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REVIEW **Open Access**

Characterization of necessary elements for a definition of resilience for the energy system

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Abstract

Background To reduce the effects of climate change, the current fossil-based energy system must transition to a low-carbon system based largely on renewables. In both academic literature and non-academic discourse concerning the energy transition, resilience is frequently mentioned as an additional objective or requirement. Despite its frequent use, resilience is a very malleable term with different meanings in different contexts.

Main text This paper seeks to identify how resilience is understood in the field of the energy system and whether there are similar aspects in the different ways the term is understood. To this end, we review more than 130 papers for definitions of energy system resilience. In addition, we use different aspects to categorize and examine these. The results paint a diverse picture in terms of the definition and understanding of resilience in the energy system. However, a few definition archetypes can be identified. The first uses a straightforward approach, in which the energy system has one clearly defined equilibrium state. Here, resilience is defined in relation to the response of the energy system to a disturbance and its ability to quickly return to its equilibrium. The second type of resilience allows for different equilibriums, to which a resilient energy system can move after a disruption. Another type of resilience focuses more on the process and the actions of the system in response to disruption. Here, resilience is defined as the ability of the system to adapt and change. In the papers reviewed, we find that the operational definition of resilience often encompasses aspects of different archetypes. This diversity shows that resilience is a versatile concept with different elements.

Conclusions With this paper, we aim to provide insight into how the understanding of resilience for the energy system differs depending on which aspect of the energy system is studied, and which elements might be necessary for different understandings of resilience. We conclude by providing information and recommendations on the potential usage of the term energy system resilience based on our lessons learned.

Keywords Energy system, Resilience, Definition, Engineering resilience, Ecological resilience, Adaptive resilience

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Background

In recent times, the resilience approach has gained recognition as a method of evaluating the response of an energy system to shocks and the ability to recover. This approach goes beyond the classical ex ante assessment, which focuses on the time during a disruption. By contrast, resilience also includes the behavior of the system after disturbances [1]. However, the term has been interpreted differently by many scientists and no consensus has yet emerged on how to understand resilience in terms of the energy system [2–6]. This has led to a variety of approaches on how to operationalize the resilience of the energy system. In previous work, we looked into different ways of operationalizing resilience and categorized these approaches according to methods used (cf. [7]).

This diversity has been identified in several literature reviews. For example, using the research areas, Francis and Bekera compared different approaches to defining and assessing system resilience in their literature review and presented their own approach using the three resilience capacities (e.g., absorptive, adaptive, and restorative) [8]. In [9], Hosseini, Barker, and Ramirez-Marquez compare different approaches to measuring resilience across various application domains and provide a classification focused on qualitative and quantitative approaches and their subcategories. Sharifi and Yamagata reviewed work on energy resilience to create a conceptual framework specifically for the urban energy system by identifying planning and design criteria [10]. Gasser et al. reviewed definitions of resilience for energy infrastructure and compared these findings based on seven categories such as assessment approach, modeling approach, and resilience phase [1]. Ahmadi, Saboohi, and Vakili reviewed different papers with respect to factors of energy system resilience according to modeling approach and type of system [11]. In [12], different characteristics of resilience are reviewed in relation to the type of disturbance. In [13], the authors focused on urban resilience and conducted a literature review to identify research gaps by classifying the field of research, type of work, and the methods applied. While numerous reviews have delved into the topic of energy system resilience, the majority tend to concentrate on assessment types, applied methodologies, or categorizations based on the field of study. One aspect that remains unexplored is the examination of how resilience is understood based on definitions and its contextual link to the energy system. To the best of our knowledge, this issue has not yet been covered by literature reviews. To address this gap, we aim to answer the following research questions:

- How do current definitions for resilience of the energy system differ?
- What relationship exists between the understanding of resilience and the energy system?
- Can we identify similarities among the definition of energy system resilience and are there grounds for grouping them together?
- Are there trends indicating the prevalence of a specific understanding?

The article starts by providing a scientific background on resilience, reviewing the concept of energy system resilience in the scientific literature. This is followed by an explanation of the methodology for the literature search and the method of categorizing the reviewed definitions. We then categorize existing definitions of resilience relating to the energy system. In addition, the links between definitions, categories, and the energy system are examined. The paper concludes with a summary of the literature search findings and recommendations on how to use the term resilience in the field of the energy system.

Resilience has emerged alongside traditional risk management to address the need for an approach that deals with the unpredictable rather than the identifiable [14]. Since systems such as the energy system are critical to modern societies, it is imperative that these systems continue to work even in the event of a disruption.

Researchers are looking for additional methods and theories to investigate system behavior in the face of disturbances. Events such as the global financial crisis of 2008 [15] and the Fukushima Daiichi nuclear disaster in 2011 [16] cannot be predicted and are therefore often not considered, although they have a significant and long-term impact on the transformation of the energy system (e.g., the nuclear phase-out in Germany [17]). On a more limited scale, the same can be said about the impact of events such as the blackouts in North America in 2003 [18], India in 2012 [19], and Turkey in 2015 [20]. Another example is the disruption to the European energy system in the wake of the Russian invasion of Ukraine in 2022. They show that not all disruptions can be avoided [21]. If disturbances cannot be avoided, a theory of system behavior under disturbance is required. One such theory is the theory of resilience. Resilience is a multi-faceted, malleable concept that has recently gained popularity across a wide range of scientific disciplines [4], including the energy system and energy transition studies [22]. The theory attempts to determine how a system responds to a disturbance and what state it eventually assumes. To make a distinction between risk management and resilience assessment, the former is considered a pre-event analysis [23], which usually results in preventive measures to minimize the frequency and consequences of disruptions. In contrast, resilience assessment not only includes an analysis of the potential disruptive event, but also a post-event analysis [1].

Scientific discussion about resilience has intensified considerably in recent years. Figure 1 shows the absolute number of published articles that contain the word resilience in their title, keywords, or abstract, as well as the relative proportion of the total number of publications in Web of Science [24] and Science Direct [25].

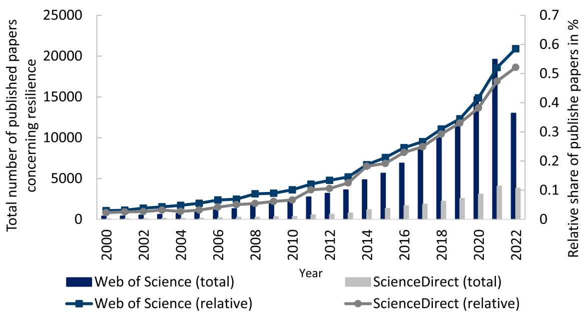

Fig. 1 Development of the term resilience in the literature (modified from [7])

Table 1 Resilience concepts and qualities (modified from [35] and [37])

Resilience concepts	Qualities
Engineering resilience	• One equilibrium • Restores to previous condition after disruption
Ecological resilience	• Multiple equilibriums • System can absorb shocks before destabilizing, then move to another equilibrium state
Adaptive resilience	• Focused on process of adaptation • System can absorb disruptions • Focus on the prepare/absorb/recover/adapt phases • Dynamic and continuous process

Resilience, however, is not a new concept. The word resilience is derived from the Latin word "resilire", which means, "to spring/bounce back" [9, 26]. Its use in a scientific context dates back to at least the nineteenth century when it was used in materials science (cf. [27]) to describe "… the ability of a metal to absorb energy when elastically deformed and then to return it when it is unloaded" [28]. A more recent use of the term resilience comes from the field of psychology, where it appeared more frequently from the 1950s onwards [29]. Within this field, the term is described as the ability of an individual to withstand a past or present personal crisis through positive adaptation [30].

In addition to materials science and psychology, resilience found its way into the realm of ecology. Here, Holling had a significant influence on the understanding of resilience in 1973 [31]. According to Barata-Salgueiro and Erkip, the operationalization of resilience for the energy system can be subdivided into engineering, ecological, and adaptive resilience [32].

Holling coined the two terms "engineering resilience" and "ecological resilience", which are widely used in resilience research. Engineering resilience is characterized by one stable point and the quick return of the system to that point after a disturbance. In addition, Holling provided a definition for ecological resilience, as he recognized that ecological systems could have more than one equilibrium state and that the system can change between these states. Ecological resilience defines a system as resilient if it can tolerate a certain level of disturbances while maintaining its main features and functions. Ecological systems that are resilient will not destabilize in the event of a shock, but will move to another stable state that provides the same function [10]. A third type of resilience was subsequently defined and is referred to as "adaptive resilience". Proposed by Pike, Dawley, and Tomaney, this concept emphasizes disequilibrium rather than one or individual equilibrium states [33]. It is interested in how complex adaptive systems adapt to stress over time [34], and focuses on the process of adaptation rather than the individual states themselves [35]. Consequently, a system may not return to an (old or new) equilibrium state after a disruption [10], but a resilient system is capable of coping in the short term and adapting in the long term [36]. Table 1 gives a simplified overview of the different types of resilience and their defining qualities.

Today, a wide variety of scientific fields has taken up the notion of resilience, with different applications of all three definitions [38].

To assess resilience, a reference to the resilience function is often made (e.g., [4, 12, 39–44]). The resilience function abstractly describes how a system behaves before, during, and after a disturbance. A disturbance can be everything that changes the ability of the system to function. The function of the system is usually defined by the researcher, user, or regulation agency, for example for the energy system it could be the ability to provide energy services. Figure 2 shows the theoretical curve of the resilience function based on the work of [45].

In this figure, the trajectory of the system has been simplified—in reality, the resilience function may be more complex—but it does show the main features of the resilience function. In collapse, the system is unable to recover and loses its function [46]. Resilient behavior is when the system arrives at the same system performance as before the disturbance [47]. In addition, the four different phases of the resilience function are indicated. While "preparation" can be defined as actions before a shock occurs, the beginning and end of the two phases "absorb" and "recover" are not precisely defined. The "adapt" phase usually starts after the recovery. However, not every paper considers this phase to be part of resilience.

Main text

We conducted the literature research in a comprehensive and replicable way. The contemporary literature on resilience consists of a vast number of publications, as shown in Fig. 1. A restriction of the selected articles is

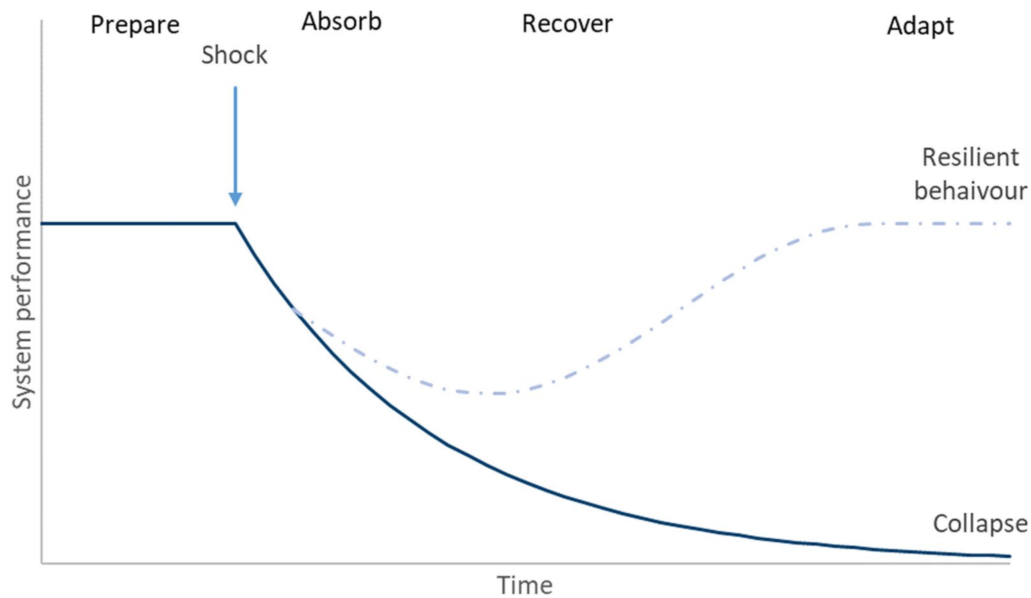

Fig. 2 Conceptual trajectories of the resilience function (modified from [45])

therefore required. In order to consider both the aspect of resilience and the aspect of the energy system and its transition, we use the expression "energy resilience" to combine both issues. A simple Boolean expression was chosen to ensure the reproducibility of the literature review [48]. The expression was used with the Web of Science database [24], while the ScienceDirect database [25] was used as a backup to verify whether the same entries appeared and to find important missing literature. In order to review the current state of research, the focus was on articles between 2000 and 2022. Since the Boolean expression frequently appears in texts, we focus on articles containing the Boolean expression in either the title, abstract, or keywords. In the next step, we selected the 25 most relevant entries of each year for further examination based on the catalog algorithm of the database. We study how they relate to the topic of energy system resilience and the transformation of the energy system. Following a manual examination of the articles and their relevance to resilience and the energy system, around 140 articles remain, which we further analyze to see if they include a definition of resilience. In the remaining articles, 71 different definitions exist. These definitions are examined to see if they differ only in terms of wording or if they are substantially different. A list of all definitions can be found in the supplementary material. Thirty-six articles do not contain an original definition but instead quote an existing definition. Twenty-seven articles do not define resilience at all. Since Holling and his work is considered the foundation of modern resilience theory, we also include his work [31] in our literature review to see what influence it has on other papers.

As per our research question, we aim to explore the link between the understanding of resilience and of the energy system. Energy system and resilience are the fundamental components of energy resilience, which is why they are logical choices for categories. We categorize resilience in the reviewed paper and definitions based on the resilience function and based on the nature of the energy. In total, we categorized the papers based on four different aspects. We look at (1) what type of system—quasi-static or dynamic—the article covers, (2) whether it examines the long-term or short-term behavior of the system, (3) what dimension—technical, economical, ecological, or social—of the energy system the paper focuses on, and (4) which phases of the resilience function appear in the paper. These categories partly relate to the three resilience concepts mentioned above. For example, system type and considered phases can indicate which resilience concept researchers are using. Quasi-static systems align with engineering resilience, while dynamic systems lean towards ecological resilience. Considering the adaptation phase usually reflects an approach similar to adaptive resilience. However, this assignment is not always precise, and researchers might employ different concepts or combinations of them. The remaining categories generally do not clearly indicate which resilience concepts is used. The categories are not always mentioned or clearly defined in the reviewed articles. Instead, they were assigned by us to the different papers. Figure 3 shows the aspects examined and the categories used. Furthermore, we use the year of publication as an additional criterion and examine the citations between the papers for more insight.

For the classification of the energy system, we distinguish between two types. On the one hand, we define the category of a quasi-stationary system, for which an equilibrium exists to which the system returns after a disturbance. On the other hand, we define the category of dynamic systems. These exist in a landscape of ideal states and typically orbit around such a state. In the case of a disturbance, the system may leave its orbit for a short time, or it may be disturbed in such a way that it orbits a new state.

Furthermore, we used temporal resolution as a category. We distinguish between studies that analyze short-term or long-term effects on the energy system. Our classification of long term and short term is qualitative, since any quantification would be problem-specific and the problems in the papers examined vary greatly.

In addition, we examine whether the energy system aspect of the studies has an impact on the understanding of resilience. We therefore differentiate between which dimensions of the energy system are considered. We make a distinction between technical, economical, ecological, and social dimensions. A paper often examines more than one dimension, which is why multiple entries are possible.

Lastly, we use the different phases of the resilience function as categories. The individual phases have different names and synonyms. To determine which synonym to use for our work, we examine which words appear most frequently in the analyzed definitions. We have chosen the terms "prepare", "absorb", "recover", and "adapt" as categories. The majority of the papers examined use these descriptions, which simplifies the classification (cf. Table 2). A detailed list of classifications made for each paper can be found in the supplementary material.

Resilience is highly dependent on context, leading to various possible categories for analyzing how a research paper understand the term. We aim to explore the connection between the understanding of the energy system and resilience. Therefore, we only focus on these two aspects for our categories. Other factors such as disturbance, the assessment method, or the research field also have an impact on resilience understanding, but are beyond the scope of this paper.

To investigate whether there is a correlation between the different aspects and categories, we first use the χ^2 value to check if two categorical values are independent. If they are not independent, we test the strength and direction of their correlation by evaluating the φ value. We calculate the χ^2 value using contingency tables. Table 3 shows a contingency table for two characteristics, i and j, with two variants, 0 and 1, for a set

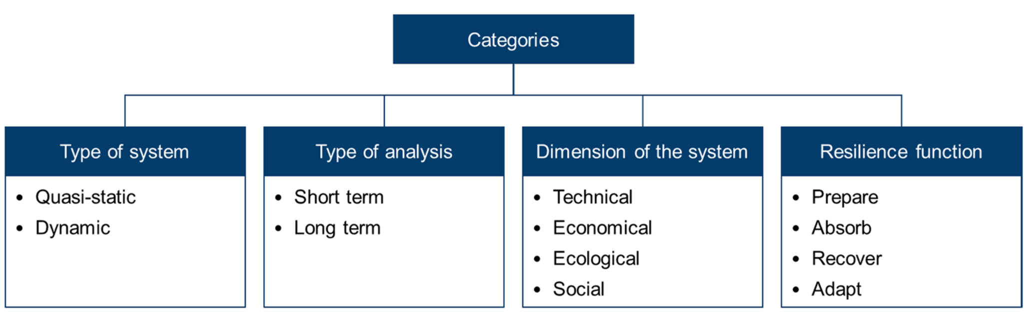

Fig. 3 Overview of categories used

Table 2 Descriptions of the different phases of the resilience function and some of their synonyms found in the definitions

Prepare		**Absorb**		**Recover**		**Adapt**	
Prepare	5	Absorb	26	Recover	33	Adapt	23
Anticipate	5	Withstand	13	Respond	10	Change	16
Plan	2	Maintain	11	Return	7	Adaptation	8
		Retain	11	Restore	5	Changing	8
		Resist	7			Changes	7
		Persistence	6			Learning	7
						Reorganize	6
						Adaptive	5

The number indicates how often the word appeared of samples with size n. The number of samples with characteristic i independent from j is given by $n_{i\circ}$.

We calculate the expected frequency $\check{n}_{ij}$ for each variant of the characteristics using the values from the corresponding contingency table (cf. Table 3):

$$\check{n}_{ij} = \frac{n_{i\circ} * n_{\circ j}}{n}.$$

Since our sample size is large enough, we choose a minimum expected frequency of five for the χ^2 test. This is a common value recommended by statistics textbooks for 2×2 contingency tables [49]. To calculate the χ^2 value for two categories, we use the following equation:

$$\chi^2 = \sum_{i,j} \frac{\left(n_{ij} - \check{n}_{ij}\right)^2}{\check{n}_{ij}}.$$

For binary categories, the degree of freedom equates to one. A significance level of 5% and a degree of freedom of one equates to a critical $\hat{\chi}^2$ value of 3.841 (cf. [50]). If the χ^2 value is greater than the critical $\hat{\chi}^2$ value, we can reject the null hypothesis with a significance level of 5%, which means that the categories correlate. To determine the type and direction of the correlation, we calculate the φ value for the significant correlation coefficients only according to following equation:

$$\varphi = \frac{n_{11}n_{00} - n_{10}n_{01}}{\sqrt{n_{1\circ}n_{0\circ}n_{\circ 0}n_{\circ 1}}}.$$

The φ value is based on the χ^2 value and takes values between -1 and 1. The larger the absolute φ value, the stronger the correlation between the two tested variables.

In addition to the correlation analysis, we perform a meta-analysis of the papers. To investigate if and how the papers and their definitions influence each other, we investigate connections between the individual papers and the influence of the date of publication.

Using the steps described above, we review and analyze the literature on energy system resilience and the energy system in transition for definitions. The more than 130 papers examined result in a large number of different definitions.

The definitions we found show to what extent the understanding of energy system resilience can differ. To compare and understand the different applications of energy system resilience, we assign the examined papers to the categories outlined above. We base the first category on the type of system in question and differentiate between quasi-stationary and dynamic systems. The assignment is not always clear, which is why some articles are assigned to both categories. In addition to the type of system, we used the type of analysis to divide the articles into those investigating long-term effects and those investigating short-term effects. Table 4 lists the number of articles assigned to the categories.

The number of allocations is relatively similar for the type of system as well as for the type of analysis. There seems to be no preference as to which type of analysis researchers choose for their studies. However, the two categories are almost equally distributed, suggesting that short term and quasi-static as well as long term and dynamic are linked.

In addition to the type of system and analysis, we consider which dimension of the energy system the papers examine. We distinguish between technical, economical, ecological, and social dimensions. Figure 4 shows how often papers can be assigned to the individual dimensions.

The technical aspects of the system are considered in most definitions, which is not surprising since the energy system is based on technical elements. Interestingly, not all authors consider the technical dimension to be an essential part of the energy system when considering the resilience of the energy system (e.g., [51, 52]). At the

Table 3 Contingency table for two characteristics

		Characteristic *j*		
		***j*=0**	***j*=1**	**Σ**
Characteristic *i*	$i=0$	n_{00}	n_{01}	$n_{0\circ}$
	$i=1$	n_{10}	n_{11}	$n_{1\circ}$
	Σ	$n_{\circ 0}$	$n_{\circ 1}$	n

Table 4 Different aspects found for the behavior

Type of system		**Type of analysis**	
Quasi-static	**Dynamic**	**Short term**	**Long term**
64	44	73	47

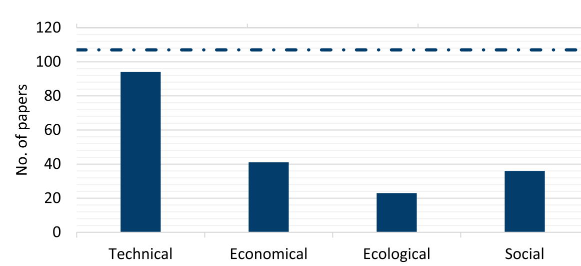

Fig. 4 Different dimensions for the systems. The horizontal line indicates the total number of papers analyzed

same time, however, there are also papers that consider the energy system as a technical-only system. The other aspects are much less frequently taken into account in the examined papers, which is due to the fact that these aspects are sometimes more difficult to operationalize.

Additionally, we use the different phases of the resilience function as categories to identify differences between definitions. Figure 5 shows how often the individual phases can be found in the analyzed literature.

While most papers consider the “absorb”, “recover”, and “adapt” phases, the “prepare” phase receives little attention. Resilience for the energy system is thus predominantly understood as an ex post concept. The high proportion of papers considering the “adapt” phase shows that at least in the definitions, the adaptation and learning of the system is emphasized. This is in contrast to the frequently used quasi-static understanding of the system, which assumes that the original state will be restored after a disturbance. To understand whether a correlation exists between individual category pairs, we calculated the φ value as an indicator. Table 5 shows the φ value for all combinations of categories.

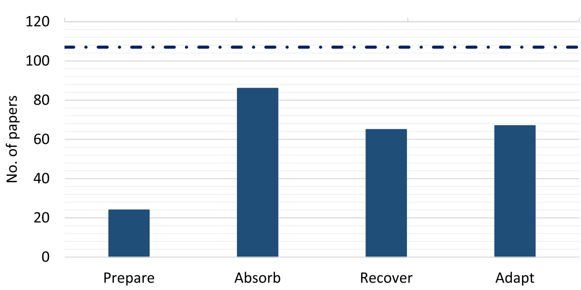

Fig. 5 Different phases found in the definitions. The horizontal line indicates the total number of papers analyzed

Non-trivial correlations are defined as $|\varphi| > 0.3$ [53], which can be found for 16 combinations. The combinations “quasi-static” and “dynamic”, “dynamic” and “long-term”, and “quasi-static” and “short term” are particularly striking. On closer examination, the dependence of “quasi-static” and “dynamic” is relatively straightforward, since they are opposing approaches. The negative sign indicates a negative correlation. The reason why it is not equal to − 1 is that there are definitions which do not specify the type of system or which consider both. The same consideration applies to the interdependence of “short term” and “long term”. The strong correlations between “quasi-static” and “short term” and between “dynamic” and “long term” show that these two concepts are mostly used together. This is reinforced by the negative correlation between “quasi-static” and “long term”. These correlations partly explain the similar distribution of these categories in the papers, which is described above. The positive correlation between “long term” and “adapt” suggests that this phase is seen in resilience research as a process that takes place over a long period. Other notable correlations are between “economical” and “ecological”, “economical” and “social”, and “ecological” and “social”. These are positive correlations, which indicate that researchers examine these aspects together. We also observe a correlation concerning the social aspects and the type of system. The papers often focus on the social aspect of dynamic systems, while papers on quasi-static systems tend to neglect the social aspects. The correlation between “technical” and “quasi-static” suggest

Table 5 φ values for all combinations of categories

	Absorb	Prepare	Recover	Adapt	Technical	Economical	Ecological	Social	Quasi-static	Dynamic	Short term	Long term
Absorb		–	–	–	–	–	–	–	–	–	–	–
Prepare			0.43	0.27	–	–	–	–	0.31	-0.30	–	–
Recover				–	–	–	–	–	0.29	-0.34	–	–
Adapt					–	–	0.21	0.30	-0.30	0.34	-0.21	0.37
Technical						–	–	–	0.34	–	–	-0.23
Economical							0.43	0.38	–	–	-0.26	0.22
Ecological								0.35	–	0.26	-0.30	0.26
Social									-0.37	0.40	-0.24	0.37
Quasi-static										-0.65	0.59	-0.42
Dynamic											-0.30	0.65
Short term												-0.45
Long term												

Correlations stronger than 0.3 or − 0.3 are highlighted in grey. If the χ^2 value is lower than the critical $\widehat{\chi}^2$ value, “ –” is entered in the table that the understanding of the system is similar to engineering resilience when focusing on technical aspects. In contrast, the correlation of “long term” and “social”, as well as “dynamic” and “social”, indicates that the understanding is closer to adaptive resilience when examining social aspects.

We subsequently investigate how the individual papers relate to each other and whether they base their definitions on each other. For this purpose, we use a directed graph diagram as shown in Fig. 6.

The graph shows that a large number of researchers cite Holling’s work. His work is considered fundamental in resilience research for systems analysis, since he distinguished between engineering and ecological resilience. However, apart from the work of Holling, articles rarely draw from similar research. The handful of other frequently cited articles include Roege et al. [54], Molyneaux et al. [55], and Sharifi and Yamagate [56]. However, these papers are cited by researchers with different understandings of resilience. This is shown by the fact that the relative distribution of the categories of citing papers is similar for the above-mentioned papers. In addition, we wanted to see if cited papers were connected by institutes, but this did not add any further insights. We can therefore conclude that none of these papers could establish a widely accepted school of thought for any of the types of resilience.

To analyze if and how the concept and application of resilience for the energy system has changed over time, we also look at the development of the categories over time. Figure 7 shows the development of the relative share for the four phases of the resilience function over time and the categories describing the system.

For the first three periods, the number of papers examined is rather small, which limits their significance. In the following periods, the shares for the phases “absorb” and “adapt” remain relatively constant. In contrast, the proportion of papers that consider the phases “prepare” and “recover” has increased in recent years. In the last period examined, half of all papers considered the

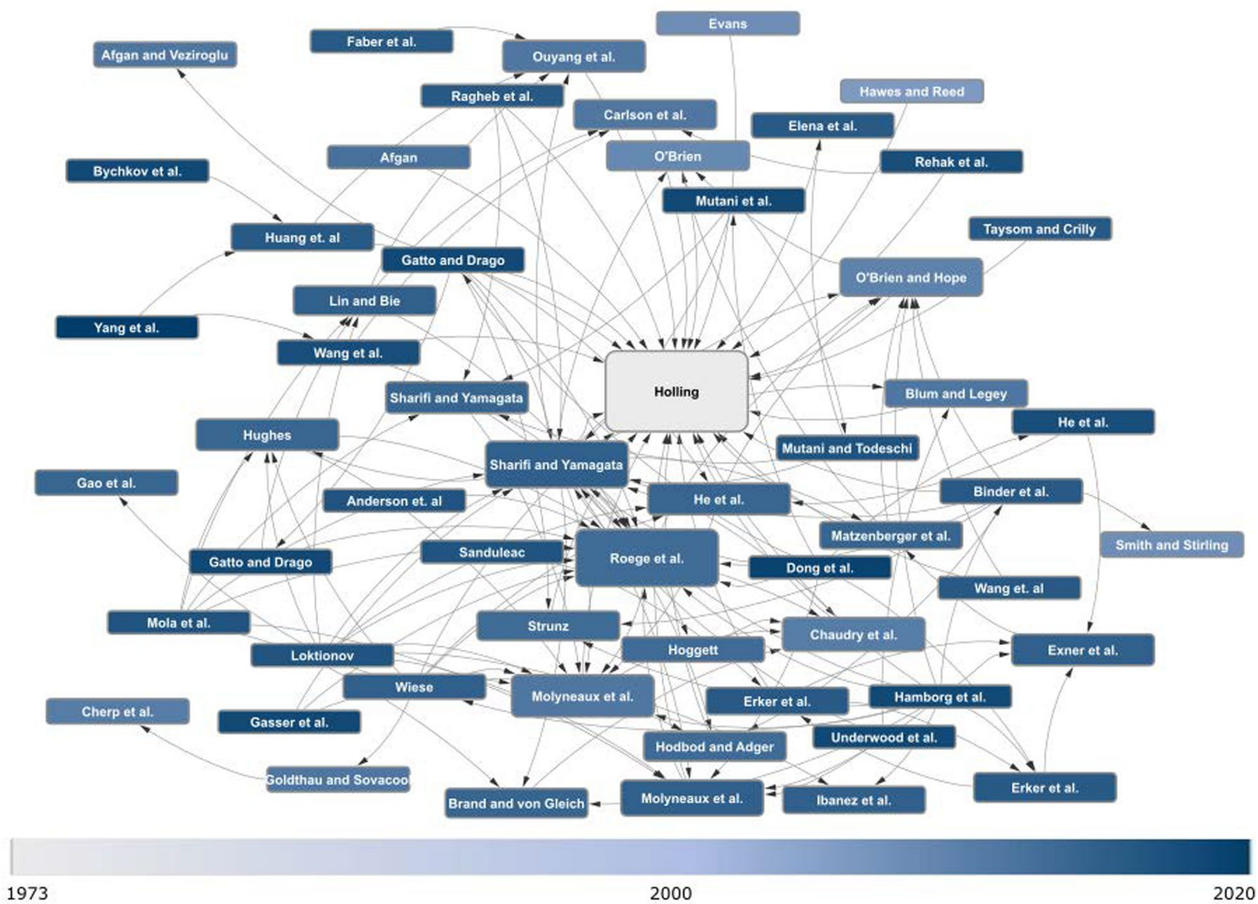

Fig. 6 Citations between the examined articles from the literature review and Holling’s work. The directions of the arrows point from the citing article to the cited source. The size of the nodes shows how often this node is cited by other nodes. The color of the nodes represents the date of publishing, with the oldest papers depicted in grey and the newest papers in blue

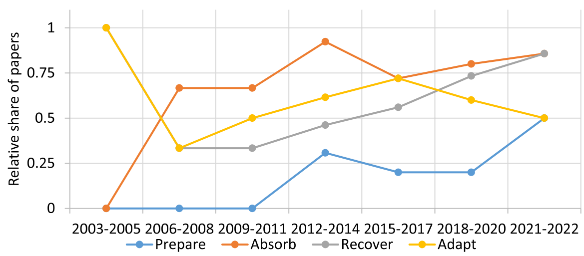

Fig. 7 Relative share of the phases of the resilience function

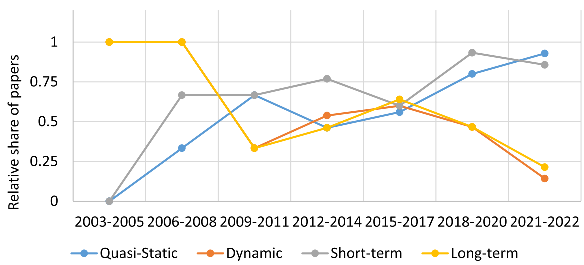

Fig. 8 Relative share of the system categories

phase "prepare". Figure 8 shows the development of the categories "short term", "long term", "quasi-static", and "dynamic".

The correlation between "dynamic" and "long term" as well as "quasi-static" and "short term" can be seen in the other categories. It is evident that in recent years, the focus has shifted towards works that understand resilience more in terms of engineering or ecological resilience. In combination with the above results, it appears that innovation in the field of energy system resilience is expressed mainly by incorporating the "prepare" phase in the understanding of engineering and ecological resilience.

Conclusions

Resilience is a term that has recently risen to prominence in the academic community. In the field of energy system analysis, interest in resilience has also increased in recent years. The increasing number of publications on the topic reflect this.

While resilience as a concept can have a deep meaning and clear relevance for the energy system and the energy transition, the (often unacknowledged) difficulties in transposing it from its original field to the field of the energy system lead to a lack of a common understanding and a lack of precision as to what resilience actually means.

We are aware that the literature research is limited by the selection of keywords and the selection of papers by the ranking of the databases. Nevertheless, we have analyzed almost 140 papers, which is a sufficiently solid sample size to prove that there is no uniform understanding of resilience in the field of the energy system. This is evident from the 71 different identified definitions and that no work in the field of the energy system has been able to establish itself as particularly important in terms of citations. While some definitions only differ in terms of words, others differ in terms of vision and consider different elements of resilience. The most frequently cited work remains Holling's paper. However, his work originated in the field of ecology.

The selected categories for resilience and the energy system underscore their diverse interpretations. While the examined studies emphasize that resilience is primarily an ex post property, the consideration of resilience phases varies. Among these phases, the "absorb" phase tends to receive the most attention.

With regard to the understanding of the energy system, the focus primarily lies on technical aspects. However, resilience is also examined within the realms of economic, ecological, and social aspects. The comprehension of both the energy system and resilience in this context is remarkably diverse, as indicated by the various definitions and categorizations found in the literature.

By linking definitions and respective analyzed systems, we were able to identify trends and recurring elements in the understanding and application of resilience for the energy system. Using previously defined categories of resilience (i.e., engineering, ecological, and adaptive resilience) allows for a broad grouping of diverse interpretations based on identified correlations.

The strong correlation between "recover" and "quasi-static" indicates that for technical systems, researchers use engineering and ecological resilience almost exclusively. Similarly, the correlation between "adaptive" and "dynamic" suggests that scientists use adaptive resilience for an energy system in transition. In many cases, however, these terms are not used by the authors. In addition, there is a limited trend over time which shows that a "static" and "short-term" understanding is increasingly used compared to a "dynamic" interpretation of resilience.

In conclusion, we have shown that a diverse understanding of resilience exists in the field of the energy system. One challenge for the application of resilience to the energy system is the lack of a single, clear definition. Since resilience is always a problem-specific property, such a definition would have to strike a balance between being too general, and therefore meaningless, and being too specific, and therefore too restrictive in its application. While the three above-stated concepts (engineering, ecological, and adaptive resilience) can be seen as special cases for contextualization, a general definition needs further discussion, which this paper aims to initiate. In our paper, we focused on comprehending resilience within the context of the energy system. Given the highly context-dependent nature of the resilience concept, additional research is needed to explore how other factors (e.g., the characteristics of the disruption) impact the overall understanding of resilience for the energy system.

Based on our research, we urge authors of work on resilience for the energy system to clearly state which type of resilience is being used, i.e., engineering, ecological, or adaptive. A good example is Senkel et al. [43], who first list the different types of resilience and then clearly state that their approach to energy system resilience is based on engineering resilience. In addition, authors should either refer to an existing definition and place it in the context of their work or create their own working definition of resilience for the context of their work. Together with the findings of our analysis, these recommendations should lead to a clearer, more concise understanding and application of resilience for the energy system in the future.

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

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Author contributions
All authors contributed to the conceptualization of the study. BJ developed the methodology, collected the data, and conducted the analysis. BJ prepared the original draft, supported by GK. All authors helped to write and review the manuscript. GK and VK supervised the study. All authors have read and approved the final manuscript.

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Declarations

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