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Review

Energy system resilience: Formulating a guiding concept for energy policymaking

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ABSTRACT

This paper aims to define energy system resilience (ESR) in a way that can guide energy policymakers in designing, maintaining, and improving energy systems. The concept of resilience has become increasingly popular in the last two decades. Particularly in energy system design, the term ESR – sometimes synonymously called energy resilience – often appears in academic works and public policy domains alongside themes such as energy sustainability, energy transition, etc. However, the literature rarely provides a normative goal for ESR, such that it is not sufficiently action-guiding for energy policymaking. In this work, we define ESR in a way that incorporates technical characteristics, socio-technical means, and an ethical goal. Beginning with the general conception of resilience as 'bouncing back', and tracing how resilience is used in energy systems, we then illustrate how ESR is used across the literature, analyse a selection of studies which provide explicit ESR definitions, and formulate a new comprehensive definition. Containing technical characteristics, socio-technical means, and an ethical goal, we define ESR as the readiness of an energy system to bounce forward amidst anticipated and unanticipated disruptions in order to provide a sufficient and stable energy supply through reliable engineering techniques, efficient management, and conducive social institutions. We then operationalise this comprehensive definition in energy policymaking. Finally, we provide a summary of this paper and indicate what might limit the impact of its findings, namely, that ESR is but one aspect to address in energy system design.

1. Background: applying the notion of resilience to energy systems

In October 2022, the European Parliamentary Research Service issued a briefing titled *Energy Policy in The National Recovery and Resilience Plans*. Its objective is to formulate national as well as cross-border strategies among the member countries to "provide households and businesses with secure, sustainable, competitive, and affordable energy" [1]. However, despite the title suggesting resilience as a guiding concept in ensuring secure, sustainable, competitive, and affordable energy, the document neither elaborates what resilience is as a concept nor explains its significance in achieving the said objective. On the academic front, particularly in energy social science and energy engineering, across the literature on energy system resilience (ESR), there is more emphasis on technical and social strategies to build a resilient energy system, and less on what ESR actually means[1] and how it could be operationalised in policymaking. This paper fills the theoretical gap by showing how a definition of ESR can be constructed such that it could guide policymakers in designing energy systems.[2]

This article aims to understand how the notion of ESR could be defined in a way which includes the desired technical characteristic of resilient energy systems, the socio-technical means to achieve it, and its ethical goal; and how this comprehensive definition could be operationalised in energy policymaking. We see resilience as a desirable component of energy systems supported by socio-technical means and this is shown in the literature in this study. Yet the ethical reason for its desirability is lacking despite it being crucial in socio-technical systems such as energy. We therefore provide ethical goal as a condition to its

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[1] For a practical reason, Peterson et al. [2] argues that a definition of resilience is not required by critical infrastructure operators. That said, we would argue that in energy policymaking where academic work often takes place, conceptual clarity is important, particularly in evaluating why a policy should take priority more than others. A guiding concept such as this work is one way to provide such clarity.

[2] It is worth noting that philosophy, in particular applied energy ethics, discusses ethical aspects of energy systems in both descriptive and normative sense. See Frigo et al. [3].

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desirability and incorporate it into the notion to guide policymaking.

There have been many angles from which researchers from engineering, social sciences, and humanities talk about the notions of 'resilience', 'energy systems', or both. From 'resilience' alone, dozens – if not hundreds – of usages have emerged. In February 2023, Mentges et al. [4] compile a fifty-page glossary listing 91 definitions of 'resilience' in the context of critical infrastructures along with other terms that often accompany it. In that glossary, 'energy resilience' or 'energy system resilience' does not appear explicitly, even if it is plausible to think of energy systems as part of critical infrastructures. This work appears to be followed up in January 2025 [5] to emphasise the gap between resilience as it is understood and measured. Their proposal to shorten the gap seems to be focused on engineering practice in resilience assessment which suits on-field engineers. In comparison to their recent take, our conceptualisation of 'energy resilience' or 'energy system resilience' as a guiding concept is directed towards energy policymaking with explicit ethical goal which is absent from Mentges et al.

Before we turn to resilience in energy systems, it is important to note that resilience is not a new scholarly term. As noted by Alexander [6], resilience originated from a Latin word *re-salire* used by classical authors in the sense of 'to leap'[3] or 'to recoil'.[4] However, the more modern, academic, usage of resilience which emphasises the ability to 'bounce back' made its debut in the work of British philosopher, Sir Francis Bacon, in his 1626 *Sylva Sylvarum* [7].[5]

Psychological studies continue the bouncing back idea and integrate ameliorative aspects. Resilience is understood as an individual's ability to survive a shock or trauma and return to the equilibrium state, or even to an improved state, thus reflecting positive adaptation (Fletcher & Sarkar, 2013 [8]) promptly [9,10]. A resilient individual or material can thus recover from external interference and, to a certain degree, resist it.

In material sciences, a resilient material is able "to absorb energy when it is deformed elastically and then recover this amount of energy upon unloading" [11]. Later on, a more systemic application of the concept of resilience was applied to evaluate an ecological system by ecologist C. S. Holling, in 1973. Holling defines resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" [12]. Resilience scholarship such as Abeling et al. [15], Eberspächer et al. [16], and the National Academies of the United States [17], consistently refer to Holling's understanding of a system's resilience.

In energy systems research, resilience is also used by energy engineers to assess energy systems, hence specifically applying the concept to energy systems instead of to a psychological state or environmental context. Engineers often use resilience approach to evaluate how an energy system technically absorbs and withstands external damage, maintains a certain level of performance during disruptive events, and recovers post-disruption [16,18–21]. Researchers such as Coaffee and Lee [22] label the resilience approach as a 'surprise-based' approach.

Social science and humanities researchers seem to view energy systems' resilience from social and political aspects, such as governance, international relations, or public acceptance [23–25]. Espinoza et al. [26] states that resilience is "the ability of a power system to withstand initial shock, rapidly recover from a disruptive event, and apply adaptation measures for mitigating the impact of similar events in the future". Roege et al. also propose a more compact definition of resilience, being "the ability of a system to recover from adversity" [27]. Different components highlighted in the resilience approach suggest that resilience can indeed be used to evaluate energy systems' performance during and after disturbances.

Various resilience approaches in energy systems indicate that there is no consensus in how to conceptualise resilience. Furthermore, what constitutes energy system resilience differs depending on the context of the energy system. The United States Military Code, for instance, conceptualises 'energy system resilience' or 'energy resilience'[6] as an instrument for *energy security* in the context of military operations [29]. Outside the military context, research centres such as the United States' National Renewable Energy Laboratory (NREL) calculate its resilience utilising probabilistic risk assessment [30–34], quantifying a system's resilience in terms of dollars lost per hour of outage. These applications suggest that ESR can be fruitful in engineering practice as well as for public policy in energy systems.

From the idea of energy systems' ability to bounce back, three things are important concerning 'energy resilience' or 'energy system resilience'. *First*, bouncing back could mean either returning to the exact previous state or improving the system during the disruption time to avoid system failure. *Second*, in resilience, there is a notion of preparedness for disruptions or unwanted situations, anticipated or not. *Third*, resilience is closely linked with security of supply, which implies the availability-reliability of energy supply.

To aid the discussion and avoid confusion between 'energy resilience' and 'energy system resilience', from this point 'energy system resilience' or ESR is used; where only 'resilience' is used, it also refers to ESR. Furthermore, to facilitate the reading, when talking about energy systems, we are mostly providing examples from power generation with its transmission and distribution for domestic and/or industrial use, even though policymaking in non-electric applications of energy systems also benefit from our conceptualisation.

This article is structured as follows:

Section 2 briefly provides literature research methods used in this paper: scanning 511 abstracts which results in a list of existing ESR definitions drawn from 28 studies. Section 3 addresses the main question: How could we define ESR in a way which includes social and technical aspects of a resilient system, while normatively guiding energy policymaking? Section 4 discusses how the proposed full definition of ESR can be operationalised in energy policymaking to design, maintain, and improve an energy system. The paper concludes with a brief summary, limitations, and indications for potential further research.

2. Method

The literature research on ESR (Fig. 2 in the Appendix section) follows the method proposed by Page et al. [35]. The search terms are based on the keywords found in the title, abstract, and author keywords downloaded from Scopus and the Web of Science. Inputs for both websites are the same, namely 'energy system' AND 'resilience understanding' under category "topic" in the Web of Science, and under category "title, abstract, keywords" in Scopus. The search was conducted on May 12, 2023. The decision to choosing 'resilience understanding' instead of 'resilience definition' was taken in order to capture papers which define resilience in or of energy systems without explicitly labelling it as such. After removing 248 duplicates, a total of 743 articles were compiled as a dataset. Further removing the papers with abstracts that do not touch on energy systems, such as those from medicine,

[3] "*…quanto minus quam in templum resiluit?*" (*Seneca the Elder, Controversiae* 1.3.4.).

[4] "*Sagitta in lapidem numquam figitur, interdum resiliens percutit dirigentem*" (Jerome, *Epistulae* 52.14 Jerome, Saint, Epistulae. Selections., Ad Nepotianum Phesbyterum, section 14 (tufts.edu)).

[5] "And if you strike a ball sidelong, not full upon the surface, the rebound will be as much the contrary way: where there be any such resilience in echoes, that is, whether a man shall hear better if he stand aside the body repercussions, than if he stand where he speaks, or anywhere in a right line between, may be tried." [7].

[6] 10 U.S. Code § 101 with the number 10 referring to the tenth title in the fifth supplement of the 2006 edition of the U.S. Code. This supplement was added in 2011, effective as of January 3, 2012, and regulates matters related to the United States Armed Forces' military facilities and its operations [28].

oceanography, agriculture, and so on, reduced the number to 511 papers, of which 93 characterise what resilience is without labelling this as a 'definition'. While these 511 studies are enough to search for trends via keywords visualisation, (Fig. 3 in the Appendix), systematic analysis requires not only that the abstracts contain some characterisation of resilience, but also that the articles specifically explain what resilience of energy systems is. Further engagement with the 93 studies yielded only 28 studies which included an ESR definition. The results from these 28 studies and my full definition of ESR are provided in Section 3.

3. Fully defining energy system resilience (ESR)

In this section, we reflect on how ESR is addressed across scholarly works, and develop a full definition of ESR, which contains a technical characteristic, socio-technical means, and an ethical goal. This analysis addresses the aim: to define ESR in a way which includes social and technical aspects of a resilient system, while normatively guiding its designers, particularly, but not limited to, policymakers and engineers.

3.1. Classifying definitions of energy system resilience

Table 2 in the Appendix lists 28 studies which include an explicit ESR definition, either provided by the authors or by referring to an existing definition. While most of the studies regard ESR as technically constructed (26/28), views that regard it as socially constructed also comprise a majority (17/28). Meanwhile, energy systems' behaviour under stress is included in all papers (28/28), as bouncing back, maintaining services, absorbing damage, and so on. However, only a minority of studies contain explicit mention of ESR as instrumentally desirable (9/28). The following reflection can be inferred from Table 2.

ESR's technical characteristic is centred around recuperative behaviour under stress or disruption. The studies unanimously agree that defining ESR must include energy systems' expected behaviour or performance during disruptions. Examining Table 2 more closely, different types of disruptions or disruptive events across the studies can be natural or human-made. Meanwhile, details of energy systems' expected behaviour differ slightly from one definition to another, from being able to bounce back, maintaining services or/and performance, absorbing damage, to recovering from disruption, and so on.

ESR includes socio-technical components. That ESR is a technical and/or social feature of energy systems appears to be acknowledged across studies. While there are more studies including ESR's technical components than its social components (26/28 to 17/28), including social and technical components in our comprehensive definition will still align with the trend across studies. Technical components include engineering strategies to enable energy systems to avoid system failure, recover, and improve their performance after disruptive events. Meanwhile, social components include interpersonal, management, or even governmental strategies in enabling energy systems to achieve the same behaviour surrounding disruptive events.

ESR is not a goal in itself. While energy systems' behaviour under stress and an emphasis on both social and technical components are apparent across the studies, the same trend cannot be seen regarding ESR's normative goal. By this, we mean the idea that ESR is desirable in pursuit of another goal instead of being desirable in itself. Out of 28 studies with an ESR definition, only nine contain further goals for a resilient energy system. Some of these goals are more concrete, while some are more abstract. For instance, reducing net-economic and societal consequences associated with grid outages [36] is more concrete than enhancing individual well-being and capability [37]. That said, none of the goals proposed by these nine studies are integrated into their definitions of ESR. We argue that integrating an ethical goal into the definition of ESR is important for policymaking because it will provide policymakers with a clear reason to achieve the resilient state of energy systems as described. An ethical goal situates ESR as means to achieve something instead of an end in itself.

3.2. Defining energy system resilience

The discussion has identified three important components to include in a more developed definition of ESR: energy systems' desired characteristic indicating resiliency, socio-technical components supporting it, and the ethical goal. The first two are sufficiently highlighted across the included studies, but the latter not as much. In order to make ESR a useful guiding concept, a normative goal is important since it shows the purpose of a resilient energy system for energy policymakers and engineers. In this section, we propose our comprehensive definition of ESR with further explanation about its three components.

Reflecting on the literature analyses in Section 3, we propose to define energy system resilience as:

> The readiness of an energy system to bounce forward amidst anticipated and unanticipated disruptions in order to provide sufficient and stable energy supply through reliable engineering techniques, efficient management, and conducive social institutions.

This full definition contains three components: technical characteristics, socio-technical means, and an ethical goal.

3.2.1. Technical characteristics of ESR: readiness to bounce forward amidst anticipated and unanticipated disruptions

Throughout the studies included in Table 2, poor performance during disruptive events such as regular and/or prolonged blackouts and/or brownouts, grid collapse, or data breaching (for virtual grids) indicates non-resiliency. On the other hand, the terms 'ability' or 'capability' of an energy system and 'bouncing back' are prevalent across the studies.

That said, we will argue that *readiness* to bounce *forward* is more fundamental than the ability to bounce back. In operating and maintaining energy systems, ability implies having the physical means. For example, when there is no sunlight or wind, fossil fuel or nuclear power plants are already installed and ready to intercept. However, some disruptions are simply unanticipated, be it known unknowns such as hacker attacks on a virtual grid, or unknown unknowns, such as a war which disrupts energy supplies. With unanticipated disruptions, known or unknown, the notion of *readiness* for such disruptions is preferable because readiness does not only imply availability of means, but also a disposition to employ these means. An example of this is a passive safety feature in a nuclear power plant which is installed and regularly checked to ensure that a reactor shuts down the moment it becomes unstable. Also, it is important that the disrupted parts of the system are renewed or reinforced to better cope with future disruptions, thus making the idea of bouncing *forward* more appropriate than bouncing back.[7] For instance, necessary outage in a nuclear power plant during regular maintenance could be shortened the next time by increasing work efficiency, or even by introducing modular reactors into the system to allow partial reactor shutdown.

Last but not least, the word 'amidst' emphasises a temporal dimension when disruptions take place. The studies listed in Table 2 vary on when recuperative measures should take place, emphasising prior to, during, and after disruption. In response to this, we choose 'amidst' to flexibly incorporate the temporal frame of disruption to energy systems and the readiness required to spring back and systemically improve. Therefore, we use '*readiness* to bounce *forward amidst* disruptions' instead of 'ability to bounce back from disruptions' in our comprehensive definition of ESR.

[7] While a lot of work on resilience conceptualise it as the ability to bounce back, recent works such as from Jasiunas et al. [38], Niklas et Mey [39], and Sawislak et al. [40] increasingly emphasise the importance of forward looking in resilience, i.e. to improve a system's performance.

3.2.2. Socio-technical means of ESR: reliable engineering technique, efficient management, and conducive social institutions

Seventeen out of twenty-eight of the definitions included in Table 2 regard ESR not only as a technical aspect of an energy system, but also as a social aspect. This is not surprising, considering how energy systems are gradually coming to be regarded as socio-technical systems (e.g., Dodson, 2014 [50], Moallemi et al., 2017 [51], Lukanov and Krieger, 2019 [52], Romero-Lankao and Gnatz, 2019 [53], Jasiūnas et al., 2021 [54], Yadav et al., 2021 [55], Montoya-Rincon et al., 2023 [56]), such that resilience as one of the desired qualities is also considered as a socio-technical characteristic.

Therefore, we include 'reliable engineering technique', 'efficient management', and 'conducive social institutions' in our comprehensive definition of ESR. Energy systems are technically engineered systems, which is the reason 'reliable engineering technique' is included in the definition. Meanwhile, both 'efficient management' and 'conducive social institutions' are explicitly mentioned as a proposal to flesh out social components of a resilient energy system. Reliable engineering techniques require technical expertise centred on skilful engineers to ensure that the technically engineered system functions as intended.[8] Efficient management concerns the formal hierarchy within the engineered energy system to quickly react to disruptions[9] – e.g. coordination between operators to shut down a nuclear power plant in case of core melting. Conducive social institutions concern societal structure as a whole, such as governmental bodies, research institutes, media, and grassroots activism, which constantly reflect on energy systems' resilience.[10]

3.2.3. The ethical goal of ESR: sufficient and stable energy supply

Only nine out of the twenty-eight studies included in Table 2 provide a normative goal for ESR, and none integrate them into their definitions. For energy policymaking, it is important to integrate an ethical goal into the definition which is neither too broad nor too narrow. In this regard, some normative goals appear too broad, such as increasing individual well-being [37] or improving national security [58]. Meanwhile, some others appear too narrow, such as reducing the net-economic and societal consequences associated with grid outages due to climatological threats [36], ending corporate monopolies in the energy sector [59], and ensuring an equitable distribution of costs and benefits throughout the powersheds of the dams [60]. Resilience is but one aspect among many, and is clearly not a panacea for all energy-related ethical problems. A sizeable ethical goal allows for better understanding on specific ethical problems which it could tackle.

Contrary to the 19 listed studies which do not include a normative component in defining ESR, we propose integrating 'sufficient and stable energy supply' as the ethical goal of a resilient energy system, while realising that the amount of sufficient and stable energy supply may differ across time and place. Regarding sufficiency, scholars such as Barroca [61], Best et al. [62], and Hesse and Zumbrägel [63] highlight the complexity of determining sufficiency, since it involves reducing the amount of our energy consumption in addition to having the energy supply to perform the tasks at hand. However, in the context of Low-and Middle-Income Countries (LMICs) which still struggle to reach full electrification ratio while reducing existing outage frequency, such as Indonesia [64,65], for example, the idea of reducing energy consumption is irrelevant, because developing countries need more energy supply with less volatility for people to perform their necessary tasks. The difficulty of determining a threshold also goes for stable energy supply: the threshold of a stable energy supply can be minimalistic, such as maintaining the minimum supply needed and concentrating it to certain sectors during disruptions, or more ambitious, such as remaining unaffected even during disruptive events. Nevertheless, a sufficient and stable energy supply is important since it allows energy consumers a foundation to live a good life as well as to keep fundamental societal functions working during disruptions. As an ethical goal in policymaking, sufficient and stable energy supply is also a suitable normative component for ESR, since it leaves room for policymakers to either connect it to broader notions or apply measurable indicators for it.

In terms of what makes sufficient and stable energy supply an ethical issue in ESR, we argue that this is due to its relation to vulnerability. There are a number of philosophical reflections on the normative significance of *sufficient supply*, such as Nussbaum's and Sen's capability approach, later applied by Hillerbrand [66–68]. Mazigo and Hatingh [69] also suggest that access to energy helps to maintain fundamental human capabilities and reduce vulnerabilities. If a disrupted energy system results in insufficient supply, then the vulnerable are those who cannot perform essential tasks because there is simply not enough supply. Meanwhile, regarding the normative significance of *stable supply*, there are existing philosophical accounts of energy systems which focus on risks, such as Taebi [70] who addresses the risk from nuclear waste towards future generations, or Kermisch [71] who addresses how to properly define 'future generations' when talking about high-level radioactive nuclear waste. These accounts can give insights about the vulnerable for this analysis. Unstable supply can result from unstable systems overall, and potential problems arising from unstable systems put people at risk. People are vulnerable when they risk being impacted by unstable energy systems due to limitations in engineering or future uncertainties. Combining insights from *sufficient* and *stable* supply, the vulnerable are those who suffer most from the lack of energy supply during disruptions, as well as those who are at risk of being impacted by the shortcomings of energy systems and future uncertainties.

4. Operationalising ESR as a guiding concept for energy policymaking

In this section we lay out how ESR as defined may guide energy policymaking. Following on from the full definition which contains technical characteristics, socio-technical means, and an ethical goal for a resilient system, policymakers could operationalise ESR by the following

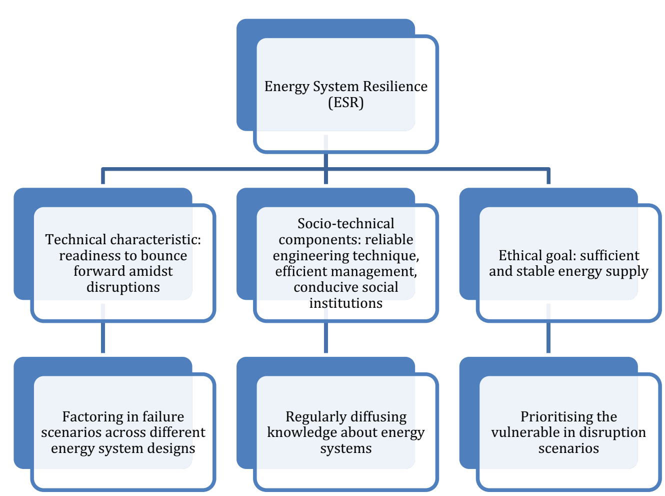

Fig. 1. Operationalisation schema from the full definition of ESR in policymaking.

[8] Engineered energy systems are reliable if they are able to sustain performance when disrupted and could be upgraded over time for better optimisation. See Valente et al. [48], Fälth et al. [49], for instance.

[9] Efficient management could also be something as simple as scheduled supply and demand in the combination of renewable and storage technology to anticipate fluctuating need during regular times. For instance, see Lari et al. [50].

[10] There are some works offering characterisation of how social institutions – including grassroots community and vulnerable groups – interacts to form energy resilience, such as Nazarahari [51–54], Hibbet et al. [55], Ryan et al. [56], and Niklas et al. [57].

Fig. 1. We consider operationalisation for a resilience concept necessary since although some previous works hint at normative elements of ESR (such as Macmillan et al., 2022 [38], Tiwari et al., 2022 [39], Jasiūnas et al., 2021 [47], Kain et al., 2021 [66], Ajaz, 2019 [67], McNally et al., 2009 [68], Kermisch, 2016 [79], Wu et al., 2023 [80], and Zimmy-Shea, 2017 [81]), it is not explicitly stated, leading to unclear application of ESR's normative element. For ESR to be guiding in policymaking, a clear map is required.

4.1. Operationalising ESR's technical characteristics: ensuring a ready-to-bounce-forward energy system by factoring in failure scenarios across different energy system designs

The idea of readiness to bounce forward in designing energy systems accepts that not all disruptions are predictable. Some are simply unknown and can only be reacted to when they happen. With that in mind, instead of listing possible disruptions to the system given its engineering design, or geographical and societal context, policymakers should rather enhance the readiness of energy systems by preparing multiple scenarios of system failures. While probabilistic risk assessments could contribute to estimating the likelihood of disruption, as well as the damage, readying the system to bounce forward requires an emphasis not on the type of likely disruption, but on the result, e.g. blackout, volatile energy price, or grid failure. In this regard, when designing a system, policymakers should already come up with multiple failure scenarios, plan countermeasures when they happen, and revisit them to improve the systems' readiness against disruptions. A real-world example where readiness to bounce forward is lacking comes from the German nuclear phase-out context, where reliance on Russian gas destabilised the nation's energy security when the Russian-Ukrainian war started (Güntner et al., 2024 [76]). Instead of estimating the likelihood of the war, one should rather think of what to do when the Russian gas is stopped or limited, regardless of the cause. Another example comes Fukushima Daiichi nuclear incident where the magnitude and the centre of the tsunami surpassed the nuclear engineers' estimates. In this situation, readiness against disruptions is reflected not in the accuracy to predict the natural disaster, but in the effectiveness of recovery measures against the grid/reactor failure.

Additionally, while resilience research emphasising on social vulnerability becomes increasingly common (e.g. from Ezzati et al. [74], Montoya-Rincon et al. [47], and Flores et al. [75]), we cannot state for certain that such an academic trend reflects common resilience practice in policymaking.

4.2. Operationalising ESR's socio-technical means: achieving reliable engineering technique, efficient management, and conducive social institutions by regularly diffusing knowledge about energy system design

Reliable engineering technique, efficient management, and conducive social institutions are the socio-technical means of a resilient energy system. While energy systems are engineered systems, their readiness to bounce back and improve when disrupted also depends on the knowledge shared between human agents. Diffusing knowledge among engineers could be achieved by ensuring robust training to ensure that they could design and maintain a robust energy system (see Friman, 2024 [77]). Meanwhile diffusion of knowledge outside of energy engineers will ensure that social *milieu*, including governmental bodies and people in general, have the necessary information about the stability of energy systems. It is important for the public to be informed about the type of energy mix they are using, or will use in the future, its efficiency, economic advantages and inconvenience, and its risk. Routine social media campaigns and public forums for educational purpose – which are analysed, among others, by Dias et al. [78,79] – are instances of knowledge diffusion here.

4.3. Operationalising ESR's ethical goal: achieving sufficient and stable energy supply during disruptions by prioritising the vulnerable in disruption scenarios

In achieving or maintaining sufficient and stable energy supply during disruptions, policymakers need to prioritise which sectors they need to attend to and/or list areas which should never be compromised. Such prioritisation could be done by mapping areas with higher vulnerability, namely, areas where lives will be most affected should the energy supply be disrupted. Alternatively, this ethical goal could also apply in the context of building new energy infrastructures to cater for rising demand. In some developing countries' contexts, ESR is viewed as a way to alleviate energy poverty such as Okeke and Onymere [80] who propose the necessity of supply chain resilience. Elsewhere, Chinwego et al. [81] place resilient rare earth recycling industry as part of stakeholder engagement. Consideration on, inclusion and prioritisation of the vulnerable is a way to apply ESR's ethical goal here.

5. Conclusion: summary, limitations, and further research

The purpose of this article was to define energy system resilience (ESR) such that it can guide energy policymakers and engineers in designing, maintaining, and improving energy systems. This has been done through three steps: showing how the notion of 'resilience' is applied to energy systems, formulating a full definition of ESR, and explaining how to operationalise ESR as defined in energy policymaking.

We define ESR as: *The readiness of an energy system to bounce forward amidst anticipated and unanticipated disruptions in order to provide sufficient and stable energy supply through reliable engineering techniques, efficient management, and conducive social institutions.* In this definition, readiness to bounce forward amidst disruption characterises ESR's technical characteristic; reliable engineering techniques, efficient management, and conducive social institutions are socio-technical means to achieve resiliency; and sufficient-stable energy supply is the ethical goal. Policymakers can operationalise this definition by factoring in failure scenarios, regular diffusion of knowledge, and prioritising the vulnerable in case of disruption.

That said, the impact of this study's findings is limited in that resilience is but one characteristic of energy systems. Energy system resilience as defined, along with its operationalisation in policymaking, can only tackle the technical, social, and ethical issues related to disruptions to the system. As such, ESR does not provide a guide to tackle other important aspects in energy system design, such as emissions (environmental aspect) or cost (economic aspect), for instance. Therefore, resilience is but one conceptual tool among potentially many others to guide policymakers in energy decision-making.

Finally, in light of applying ethics to energy systems, defining ESR is a first step to approaching energy system design, and various elements can develop from it. For example, from a philosophical standpoint, more could be said about measures to provide sufficient and stable energy supply during disruptions to reduce vulnerability. In nuclear energy ethics, one could also examine the conceptual contribution of ESR to existing notions such as nuclear safety and nuclear security, for example. Another option could be to examine how the notion of ESR contributes to guide the development of new energy technologies and their integration into energy systems, such as storage, clean coal technology (CCT), and small modular reactors (SMRs).[11] Such discussions require further exploration and will be addressed in future research and publications.

[11] Some studies approach these technologies in terms of strategies to build resilience. See Balducci et al., 2021 [82], Lari et al., 2025 [50], and Wodrich et al., 2023 [83] for instance.

Credit authorship contribution statement

Johanes Narasetu Widyatmanto: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization.

Ethical approval

Not applicable for both human and/or animal studies.

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Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

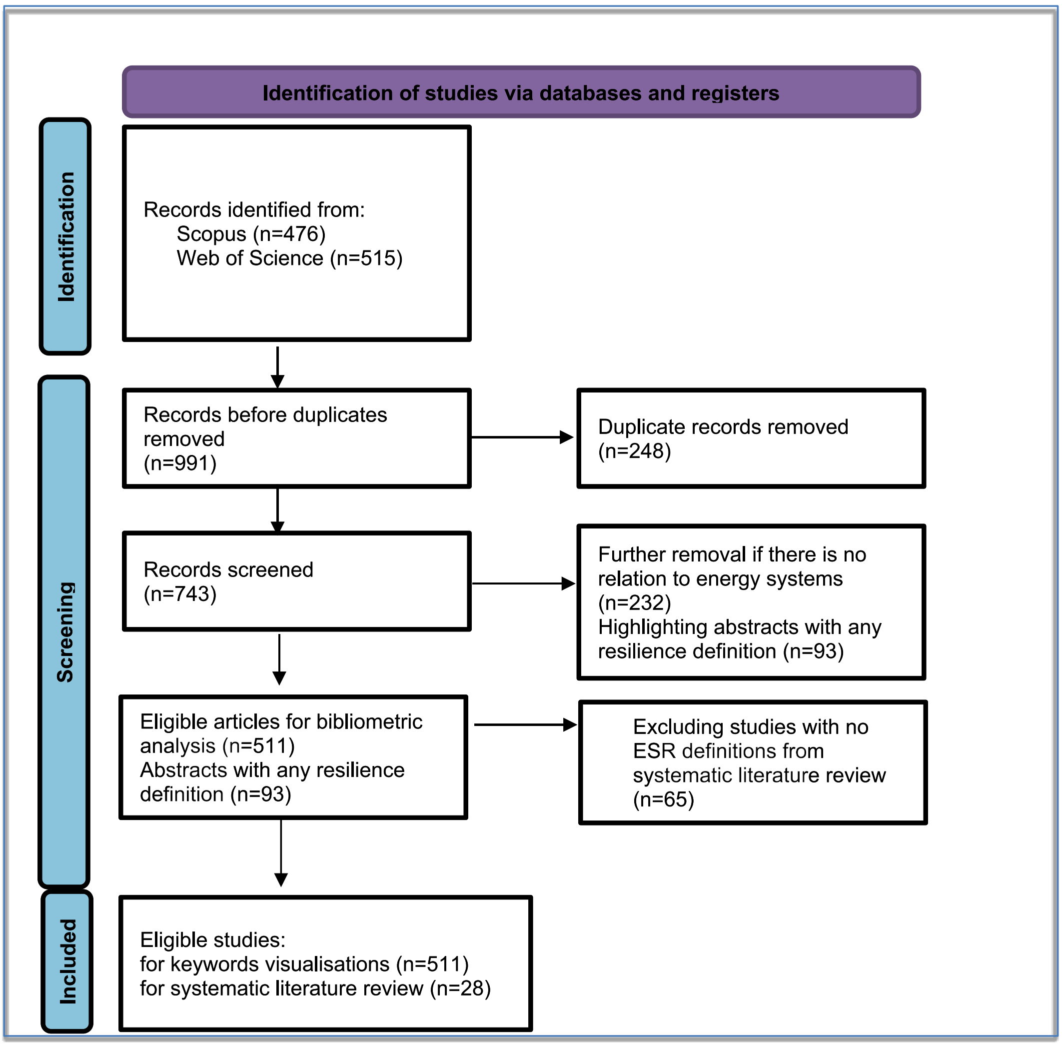

Fig. 2. Flow diagram for literature research [33].

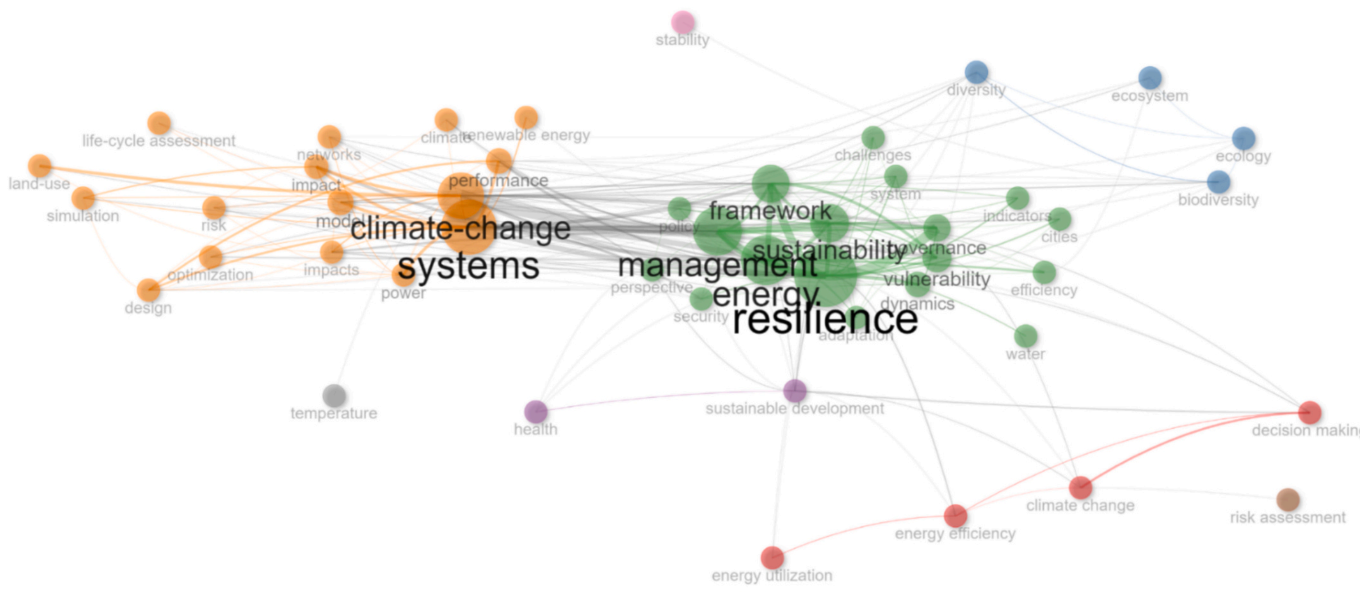

Fig. 3. Network visualisation of keywords from 'energy system' AND 'resilience understanding' entry within 'Topic' from the Web of Science and 'title, abstract, Keywords' from Scopus on May 12, 2023.

Table 1
List of co-occurring keywords in each cluster ordered by appearance frequency.

Clusters (n = 8)	Keywords, in order of appearance frequency (n = 48)
Green (18 keywords)	Resilience, energy, management, sustainability, framework, vulnerability, dynamics, governance, system, security, water, efficiency, policy, cities, perspective, indicators, adaptation, challenges
Orange (16 keywords)	Systems, climate-change, model, performance, design, power, impact, impacts, networks, risk, renewable energy, optimisation, simulation, land-use, climate, life-cycle assessment
Blue (4 keywords)	Biodiversity, ecology, diversity, ecosystem
Red (4 keywords)	Decision making, climate change, energy efficiency, energy utilisation
Purple (2 keywords)	Sustainable development, health
Pink (1 keyword)	Stability
Brown (1 keyword)	Risk assessment
Grey (1 keyword)	Temperature

Table 2
List of 28 included studies with explicit definitions of ESR in the main text. The entries in the column 'Inclusion of behaviour under stress' indicate the behaviour that a resilient energy system should exhibit vis-à-vis disruptions. The entries in the columns 'Inclusion of technical aspects', 'Inclusion of social aspects', and 'ESR's normative goal provided' indicate whether or not the papers regard ESR as a social component of a system, a technical component, or both, and whether or not a resilient energy system has a moral significance.

ESR definitions (n = 28)	Inclusion of behaviour under stress (n = 28)	Inclusion of technical aspects (n = 26)	Inclusion of social aspects (n = 17)	ESR's normative goals provided (n = 9)
Ability of the energy system to prepare and plan for, absorb, recover from, and then adapt to adverse events (Tiwari et al., 2022 [37]).	Yes	Yes	Yes	Yes (enhancing individual well-being and capability)
Ability of power and energy systems to withstand and recover from acute climatological threats, such as severe weather events, while also maintaining their ability to provide reliable and sustainable energy services (Macmillan et al., 2022 [36]).	Yes	Yes	Yes	Yes (reducing the net-economic and societal consequences associated with grid outages caused by acute climatological threats)
Ability to preserve, re-stabilise, adapt, and/or transform (Jesse et al., 2019 [25]).	Yes	Yes	Yes	No
Ability of energy systems to withstand shock; to adapt to shock in order to provide an available, accessible, affordable, and acceptable energy supply; and to learn from that shock to increase coping capacity (Underwood et al., 2020 [84]).	Yes	Yes	Yes	Yes (providing an available, accessible, affordable, and acceptable energy supply)
Ability of the power distribution grid to withstand and recover from disruptions caused by natural disasters (Galvan et al., 2020 [85]).	Yes	Yes	No	No
Ability of the system to deal with low-probability events with severe destructive effects by using an efficient method in such a way that the minimum possible load is interrupted and the	Yes	Yes	No	No

(continued on next page)

Table 2 (*continued*)

ESR definitions (n = 28)	Inclusion of behaviour under stress (n = 28)	Inclusion of technical aspects (n = 26)	Inclusion of social aspects (n = 17)	ESR's normative goals provided (n = 9)
system quickly returns to normal operation (Younesi et al., 2022 [86]).				
Ability of power systems to prepare for, absorb, adapt to, and recover from long-duration, high-cost outages caused by natural disasters (Anderson, 2021 [31]).	Yes	Yes	No	No
Ability to prepare for and anticipate disruptions, absorb the impact of disruption and minimise damage incurred, adjust operations and adapt to changing conditions, and recover operations to either return to the original state or achieve a new steady state (Chrisandina et al., 2022 [87]).	Yes	Yes	Yes	No
Ability to maintain its functionality even when affected by disturbances/shock (Ioannou and Laspidou, 2022 [88]).	Yes	Yes	No	No
Ability of an energy system to support critical loads before an event, during an event, immediately after an event, and in the recovery from an event back to a normal operating state (Kain et al., 2021 [58]).	Yes	Yes	Yes	Yes (national security)
Ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions; also ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents (Ajaz, W., 2019 [59]).	Yes	No	Yes	Yes (end corporate monopolies in the energy sector)
Ability of an energy system to withstand and recover from disruptions or disturbances (Jasiūnas et al., 2021 [38]).	Yes	Yes	Yes	Yes (reducing economic loss and social costs caused by power outages)
Capability to suitably resist and subsume flexibly (Sonal and Ghosh, 2021 [89]).	Yes	Yes	No	No
Ability to prepare, absorb, recover from, and adapt to unexpected events (Wu et al., 2023 [72]).	Yes	Yes	Yes	Yes (energy security)
Ability of the system to speedily respond to and/or recover from a disturbance (Månsson et al., 2014 [90]).	Yes	Yes	No	No
Complex human-environmental system's ability to adapt to permutations and change within these systems (McNally et al., 2009 [60]).	Yes	Yes	Yes	Yes (ensure an equitable distribution of costs and benefits throughout the power sheds of the dams)
Ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions (Venkataramanan et al., 2019 [91]).	Yes	Yes	No	No
Organisational ability to respond or 'bounce back' from untoward, surprising or disruptive events (Grabowski and Roberts, 2019 [92]).	Yes	No	Yes	No
Ability of a system to overcome changes in its surroundings so as to maintain operation (Gerbaud et al., 2020 [93]).	Yes	Yes	No	No
Ability to have uninterrupted supply, maintain system stability, and avoid system failure (Zuo and Wu, 2022 [94]).	Yes	Yes	No	No
Ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions; in this paper's context, it is the ability to respond to long duration outages (Marqusee and Jenket, 2020 [95]).	Yes	Yes	No	No
Ability of a socio-technical system to maintain its services under stress and in turbulent conditions (Their and D'Or, 2020 [96]).	Yes	Yes	Yes	No
Ability to persist, adapt, and transform amidst disruptions (Voisin et al., 2019 [97]).	Yes	Yes	Yes	No
Ability of an entity or system to maintain function (e.g. continue producing) when shocked (Matzenberger et al., 2015 [98]).	Yes	Yes	Yes	No
Ability of an energy system to resist disruption and recover quickly after a disaster event (Zimmy-Shea, 2017 [73]).	Yes	Yes	Yes	Yes (improving community resilience)
Ability of the power grid to quickly recover and restore critical services in the case of disruptions, both natural and manmade (Egbue et al., 2016 [99]).	Yes	Yes	No	No
Ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially catastrophic event (Eshghi et al., 2016 [100]).	Yes	Yes	Yes	No
Intrinsic ability of a system to adjust its operation prior to, during, or following changes and disturbances, so that it can sustain required operation under both expected and unexpected conditions (Kim et al., 2018 [101]).	Yes	Yes	Yes	No

Data availability

No data was used for the research described in the article.

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List of abbreviations

ESR: energy system resilience
DLR: Deutsches Zentrum für Luft- und Raumfahrt
NREL: National Renewable Energy Laboratory
CCT: clean coal technology
SMRs: small modular reactors