European Journal of Futures Research

REVIEW
Open Access

A review of renewable energy scenarios in Europe: methodological approaches and societal elements amid geopolitical tensions

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Abstract
This systematic review focuses on the role of renewable energy in shaping the future of the European energy system. It explores the scientific renewable energy scenarios and offers insights into how broadly European-level scenarios have scanned future energy landscapes and the types of utilised scientific knowledge amid geopolitical tensions. To explore the dimensions of the scenario studies, the analysis applies the PESTE framework, which reflects the results on multidisciplinary three perspectives framework for the energy transition. The results underscore a prevailing positivist paradigm in scenario studies of energy transition, conceptualising it as a future characterised by inevitable advancements in techno-economic drivers while other societal as well as biophysical elements tend to play a minor role. However, it is evident that this approach has not been, and will not be in the future, capable of anticipating implications of geopolitical disruptions of the kind witnessed in recent years, for instance. Consequently, there should be more scenario studies based on disciplinary insights beyond techno-economic drivers to increase the understanding of the future of renewable energy. Indeed, there is still an engagement gap in how to effectively deepen dialogue between different disciplines in scenario studies to best describe the energy transition.

Keywords Energy transition, Renewables, Scenarios, Europe

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Introduction

The hard-to-predict Russian invasion of Ukraine was a significant driving force behind the change in energy policy in Europe at both national and European Union (EU) levels. Consequently, to ensure national energy security, many European countries decided to reduce the reliance on Russian energy sources. Similarly, from the standpoint of EU policymaking, the energy transition has been shaped by geopolitical considerations [1]. Since 2020, although the EU has declared strategic autonomy, it was only the war that accelerated the decoupling of its member states from Russian fossil fuels.

Published in 2022, the REPowerEU plan signifies the EU's strategic intent to boost renewable energy, diversify energy import sources and enhance energy efficiency. It was followed with a roadmap in 2025 with actions to complete termination of EU dependency on Russian energy by 2027 [2]. Since the non-member European countries also play a significant role in shaping the European energy landscape, Europe or the EU should therefore not be regarded as a unified entity in terms of shared values in energy politics. However, the EU establishes objectives for its member states and its energy policy is critical for European competitiveness and security and to achieving climate neutrality. Energy policy is thus a shared competence between the EU and its member countries [3].

While in general energy domain could be argued to be filled with uncertainty due to e.g. emergence of new technologies and related structural change towards sustainability [4], the recent sociopolitical shocks, also including the unpredictability of the Trump administration towards the EU came as a surprise to many. One of the possible rationales may be a sociotechnical vision guided by a belief in a liberal and market-driven world that neglected drivers questioning this vision [5]. Similarly, the foresight concerning security in the energy domain commonly narrows down on issues of supply that tend to neglect broader uncertainties such as climate change and biodiversity loss, but also other related societal concerns such as concerns of justice [6, 7]. These common limitations of foresight concern both policy and research, while there is an increasing plea to better account social but also biophysical dynamics with interdisciplinary engagement [8–11].

The present study focuses on renewable energy futures in Europe. It explores and describes scientific scenarios and offers insights into comprehensive energy policy foresight. The focus is on the methodological approaches employed in the scenarios and the manner in which various societal dimensions are interpreted. The study systematically reviews how current scientific scenarios account for the broad societal dynamics of the energy transition and what kinds of assumptions, constraints, and methodological choices underpin energy transition scenario studies. The article is structured as follows: "Research design" section describes the research design; "Results" section presents the results of the analysis; "Discussion" section discusses the findings and "Conclusion" section concludes the review.

Scenarios pointing the way

There is widespread demand for scenario studies, and related futures-orientated approaches such as socio-technical pathways, to reduce uncertainty, provide clarity, and therefore enhance shared understanding of the future energy transition [10, 12]. Over recent years, this demand has resulted in a substantial body of research, encompassing diverse energy sectors, as well as the energy system as a whole [8].

In general, scenarios have been widely used by organisations and communities for strategic planning [13, 14], by governments for political decision making, and of course, by researchers in different contexts imagining alternative futures. The scenario techniques migrated to the business world via the RAND Corporation and Royal Dutch Shell after the scenario planning was first initiated in the military (the US Department of Defence) [13, 15, 16]. For advancing foresight on energy transition, the use of scenario planning helps to evaluate the overall impacts of, e.g. technological choices, policy packages, and at best shows the feasible pathways to stated goals [17, 18]. Furthermore, various scenario typologies have previously been identified, e.g. predictive, explorative and normative, based on probable, possible, or preferable futures [15].

Addressing methodological imbalance in energy scenarios

Scenario studies on energy are characterised by a methodological imbalance. The most used techno-economic approach gives only one, and therefore incomplete, perspective to the energy transition. Acknowledged in many contexts [10, 19–21], the research on the energy transition needs to expand its perspective and prioritise the interplay between evolving societal frameworks and the energy system. One possible solution has been an iterative combination of a qualitative storyline with quantitative modelling when constructing scenarios [22, 23]. In terms of policy making, Burger et al. [10] noted that only by addressing many different fields in the societal sphere can the future low-carbon energy system set by the Paris Agreement be achieved.

To analyse national energy transitions, Cherp et al. [19] created the three perspectives framework stating that economic development, technological innovation, and policy change are especially prominent factors shaping energy transitions. In this framework techno-economic systems, socio-technical systems and systems of political actions co-evolve in three senses. First, they have different boundaries, elements and connections; second, each of the three systems can evolve autonomously, independently from the other two; and thirdly, the co-evolving systems affect each other. Indeed, the three perspectives framework (techno-economic, socio-technical and political) by Cherp et al. [19] provides a reflection for this review, which will be explored in the discussion section.

From the perspective of geopolitics, Blondeel et al. [20] emphasised that geopolitics has a dual quality of simultaneously accelerating and hindering the energy system transformation process. Similarly, Cherp et al. [19] expressed how policies may change because of altered perceptions of energy security or other political shifts, are not necessarily in sync with energy flows or technology change, which is what happened when Russia invaded Ukraine. In response to the energy crisis caused by the Russian invasion of Ukraine, the EU implemented policy instruments to phase out Russian fossil fuels and solve the crisis. The policy was designed to influence the direction of energy flows and technological development, with the objective of promoting the transition towards a stronger focus on renewables. This fact is enhanced by the notion of Cherp et al. [19] that the three perspectives framework elevates the role of political science since policies might be increasingly prominent in shaping the 21st century energy transitions. However, Cherp et al.'s study [19] was published in 2018 and since then the European geopolitical landscape has substantially changed. As the EU is seeking to increase its geopolitical actorness where energy plays a significant role [1], this dimension requires a more detailed scrutiny in foresight.

Research design

The study provides an interpretative analysis of the existing renewable energy scenarios [24]. From an epistemological perspective, the knowledge produced by the analysis is subjective and is informed by the authors' scientific backgrounds including both social and natural sciences and experience.

Objective and research questions

We present an overview on the scenario construction with an objective to assess two aspects of scenario planning: the methodology and the content of the scenarios. While the research question is what kinds of approaches the scenarios apply and how the various societal elements are perceived in the scenarios, the sub-question related to methodology is concerned with identifying the change drivers that are the basis for the scenarios. The sub-question regarding societal elements is associated with specific topics that form the foundation of the scenarios. These topics are geopolitical and economic factors, biodiversity, climate change, spatial and energy justice issues. The choice of the topics is based on an understanding of the implications of renewable energy deployment for societies as a whole and their critical role as key societal functions [10, 25].

The scientific contribution of this study is primarily empirical. To scrutinise the future of renewable energy uptake in Europe, the study applies existing frameworks. The review of renewable energy scenarios provides an understanding of their feasibility in a world with increasing geopolitical tensions. Although the findings of this study can be generalised within the European context, given the complexity of the issue, there can be significant variations in national energy policymaking from a Europe-wide standpoint. Consequently, it is not advisable to draw conclusions about national energy policies, and these should be studied separately or as part of a broader study.

Methodology and frameworks

The methodology employed in this study is based on a systematic review with a framework-driven analysis. A systematic review aims to provide a comprehensive, unbiased and replicable summary of the state of knowledge on a well-defined issue [26]. This review consists of two rounds of literature search, the second of which complements the first. The review process was structured in the following phases: (1) setting the research design; (2) a systematic search of the available literature using defined search terms; (3) initial classification and analysis; (4) a further systematic search of the available literature using adjusted search terms; and (5) further classification and analysis (6) synthesising the results.

The analysis phase employs the PESTE (Political, Economic, Social, Technological, Environmental) framework, a widely utilised approach in futures studies, and especially in scenario planning [27, 28]. A similar approach is frequently employed in the formulation of scenarios to emphasise desired dimensions. For example, Ansari and Holz [29] had used a relatively similar STEMPLE+ framework to develop scenarios for global energy and societal development until 2055. However, Andersen [30] has noted that the use of the PESTEL or similar frameworks are considered usually just a checklist rather than a concept that can be theoretically underpinned and empirically verified. In this analysis, the PESTE framework is utilised to facilitate the analysis and the decomposition of the scenario studies and is described in more detail in ("PESTE analysis – review of drivers of change and key topics" section).

Inclusion and exclusion criteria

The criteria for the selection of the scenarios were created in accordance with the requirements of the research design. Given the abundance of scenario studies available, the quality of the sample depends on a rigorous process of inclusion and exclusion. As the focus is on recent scenarios, the choice regarding the time frame was made to include scenarios since 2018 until 2025 (May). This limitation provided us with a feasible number of scenario studies for a comprehensive analysis. The time frame also includes a few years prior to the later global geopolitical developments. This enables us to determine whether these developments impacted the scenario studies. This choice was also motivated by the fact that the study by Cherp et al. [19], which is a reflective component of the study, was published in 2018.

In the geographical context, the choice was made to focus only on the European-wide scenarios. However, the selection process did not differentiate between Europe and the EU. Consequently, there are studies included that deal with both the EU and Europe, including non-member countries. A focus on the EU alone would have resulted in a sample of insufficient size to be considered meaningful. Though it is important to acknowledge that national governments have the mandate to govern energy systems, the EU has a motivational force on national policies. Moreover, there is the issue of research ergonomics. By including national energy scenarios in addition to the European-wide scenarios, the number of scenario studies would have increased considerably, which would have affected the cohesion and quality of the analysis. Furthermore, incorporating such elements would have introduced national-level emphases into a study whose principal contribution lies at the European level.

The review and the analysis are not restricted in terms of the main renewable energy technologies (solar, wind, bioenergy, hydro, geothermal) or energy sectors (electricity, heating, transport). The reviewed scenario studies include both broad energy system-wide studies and narrow studies focusing on a single technology. Scenarios pertaining to so-called clean hydrogen (an energy carrier that is produced with water electrolysis based on clean electricity from renewable energy sources) have been incorporated due to its close association with renewable energy uptake and, for instance, with geopolitical dimensions [31]. Clean hydrogen is also strongly linked to the REPowerEU plan. Moreover, it is a strategic enabler to maximise the use of renewables, provide energy system flexibility, and decarbonise sectors where renewables alone are not enough [2].

The review only incorporates peer-reviewed articles from academic publications written in English, thus excluding grey literature such as scenarios or roadmaps produced by stakeholders and companies e.g. [32, 33]. In the classification phase of the analysis, scenario studies that have not created their own scenarios but have used scenarios borrowed from others in their own framework have also been excluded. This delimitation proved to be significant, as there is a substantial amount of such studies. In the end, efforts were made to ensure that the scenarios were clearly future-oriented, with a defined target time frame.

The search, selection and scaling

The process of this study was iterative, and the research design underwent changes during the process. To ensure the quality of the sample, the search phase was carried out in two rounds: the first round took place in June-August 2024 and the second in May 2025. Both rounds included the scaling of the different elements of the scenario studies, which is described below. The searches were conducted on Google Scholar and Web of Science. Conducted by six researchers, the first round started with a raw selection based on article titles and abstracts. At this stage with several search strings, the exact number of hits, which was in the thousands, was not recorded. In the first round, 42 scenario studies were examined in more detail, of which 24 were selected for further analysis based on exclusion and inclusion criteria. After the first round, the criteria were slightly adjusted, dropping eight scenario studies from the first-round sample. In the second round, 45 scenario studies were examined in more detail, of which 18 were selected for further analysis. During the entire selection process, 87 scenario studies were selected for detailed examination, of which 34 were included in the final sample. The articles were published in 20 journals, which are listed in Appendix A. The summary of the search and selection is described in (Fig. 1). The search terms used in the searches are presented in Appendix B.

In the scaling phase, the elements (societal and technological, see appendix C) in the scenario studies were scaled using numbers to indicate the extent to which each element was covered in the studies. The elements were scaled from 0 to 3, with 0 indicating that they were not addressed at all and 3 indicating that they were strongly emphasised. While a value of 1 was used to indicate a single or a handful of mentions, a value of 2 was used to indicate a relatively abundant treatment of the topic. The analysis of the scenarios also included a methodological review, where the methodological approaches, locus of change and utilised data were identified.

Results

The results presented in this section are divided into two categories. Firstly, the review of methodological characteristics of the scenario studies is presented. Secondly, the representation of (geo)political, economic, social, technical and environmental (PESTE) aspects are examined. The detailed analysis chart with scaling described in the research design (see "The search, selection and

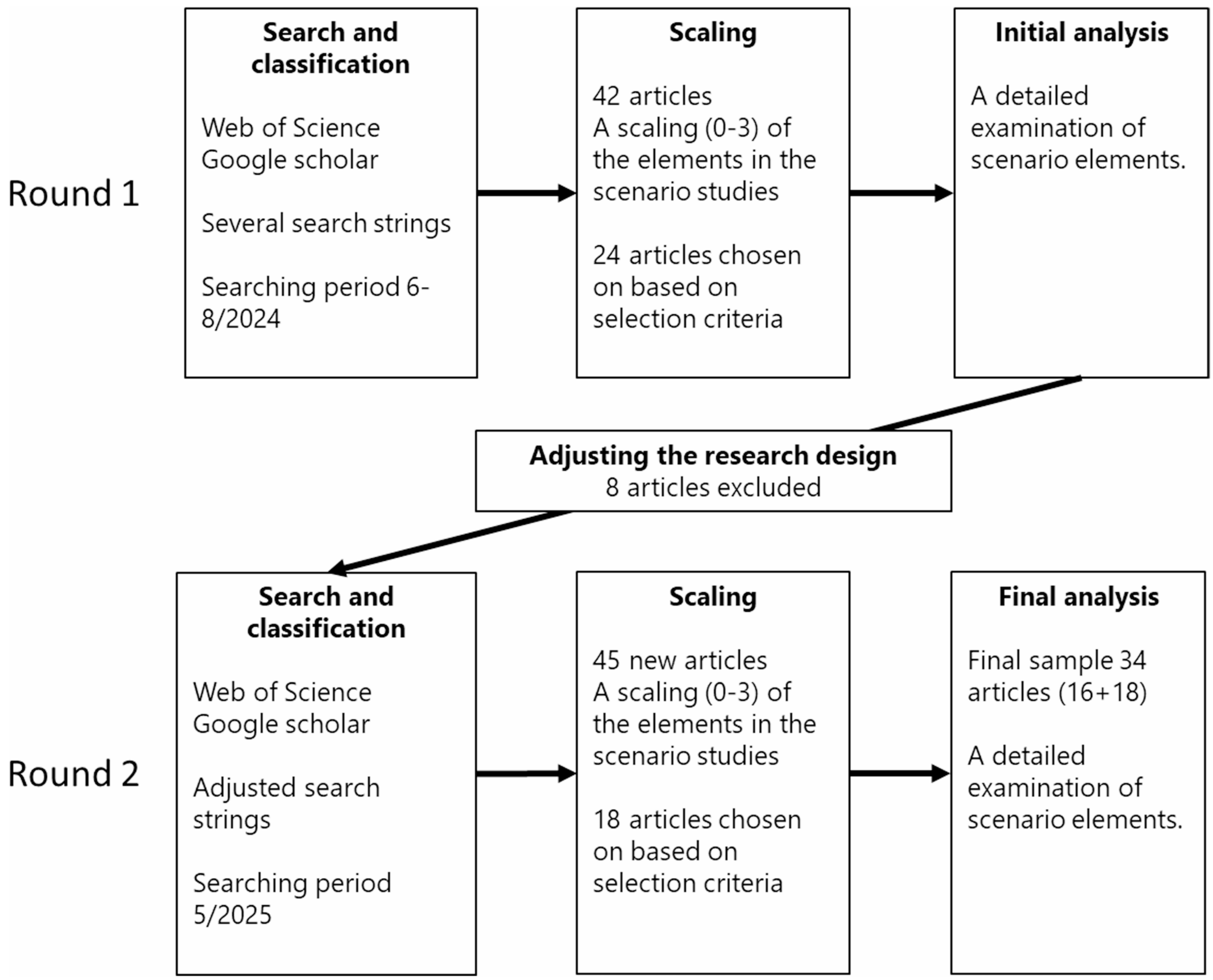


Fig. 1 A summary of the search and selection

scaling" section), on which this section is based, can be found in Appendix C.

The methodological characteristics of the scenario studies

The key characteristics and methodological choices of the scenario studies were analysed including the scenario approach, time perspective, locus of future change, methodological approach, use of future studies methods and utilised data. The framework for analysis is presented below in Table 1 and it was applied with slight changes compared to the study by Aro et al. [34].

In general, the scenario studies considered a system-level transition due to renewable energy growth led by the European climate and emission targets, with a varying focus on the scope or part of the system. Some studies aimed ambitiously at a 100% renewable energy system in the scenario modelling or presented a perspective on system feasibility, requirements, grid integration, development, and cost optimisation at the EU level to achieve a 100% renewable electricity system e.g. [46, 48, 49]. There were also technological weightings in the scenarios, which are discussed in more detail in "PESTE analysis – review of drivers of change and key topics" section.

Most of the studies focused on the energy transition, while one study focused specifically on the low-carbon transition [50]. According to Cherp et al. [19], varying concepts of energy, low-carbon, or sustainability transitions are closely linked and share similar elements, yet they still may differ in the research context on, e.g. their theoretical base. Based on the typology by Rosenbloom [11] – as well as similar perspectives for the energy transition discussed by Cherp et al. [19] – by dividing the foresight concerning transitions into techno-economic (energy flows and markets), bio-physical (availability of natural resources and the ecological and physical constraints that limit energy system development), and socio-technical (knowledge, practices and networks associated with energy technologies) pathways, most of

Table 1 The analysis framework for the methodological review (applied [34])

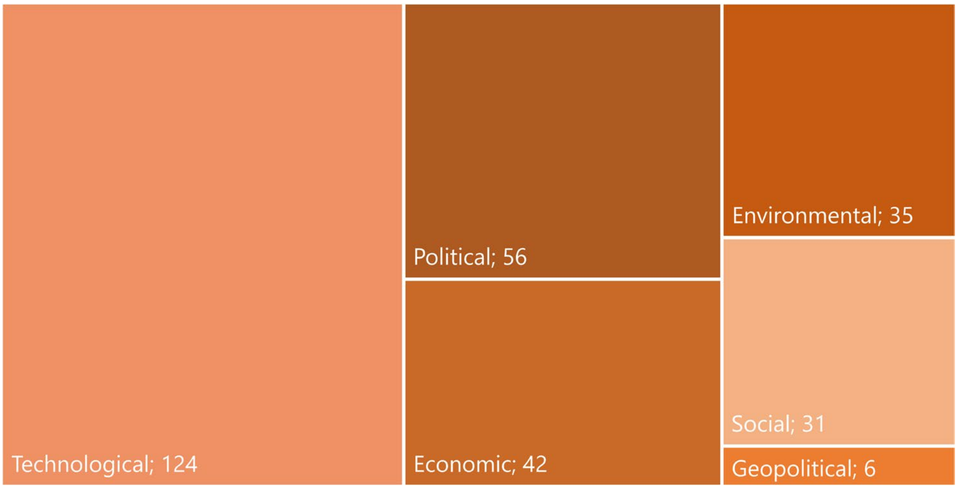
Scenario approach	**In-depth techno-economic modelling** The majority (32 studies) of scenarios had an in-depth techno-economic approach.	**Focus on holistic and societal change (bio-physical or socio-technical)** Two studies [35, 36] had a bio-physical approach, and four studies had a techno-economic and bio-physical approached combined. Only one study was clearly socio-technical [37], and three studies combined techno-economic and socio-technical approaches.	**Policy oriented approaches** Two studies [38, 39] combined socio-political elements to techno-economic modelling.
Time perspective (from the date of publication or announced starting date of the project)	**Not defined** All studies defined a certain time frame for their scenarios.	**Short-medium term (5 to 10 years)** In one study, the time frame was a medium term, varying from 4 to 15 years [38]	**Long term (over 10 years)** In all other studies, the time frame ranged up from 2040 to 2100 but was mainly set to 2050, referring to the European Union's net zero target for 2050.
Locus of future change	**Inside the system** The scenarios and locus of change in the seventeen studies focused on either the energy system, changes inside the system or a specific part of it.	**The system as part of society** The scenarios and analysis in nine studies e.g. [40–42] took into account the changes in the system as a part of society.	**Transformative change** None of the reviewed studies had a holistically transformative approach.
Methodological approach	**Quantitative** With the exception of one study, the methodological approach was quantitative (modelling) in all of the studies.	**Qualitative** None of the studies were purely qualitative.	**Combination** One study was primarily qualitative [38]. However, the approach was more of a combination of qualitative and quantitative scenario building. Four studies combined quantitative approaches with some level of qualitative analysis e.g. [35, 43].
Use of future study methods	**What-if quantitative modelling** 27 studies can be classified as quantitative what-if modelling, e.g. [44, 45] Some studies also combined elements of a qualitative foresight analysis.	**Projections based on statistics & time series** Six of the studies can be classified to be more like projections e.g. [43, 46].	**Qualitative foresight analysis** One study [38] mainly used a qualitative foresight analysis. Four studies e.g. [37, 40, 47] used some kind of qualitative foresight analysis combined with quantitative modelling (what-if scenarios).
Utilised data	**Statistics, estimations** Almost all studies used either historical data, varying sources of data sets and estimates, or statistical values in scenario modelling.	**Surveys, interviews** No data from surveys or interviews was directly used in the studies.	**Participative, interactive workshops** None of the studies used participative or interactive workshops.

the reviewed studies focused on techno-economic perspectives. Though almost all the studies used in-depth techno-economic modelling, some studies combined bio-physical e.g. [51–53], socio-technical [49, 50] or socio-political (political actions and policies) [38] elements in the scenario building with a techno-economic approach, while only a minority of the studies were categorised as bio-physical [35, 36] or socio-technical alone [37].

All the studies had long-term time horizons from 2040 up to 2100, with most set to 2050 according to the European Union's climate neutrality target by 2050. In one article [38], the medium-term time frame was defined based on the pace of the transition.

The locus of future change was also reviewed as either happening inside the energy system, or as part of society and surrounding systems, i.e. whether the scenarios consider societal or environmental factors and impacts in the modelling, or whether the scenario modelling views the energy transition as a broader more radical societal transformation [54, 55]. While the studies included transformative elements for the energy system itself (such as hydrogen applications and deployment or large-scale sector coupling), they were categorised to focus on the system level or the subsystem level. None of the studies had a holistically transformative locus of change across the sectors. Nine studies e.g. [40–42]. were categorised to consider the future change in the energy system as a part of society either considering acceptability, land use impacts on society and biodiversity, and international trade dynamics or climate change impacts, or otherwise considering societal aspects of the energy transition in their scenario analysis. Almost all the studies which used elements from qualitative foresight focused on the energy system as a part of society. In the rest of the studies, the locus of future change focused on transition on the level of energy system.

Table 2 Number of recognised drivers and variables per category



In their scenario building, all studies mainly used mathematical modelling. The scenarios were either completely or partly built with quantitative modelling methods and none of the studies were purely qualitative. Some studies [40, 41, 51] combined quantitative and qualitative approaches with varying levels. The combined approach included studies that used either some level of qualitative data or qualitative scenario descriptions (e.g. Shared Socioeconomic Pathways) to support the scenario modelling and background assumptions. While one study used a cross-impact analysis as a method for its scenarios, which is neither a purely qualitative nor a quantitative approach [38], several studies used a qualitative analysis, yet the scenario building was based on mathematical modelling [37, 39].

To analyse the use of future study methods, a classification using Börjeson et al.'s [56] typology was utilised as a background support. The scenario studies were categorised by whether they include what-if scenario modelling considering scenario trajectories happening "on the condition of some specified event/s" [56] or if the scenarios are more like projections based on statistics and a time series. In their use, projections can be considered more specific compared to what-if scenarios or qualitative foresight analyses. Most of the studies could be categorised as what-if scenarios and six studies e.g. [43, 46]. were analysed to lean more into projections based on statistics or a time series. According to Börjeson et al. [56], mathematical scenario models could be categorised as time-series analyses, explanatory modelling and optimising modelling. In the reviewed studies, all types were used. Though most of the studies' scenarios used optimising modelling, there were also varying combinations of modelling and data approaches.

Lastly, the qualitative foresight analyses employed in the studies were of interest. Here, four studies [37, 40, 41, 47] were categorised by using either storylines or narratives constructed with qualitative methods and with clear integration in the quantitative scenario building (what-if scenario modelling). Though one study's approach was primarily qualitative foresight [38], several other more studies used a combined approach. However, in these above-mentioned studies, a description was given regarding how their modelling framework and scenario analysis were constructed with qualitative foresight analyses.

The data used in the studies varied from different data sets, such as historical data, statistics, or estimations, to data assumptions. None of the studies used data from surveys or interviews directly in the scenario building or any participatory or interactive expert-guided workshops to build their scenario narratives or pathway descriptions.

PESTE analysis – review of drivers of change and key topics

The PESTE framework was utilised to facilitate the analysis and the decomposition of the scenario studies. First, the obvious scenario variables or drivers that were part of the scenarios impacting the future state of renewable energy development are listed and categorised. These variables are not listed in detail, but rather at the headline level of the variables or drivers of change. Second, the key topics included in the scenarios are divided into corresponding PESTE categories (see Table 2). The political (P) category is focused on geopolitics, with an inclusion of energy security, as this study underscores their impact. The economic considerations are in the (E) category. In the (S) category, subjects related to energy justice and spatiality are included. The technological dimensions of renewable energy fall under the (T) category, while the second (E) category encompasses climate change and biodiversity issues. We also examined the sample in terms of its legal (L) dimension as the framework could be utilised as a PESTEL framework. While there are a few references to the legal dimension, these relate to climate legislation and the regulatory frameworks underlying the scenario studies. There was no detailed analysis of the legal dimension or connections to international law in relation to geopolitics.

The obvious technological drivers (124 drivers) were prominent but also played a key role in achieving a clean and renewable energy system. The drivers of change or variables could be summed up relating to the technological development and deployment, rate of innovations as well as technological weighting at the system level. Additionally, economic drivers (42 drivers) were somewhat emphasised.

Only six drivers or variables of political category were explicitly related to geopolitics or energy security. However, political drivers were important (56 drivers) in the scenario settings, mostly related to the EU energy and climate policy. Regulatory, policy and governance from a technological perspective, as well as the future allowability of certain renewable energy technologies or solutions could be associated as uncertainties according to the analysed drivers of change. Though there was also a clear uncertainty related to the political will and how it will evolve, policies play a crucial role in European level energy transition.

In the reviewed scenario studies, slightly less focus was placed on the social (31) and environmental (35) drivers. Social drivers or variables category included human related variables ranging from social acceptance, conflict risks, demand patterns or lifestyles to social engagement and level of collaboration, for instance. However, the category also included societal drivers that are more related to structural changes, actors' roles, land use, governance or even social-economic aspects. Spatial issues and energy justice are analysed in more detail in the "Social: spatiality and energy justice" section. Environmental drivers were mainly linked to climate objectives or climate change impacts (see more in "Environmental: climate change and biodiversity" section).

The reviewed studies provided transparent explanations of the drivers they selected, as well as the assumptions, limitations and methodological constraints underlying their analyses. Although the methodological approach and the specific research focus naturally shape which parameters and variables are included, the studies articulated the rationale behind these choices. For instance, a study utilising qualitative narratives [50] explicitly described that alternative scenario narratives were reduced to two, and quantitative estimates were based on the modellers' interpretations of narrative data. The study found that the conversion from the narrative storylines was considered challenging from a methodological perspective, particularly with regard to the exclusion of social and institutional dynamics from the modelling process.

Moreover, emerging clean technologies are inevitably characterised by uncertainties relating to assumptions, scalability and availability. In the reviewed studies, these technological assumptions and related uncertainties were openly reported. For instance, one study [57] excluded certain feasible emerging technologies, such as concentrated solar heating and geothermal heating, from their scenarios due to limitations in the model. The emphasis of model-based scenarios among the reviewed studies explains why they focus on technical, political and economic variables: these are easier to operationalise in model-based approaches. Social and environmental dimensions are recognised as important but are often left out due to modelling constraints, data availability and the difficulty of quantification. This emphasis is not new and is linked to the prevailing techno-economic approach in energy research.

Political: geopolitics and security

The review of the studies reveals that the geopolitical and security dimensions have not been a priority in recent years in the renewable energy scenarios. Indeed, they incorporated a minimal geopolitical analysis, with only one study devoting meaningful attention to geopolitics.

In their study, Nuñez-Jimenez and de Blasio [41] analysed the geopolitical aspects of renewable hydrogen with three strategic scenarios in which the EU prioritises either energy independence, cost optimization or energy security. The authors of the study bridge the gap between qualitative studies of geopolitical and market implications and scattered quantitative evaluations of production potentials and costs. In their conclusion, Nuñez-Jimenez and de Blasio state that geopolitical implications of their scenarios are significantly different in terms of energy independence, supply costs, and security of supply. In understanding the dynamics of geopolitics, their analysis of how the European Union's security of supply and strategic autonomy would develop in different scenarios is of value. Indeed, this is the only study which deals with interstate relations and gaining geopolitical power with the energy transition. The article concludes that only by working together can the EU become a global leader in renewable hydrogen innovation and simultaneously contribute to its climate and energy security goals, a more robust economy, and a more integrated union.

If there was only one study that conducted a geopolitical analysis in the scenarios, there were ten studies e.g. [49, 51, 58]. that mentioned either energy security or security of supply, at least in some form, but did not carry out an in-depth analysis. For instance, Kiesecker et al. [52] stated that continued dependence on imported fossil fuels is rapidly becoming unsustainable in the face of the twin challenges of global climate change and energy security demands in Europe, which were motivating factors for creating scenarios. Conversely, a major proportion of the reviewed studies did not address the geopolitical or security dimensions at all.

Economic: economic cost analysis of the renewable energy transition

Economic analyses of the renewable energy scenarios focus mostly on the costs and cost savings, whereas aspects such as job creation or market mechanism design are generally given less consideration. The primary objective of two studies [46, 48] was to analyse the aggregate system costs of transition, while a few others also had strong economic focus. In contrast, in some scenarios the economic considerations were entirely excluded, e.g. [35, 43, 52]. Though most studies did not explicitly include broad economic considerations, underlying economic assumptions were nevertheless implicitly made through modelling choices. In such studies, the emphasis was on technical or environmental dimensions, and economics could be viewed either as necessary building blocks in a larger model or constraints secondary to climate targets. Elsewhere, several studies successfully compared the economic and climate aspects with other important dimensions of the energy transition such as energy security [41], land-use and social acceptability [42, 46, 59].

The transparency of models' economic assumptions varied. Information considering these assumptions was omitted from some studies – sometimes even when the model was cost optimising by design – and instead the implications on energy shares of different technologies and climate emissions was highlighted.

The vast economic costs of the necessary transmission grid improvements were identified. However, the transmission grid expansion, although uniformly considered to be among the economically optimal actions, can conflict with public acceptance and politics, as recognised by [59]. Moreover, the impact of sector-coupling in providing flexibility was found to have an economically important positive impact on the transition [45, 59, 60].

Based on their models, some researchers emphasise that the energy transition is not an economic burden and could well lead to cost savings even without considering the climate damages, which were typically left outside the economic analysis. However [48, 61], diverged from this, although the latter focused on a single "worst-case" weather year instead of a larger representative sample. To summarise, discussion on the cost of the energy transition is spread, but optimism seems to be the more common stance in the studied literature.

Some system-wide models used the Levelized Cost of Energy (LCOE) as the objective function for economic optimization. Since LCOE has the significant drawback of omitting indirect system costs, the more realistic total system costs were also widely utilised instead. Yet total system costs omit analysis on changing consumer behaviour, and a more complete framework is provided by partial equilibrium models like TIMES and PRIMES which minimise system costs with demand elasticities, while leaving the rest of the economy exogenous. This approach is considered equivalent to maximising consumers' and producers' surplus [62].

Social: spatiality and energy justice

In this study's application of the PESTE framework, the themes of energy justice and spatiality have been included in the social category. To help the distinction between spatiality and the wider concept of socio-spatiality [63], spatiality in this analysis is understood purely through the lens of land use and space allocation, covering topics such as the geographical placement of renewable energy infrastructure or energy crop production. In this study, the term justice is used to refer to the concept of energy justice, which has been developed to analyse the ethical dimensions of energy [64] and energy systems [65]. We also acknowledge here that justice related issues are also often considered as part of broader considerations of social acceptance of renewable energy technologies.

Spatiality in the land use of renewable energy Themes related to spatiality were identified in nearly three out of every four scenarios, but in-depth discussion on the topic was rare. Within 26 of the 34 scenario studies, spatiality was either mentioned or discussed on some level. Only in passing did 17 studies mention spatiality e.g. [66–68], providing a brief mention on topics such as the distribution of renewable energy infrastructure e.g. [47, 59, 61], land-use of biomass, biofuel, or hydrogen production e.g. [58, 69, 70], or regional potential in renewable energy production [35, 60, 71].

Therefore, deeper discussion on spatiality or spatiality-related themes were only included in nine of the studies. Seven of these went into slightly more detailed discussion, with three focusing on topics of renewable energy production infrastructure siting criteria or restrictions [43, 48, 53], with an additional three studies including a transmission infrastructure related discussion [39–41]. On the other hand, though more in-depth discussion on the land-use requirements for biofuel crop production was only identified in one study [51], this might be reflective of the minor role it has been given within the current energy transition. Finally, in two of the studies, spatiality could be considered central to the paper. In their study, Chen et al. examined land use changes resulting from the energy transition [42], while Kiesecker et al. explored themes relevant to potential land use conflicts, such as land availability and capacities [52].

Energy justice In this section, energy justice is limited to only covering the effects on communities and people, as environmental effects are considered in the following section on biodiversity. Energy justice can be divided into different sub-categories, such as distributive justice, procedural justice [64], and recognition justice [72]. These sub-categories were searched from the reviewed studies with relatively little success. Among the studies, just ten e.g. [42, 52, 73]. mentioned themes of energy justice, with none going to any form of in-depth analysis on the topic.

In the reviewed studies, the rare mentions of energy justice were often identified as distributional justice mentioned alongside spatiality in the scenarios by e.g. [47, 48, 70]. In nearly each of these studies the themes of energy justice arose from the potential social acceptance related issues regarding renewable energy infrastructure, with the sole exception being the paper by [70], which compared the toxicity and human health effects of blue and green hydrogen. Only the studies by [68] and [73] were found to include themes of energy justice while not mentioning the theme of spatiality, and in these two articles, the discussion regarded procedural and recognition justice through policy design and implementation recommendations.

Technological: renewable energy technologies

Wind and solar power were the backbones of most scenario studies and would serve as the main technology providing most of the produced electricity with a holistic scenario approach. Other technologies were typically assigned supporting roles in complementing and balancing wind and solar production. The weather induced, uncontrollable fluctuation in the output of variable renewable energy sources and the potential mismatch with the energy demand and supply was considered the main challenge in the scenario studies.

Solar power was treated mostly in terms of photovoltaics. There are also other technologies, e.g. concentrated solar power, which had a lesser role in the scenarios. Many scenarios envisioned very large solar shares of electricity output, e.g. [49]. Hydropower, including pumped hydro as a storage, was included in many scenarios, though more in the background, providing flexibility for the energy system and balancing electricity generation. One scenario study [66], focused on water utilisation and the water footprint related to renewable energy system, was mainly linked to hydropower generation. Although geothermal energy was mentioned and considered in several scenario studies, this was to a lesser extent. However, one article [71] stated that geothermal energy could cover up to 7% of power generation in 2050 in Europe.

In many of the reviewed studies, the current role of bioenergy was identified and included. Although two studies focused solely on the future role of bioenergy [51, 69], primarily the studies focused on other renewable energy sources. In some cases, bioenergy was entirely excluded from the scenarios, which is likely to be attributable to the fact that many of these studies were based on a general policy orientation that emphasised the promotion of non-fuel-based renewable energy sources in climate change mitigation. As noted in the study by Wu and Pfenninger [51], bioenergy was identified as a controversial energy source in Europe, and its future was therefore deemed uncertain, although its potential to balance the energy system in the face of increasing weather-dependent energy production was recognised.

Five articles focused on hydrogen, either through strategic scenarios, the supply and role of hydrogen as part of carbon-neutral energy systems, the development of the hydrogen market, and the climate and environmental impact of green hydrogen in hard-to-abate sectors e.g. [41, 60, 70]. However, hydrogen has several unresolved issues, as it currently lacks the transportation infrastructure and incurs losses when stored due to gas leakage. Nevertheless, hydrogen is a very topical, up-and-coming technology with high ambitions embedded, as shown by [41, 60, 70]. Power-to-X, referring to the conversion of electricity into products or different forms of energy, was also mentioned or discussed in the articles. This was mainly addressed in five articles e.g. [45, 49], with Breyer et al.'s [49] scenario study characterising the future energy system as a Power-to-X economy, where electricity is expected to dominate as the primary energy form, either directly or indirectly. Elsewhere, the Power-to-Heat perspective was considered in two scenario studies [67, 73], mainly focusing on the heating sector.

Alongside the increasing share of renewables, carbon capture and storage technologies (CCS) were highlighted in some of the studies analysed as a means of sequestering carbon dioxide to combat climate change. In many of these cases, CCS were also linked to bioenergy. However, carbon capture and utilisation (CCU) and the usage of recovered biogenic carbon to produce synthetic fuels were considered in a smaller number of the studies analysed. For example, Thellufsen et al. [74] still mentioned that e-fuels have an important role in reducing emissions in marine traffic, aviation and heavy-duty transport, i.e. those applications where full electrification is challenging.

Energy storage technologies play a substantial role in renewable energy-based energy systems and were particularly emphasised in three scenario studies [49, 59, 61], although they were noted to some extent in most of the reviewed studies. In these studies, different electricity storage solutions were examined, e.g. large-scale and consumer batteries, pumped hydro and battery electric vehicles. In addition, varying forms of heat storages and hydrogen as an energy carrier were considered.

Sector coupling, integrating power, heat and transport, was examined in more detail in five scenario studies e.g. [45, 59, 74]. This process has been regarded as fundamental driver for the energy transition and anticipated to reduce storage needs, increase efficiency while improving system flexibility e.g. [49, 74]. According to Gea-Bermúdez at al. [59], sector coupling may increase demand for renewable energy and help reduce GHG emissions. These authors also noted "that the carbon neutrality European target for 2050 might not be reached without sector coupling". According to one scenario study, sector coupling may mitigate price volatility associated with high VRE yield and support the market value of renewable energy [45]. Trans-European interconnections and the development of the transmission network were also considered in several of the scenario studies e.g. [40, 75]. Moreover, in one study [38] focusing on the European energy transition, interconnections played a significant role in enabling the transition with the possible contribution of the North African desert power concept, Desertec.

Environmental: climate change and biodiversity

In this study, the environmental category of the PESTE framework includes the topics of climate change and biodiversity. Climate change formed the background of all the scenario studies, as would be expected, given the fundamental nature of the energy transition. In contrast, biodiversity issues were given very little attention, so it seems that its importance is not strongly reflected in the scenario studies. For instance, biodiversity is threatened by land-use change [76], which also links it to the spatial dimension of the analysis.

Climate change All the reviewed studies addressed climate change mitigation or the energy transition to emphasise the importance of their research. Mostly, this referred to specific climate targets or scenarios, but some studies also described the history of climate policies [49] or extreme climate events caused by the changing climate [52].

Many articles based their scenario or model target assumptions on climate change mitigation targets such as the Paris Agreement and the European Green Deal, containing the EU climate neutrality 2050 target e.g. [37, 60, 71]. These target assumptions were used as a basis for energy system modelling, using a specific greenhouse gas emission reduction target e.g. [47, 58, 77], or a renewable energy target share e.g. [46, 48, 57]. To do this, greenhouse gas emissions were calculated for different scenarios in several studies e.g. [62, 73, 75]. Some studies referred to climate policies as the background to their research, such as Renewable energy Directives e.g. [39, 49, 78], or REPowerEU e.g. [51, 73, 77].

Several articles also discussed indirect emissions caused by the energy transition, such as land use or indirect land use change related to different renewable energy technologies [42, 51], carbon sinks [58], hydrogen leakage [58, 70] and mineral resource depletion and resulting higher energy demands in the refining process [70].

While most studies focused solely on climate change mitigation, others also examined its impacts on energy production. Martinez et al. [35] assessed the impacts of future wind patterns on the wind power capacity based on climate scenarios, showing that wind power density is expected to decrease due to climate change. In their studies, Yang et al. [36] and Ravestein et al. [53] explored wind and solar power potential in different climate change scenarios, with Ravestein et al. [53] also accounting for the natural variability of climate patterns. Although Child et al. [46] and Zappa et al. [48] noted these effects, they did not directly consider the effects of climate change on renewable power. While Lohrmann et al. [66] discussed the impacts of climate change induced droughts on water-dependent energy production, Salim et al. [73] noted that climate change may impact space heating and cooling needs, although they did not account for this in their scenarios.

Biodiversity Most studies failed to consider the biodiversity impacts of energy systems. While climate change contributes to biodiversity loss [79], here we only address other biodiversity impacts associated with the energy transition. Only one study, conducted by Kiesecker et al. [52], focused on the effects of the energy transition on biodiversity, identifying areas of low conflict with biodiversity that have the potential for wind and solar power construction. Though several other studies mentioned the theme e.g. [47, 58], biodiversity or nature values were completely absent in the majority of the studies.

Only a few of the studies made a direct connection between land use and biodiversity aspects e.g. [43, 46, 58]. Studies also mentioned the effects of land use on ecosystems and the earth's surface albedo [70], bioenergy-related land use impacts [49, 51, 58, 67], the pollution of forests and oceans [37], and saving sensitive ecosystems by importing electricity from less biodiverse areas [38].

In several articles, nature or biodiversity values were considered by excluding protected areas, wetlands, forests or water bodies from the potential area for renewable energy construction e.g. [36, 43, 62]. In contrast, several studies included biodiversity-related criteria in their analysis without directly considering biodiversity aspects. In their study, Shen et al. [70] analysed life cycle environmental impacts, e.g. freshwater ecotoxicity and acidification and land use, of hydrogen production scenarios. This study also noted other adverse effects of wind and solar on ecosystems and biodiversity, such as bird deaths, aquatic nature impacts, and species loss. Without considering biodiversity directly, Lohrmann et al. [66] studied the water impacts of electricity sector.

Discussion

From the perspective of this study, the meta-theoretical framework of three perspectives (techno-economic, socio-technical, political) presented by Cherp et al. [19] contributes to the study of the non-national energy transition. Their framework for the national energy transition sketched top-level variables. By comparing these variables with the issues examined in this study on the European level and focusing on renewable energy scenarios, the following observations emerge. The results underscore a prevailing positivist paradigm in scenario studies of the energy transition, conceptualising it as a future characterised by inevitable advancements in techno-economic drivers.

Among the reviewed societal elements, the underlying economic factors were the most influential and deeply discussed dimension in the scenario building. Though the overarching rationale for developing the scenarios was to achieve climate targets, this was often a more implicit premise rather than a comprehensive examination of climate-related issues. On the one hand, these targets also converge with the political perspective in terms of policy interventions and target setting, while, on the other hand, climate targets are closely linked to the socio-technical perspective, as the technological development of renewable energy and the related innovation systems support their uptake. The consideration of biodiversity in the renewable energy scenarios was rather limited, but it is embedded in the socio-technical approach, as, for example, the construction of wind or solar power can conflict with biodiversity. Moreover, it can lead to social conflicts. However, rather than any of the perspectives presented in the framework [19], climate and biodiversity issues represent the socio-ecological aspect of the energy transition [80].

Spatial considerations received noteworthy attention in the scenario studies, but its in-depth analysis was rare. Issues related to geopolitical factors, biodiversity and energy justice were marginal. Since the techno-economic approach is the predominant way in scenario building, it is obvious that variables related to the techno-economic perspective (resources, demand, infrastructure) play a central role in the reviewed scenarios. In general, the studies covered widely renewable energy technologies, but it was remarkable that for instance the future of bioenergy was considered very little, regardless of its significant role in the energy mix [51]. We consider this limitation impacts the credibility of foresight due to its significance. Closely associated with the renewable energy transition, clean hydrogen was discussed in more than half of the studies, hydropower and geothermal energy were minimally addressed.

The economics of different scenarios were studied in the reviewed literature at aggregate level, abstracting away details of market dynamics. Specifically, money flows from energy markets back to the producers were omitted, making the models stock-flow inconsistent, meaning they do not enforce supply-side profitability. In other words, they do not explicitly address the profit motive and revenue requirements of firms. Although model size and complexities make these choices understandable, it is important to note that the reviewed literature leaves questions about profitability, market design and market coordination unanswered [81]. Effectively the scenario studies make an implicit assumption that energy market regulation and policies are freely adjustable in their models to provide sufficient compensation for all market participants.

Whether this aggregating approach to economic analysis results in idealized models with overstated benefits or can in fact be implemented in practice was left out of the scope of the reviewed studies. We recognise a research gap in integrating higher level energy system scenarios with more detailed analysis of energy market design. By studying the conditions and policies the scenarios require in real-world energy markets advances the understanding on how to ensure efficient market coordination in future energy systems [82].

Proper socio-spatial capacity estimations for the production and distribution of renewable energy infrastructure requires an understanding of social and environmental constraints, for which the concept of energy justice can be helpful [83] and similarly the concept of social acceptance where studies integrating social aspects to modelling exist [12]. In the spatial dimension, the socio-technical perspective explains the development of renewable energy and can also be linked to a political perspective on the direction of potential land use conflicts. Considering the increasing land use requirements for renewable infrastructure deployment [84, 85], including the themes of land use and space allocation is of extreme importance for scenario studies discussing the expected (or unexpected) results of the coming energy transition. However, a more complete picture of spatiality and true land use capacities requires the inclusion of social and environmental aspects [63, 83]. Potential energy justice issues regarding earlier phases of the renewable energy supply chain, such as the acquisition of critical minerals or building and transporting the components required for renewable energy infrastructure, are unavoidably related to both socio-technical and political perspectives [19].

In terms of geopolitics, the decoupling of Russian fossil energy from the EU energy mix can be equated with what

Cherp et al. [19] call a state goal in their political perspective. This was seen as a background driver in some scenarios prepared after 2022. However, the discussion of geopolitics in the scenarios was minimal, which does not support the idea of an increasing European actorness in energy geopolitics [1]. This would require an analysis of political interests, which was one of Cherp et al.'s [19] political variables. Nevertheless, such an analysis is practically non-existent. This conclusion complements the findings by Blondeel et al. [20], who conducted a review of the geopolitical analysis in the global energy scenarios generated by organisations. In their review, they found that few scenarios considered geopolitics in any depth. Indeed, the convergence of geopolitics with the techno-economic perspective is difficult and was only present in one scenario study on hydrogen [41].

The reviewed studies did not address the issues related to the securitisation of the energy transition, which have recently been addressed by some researchers e.g. [86–88]. From a securitisation perspective, discourses are used to dominate the role of geopolitics over other dimensions. This is also in line with Cherp et al.'s conclusion [19] that the role of politics in the energy transition is growing. The use of discourses as a geopolitical tool could be included in the scenarios which could increase the contribution of political science or even linguistics to the study of the energy transition. This could simultaneously fill a gap identified by Vakulchuk et al. [89] that many publications on geopolitics of renewable energy have limited use of scenario building or foresight methodologies. This could be established by assessing competing discourses surrounding the future of energy prospects, particularly among the EU, European states and Russia not to mention other major powers such as the US, China and India. Such an approach could combine, at least on a discursive level, the techno-economic, socio-technical and political perspectives and bring them closer to each other.

The limitations and uncertainties of this study are related to the sample and the research design. Due to the vast number of renewable energy scenarios currently being developed, there are uncertainties in finding a representative sample. In this case, the search process was carried out twice, which provides a robust backbone for the quality of our data. As we have only considered the European-wide scenarios, it should be acknowledged that in the national energy scenarios of European countries the outcome of the study could be different, as different issues may be more predominant at the national level than at the continental level. Moreover, a range of scenario analyses produced by public institutions and state-owned enterprises were not considered in this review, yet they could serve as a valuable complement to typology analyses aimed at exploring the conditions enabling the energy transition. These are therefore a potential area for further research in the future.

Conclusion

To conclude, all the while a range of frameworks and methodologies [12, 17, 21] have been proposed for integrating a range of elements shaping energy transition, we noted fairly limited interdisciplinary dialogue. This review connects with the dialogue to acknowledge issues and challenges of interdisciplinarity in energy research [26] and integration of social and qualitative aspects to scenarios and modelling [8, 17, 21, 90]. We stress the importance for continuing dialogue between social, natural and technical sciences, as energy futures cannot be comprehensively grasped with a single discipline.

However, integrating quantitative and qualitative approaches is not a silver bullet that can solve the complexity of designing an energy scenario. If these approaches are siloed and carried out in stages, they only serve to complement each other. The aim should be to produce information through collaboration throughout the entire process. In any case, the incorporation of multidisciplinary perspectives into energy scenarios is a methodological issue. It is necessary to understand, synthesise and reconcile the information produced by different disciplines. Therefore, it is important that scenario designers also consider their own knowledge production from epistemological and ontological perspectives in order to understand what can be achieved. Breaking down the silos between quantitative and qualitative approaches requires extensive knowledge and experience, as well as an understanding of the philosophy of science. Conducting such comprehensive studies can, however, be hindered by barriers related to the availability of quantitative and qualitative research method competencies, as well as the research resources required to apply multiple scenario methods within a single project. Therefore, research funding instruments must be available on a scale that does not restrict the use of combined methodological approaches. It is also worth noting that multidisciplinary and academically diverse research projects require publication platforms that can accommodate their scope. When journal scopes or article length limitations are too strict to support such studies, publication venues should offer flexible options that preserve the depth and quality of multidisciplinary research.

To provide decision-makers with valuable information on renewable energy, it is recommended that the energy research community continues to integrate different perspectives, such as techno-economic, socio-technical and political, as well as others. While there is also techno-economic focus in the actual crafting of energy policy in the form of strategies and roadmaps, by generating credible interdisciplinary scenarios could also potentially broaden the scope of foresight in policy. As this facilitates the effective deployment of renewable energy in Europe, such action is particularly important in times of frequent geopolitical tension.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40309-026-00268-w.

Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

Acknowledgments

Not applicable.

Authors' contribution

OMM: conceptualization, data curation, methodology, writing – original draft, writing – review and editing, project administration NE; conceptualization, data curation, methodology, writing – original draft, writing – review and editing SH: conceptualization, methodology, writing – original draft, writing – review and editing, SL: conceptualization, writing – original draft, PR: conceptualization, writing – original draft LS: conceptualization, writing – original draft, TN: conceptualization, writing – original draft PR: conceptualization, methodology, Supervision, writing – review and editing

Funding

The authors gratefully acknowledge financial support from the European Union REPowerEU funding (Council of the European Union, implementing decision 15836/23).

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests

Received: 3 December 2025 / Accepted: 8 April 2026

Published online: 29 April 2026

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