life (cf. [6]). For energy transitions, focusing on the basic function is likely to be more suitable than concentrating on the structure of the system, since the transition is based on a change. The question of whether the disturbance is a shock or a stress is also discussed with regard to the resilience of energy systems. For the investigation of engineering resilience in the papers considered, shocks were mainly examined, since they represent a clear deflection from the stable state. In their work on ecological

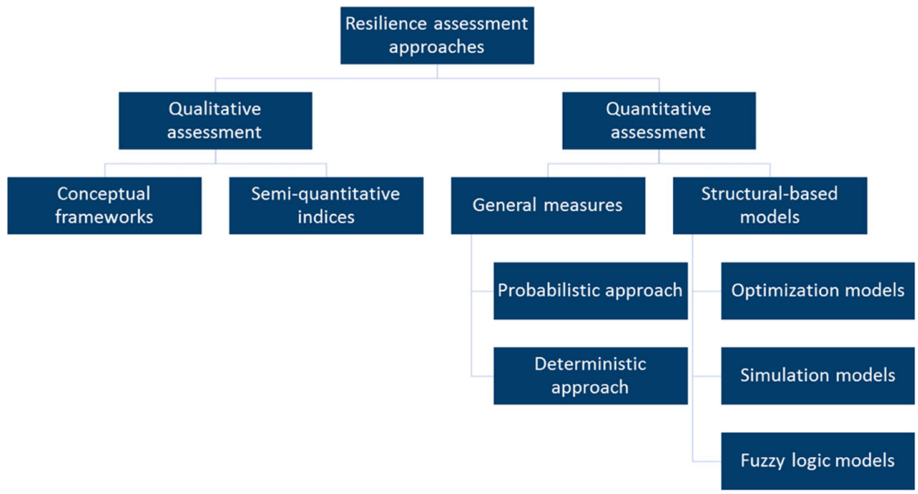

Fig. 7 Categories for assessing resilience (redrawn from [24])

resilience, Erker et al. investigated both types of disturbances and came to the conclusion that while the reaction of the system is different, the theory of resilience can consider both types [18]. The choice between shock and stress for energy systems in transition depends on the question of "resilience of what against what" and must be made for each specific case. Furthermore, different hypotheses are used with respect to the question of the state after a disturbance of a resilient energy system. For instance, the examples of engineering resilience assume that the state after recovery is the same as the state that existed before the disturbance. This is not always the case for investigations of energy systems that work on the understanding of ecological resilience. In particular, the state before and after the observed disturbance differ when there is a focus on concepts such as adaptive capacity or the ability to learn. Depending on the question and the target function, the choice of the desired state after the disturbance differs for energy systems in transition. The question also has an influence on whether measures which were taken before the disturbance, belong to the resilience. For methods such as the one given by Afgan and Veziroglu, it is not the point in time at which an action starts is important, but rather how this action affects the system behavior after a shock. For questions that seek to determine which actions affect the resilience of a system in which way, the action taking effect before a disturbance can be important. In this review, examples of both can be found. For the resilience of energy systems in transition, it is dependent on the question of whether or not the consideration of the measures is important. Finally, there is the question of a suitable representation of power in the theory of resilience. However, this question remains unanswered, even with the approaches considered here, which resolve the problem by including only the relevant stakeholders. Overall, the issue of the balance of power is only necessary for ecological resilience, since engineering resilience does not take the actors into account. Nevertheless, the actors are important for the successful transition of an energy system, which is why the distribution of power should not be neglected. The way in which this should be taken into account, however, must be resolved on a case-by-case basis.

On the basis of these observations, a recommendation can be derived for dealing with resilience and energy systems in transition. When working with resilience, it is important to first answer the question of "resilience of what against what". Based on the findings, a determination must be made regarding which type of resilience is better suited to answering specific research questions. If engineering resilience is identified as suitable, frameworks can help to assess resilience. An example of such a framework, which came up in the review, was designed by Tran et al. [81]. The framework consists of five steps, which are listed in Fig. 8.

The five steps clearly show that engineering resilience requires detailed knowledge of the system and the disturbances. However, the proposed method allows for a quantitative evaluation of system resilience. If ecological resilience is selected as a concept, there are different approaches to evaluating the resilience of an energy system. The approach outlined in Fig. 9 is an elaborate approach presented by Erker et al.

Their approach is based on the analysis of a factual level and a value level, thus allowing both the social and the technical aspects to be considered. The aim is not to quantify resilience but to derive policy recommendations. However, whether one of these two proposed

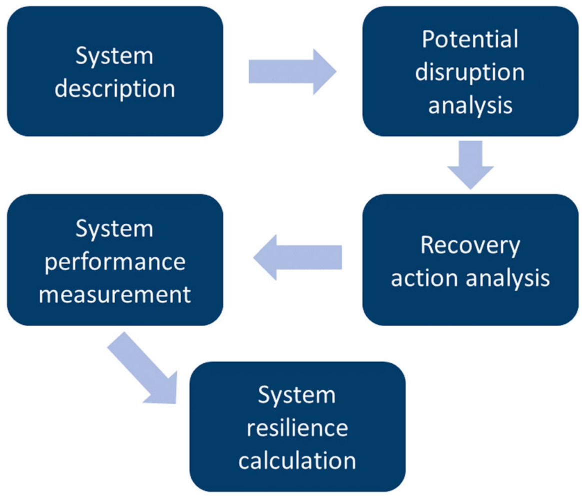

Fig. 8 Engineering resilience assessment (based on [81])

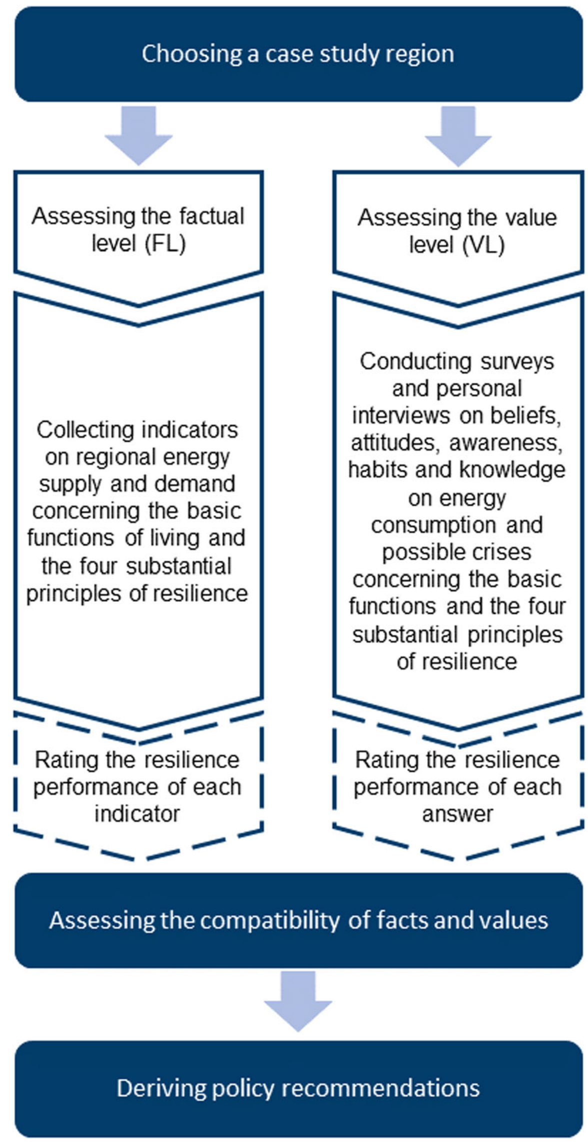

Fig. 9 Ecological resilience assessment (redrawn form [18])

approaches is suitable for considering the resilience of the energy system to be investigated is something that is case-specific and depends on the research question. The findings from this literature review can help to apply the concept resilience to energy systems. It is essential to distinguish between engineering resilience and ecological resilience. In order to decide which of the two is to be used, it is important to be aware of what type of analysis is desired and what information is available about the system and disruption to be investigated. Engineering resilience is particularly suitable for analysis when the state of the system after the failure should be relatively equal to its state before the failure, if the system is to recover. However, for such a consideration, it is necessary that the system and its behavior are known, as well as the disturbance and its effects on the system. A system performance index is a good way to quantify this kind of resilience, as shown in the example of Afgan and Veziroglu (cf. [70]). The system performance index can be a variation of values, such as a sustainability index or the degree of coverage. Engineering resilience is therefore particularly suitable for techno-economic analysis, which is also reflected in Table 5. Ecological resilience, on the other hand, is suitable for the analysis of systems whose state domains are more complex. In addition, the concepts of adaptability and transformability are more extensive for ecological resilience. The methods presented in this review allow social aspects to be taken into account and allow an assessment of the resilience of the energy system without detailed knowledge of the disturbance and its consequences. However, this often leads to the fact that a quantification of resilience is no longer possible or only partially possible.

Conclusions

Resilience has gained in importance within the field of systems analysis in recent years and has also become increasingly important in the consideration for energy systems. However, there is no uniform understanding in the literature and the applications differ. One reason for this is that there are two types of resilience: engineering resilience, where systems are located near a stable point and always return to it after a disruption, and ecological resilience, where it is assumed that the system under consideration does not rest in an equilibrium but is continuously in motion. In addition, this type of resilience assumes several basins of attraction between which an unsustainable system switches, while a sustainable system remains in one basin.

Previous works that use the theory of resilience can be classified into different categories, according to whether they use engineering resilience or ecological resilience. They can also be categorized by context, concept, and whether they make a qualitative or a quantitative assessment. One reason why resilience is often intangible is that in previous works, the kind of resilience used is often not mentioned. Furthermore, there is no generally accepted definition or method of quantification for either engineering resilience or ecological resilience. Other criticisms are that existing definitions are vaguely formulated and important aspects, such as the state after recovery, are not precisely specified. However, since these aspects must usually be answered on a problem- and system-specific basis, there can be no generally valid definition of resilience. The theory is now also being used in the field of energy systems, with examples of engineering resilience as well as concepts that investigate the ecological resilience of energy systems. When translating the theory into an energy system, unanswered questions such as the duration of disruption or the time of actions still have to be addressed. However, there is no generally applicable answer and many aspects have to be decided in a problem-specific manner. The findings presented in this paper can help and provide possible solutions to apply resilience to energy systems.

Abbreviations
CAS: Complex adaptive system; FL: Factual level; *L*: Latitude; Pa: Panarchy; Pr: Precariousness; *R*: Resistance; VL: Value level

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Authors' contributions
BJ collected and sorted the publications and information material, prepared, and helped in writing the manuscript. HH helped to analyze and interpret the data and assisted in writing of the manuscript and reviewing of all versions. WK took a critical look at the manuscript and provided input for the final version. All authors read and approved the final manuscript.

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Not applicable.

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