

Designed for a secure transition – a systematic review of supply security in energy system models

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ABSTRACT

While renewable electricity has gained traction, the transition to a low-carbon energy system is still subject to large uncertainties about future energy use and supply portfolios. In the light of recent disruptive events such as geopolitical tensions and trade restrictions, it is evident that energy transition strategies should consider unforeseen disturbances. In this paper, we conduct a systematic review of 179 energy system modelling studies from Scopus and Web of Science based on the PRISMA guidelines. We include articles considering various aspects of energy security, focusing on large-scale system models with a long-term techno-economic design perspective. Our analysis reveals significant variation among studies in three key areas: the security aspects evaluated, the types of disruptions considered, and the methodological approaches employed. While weather variability is commonly examined, other security threats such as climate change or geopolitical disruptions receive less attention.

1. Introduction

With global energy-related greenhouse gas emissions at a record levels [1], alarming rates of ecosystem degradation [2] and increasingly devastating impacts of climate change for communities worldwide [3], we are in urgent need of a swift transition to a more sustainable mode of living. The rapid expansion of renewable electricity sources has begun to transform the energy sector [1]. At the same time, the shockwaves of recent geopolitical crises such as the Russian military aggression against Ukraine [4], US-Israel attacks on Iran [5] and tensions between the US and Europe [6] are putting the transitioning energy systems to a test. The notion of “energy security” is invoked both as a challenge to the renewable energy transition, referring to e.g. the changes required to cope with variable energy sources and new dependencies on critical materials, and as a benefit in connection to reduced dependence to fossil fuels [7].

1.1. Conceptualization of energy security

While the energy security concept has been used for decades, the practical interpretations vary widely, ranging from the mere availability of energy at any time to understandings involving e.g. environmental,

social and economic aspects [8]. A variety of indices have been constructed and employed in attempts to quantify different perspectives on energy security [8,9]. Their diversity demonstrates that no coherent understanding of the meaning of energy security is established in the literature.

A much referenced definition of energy security is “uninterrupted availability of energy sources at an affordable price”, as stated by the IEA [10]. However, Cherp and Jewell [11], drawing upon the work of Baldwin [12], argue that a definition of energy security should address at least three fundamental questions:

- “Security for whom?”
- Security for which values?
- From what threats?”

Applied to the IEA definition, these inherently normative questions reveal that energy security often leaves room for different interpretations about whom energy should be affordable for and in which situations energy should be available without interruption. Other scholars have also described energy security as a relative rather than an absolute state [13].

The conception “low vulnerability of vital energy systems” offered by

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Cherp and Jewell [11] allows for a broader understanding of energy security, encompassing dimensions identified in many recent studies [8, 14] beyond the availability- and affordability-focused definition of the IEA. Vulnerabilities are understood to emerge from the combination of risks and the resilience of a system, while vital energy systems are thought to be energy systems that support critical social functions [11]. Because both the relevant risks and the critical social functions must be defined for each context under consideration, this accommodates a wide range of more specific approaches to energy security. We therefore adopt this conception as the overarching understanding of energy security in this review, which encompasses studies with very different contexts and understandings of energy security. We do however acknowledge that while the adoption of a harmonised definition could be beneficial, no existing definition has been adopted universally, and other, more specific definitions may be more fit for other purposes. Finding a suitable universal definition for energy security is out of the scope of this review.

Several concepts, such as *resource adequacy*, *reliability*, *security of supply* and *resilience*, are often used in connection with energy security. These terms describe the vulnerability of energy systems with focus on different timescales and system boundaries. Here, we will briefly discuss each of them.

Resource adequacy or system adequacy is a prevalent term in energy systems analysis. This concept is usually much narrower than energy security and is formally established e.g. through its use in the European Resource Adequacy Assessment (ERAA) [15], which investigates the ability of the European electricity system to fulfil all expected demands under a range of circumstances.

Reliability is a similar concept, also referring to the fulfilment of demands. Drawing upon previous work by multiple authors, Schmitz et al. [16] position reliability as the short-term probability of fulfilling energy demand, in contrast to adequacy, which is seen as a long-term aspect.

Reliability and resource adequacy can be used to constitute *security of supply*, which is seen as one aspect of the broader concept of energy security [16]. Security of supply often relates more strictly to the availability of energy than energy security [e.g. in 14,17] but the terms are also subject to overlapping use [e.g. in 18,19].

Resilience is also a prevalent term in connection with security. The term has, in the context of energy systems, often been used with a rather technical understanding that relates to the system springing back to its original state after a shock, sometimes called engineering resilience [20]. Socio-ecological approaches expand beyond this robust capacity to include adaptability and transformability as part of resilience [20,21]. Energy system resilience can be framed as aspect of energy security [11, 16]. On the other hand, following the socio-ecological perspective on resilience, energy security would be one of many aspects of societal resilience.

A common denominator of the concepts is that they describe the reaction of a system to disruptive events, which is at the core of the concept of vulnerability. Disruptive events can be separated into shock events and stresses (or slow-burn processes), referring to the different temporal patterns [11,16]. Wijesinghe et al. [22] instead use the cause of the disruption to identify four types: Natural, human-caused intentional, socio-political and economic.

1.2. Energy security in the energy system modelling context

The transition to a more sustainable energy system will fundamentally alter both the composition and operation of energy infrastructure. Since implementing and testing full-scale design proposals is infeasible, one alternative is to study system models instead. For decades, various types of energy system models have been used as tools for studying different development pathways [23]. These models are viable tools to examine energy security in systems that have not yet been realised.

It should be noted that energy security is closely related to

uncertainty and risk in the conditions that a future energy system will operate under. Uncertainty assessments are often part of studies on energy systems through the use of sensitivity analyses, but also more formal approaches such as stochastic optimization, Monte Carlo analysis, robust optimization or modelling to generate alternatives [24]. It is infeasible to review all publications utilizing these uncertainty investigations in a non-automated way. This review therefore focuses on papers with explicit security emphasis, including uncertainty-related methods only when authors explicitly connect them to energy security or reliability.

Several comprehensive reviews have been conducted with emphasis on conceptualization of security [e.g. 14,16] or security indices [e.g. 8, 9] but without a focus on modelling approaches. On the other hand, reviews with emphasis on energy system modelling approaches but not security are also established in the literature [e.g. 23–25]. The novelty of this review is the intersection between the security and energy system modelling realms. Although security-related aspects in energy systems analysis have gained attention through recent geopolitical events, to the best of our knowledge, no systematic assessment of the diversity of security-related approaches in energy system modelling has yet been conducted.

1.3. Aim of this review

In this paper, we present a systematic review of 179 energy system modelling approaches, pursuing the following research questions:

RQ1. Which aspects of energy security and supply security are investigated in energy system modelling studies for the low-carbon transition?

RQ2. By which methods are energy security and supply security during the transition to a low-carbon energy system assessed in the energy system modelling context?

The scope is further limited to international, national or large regional models, as opposed to models of cities, industrial parks or building complexes. This focus is aligned with security policies which are usually aligned with national energy systems, same as energy reserves and import routes which are critical for energy security. Furthermore, we limit results to studies with a techno-economical system design perspective, as opposed to a pure focus on market design, supply chains or operational aspects.

2. Method

This section details the PRISMA-compliant review methodology, followed by a brief discussion of methodological limitations.

2.1. Review methodology

This review is based on the PRISMA guidelines [26] to secure transparent documentation. An illustration of the source selection process is shown in Fig. 1. The search was conducted on the academic databases Scopus and Web of Science, using the 21st of April 2026 as limit for the new database entries. The databases were used to achieve a wide coverage of entries while limiting the search to peer-reviewed publications. The search string is divided into components aimed at different aspects of the scope and shown in Table 1. Following the conceptual discussion in section 1.1, energy security aspects are searched via the different related terms listed there, acknowledging that some of these terms will generate results focusing on just one aspect of energy security (e.g. supply security).

The proximity operator *W/4* is used to cover terms such as “security of low-carbon energy supply”, where is sufficient for the words “security” and “supply” to be within 4 words of each other. Generally, the vague and multifaceted nature of the energy security concept made it

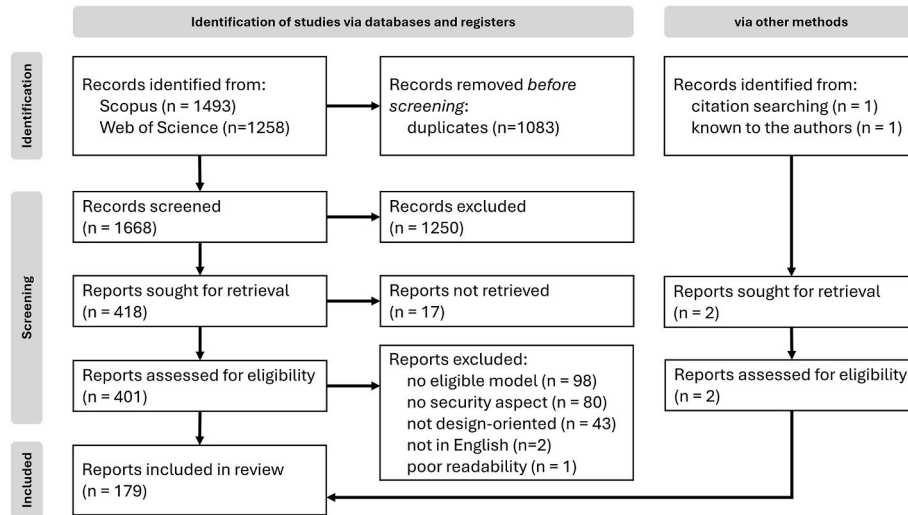


Fig. 1. Overview of the PRISMA-compliant review process applied to this study. Modified from Page et al. [26] under CC BY 4.0 license.

Table 1

Search string components used in Scopus for this review. The search string in Web of Science did use the equivalent operators NEAR/4 instead of W/4 and TS = instead of TITLE-ABS-KEY. Both searches were also restricted to the document type “article” and to entries added before 22nd April 2026.

aspect to be covered	string
	TITLE-ABS-KEY ((
energy security aspect investigated	((adequacy OR security OR robustness OR robust OR resilience OR resilient OR reliability OR reliable) W/4 (energy OR supply OR system OR generation OR resource))
system perspective	AND (“energy system” OR (energy W/4 (transform* OR transition OR pathway)))
low-carbon transition perspective	AND (“net zero” OR “carbon neutral*” OR “climate neutral*” OR “low carbon” OR decarboniz* OR sufficien* OR (future W/4 system) OR “just transition” OR “green transition”)
model use	AND (model* OR optim*)
large system	AND NOT (microgrid OR “off grid” OR “small island” OR urban))

hard to collect relevant papers in a search string with high specificity. Initial attempts to find search strings excluded too many relevant papers that we already were aware of. To avoid cutting out too many results from the start, a very broad search string with many synonyms was used, resulting in a high number of papers that were manually discarded during screening.

The results were first screened by their abstracts by one author, considering the following criteria:

1. Energy security in the meaning of the adopted definition from section 1.1 should have been analysed, including focused studies on supply security, system adequacy, reliability, and energy system resilience.
2. Studies should have a low carbon design perspective, marked by the consideration of multiple configurations of a future energy system with different generation technologies, at least one of which should lower the greenhouse gas emissions of the system. Pure considerations of market or policy design are excluded, as well as purely operational optimisations.
3. Studies should include energy system models of large systems. In this study, large systems were identified by a peak demand above 1 GW. This threshold was chosen to exclude most municipalities and industrial parks while including most national and large regional studies aligning with the focus of this study.

Concerning the first criterion, during abstract screening, it was considered enough if studies made a connection between study results and energy security, e.g. “the resulting scenarios are assessed through a number of indicators on affordability, supply-security and sustainability.” [27]. However, in many cases, energy security was only mentioned as motivator or relevant context for the results, e.g. “the findings underscore the need for continued research [...] to optimize these fuels, ensuring their contribution to a cleaner, more resilient energy landscape” [28]. These studies were excluded. Additionally, a high number of studies concerned much smaller energy systems than targeted by this review. In total, of the 1493 records identified by the initial search, 1108 were excluded during abstract screening. Of these, 685 did not contain an eligible model, 229 had no security focus and 170 were not design-oriented. 26 documents were excluded because they were other document types than original research articles, such as reviews or editorials. 4 records were excluded because they had been retracted.

Following the abstract screening, full texts were retrieved and reviewed by one author. 368 out of 385 studies could be retrieved. One additional study was identified through citation searching in the retrieved studies, and one study was identified through the authors’ prior knowledge but did not appear in the search results. Both were subject to the same eligibility criteria as the other articles. During full-text screening, 224 studies were excluded following the criteria described above. 98 did not use an eligible model following the criteria above. 80 studies lacked a security focus and 43 were not oriented towards low-carbon energy system design. Two studies were excluded because they were in other languages than English, and one study [29] was excluded because the relevant elements of the study were presented in a very low-resolution figure that rendered the contained text unreadable. Because each study was assigned a single exclusion reason, these categories are not mutually exclusive.

2.2. Limitations

This study is subject to several methodological limitations. Among these is that the screening and eligibility assessments have been conducted by a single researcher, introducing reviewer bias. To mitigate this at least partially, we defined transparent inclusion criteria. However, it is possible that some eligibility decisions would have been different if multiple researchers had reviewed each decision. Another limitation is the focus on articles in English, potentially excluding interesting results written in other languages.

3. Results

In the following section, we first outline the temporal and regional scope of the eligible studies. Next, we analyse the security aspects and disruptive events considered. Finally, we review the methodological approaches and modelling choices employed. The underlying classifications can also be found in the supplementary material (Appendix A).

3.1. Temporal and regional scope of eligible studies

The screened results show a strong uptake in publications since 2020, as can be seen in Fig. 2. This should be seen in relation of the overall uptake in publications since 2020.

Fig. 3 shows the geographical scope of the eligible results. While countries from Africa, East Asia, Central Asia and South America have been subject to very few studies, most focus on Europe, China and the US. Germany, the UK, Poland, France, Finland, Belgium, Sweden, Spain, Italy, Switzerland, China and the Netherlands were subject of more than 25 studies each. Most studies ($n = 99$) model a single country,¹ fewer ($n = 36$) model multiple countries, with most focusing on Europe. As a special case, 4 studies fully model multiple countries but focus on a single country in the evaluation. Some studies consider subnational regions ($n = 26$) and only very few ($n = 7$) model the global energy system.² Furthermore, some studies ($n = 7$) are conducted on synthetic systems without the intention to depict a real-world region.

3.2. Aspects of energy security

A variety of security-related aspects is investigated in the eligible articles. This section reviews aspects that are explicitly linked to energy security, reliability or adequacy by the respective authors. An overview can be found in Fig. 4.

The most investigated aspect is energy not served (ENS) [e.g. in 30–33], meaning the energy quantity demanded but not delivered. This term is sometimes described as loss of load, load shedding or demand not supplied. It is closely connected to the loss of load expectancy (LOLE) [e.g. 34] or loss of load duration (LOLD) [e.g. 35] which describe the time during which some energy demand is not met. The loss of load probability (LOLP) [e.g. 36] describes the probability of LOLE for a given time period. Finally, the loss of load frequency (LOLF) [e.g. 37] measures the number of occurrences of unmet demand per time period. All measures of lost load have been counted as part of the same aspect here.

A related, less common measure is the ENS cost, meaning the cost caused by demands that could not be met [e.g. 38,39]. This aspect is connected to the assumption of a value of lost load (VOLL), which will be discussed in section 3.3.3. Opposed to this, the cost of ENS abatement seen in only few studies [e.g. 40–42] measures the extra cost incurred by forcing the system to fulfil all demands.

The *capacity margin* or residual load measures the difference between load and maximum available capacity [e.g. 43–46], where the latter in some cases is restricted to only firm or only variable technologies. Residual load can be evaluated at different points, e.g. at the highest need for dispatchable technologies or flexible demand [47]. In some cases, a reserve margin is subtracted from this difference as a measure to increase security of supply [e.g. 30]. In the context of system margins, many studies also evaluate the *backup capacity built* [e.g. 48–50]. Sometimes, a margin for transmission capacities is also analysed in the form of *congestion* metrics, such as line utilization [e.g. 51–53] in electricity systems or pressure swings and pressure violations in gas systems

[e.g. 33,54].

Some studies apply measures of technology-specific or overall efficiency. In this context, some studies evaluate *capacity credits*, which measure the contribution of a technology to demand fulfilment in critical situation [e.g. 55–57]. Other studies analyse *capacity factors*, meaning the utilization of capacities as a share of their maximum possible output [e.g. 55], or conversion efficiency [58]. Furthermore, some studies use *curtailment* [e.g. 59], the discarding of renewable energy potential, as measure of inefficiency. Other prevalent measures include energy use or *energy intensity*, the use of energy per unit of GDP or per capita [e.g. 55,60,61].

The second most found aspect is *imported energy* [e.g. 62–65]. It is often expressed as a share of overall energy demand, forming an import dependency or, conversely, self-sufficiency metric. Connected to import risks, a range of studies also analyse *supplier diversity* [e.g. 66–68], and in some cases political reliability measures for trading partners. Much fewer studies analyse *imported materials* [55,67], although this might be much more common in non-energy-specific research areas. A few studies also review *exported energy*, both as positive for energy security [56,63] and as negative [69].

A considerable number of studies [e.g. 70–72] investigate *energy diversity* as a measure of generalized resilience against shocks. Most studies consider the even distribution between multiple energy sources to be diverse, although some recognize that benefits from this kind of diversity can be easily overrun by trade-offs with negative impacts [73]. Diversity is often measured through the Shannon-Wiener Diversity Index (SWDI) [e.g. 57] or Herfindahl-Hirschman Index (HHI) [e.g. 61, 74] and sometimes through the share of the largest energy source [e.g. 75]. While most studies consider a diversity of different energy carriers in the system to be more resilient, one study [76] argues that the reliance on hydrogen and electricity imports on top of fossil gas imports would affect energy security negatively because maintaining only infrastructure for fossil gas would be less complex than transmitting hydrogen and electricity in addition.

Concerning the energy transition, some studies [e.g. 55,61] measure *renewability*, the share of renewables in the energy mix, or electrification [58] as aspects of energy security. The former is sometimes expressed conversely as fossil dependence.

Though many studies are concerned with system cost through the optimization methods used, only a few directly analyse *energy price*, *price volatility* or other costs as energy security aspects [e.g. 44,71,77]. A small number of studies also review *environmental* [e.g. 61,78] or *social* [71] criteria, although many more consider these outside of the energy security realm.

A few more uncommon metrics were also used in different contexts, such as the age of infrastructure [79], or energy reserve to production ratio [79].

Finally, a few studies reviewed here [e.g. 80–82] use probability metrics as their main consideration for energy security. These are specific for the different approaches, such as constraint violation probabilities for chance-constrained approaches. The loss of load probability seen in many studies was excluded from this aspect.

Overall, some of the most prevalent aspects are linked to the availability of energy as a measure of vulnerability, including energy not served, capacity margins and backup capacities, which reflect the ability to provide additional energy. This raises the critical question “security for whom?”, as the groups affected by energy unavailability may vary significantly. For example, the governments of the UK and Germany have implemented policies prioritising emergency supply of energy for vital needs [83,84]. Vital needs are not explicitly defined in this context and may change depending on the characteristics of the disruption. However, the concept of decent living standards [85] and their connected energy needs [86], such as healthcare, heating/cooling, lighting, education and access to clean water, could serve as a foundational reference. Consequently, it is likely that certain industrial and commercial loads will be interrupted before essential services are affected.

¹ Note that it is not always straightforward to separate national from regional studies. In this review, we consider studies that cover more than two thirds of the land area and population of a country to be national studies.

² Additionally, 2 studies contained both regional and national-scale investigations.

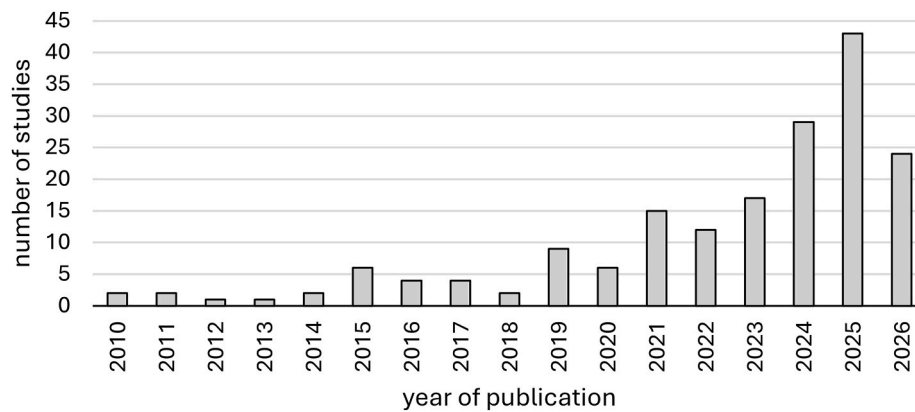


Fig. 2. Temporal distribution of screened studies.

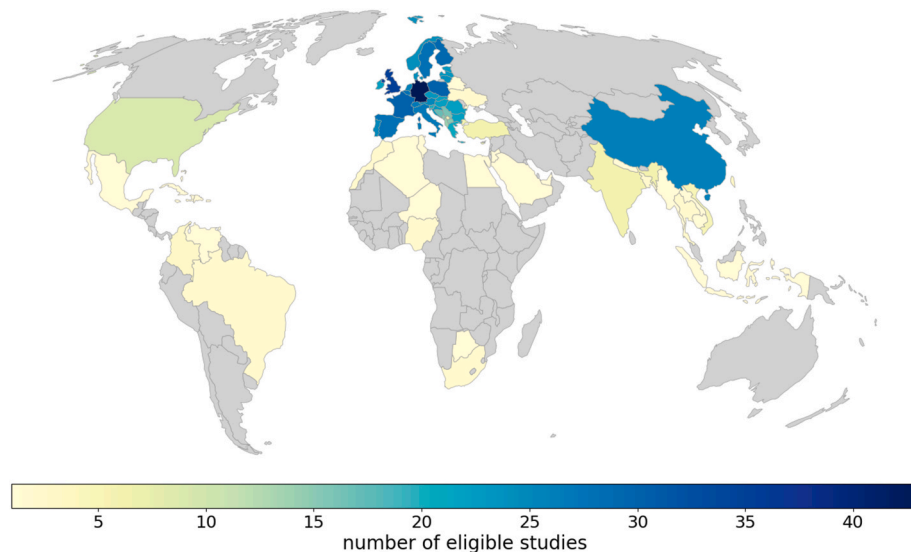


Fig. 3. Geographical scope of eligible studies. Territories with no eligible studies are shown in grey. Small Island states not visible in the map are not present in the result as their energy systems are very small. Greenland is shown separately from Denmark, French Guyana separate from France and Alaska separate from the contiguous US.

Furthermore, unserved demands may be unevenly distributed across geographical regions, income groups and industrial sectors.

When considering vital energy needs, the overall impact of unserved demands also depends on the duration of the disruptions as well as many factors that are not explicitly modelled. These include the institutional, economic, and social capacity to prioritise demands, distribute limited resources, deploy recovery measures in the event of infrastructure damage and establish interim solutions, such as public heated spaces in winter. The impacts also depend on how ‘vital energy systems’ are defined and raise the broader question ‘security for which values?’. The implications for vital energy needs and decent living standards may differ substantially from the economic impacts on industrial customers. For example, discussing infrequently occurring small amounts of unserved demands without considering their expected impacts may obscure how different groups could be affected, as such disruptions may affect industrial and commercial consumers more directly than households.

This limitation is partly attributable to the limitations of energy system models, which are the focus of this study. They are not designed to adequately represent all the aforementioned factors. While it is possible to model different demands explicitly and explore the effects of alternative priorities, it is considerably more difficult to model the multitude of possible reactions to a crisis. The effectiveness of energy-

saving practices and interim solutions in reducing demand under a specific future scenario is hard to predict. Moreover, because institutions, social norms and legal frameworks play central roles in disaster preparedness and resilience, many relevant factors cannot be modelled endogenously using cost-optimizing models. Thus, the focus on availability and security of supply in the results is consistent with this study’s focus on techno-economic energy system modelling.

Nevertheless, to better connect the unavailability of energy to its consequences for different groups, it would be valuable to examine the duration and magnitude of unserved energy, as well as the composition of demands at the time when unserved energy occurs. Connecting energy system modelling results to other domains of energy and social research could provide further insights into the consequences of crises and potential mitigation options.

3.3. Disruptive events

With respect to the question “security from what threats?”, different disruptive events can be identified. We count occurrences of disruptive events if the effects of the disruption in question were investigated either through scenario design, uncertainty-related methods or through ex-post investigation related to the specific event. Accordingly, all studies that analyse the amount of imported energy in connection with energy

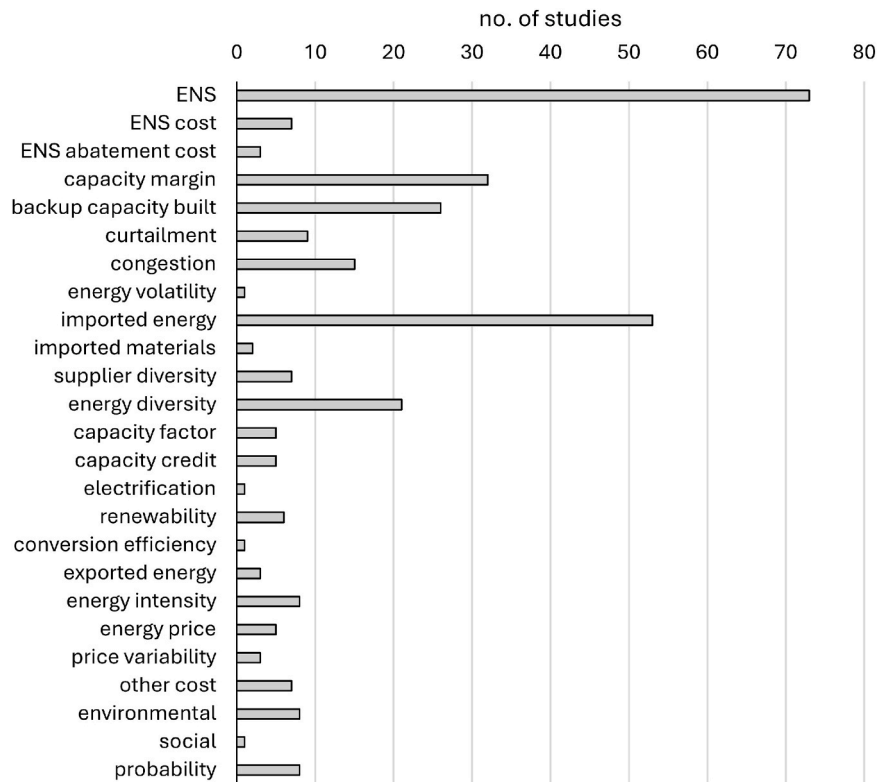


Fig. 4. Energy security aspects found in the eligible studies. Observe that aspects were only counted if they were directly connected with energy security assessment in the study. ENS: Energy not served.

security were counted as studies considering import disruptions, and all studies that consider a set of different emission trajectories were counted as studies considering emission reduction ambition. We also counted all studies that evaluate external restrictions or mandates to the available technologies under the theme of “technology preference” as they implicitly consider the effects of societal preference, e.g. due to environmental impacts or security concerns.

Analogous to other literature [11,16], we classify disruptive events into shock events, meaning short-term developments with potentially severe impacts, and stresses, meaning long-term shifts. As can be seen in Fig. 5, for stresses, technology preference and emission reduction ambition are two heavily investigated themes, followed by demand change, technology costs, interconnection levels and fuel costs. Fewer studies consider different carbon prices, effects of climate change and potentials for different renewable energy sources.

For shock events, weather variability and import disruptions are much-studied subjects, with some attention given to component failure [e.g. 39] but much less studies on natural disasters, material availability, fuel prices and social acceptance. Weather variability contains both variation in intermittent photovoltaic (PV) and wind power production and hydrological scenarios for hydropower and cooling water availability, such as droughts. In contrast, natural disasters are here defined as scenarios where part of the infrastructure is no longer functional as consequence to e.g. a storm [87].

Looking deeper into the “technology preferences”, wind and PV are the most investigated technologies, followed by nuclear, different storage technologies, carbon capture and storage (CCS) and coal, as can be seen in Fig. 6. The prevalence of wind and PV could be explained by the common use of renewable shares as design targets, which sometimes are considered instead of an explicit emission reduction target. Different distributions between PV and wind in future low carbon systems are frequently investigated. Storage is an important area of investigation as it is essential to systems based on wind and PV and several new technologies such as compressed-air storage, batteries, thermal storage and

hydrogen storage are investigated. For CCS and nuclear, the often-controversial discourse around these technologies, relating e.g. to costs, risks, lock-ins and technological maturity, likely makes them especially interesting for scenarios.

Considering technology costs including fuel prices, gas is the most investigated technology, reflecting the widespread import dependency of and volatile prices for fossil gas. PV and wind are also subject to different technology cost scenarios. This could be attributed to their dominance in most low-carbon energy system designs as well as the historically fast decreasing cost trajectory for these technologies.

3.4. Methods applied to energy security

In the following, we will review the methods used to analyse energy security. Firstly, we will give an overview of models and general modelling aspects, followed by a discussion of security-specific methodological approaches grouped into four themes: Ex-post analysis, scenarios, stress tests and uncertainty-driven approaches.

3.4.1. Model frameworks and modelling resolution

Energy systems are modelled with a variety of different models and tools. In the results of our search, TIMES/MARKAL, PyPSA and OSeMOSYS are seeing somewhat more frequent use, as can be seen in Table 2. Still, most studies either make use of an unnamed model or mark the only use of their respective models in this review.

The models differ much in spatial resolution. As shown in Fig. 7, most studies consider only a single node, with no transmission between regions or spatially differentiated results. Fewer studies include multiple regions. Capacity-optimizing approaches show a similar distribution to approaches without capacity optimization, except that the latter have an even stronger emphasis on models with only one spatial node. However, non-optimizing approaches cover a more diverse range of model types, some of which are inherently single node. Including more than 40 nodes is rare. Still, even amongst studies with similar numbers of nodes, the

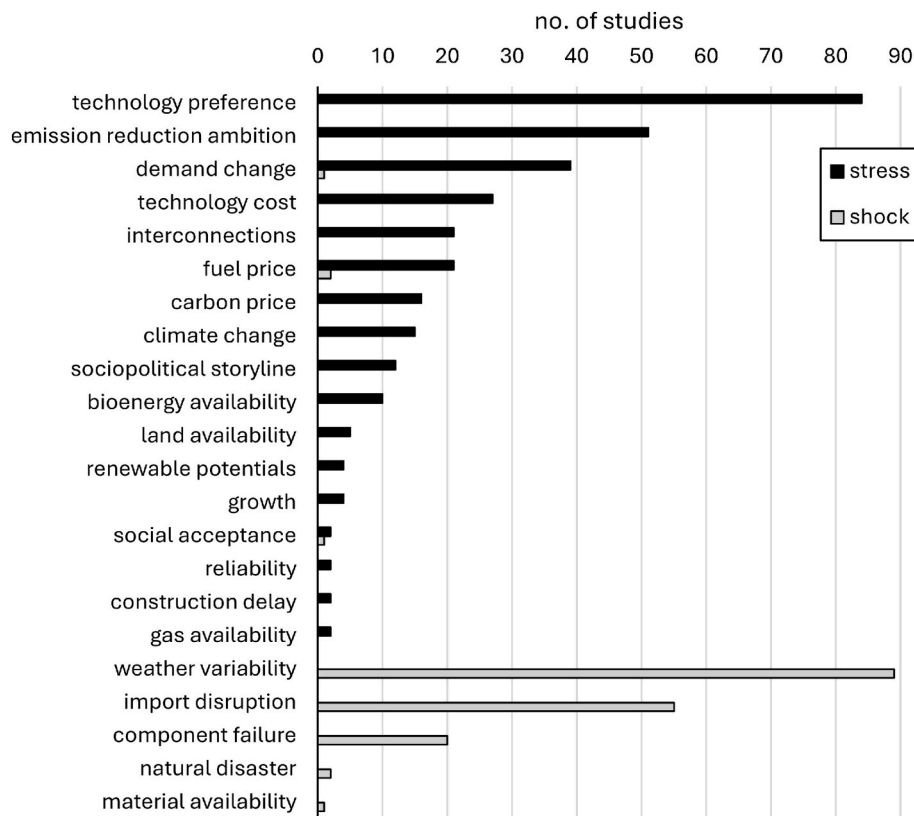


Fig. 5. Disruptions in the eligible studies.

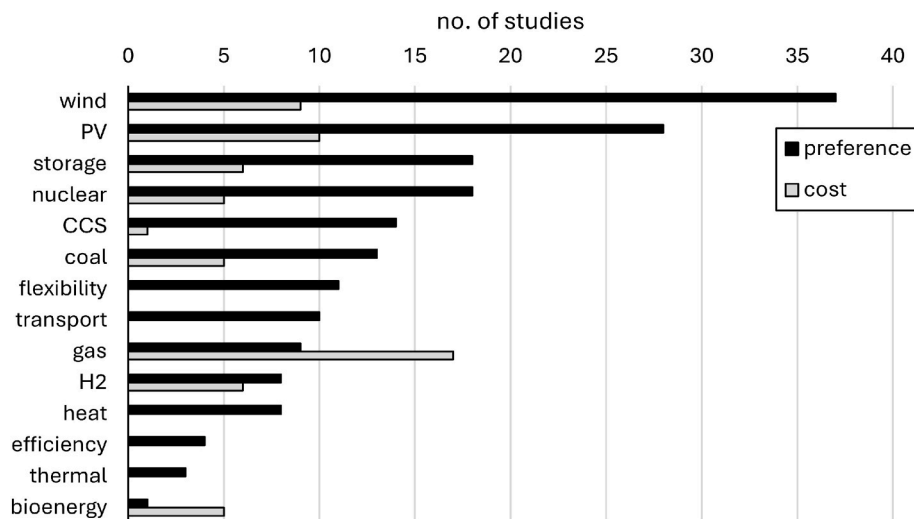


Fig. 6. Technologies considered for disruptions in preference and cost. Observe that technology cost includes fuel prices in this figure. Only technologies considered in 3 or more cases are shown here. CCS: Carbon Capture and Storage, CSP: Concentrating Solar Power, H2: Hydrogen, PV: Photovoltaics.

area and population represented by the nodes varies substantially.

Temporal resolution is also very different between studies, reaching from full hourly resolution of entire years [e.g. 88] to representations with only 8 time periods per year [e.g. 89] or even one time step per year [90]. The temporal scope of the models does also differ, with many models aiming for carbon neutrality either associated with years between 2045 and 2060 [e.g. 66,91,92] or without a timeline. Other models look at the mid-term future up until 2035 [e.g. 59,93], and a few studies model up to the year 2100 [e.g. 94,95].

Many models lack the option to include major technological options

such as battery storage, heat storage, hydrogen storage or sector coupling. When it comes to sector coverage, a considerable majority of studies model electricity systems only, while far fewer include infrastructure for hydrogen, methane, or heat, as shown in Table 3. Only 13 studies consider all these sectors while 16 studies model all except one.

Different objectives are seen, e.g. minimizing emissions [65], but cost clearly dominates the optimization-driven studies. The valuation of costs related to carbon emissions through emission penalties in the objective differs between the models. Many models instead enforce one or several different fixed emission constraints.

Table 2
Models and model frameworks used in eligible studies.

model/framework	uses
TIMES	14
PyPSA	9
OSeMOSYS	8
MARKAL	7
EnergyPLAN	6
LEAP/NEMO	5
PLEXOS	5
ETHOS.FINE	4
REMix	4
Backbone	3
GCAM	3
LUT-ESTM	3
MESSAGE	3
Nexus-e	3
AMIRIS (FAME)	2
Antares	2
Calliope	2
ESO	2
Power Plan	2
TEMOA	2
named, single use in eligible studies	45
unnamed	57

In total, we observe quite diverse model usage with different focus areas across the topic of energy security. However, models are often subject to significant computationally induced or data-driven trade-offs that omit either technical, temporal, or spatial detail. In the case of technical detail, energy storage options and conversion between carriers are essential to security of supply because these technological options can substitute for other energy sources. Transmission bottlenecks can be overlooked when decreasing spatial resolution, and critical supply or demand spikes can be smoothed when decreasing temporal resolution. As these dimensions have the potential to significantly alter the results, it is critical to assess the potential influence the chosen levels of technical, spatial and temporal detail and rethink study design if necessary.

3.4.2. Approaches to energy security

In this section, we present different methodological approaches seen in the investigated studies that deal with security-related issues. We group different approaches under four different themes: (1) Ex-post analysis, (2) scenarios with security-driven constraints, (3) stress tests,

and (4) uncertainty-driven approaches. Note that some studies apply multiple approaches at once. An illustration of the approaches can be found in Fig. 8.

3.4.2.1. Ex-post investigation, indicators and indices. Several studies measure indicators of supply security after the design and operation of a system have been determined. This section reviews studies that apply such ex-post metrics. Many studies with specifically security-driven methods also apply some kind of metric to the results. However, in this section we focus on studies that use ex-post evaluation as their only security-adapted method.

Two kinds of ex-post analysis can be differentiated: (1) Analysis by a set of metrics, and (2) analysis with composite indices created from several metrics. Note that many studies review qualitative aspects in addition to the metrics discussed here. Additionally, many studies consider environmental aspects, costs and sometimes social aspects but often separate them from energy security. Only metrics that are explicitly linked to energy security in the results are discussed here.

As can be seen from Fig. 9, import dependencies, energy not served (ENS), measures of diversity and capacity margins are the most common metrics used for indicator-based approaches. Somewhat less common are backup capacity built and price metrics.

The diversity of indicators for energy security shows that ex-post assessments are used to retrieve information about many different dimensions of energy security. However, imported energy, energy not served, energy diversity, and capacity margins are clearly dominant over all other aspects, including environmental and social measures. This highlights the tendency of techno-economic models to focus primarily on supply-side vulnerabilities, while giving less attention to the social

Table 3

Coverage of energy infrastructure combinations in the eligible results. A study was considered to model a sector if it included storage or transmission components for the respective energy vector. This implies that e.g. the methane sector was not considered to be modelled if only demands or conversion points were modelled, e.g. if the electricity system included gas turbines.

	electricity	hydrogen	methane	heat
electricity	153	48	26	34
hydrogen		50	16	24
fossil gas			27	15
heat				34

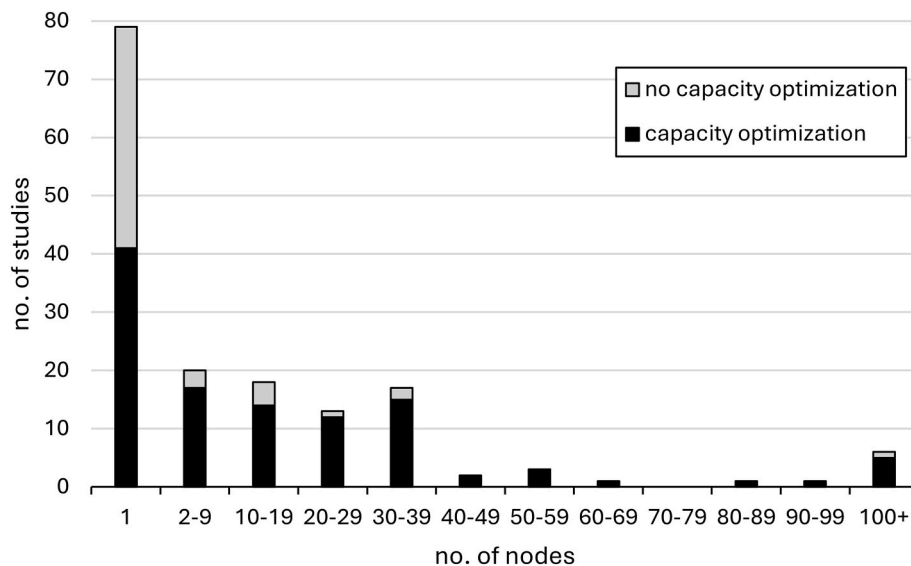


Fig. 7. Number of nodes in the eligible papers. The number refers to the number of nodes that are in the focus area of the study and modelled with demand, excluding pure import or export nodes as well as nodes in other regions that are modelled but not part of the analysis.

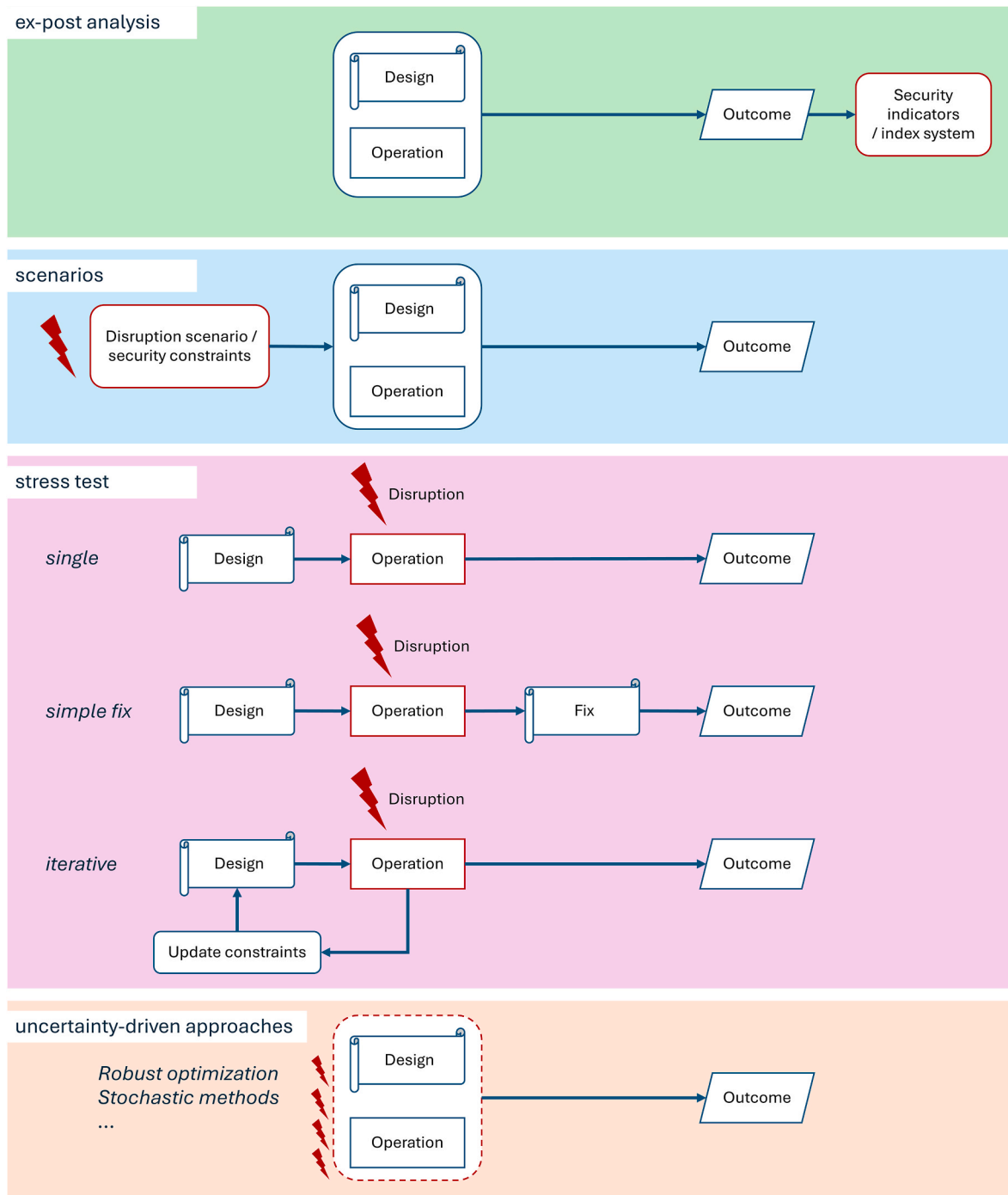


Fig. 8. Visualization of different security-focused energy system modelling approaches.

and environmental impacts of disruptive events. Extending the assessment of disruptive events to include potential environmental or social impacts through additional indicators could therefore provide a more comprehensive characterisation of energy security risks.

Energy system optimization problems are most often constrained to fulfil all demands. To still get insight into stress periods, different methods have been employed. Capacity or reserve margins can serve as indicator for system robustness, either measured at peak supply-demand mismatch [41,48] or aggregated over the entire time period [30,63]. Several studies assign a cost for unmet demand, assuming a value of lost load (VOLL), which is further discussed in section 3.3.3. In a different approach, Grochowicz et al. [88] employ a shadow-price based analysis to gain insight into system stress periods.

A few studies rely on composite indices derived from a larger number of indicators. As shown in Table 4, indices use very different combinations of metrics but imported energy and capacity factors are common. Sometimes, the index is itself used to construct broader indices [67]. While other methods allow for an individual, normative evaluation of different aspects, indices incorporate pre-made trade-offs between different aspects. The selection and weighting of indicators determine the outcome, also when using formal weighting methods. Often, neither of them is explicitly discussed, hiding the normative decision whether something is an adequate measure of security and how important it is in relation to other measures. For instance, a maximally diverse system would often be seen as desirable. However, such a system will incorporate fossil fuels, which force environmental-social damage and, for

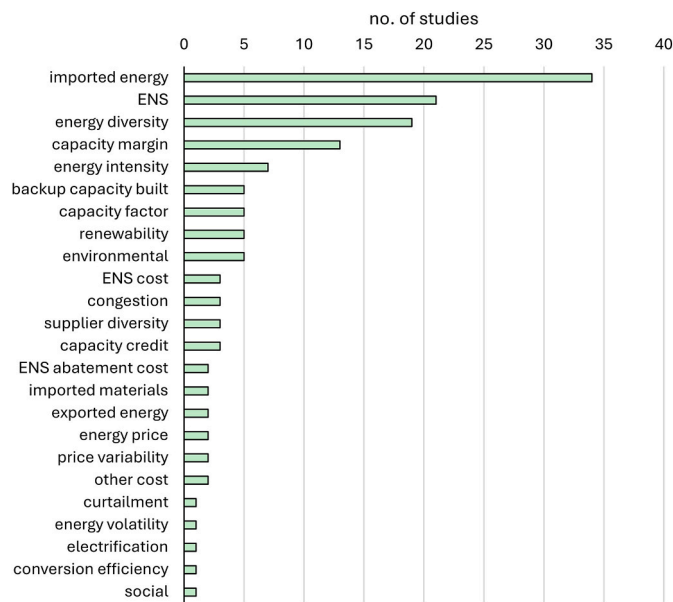


Fig. 9. Indicators used in ex-post assessments [27,30,38,40,41,47,51,52,5460–6570–7589–91,94,9596–99100–109110–119120–133]. Note that only studies with ex-post assessment as their only security-focused method are counted here, and that indicators are only counted if they are explicitly linked to energy security by the authors of the respective study.

Table 4

Overview of studies using index-based approaches for energy security assessment. x – aspect covered and explicitly linked to energy security. CF: Capacity factor; ENS: Energy not served.

Ref.	Energy diversity	Energy use	Imported energy	Import risk	CF/curtailment	capacity credit	imported materials	Additional indicators
[55]	x	x	x		x	x	x	renewable share
[56]			x	x	x	x		energy volatility, exported energy, capacity margin
[58]	x	x	x		x			electrification, conversion efficiency, forest cover
[67]			x	x	x		x	
[134]					x			ENS

most countries, considerable import dependency. The relation between the different security indicators of diversity and import dependency would have to be quantified to form a composite index. Amongst the formal methods for weighting are Analytic Hierarchy Process [134], Principal Component Analysis [58] and Hellwig's Method [56] or exploring many different weight combinations [67].

In a somewhat different approach, Azzuni et al. [71] employ a range of indicators and aggregate them into dimensions, but only note the tendency of each indicator (positive or negative). Gracceva and Zeniewski [96] utilize a framework conceptualization to structure a mix of qualitative and quantitative aspects of energy security.

3.4.2.2. Scenarios with security-driven constraints. Several studies define scenarios with security-driven constraints while allowing the model to adapt its configuration to the scenario. As many studies utilize scenarios in general, we focus specifically on scenarios with explicit security relevance in this section. The defining feature for “security relevance” in this case is whether the authors at least indirectly state their intention to investigate an aspect of energy security with the help of the scenarios.

The scenarios follow different approaches. One type of studies specifies security metrics to be met, e.g. minimum import diversity [66, 68,135,136], maximum import share [57,66,76,89,108,135,137–140] of a set of energy carriers, minimum generation capacity diversity [57], different reserve requirements [58,141–143],³ or maximum demand not served [105]. Pfenninger and Keirstead [40] use a constraint on allowed energy not served (ENS) and measure how much additional costs are incurred by fulfilling the last 5 % of demand. These studies aim to design a system with a generalized resilience against one or several types of threats. An overview is presented in Table 5.

Another type of scenarios incorporates the effects of a disruptive event, e.g. fuel or material supply chain disruptions [55,68,92,96,143, 145,146], or storms or droughts that cause generation shortfalls or plant outages [99,147–150]. These studies aim to secure the system against a specific threat. They are presented in Table 6.

It should be noted that also amongst results that apply other security-specific methods, many eligible studies consider variations in fuel cost [e.g. 99,143], technology cost [e.g. 54,91], carbon emission reduction constraints [e.g. 91,92], interconnection level [e.g. 31,87] and energy demand [e.g. 68,96] in scenarios. These scenarios can be of relevance to energy security but are most often not explicitly linked to security as a subject of investigation. Fig. 10 gives an overview of the scenario themes found in all eligible studies. It is evident that restrictions in the generation portfolio, i.e., minimum and/or maximum shares of different technologies, are the most prevalent type of scenario, followed by different emission reduction ambitions and technology costs. The most prevalent technologies that were investigated in generation portfolio

variations were renewables, nuclear power, carbon capture and storage, energy storage, and different types of flexibility options such as flexible sector coupling.

3.4.2.3. Stress tests and model coupling. Many studies evaluate the supply security of a fixed system configuration through subjecting it to different operating conditions. This is sometimes called a stress test [e.g. in 93,172] or cross-validation [e.g. 50,88].⁴ The defining difference to scenario-based studies is the limited design freedom which resembles the way a real system is not optimally designed for unforeseen conditions. Still, there are edge cases which could be framed either as scenario with design constraints or as stress test with much freedom of design response [e.g. 173]. An overview of different studies is shown in Table 7, Table 8 and Table 9.

A major difference between the studies is the way the system configuration is obtained, most often through a fictional scenario or forecast but also as a result from earlier optimization. In the case of optimized designs, many studies utilize model coupling. Typically, a

³ Reserve requirements are present in a lot of studies. These studies stick out because they implement a set of scenarios where the reserve requirement is varied.

⁴ Cross-year modelling in Öberg et al. [50].

Table 5

Overview of studies utilizing scenarios with security-driven constraints. Observe that there are more results utilizing reserve constraints, these results were chosen because they implement scenarios where reserve requirements are varied. x – metric used to define scenario. ENS: Energy not served; SWDI: Shannon-Wiener Diversity Index.

Ref.	import diversity (SWDI)	max. shares for suppliers	import limit	max. capacity share for technologies	different reserve constraints	max. allowed ENS
[66]	0 – 1		0 – 50 %			
[135]		33 %	50 – 67 %			
[68]		20 %				
[136]		30 – 40 %				
[89]			phase-out			
[76]			0 %			
[57]			0 – 20 %	20 – 40 %	x	
[137]			46.5 %			
[138]			x			
[108]			x			
[139]			0 – 100 %			
[140]			0 – 100 %			
[144]					x	
[141]					x	
[142]					x	
[105]						1-20 %
[40]						0-5 %

Table 6

Overview of studies utilizing disruptive scenarios.

Ref.	Scenario
[68]	transit of fossil gas via Ukraine is blocked
[145]	cost of fossil gas varies by factor of 20
[55]	availability of materials for renewable technology is limited (different storylines)
[146]	availability of materials for renewable technologies and availability of biomass are limited
[143]	availability of fossil gas from Russia reduced by 75-100 %
[92]	availability of fossil gas from Russia reduced by 100 %
[96]	oil/shale gas/nuclear power availability reduced by 75-100 %
[99]	winter storm causing 5-46 % lower plant availability for fossil gas, coal, nuclear & wind
[147]	drought causing lower hydropower availability
[148]	drought and flood scenarios causing different hydropower availability
[149]	drought causing lower cooling water availability
[150]	Dunkelflaute event causing lower renewable availability

long-term capacity expansion model is linked to one or several short-term operational models that have higher technical detail [e.g. 13,33,34,43,48,154,162–164,183,184,188,189].

Furthermore, studies differ in the kinds of stress the system is subjected to. Most prevalent is historical weather, ranging from a single

year [e.g. 156] to 62 years [31]. Other stressors include climate change realizations [e.g. 43], extreme weather events such as droughts [e.g. 93], heatwaves or Dunkelflaute [e.g. 32], import disturbances [e.g. 181], demand change [e.g. 173] and component failure [e.g. 187].

Another difference is how much the design can still be altered as a response to stress. Many studies make a pure operational run and determine where demand cannot be fulfilled [e.g. 32,88,176] while others allow the construction of certain additional capacities in order to fulfil all demands [e.g. 49,51,158]. Some studies fall in between these categories as they review residual loads or unfulfilled demand and use them to construct the “backup capacity need” without rerunning the model or explicitly modelling a source of energy [e.g. 44].

Where additional capacities are added, it is sometimes done iteratively, performing a full re-optimization of the system [e.g. 34], and sometimes with simple but rather limiting assumptions, such as allowing only fossil gas plants [e.g. 48,160] as additional capacities. For the iterative studies, some information must be updated for each design run to obtain a more stress-resistant system. One way is to use a constraint which ensures that aggregated capacity is above a threshold. Some studies [e.g. 34,111,164] use capacity credits which credit every technology with a certain contribution factor for this constraint. These capacity credits are typically high for dispatchable sources that are likely to deliver close to their nominal capacity a peak demand situation and

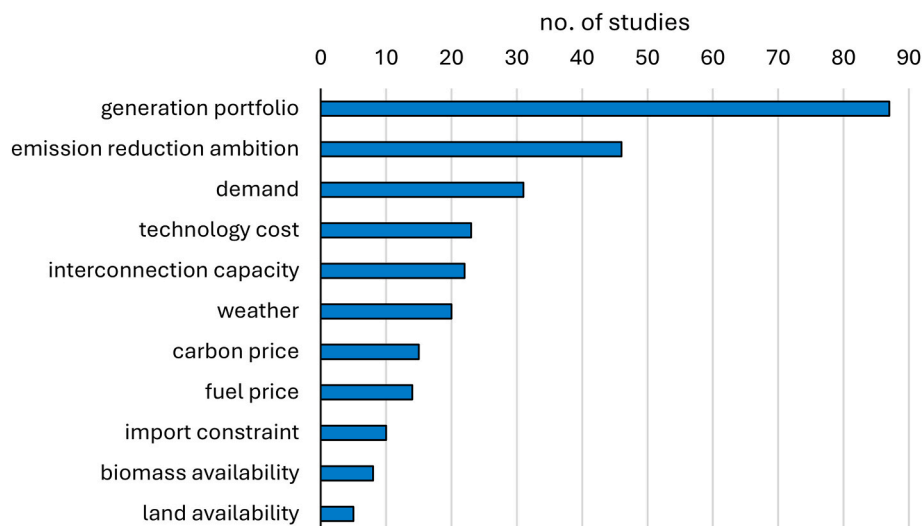
**Fig. 10.** Most prevalent scenarios in the eligible studies.

Table 7

Overview of studies subjecting energy systems to historical weather with limited design adjustment allowed ("stress tests"). Bio-CHP: Bioenergy Combined Heat and Power; CC: Capacity Credit; dyn.: dynamic; GT: Gas Turbine; H2: Hydrogen; iter.: iteration; LOLE: Loss of Load Expectancy; opt.: optimization; PP: Power Plant; scen.: scenario; rand.: random; TS: Time Series; WY: Weather Year.

Ref.	Stressor	Design origin	Design flexibility	Iterations
Operational validation (≤ 1 weather year)				
[36,46,69,77,151–153]		scen.	-	single
[49]		scen.	H2 GT	single
[13,53,154,155]		opt.	-	single
[156]		opt.	GT storage grid expansion sector coupling	single
[157]		opt.	battery storage	criterion (convergence)
[158]		opt.	all (dyn. TS)	criterion (LOLE = 0h)
[159]		opt.	backup capacity	criterion (LOLE = 0h)
[160]		opt.	fossil GT	criterion (LOLE < 7h)
[161]		rand.	-	single
Historical or stochastic weather				
[31]/[88]/[162]	62 WY/40 WY/3 WY stochastic based on 35 WY	opt.	-	single
[35]	stochastic based on 22 WY	opt.	-	single
[163]	multiple WY	opt.	PV/wind	criterion (LOLE = 0)
[164]	10 WY	opt.	all (static CC)	criterion (LOLE < 3h)
[50]	31 WY	opt.	GT el. boilers batteries H2 storage	single
[34]	38 WY	opt.	all (dyn. CC, dyn. demand, dyn. objective)	criterion (LOLE < 3h)
[165]	11 WY/14 WY	opt.	all (iter. 1–3)	5
[166]/[167]	5 WY	scen.	bio-CHP (iter. 4)	single
[168]	30 WY	scen.	- (iter. 5)	single
[169]	10 WY	scen.	batteries	single
[170]	38 WY stochastic based on 7 WY	scen.	backup capacity	single
[171]		scen.	GT	multiple manual
[37]		scen.	H2 storage	single
		scen.	H2 PP	criterion (LOLE < 5h)

low for intermittent renewable energy sources. A subset of studies does not specify capacity credits but allows only certain capacities to contribute to the peak capacity constraint, equivalent to assigning a capacity credit of 0 to all excluded and a credit of 1 to all included technologies [e.g. 159]. In some studies, capacity credits are fixed parameters, and only the threshold in the constraint is updated [e.g. in 159,164]. In other cases, the capacity credits are determined by the actual contributions of different technologies in the designed systems and therefore updated [e.g. in 34,111]. Rosendal et al. [34] compare capacity credits to two other methods to update the optimization: To introduce a fictive demand added to yearly balance constraints based on demand not served in previous iterations, and to add a profit signal to

Table 8

Overview of studies subjecting energy systems to historical or synthetic extreme weather events as well as climate change while giving limited design freedom ("stress tests"). Clim.: climate; CM: Capacity Margin; GT: Gas Turbine; LOLE: Loss of Load Expectancy; opt.: optimization; scen.: scenario; TS: Time Series; WY: Weather Year.

Ref.	Stressor	Design origin	Design flexibility	Iterations
Historical or synthetic extreme weather events				
[174]	3 hydro availability scenarios (El Nino/La Nina)	scen.	-	single
[172]	3 WY with lowest irradiation	opt.	-	single
[93]	1 hydro availability scenario (1942 drought)	scen.	-	single
[167]/[175]	1 hydro availability scenario (8 %/31 % lower inflow)	scen.	-	single
[48]	1 hydro availability scenario (extremely dry El Nino event)	opt.	fossil GT	criterion (LOLE < 7.2h)
[87]	catastrophic event causing regional grid outage	opt.	-	single
[32]	Dunkelflaute event	scen.	-	single
[33,176]	Dunkelflaute event	opt.	-	single
[173]	extreme event causing lower renewable generation	opt.	-	single
[39]	Dunkelflaute events Heatwaves	opt.	-	single
Climate change impacts				
[45]	11 WY from 1 climate scenario	scen.	-	single
[177]	473 WY from 43 clim. scenarios	scen.	-	single
[42]	36 WY from 12 clim. scenarios	opt.	-	single
[48]	3 hydro availability scenarios from 3 climate scenarios	opt.	fossil GT	criterion (LOLE < 7.2h)
[44]	150 WY from 3 clim. scenarios	opt.	backup capacity	criterion (CM > 0)
[43]	100 WY from 100 clim. scen.	opt.	all (dyn. TS)	2
[87]	1 climate scenario	opt.	-	single
[178]	9 WY from 1 climate scenarios	opt.	-	single
[179]	2 of 480 WY from 16 clim. scen.	opt.	-	single
[180]	12 WY from 4 climate scenarios	opt.	-	single

the objective function based on the profitability of different generators in the operational simulation.

Lastly, further differences between studies are seen in the operational restrictions. Some studies ease constraints such as biomass availability [50] or emission limits [31,39,88] from the optimization stage, assuming that a system is designed for an environmental goal but is allowed to deviate from it under harsh operating conditions.

3.4.2.4. Uncertainty-driven approaches. A range of studies employ special approaches such as chance-constrained programming, stochastic programming, robust programming, Monte Carlo methods or modelling to generate alternatives (MGA). These approaches have in common that they systemically deal with uncertainty. As summarized in Table 10, energy demand and renewable power availability are the most prevalent uncertainties investigated, followed by fewer occurrences of plant availability in general and technology cost.

Stochastic methods utilize probability distributions to capture uncertainties [187,190,195,196,201,203]. These studies usually also have

Table 9

Overview of studies subjecting energy systems to trade disruptions, geopolitical events, sociotechnical developments and component outages with limited design adjustment allowed ("stress tests"). Biom.: biomass; dyn.: dynamic; LOLE: Loss of load expectancy; LOLP: Loss of load probability; opt.: optimization; PV: Photovoltaics; scen.: scenario.

Ref.	Stressor	Design Origin	Design Flexibility	Iterations
Trade disruptions and geopolitical events				
[87]	self-sufficiency requirements transmission interruption	opt.	-	single
[44]	gas price shock (+240 %)	opt.	-	single
[39]	fuel price shocks (+100–200 %) import disruption (gas, biom.)	opt.	-	single
[181]	import disruption (hydrogen, solar)	opt.	-	single
[182]	import disruption	scen	-	single
Sociotechnical development				
[173]	demand change (+10–20 %)	opt.	-	single
[163]	demand change	opt.	PV/Wind	criterion (LOLE = 0)
[181]	demand change, acceptance of wind turbines	opt.	-	single
Component outage				
[183]	transmission (probabilistic)	opt.	all (dyn. grid expansion)	3
[184]	transmission (probabilistic)	opt.	grid expansion	criterion (convergence)
[185]	transmission (probabilistic)	opt.	-	single
[39]	transmission (n-1)	opt.	-	single
[33]	generators, transmission (n-1)	opt.	-	single
[186]	generators (aggregated)	opt.	-	single
[169]	generators (probabilistic)	scen.	backup capacity	single
[187]	generators (probabilistic)	scen.	-	single
[32]	generators (aggregated)	scen.	-	single
[182]	all system nodes (aggregated)	scen.	-	single

Table 10

Stochastic elements in the eligible studies.

Ref.	Demand	Renewable availability	Plant availability	Technology cost	Other
[34,37,187]	x	x	x		
[190]	x	x	x		imports
[191]	x	x		x	land availability
[192]	x	x		x	carbon price, grid availability, technology preference
[30]	x	x		x	
[193,194]	x	x			fuel prices
[163,195,196]	x	x			
[197]	x			x	carbon credits, social acceptance
[198]	x				carbon price
[68]	x				gas availability
[80,118,199,200]	x				
[201]		x	x		
[202]		x		x	emission reduction ambition
[81,203]		x			
[36]			x		
[66]				x	
[183]					contingencies
[142]	x	x	x		
occurrences	15	12	6	4	

probabilities, e.g. of unserved demand, as result. Chance-constrained approaches expand upon this by using constraints with a specified probability, thereby allowing modelers to derive a desired level of supply security by incorporating such a constraint for demand satisfaction [80,81]. In a similar-looking but mathematically different approach, other scholars have applied fuzzy programming to specify desired reliability levels [82].

Multistage stochastic approaches make design decisions before the outcome of uncertain factors is known, and secondary decisions after uncertainties are revealed [68,118,193,197–200,202]. Some studies combine a stochastic approach with interval parameter programming, which defines an upper and lower bound for each variable [118,200]. Suo et al. [114] use interval parameter programming without other stochastic methods.

As an alternative to stochastic approaches, robust optimization aims to design a system that is feasible under worst-case conditions, avoiding the difficulties associated with the estimation and use of probability distributions. The optimization can be divided into a top-level investment problem and sub-level dispatch problems, which are iteratively solved and updated [42,198,194,204–207]. A drawback is that solutions can be overly conservative [42]. Other studies apply several stages [208, 209]. An important distinction between two-stage and multistage models is that the former usually assume perfect foresight while the latter adhere to non-anticipativity, meaning that more decisions are made before uncertainty outcomes are known [209].

Monte Carlo methods have been used to explore a wider range of uncertain scenario parameters [30,34,36,66,192]. Frey et al. [30] combine this with a pseudo-correlation matrix to avoid implausible parameter combinations.

Modelling to generate alternatives (MGA) is a method that widens the solution space by allowing deviations from the cost-optimal system, up to a given additional cost. This enables investigation of different system designs with similar cost but potentially vastly different performance in other areas, acknowledging that a real system reasonably deviates from mathematical planning. Van Greevenbroek et al. [191] obtain a more robust solution space by intersecting multiple near-optimal solution spaces with varying weather, costs and land availability.

Another solution space-widening method is multi-objective programming. Prina et al. [65] obtain a pareto front between reduced emissions and cost, measuring security of supply for each pareto-optimal solutions through the import share of fossil fuels.

3.4.3. Security-related modelling aspects

This section briefly reviews four security-relevant aspects of modelling seen through all methodological approaches, namely the (1) coverage of forced outages, (2) modelling of reserves, (3) treatment of self-sufficiency constraints and (4) value of lost load.

The forced outage of plants is covered to different extents in the eligible studies. While many studies simply assume that all capacities built will be available, others either model individual plant outages stochastically [36,169] or implement an aggregated availability for an entire technology [32,43]. The former might not be feasible for models that reach computational limits even without explicitly modelling individual plants.

The modelling of reserves and reserve constraints is also a security-relevant matter. While some studies focus on operational modelling differentiate primary, secondary, tertiary, up, and down reserves, long-term models often make simplifying assumptions or leave out reserves entirely. Amongst the simplification approaches, many studies use capacity credits as discussed in the “stress test” section above. Other studies employ static margins, assuring that the system overbuilds capacity either just at peak demand or in each time period. An overview of reserve modelling approaches is given in Table 11.

Another interesting difference, especially between multinational studies, is whether the design is forced to distribute capacities so that each country can satisfy at least a substantial part of its own demand domestically. Without such a constraint, results can be perceived as politically unrealistic, as many countries would rely on cheaper potentials abroad without constructing even a minimal level of domestic supply in case of transmission disruptions or geopolitical tensions. In a European study, such constraints have been implemented with e.g. 75 % [191] or 80 % [156] domestically sourced energy. Cao et al. found that this constraint had a small impact on system cost [191].

Finally, a common modelling challenge is the value of lost load (VOLL). In cost-minimizing models, leaving the model the option to discard demands is usually connected to a cost of doing so. While many studies utilize a VOLL, not all of them document the parameter value. A number of studies just specifies that a high cost was used to force the model to use load shedding only as measure of last resort [e.g. 30,88,173]. An overview of values identified from the eligible studies is given in Fig. 11, showing a median of 3509 EUR/MWh. Most often, VOLL is static, assuming that all demands lost have equal value across different regions, sectors, points in time, and total amount of lost load. Two studies included differentiated levels of VOLL between regions and sectors [130] or different shares of demand [207]. Some studies utilize different weights or values for VOLL to analyse the system design depending on different priorities in different scenarios [130,147,211]. In three cases, load shedding was additionally restricted to a share between 5 and 25 % of total demand [40,53,91].

3.5. Energy security aspects across different approaches

The aspects discussed earlier are used differently across the approaches discussed in section 3.3.2. A summary is shown in Fig. 12. It is

Table 11
Overview of reserve modelling approaches.

Ref.	Reserve modelling
[40,70,82,106,162,172,186,209,210]	static margin (2 – 25 % or unspecified, either of peak demand or at every time period, sometimes only for firm capacity)
[63]	dynamic margin
[57,91,99,164]	static capacity credits (either of peak demand or at every time period)
[34,111,141,205]	dynamic capacity credits (either of peak demand or at every time period)
[53,59,108,141,142,155,183,184,202,204]	differentiated reserves (e.g. primary, secondary, tertiary, up, down)

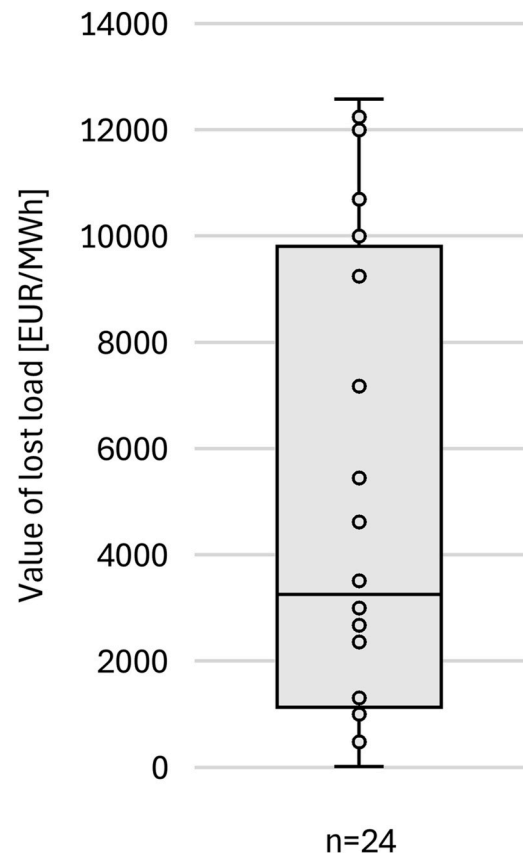


Fig. 11. Values of lost load in the results [31,32,34,37–40,52,53,59,91,99,115,128,130,154,158,186,193,207,211]. One extremely high outlier (10^{12} USD/MWh) was excluded [174]. For one study with many different levels of VOLL, the average value was used [130]. Values from studies prior to 2024 have been inflation adjusted to 2024.

especially notable that stress tests emphasize ENS-related aspects, capacity margins, backup capacity and congestion. These aspects fit very well into the operational focus of these studies and align with the focus on energy availability. On the other hand, scenario-based studies and ex-post approaches have a much greater emphasis on long-term metrics such as imported energy, and, in the case of ex-post approaches, energy diversity and energy intensity.

4. Conclusions

4.1. Design for a secure energy transition

Security is a core challenge of energy systems design. Future systems are expected to cope with a variety of stresses and uncertainties. Still, the coverage of some security threats is sparse in energy systems modelling. While the impacts of many long-term stresses such as technological developments and preferences or changing demands on the energy system have been investigated, research on short- to mid-term events is mostly focused on weather variability. Imported energy is also a prevalent theme but research often stops at the annual share of imported energy or a fixed higher commodity price. Recent trade disruptions however exemplify the need to investigate the resilience to geopolitical shocks in depth. Import disruptions can also result in situations where the transmission of energy carriers is temporarily limited regardless of price, and may affect only a subset of regions. Particularly in spatially explicit models, more detailed research on transmission and import disruptions could bring valuable insights.

It should also be noted that many methods focus on aspects of security closely related to the uninterrupted availability of energy. While

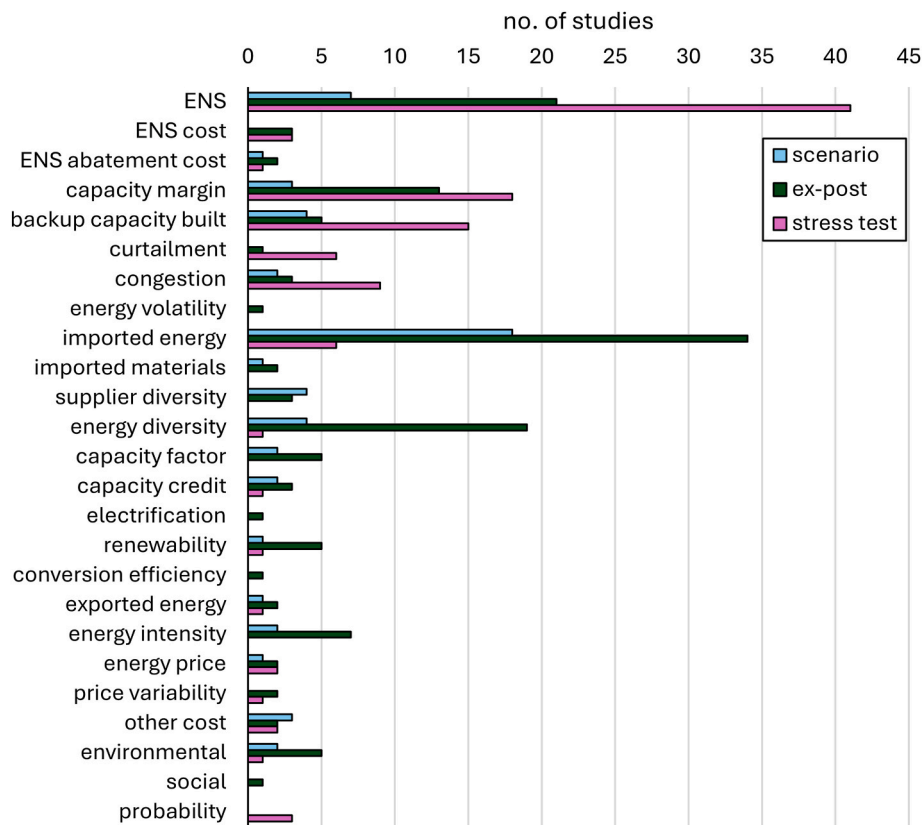


Fig. 12. Energy security aspects found in the eligible studies differentiated for different approaches. Observe that aspects were only counted if they were directly connected with energy security assessment in the study.

this aspect is important and comparably easy to describe with a techno-economical model, a complete description of energy security should differentiate how different groups and values are affected by the scenarios explored, answering who is vulnerable and which vital systems are affected.

We notice that three aspects of energy security are especially prevalent and associated with different approaches: (a) Energy not served, often measured in stress tests, (b) import dependency, often measured in scenario-based and ex-post approaches and (c) energy diversity, mostly seen in ex-post assessments. A range of other metrics is also employed but used less frequently. The multitude of other aspects demonstrates that energy security is a fuzzy term with no consensus in the literature on a common definition.

Regarding the models found in the results, the number of sector-coupled, spatially resolved studies is quite small. Especially the absence of long-term storage technologies for heat, hydrogen and hydrogen derivatives, which take on important roles for security of supply, seems to be a blind spot of many security-focused studies. In addition, new transmission infrastructures such as hydrogen pipelines have the potential to create bottlenecks and critical points of failure. At the same time, they can provide flexibility. Both aspects make them interesting to include in future studies about supply security.

Energy systems design must strike a delicate balance between generalized security against a large set of possible disruptions and the adequate use of limited natural and economic resources. At the same time, environmental and social impacts such as emissions, land use, and health must be considered. It is essential to consider for whom security should be created and from which threats to determine which level of security is desirable. To enable well-informed decisions, research should be more transparent in these questions. Reducing many aspects of energy security to a set of indicators or a single number without proper discussion of inherent trade-offs or assumptions is of little use if not

counterproductive. Future research should therefore strive to be clear in the aspects of energy security that are assessed and under which conditions the findings are valid.

4.2. Limitations and prospects

This review includes studies with diverse modelling paradigms, such as optimization models, simulation tools, and equilibrium models, provided that they meet the inclusion criteria, including a design perspective. The review also covers both narrowly focused studies on specific aspects of energy security as well as works with a broader focus. The study focused on the intersection of energy security, energy system design and the energy transition, resulting in a high-level analysis. In contrast, studies centred on one specific aspect of security, a specific modelling paradigm or a particular threat could gain much deeper insights into the associated modelling challenges. Such focused studies may be particularly valuable for examining the under-researched threats and aspects of security identified in this review.

Author contributions: CRediT

Jens Zimmert: Conceptualization, Methodology, Investigation, Writing – Original draft, Visualization. **Theresa Klütz:** Writing – Review & Editing, Supervision. **Jochen Linßen:** Writing – Review & Editing, Supervision. **Heidi Heinrichs:** Writing – Review & Editing, Supervision.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used DeepL Write, Mistral Vibe and ChatGPT to suggest rephrasing of single sentences and paragraphs for improved readability. At no point have AI tools been used

to create new paragraphs or sections. Upon receiving rephrasing suggestions, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.esr.2026.102370>.

Data availability

All relevant data is attached in Appendix A.

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