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Review

Towards economic, environmental, and societal sustainable world: Reviewing the interplay of methodologies, variables, and impacts in energy transition models

Vincenzo Del Duca [a], Cristina Ponsiglione [b,*], Simonetta Primario [b], Serena Strazzullo [b]

[a] Department of Chemical, Materials, and Industrial Production Engineering, University Federico II, Piazzale Tecchio, N° 80, 80125, Napoli, Italy
[b] Department of Industrial Engineering, University Federico II, Piazzale Tecchio, N° 80, 80125, Napoli, Italy

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ABSTRACT

Green energy transition models provide frameworks for policymakers, businesses, and stakeholders to plan and implement the shift toward more sustainable energy systems. These models evolve as technologies advance, policies change, and societal priorities shift, highlighting the importance of flexibility and adaptation in energy transition planning. This study presents a systematic literature review of 115 papers to elucidate methodological approaches, variables, and assessed impacts involved in these models. The descriptive analysis of the sample reveals a burgeoning interest in this pivotal domain alongside a conspicuous dearth of consolidated model and methodological approaches for evaluating the multifaceted environmental, societal, and economic impacts of green energy transition processes. Our results show a broad spectrum of methodological approaches proposed in the literature, with Agent-Based Modeling & Simulation and Statistical Methodologies emerging as prominently featured methodologies. Through a rigorous content analysis of the article sample, we developed a taxonomy of variables that encompasses environmental, economic, societal, governance, knowledge, and technological domains. Then, to elucidate the intricate relationships between output variables and methodologies, we utilised Sankey diagrams and a conceptual map to clarify the complexity inherent in studying related processes. Lastly, a meticulously crafted research agenda is outlined, derived from critical themes identified in the articles, to guide future research endeavours and contribute to advancing knowledge in the green energy transition modelling field.

1. Introduction

The transition towards a sustainable and green energy paradigm has become a pivotal focus for policymakers, researchers, and practitioners in response to pressing global challenges. This transition involves a shift from traditional, non-renewable energy sources, such as fossil fuels, towards renewable and sustainable energy sources, such as solar, wind, hydroelectric, and geothermal power (IEA, 2023; IRENA, 2023). By the end of 2023, renewable energy accounted for 43% of the world's installed power capacity. Despite the remarkable increase in renewable energy additions in 2023, the global efforts are still insufficient to meet the 28th Conference of Parties (COP 28) goal of tripling the installed renewable power capacity by 2030 to achieve 11 TW (IRENA, 2024).

The urgency of this transition is underscored by the need to mitigate the impacts of climate change (Osman et al., 2023; Sayed et al., 2021), reduce greenhouse gas emissions, and ensure energy security for future generations (Axon and Darton, 2021; Tansel Tugcu and Menegaki, 2024).

In this context, the Intergovernmental Panel on Climate Change (IPCC) has highlighted the critical importance of transitioning to sustainable and green energy systems to limit global warming to 1.5 °C above pre-industrial levels (Mor et al., 2023). This imperative has been echoed in international agreements such as the Paris Agreement, where signatory countries have committed to enhancing their efforts to mitigate climate change and adapt to its impacts by promoting sustainable energy solutions (Belaïd et al., 2023; Fay et al., 2015; IPCC, 2014).

In this context, COP 28 has taken on a crucial role, not only marking the midpoint between the 2015 Paris Agreement and 2030, the target

* Corresponding author.
E-mail addresses: vincenzo.delduca2@unina.it (V. Del Duca), ponsigli@unina.it (C. Ponsiglione), simonetta.primario@unina.it (S. Primario), serena.strazzullo@unina.it (S. Strazzullo).

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year for achieving key climate milestones such as reducing emissions and expanding renewable energy but also representing a significant step forward with the commitment of all 195 nations to transition away from fossil fuels. As Nevitt (2023) highlights, however, further discussion is needed to define what this entails, considering issues of social justice, economic impacts, and the specific needs of developing countries. Moreover, with the next two years being critical, it will be essential to observe how different nations will interpret these directives and strategically implement the enabling policies, particularly as they prepare for COP 29 and COP 30. These upcoming conferences will require governments not only to establish a new climate finance goal but also to present new nationally determined contributions that are comprehensive, economy-wide, and fully aligned with the 1.5 °C temperature limit (United Nations Climate Change, 2023).

Specifically, COP28 encourages parties to consider, in consultation with technical experts, practitioners, researchers, and other stakeholders, the development of methodologies and tools, including modeling tools, to assess and analyse the environmental, economic, and social impacts of implementing strategies for sustainable energy transition (UNFCCC. Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA), 2023).

The urgency of achieving a sustainable energy transition necessitates a comprehensive understanding of the intricate interplay between economic, societal, and environmental factors (Baker et al., 2014; Hariram et al., 2023). The pervasiveness of fossil fuels throughout our industrial infrastructure renders the transition to renewable energy a challenge that defies easy modelling (Hoekstra et al., 2017; Holechek et al., 2022; Wright et al., 2022).

Nonetheless, the literature proposes diverse methodological approaches tailored to address the multifaceted nature of this subject. These approaches encompass a broad spectrum of disciplines, including economics, sociology, engineering, and environmental science, each contributing a unique lens to the complex dynamics of the energy transition (Castrejon-Campos et al., 2020; He et al., 2021).

The fragmentation of the literature on how this transition can be modelled, which variables must be considered, and which impacts are involved makes it difficult to identify the most effective methodological approaches or propose new models.

Modelling this transition is also challenging due to factors such as behavioural changes (Niamir et al., 2018), integrating intermittent renewable sources (Cosgrove et al., 2023; Mlilo et al., 2021; Nastasi and Lo Basso, 2016), and addressing technical and social concerns (Bolwig et al., 2018; Hainsch et al., 2022).

Researchers are working to address these challenges, but more is needed to develop models and propose approaches that adequately capture the complexity of the transition to renewable energy.

This is important because the success of the transition will depend on the ability of models that can jointly consider the economic, environmental, and societal impacts of different scenarios (Child et al., 2018).

To inform policymakers, researchers, and practitioners how to study the transition from fossil fuels to renewable sources and energy, we propose a systematic literature review (SLR) focused on methodological approaches, variables, and impacts that comprehensively embrace the intricate and interrelated aspects of the energy transition phenomenon. In particular, we aim to answer the following research question.

- What methodological approaches are proposed by the literature to study the transition to green energy? (RQ1)
- Which variables, such as input and output, do such methodologies involve? (RQ2)
- To what extent are economic, environmental, and societal impacts jointly assessed, and which combinations of methodological approaches and variables are adopted to perform this assessment? (RQ3)

Previous literature reviews on energy transition modeling have been first considered and studied to find insights into these questions. However, to the best of our knowledge, none of the recent reviews address the topic under consideration. The 2015 published review of Li et al. (2015) highlights the need to assess socio-technical models in the energy studies domain to find a bridge between quantitative modeling from a policymaking point of view and mostly conceptual elements present in socio-technical transition theory. The review is focused on specific industries like transport, energy supply, and building. The paper of Hansen et al. (2019) adopts a systematic literature review to identify relevant literature studying energy transition through agent-based modeling. In this review, the 62 selected articles use this specific modeling approach and are classified according to the way they cope with different areas of complexity characterizing the energy transition process.

Chang et al. (2021), based on past reviews and experts/developers' opinions, assess energy systems models focusing on tools for energy planning, with a technical and analytical orientation. The review of Hafner et al. (2020) systematically assesses non-optimization macroeconomic ecological models evaluating their capability to address features related to complexity and uncertainty of low-carbon energy transitions. The starting point, in this case, is the analysis of macroeconomic approaches, with the specific aim to underline characteristics of models able to cope with the increasing elements of complexity characterizing the energy transition phenomenon.

Differently from the studies above, the present review aims to combine various methodological approaches, variables and impacts into a unique analysis. As briefly discussed, past reviews often focus on specific methodologies or sectors (e.g., Li et al. (2015), on socio-technical models, or on agent-based modeling (Hansen et al. (2019)); the present research, instead, offers a broad examination across multiple frameworks, disciplines and modeling approaches.

Following a systematic review process, we selected 115 papers, of which 56 were particularly relevant since they proposed models that integrate environmental, social, and economic impacts. A descriptive analysis based on bibliometric measures was conducted to provide a quantitative overview of the research field by examining patterns in scholarly publications, citations, and authorship. Subsequently, a comprehensive content analysis was undertaken to delve into the fundamental components of the proposed models. This entailed a meticulous dissection of their methodological approach, considered variables, and the impacts measured, providing a detailed insight into the intricacies of each model.

Our efforts are reflected in the ensuing discussion, where we synthesise our findings to articulate a nuanced understanding of the state-of-the-art in green energy transition modelling. This synthesis not only highlights the strengths and limitations of the existing models but also serves as the foundation for future researchers who aim to model this process. For this purpose, a taxonomy of involved variables is proposed as one of the outcomes of the content analysis of the articles' sample. Our results describe the intricate relationships between methodological approaches and input-output variables in studying the transition from conventional-fossil to renewable and green energy systems.

The development of a detailed taxonomy of variables and the use of conceptual maps to illustrate the relationships between methodologies and variables are novel contributions. These tools help in identifying trends and gaps in current research, providing a clear path for future studies.

We end with a research agenda highlighting the identified open issues, implications for policymakers, and a resounding call to action for the collective advancement of knowledge in the dynamic field of green energy transition modelling.

2. Methodology

To comprehensively examine the current state of the research topics under investigation and answer research questions stated above, this study employs a systematic literature review (SLR). According to

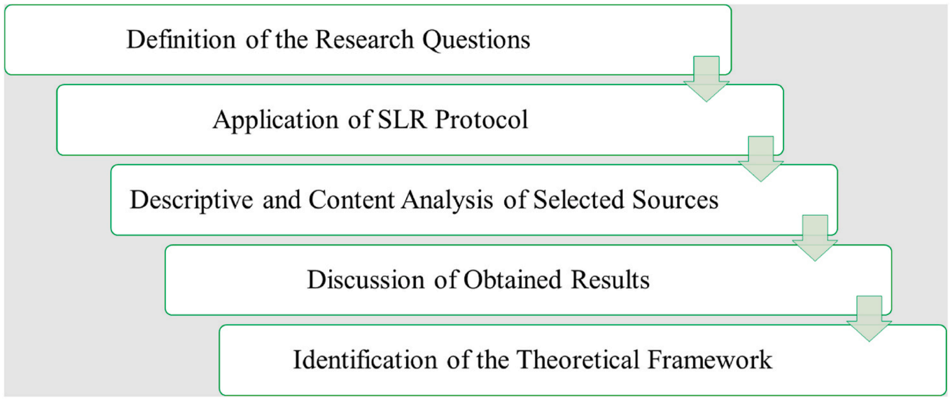

Fig. 1. Steps of the methodology.

Massaro et al. (2016), we recognise that, in general, conducting a rigorous SLR facilitates the generation of reliable knowledge about the existing research landscape. This approach aids in identifying research trends and pathways to establish a solid framework.

Tranfield et al. (2003a) emphasise that SLRs employ a replicable process involving manual filtering. This meticulous approach significantly reduces bias in the findings. In contrast to automated filtering methods, manual filtering allows authors to carefully identify and synthesise all relevant contributions, ensuring a transparent review process.

The SLR methodology, in particular, allows for comprehensive research aggregation, ensuring that all relevant methodological approaches are considered (RQ1). Furthermore, due to the choice of a broad and comprehensive research string (as outlined in the following sub-paragraphs), the SLR allows us to identify and categorize the variables used in the literature, thus providing a robust framework for understanding the input and output variables involved in these methodologies (RQ2). Finally, the SLR's structured approach enables a detailed analysis of how economic, environmental, and societal impacts are considered and assessed across different studies, thereby directly addressing the last research question (RQ3).

Furthermore, our methodology integrates SLR and a descriptive analysis based on bibliometric measures to provide a holistic view of the research landscape. Indeed, the systematic literature review allows us to identify and synthesise relevant studies (Tranfield et al., 2003b) while the descriptive analysis helps visualize the structure and dynamics of the research field (van Eck and Waltman, 2010). By combining these approaches, we aim to achieve a comprehensive understanding of the key themes, trends, and gaps in the literature, thereby addressing our research questions effectively (Snyder, 2019). Consequently, this approach offers a comprehensive overview of both quantitative and qualitative aspects.

Our methodology consists of five different phases, as shown in Fig. 1.

Massaro et al. (2016) suggest that the first step is defining the research questions. The second step involves developing and employing an SLR protocol. Here, the SLR protocol plays a crucial role in guiding the selection and analysis of papers. It allows researchers to determine the sources of information to be used, establish the criteria for including or excluding papers, and identify the methods, tools, and software for exploring and synthesising the collected articles (Petticrew and Roberts, 2006). We conducted a keyword search within the Scopus database to gather relevant academic contributions. Scopus was selected due to its extensive coverage of scientific, technical, and societal science literature. It provides a comprehensive collection of scholarly materials and offers a wide range of metrics to assess the impact and relevance of publications (Thelwall, 2018; Waltman, 2016). Then, we adopted a comprehensive search string to ensure inclusiveness and minimize the risk of overlooking relevant studies. We aimed to encompass a wide range of potentially valuable research by employing a search string with broad terms and keywords. Specifically, we connected our key search terms – such as "green", "economic energy", "transition", "model*" – using boolean operators AND/OR (see Fig. 2). The asterisk in the search string represents the truncation. In this way, it was possible to find all studies, regardless of the variants of the term (i.e., we could retrieve papers including "models", "modelling", and so on).

The search timeframe was confined to January 2015–December 2022. The selection of 2015 as the starting year was based on the significant milestone of the Paris Agreement[1] on greenhouse gas emissions reduction. Paris Agreement represents a "turning point" in the global transformation towards a low-carbon economy (Kinley, 2017), determining a paradigm shift in developing approaches, methods, and policies to climate change mitigation (Kern and Rogge, 2016). The articles search was limited at the end of 2022 due to the study's timeline, which was completed before most 2023 publications became accessible.

Following the initial keyword search, the results underwent filtration based on predefined exclusion and inclusion criteria. Consistent with prior research (Vrontis and Christofi, 2021), only articles at the final publication stage, written in English, and published in peer-reviewed journals were included. Excluded materials comprised conference papers, book chapters, books, short surveys, notes, conference reviews, editorials, and letters.

Employing the PRISMA framework (Moher et al., 2010), the initial pool of 7205 contributions identified via the specified search string was refined. By applying exclusion criteria related to document type, publication stage, source type, and language, the number of relevant papers was reduced to 2851. These 2851 papers were further filtered to exclude journals not intersecting with business, management, and organization research areas.[2]

Subsequently, specific keywords not pertinent to the study's focus were used for exclusion, such as non-human, metabolism, green fluorescent proteins, green fluorescent protein, animals, genetics, unclassified drug, chemistry, animal, physiology, biological model, and cytology, resulting in 684 articles. These 684 contributions were then uploaded into the biblioshiny package in R,[3] where Bradford's Law was applied to retain only articles from journals classified in zones 1 and 2.

[1] The Paris Agreement under the United Nations Framework Convention on Climate Change", Agreement on Climate Change adopted on December 12, 2015, at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change held in Paris, France.

[2] We excluded journal focused on research areas like physics and astronomy; materials science; biochemistry, genetics and molecular biology; chemistry; medicine; agricultural and biological sciences; chemical engineering; mathematics; earth and planetary sciences; computer science; immunology and microbiology; neuroscience; pharmacology, toxicology and pharmaceutics; arts and humanities; psychology; nursing; health professions; veterinary; dentistry.

[3] https://www.bibliometrix.org.

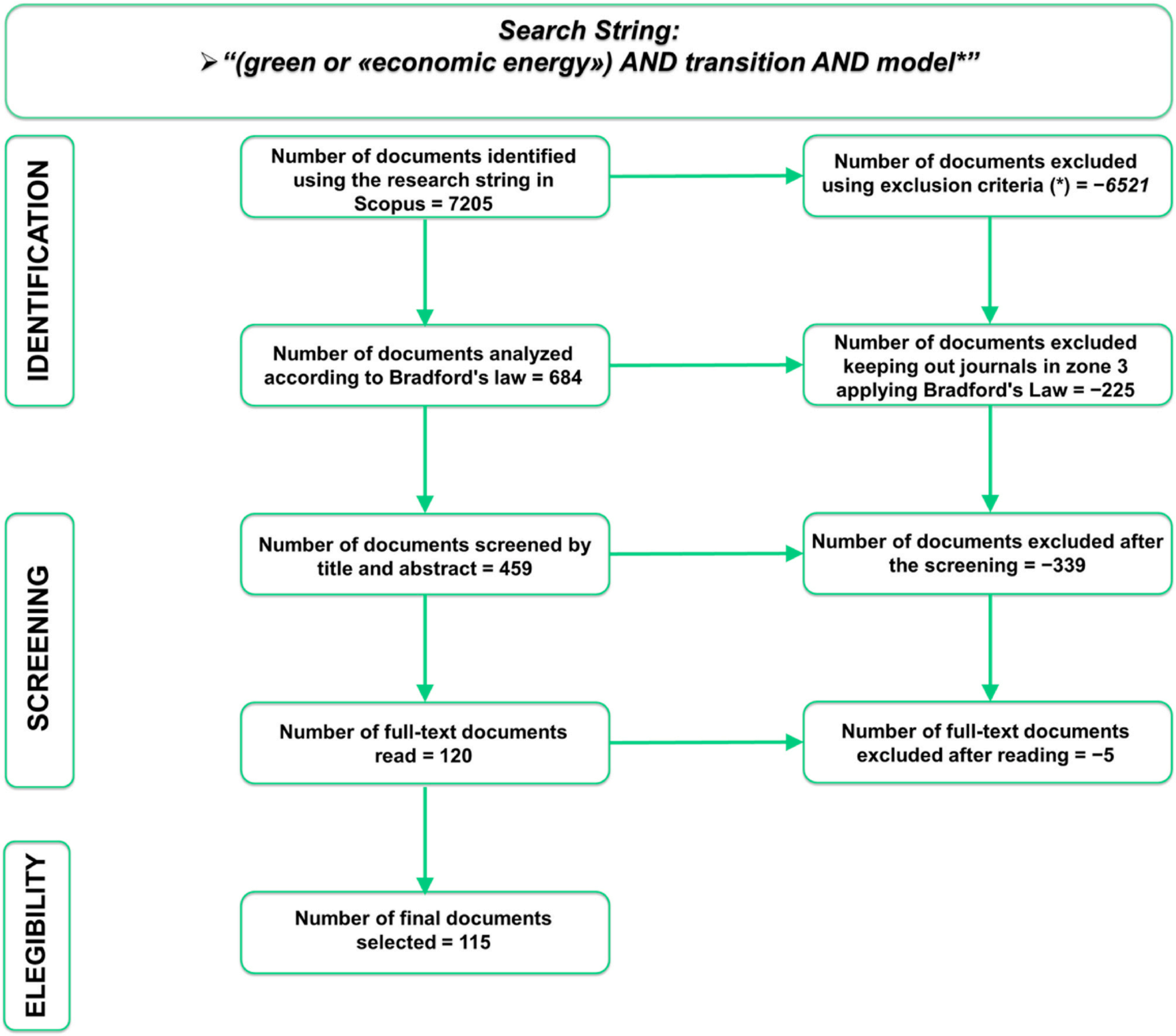

Fig. 2. PRISMA flowchart of the study.

This refined sample underwent a meticulous assessment of titles and abstracts, conducted independently by two reviewers, to identify studies proposing models and methodological approaches for evaluating the multifaceted environmental, societal, and economic impacts of green energy transition. Discrepancies between the reviewers were resolved through consultation with a third expert, leading to the exclusion of 339 papers that did not align with the core theme of our investigation.

Finally, a full-text review of the remaining 120 papers was conducted, excluding 5 papers that did not address the research question. Consequently, 115 papers were included in the final sample. Fig. 2 illustrates the flowchart for the search strategy and screening process.

3. Results

The findings of this study will be delineated in the following paragraph, which is structured into two main sections: 'Bibliographic General Overview' and 'Content Analysis'. This organisational structure is designed to provide a thorough understanding of the results and implications derived from the research.

3.1. *Bibliographic General Overview*

The articles included in the final sample were first analysed according to different bibliometrics indicators. Specifically, we evaluated the literature's evolution in terms of publication year, number of citations, journals, co-authors network, keywords network and bibliographic coupling.

Fig. 3 shows the number of papers published in Scopus from 2015 (year of the Paris Agreement) to December 2022. The graph shows a steady increase in the number of papers published over the years, with a slight decrease in 2019, a steady rise in subsequent years, and a peak in 2022 with 28 papers published. Fig. 3 shows active and continuous research activity and increasing participation in the scientific community. This phenomenon can be attributed to the growing interest of the scientific and non-scientific community in sustainability issues and the imperative to address the challenges posed by the transition to green energy. In broader terms, this interest is confirmed by the Sustainable Development Goals (SDGs), established in 2015 by the international community as part of the UN 2030 Agenda for Sustainable

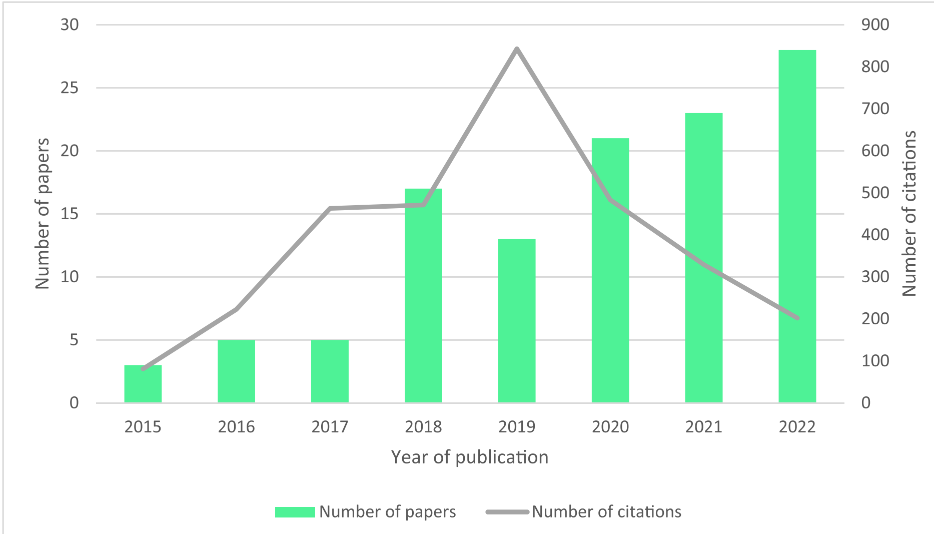

Fig. 3. Number of published papers over time (2015–2022).

Development[4]. The establishment of the SDGs has triggered not only political action (Biermann et al., 2022), but also mobilized the scientific community (Leal Filho et al., 2018), encouraging a multidisciplinary approach and promoting new areas of research (Global Sustainable Development Report, 2023, 2023, 2023). This increase reflects a growing awareness and urgency in addressing global challenges as part of the UN Agenda 2030 for sustainable development (Tsalis et al., 2020).

Regarding the evolution of citations, it is notable that while the number of papers has consistently increased over time, the citation counts do not necessarily exhibit the same trend. This suggests variations in the impact of the papers, with some receiving higher citation counts than others despite the overall growth in the number of publications. These results can be matched with data in Table 1, which displays the sources of publications, listing the journals with the highest h-index, citations, and number of contributions. Here, the top positions are occupied by the highest h-index journal. Specifically, the table features the following three journals: Renewable and Sustainable Energy Reviews, Science of the Total Environment, and Journal of Cleaner Production. These journals have garnered significant attention and recognition from other researchers, as reflected in their high citation counts. Moreover, their aims and scopes highlight the twofold commitment to interdisciplinary research, environmental sustainability, and efficient resource utilisation.

Firstly, these journals emphasise the significance of interdisciplinary research, which is crucial to addressing the complexity of environmental and energy-related issues. For instance, the mission of Renewable and Sustainable Energy Reviews is to bring together the research community, private sector, and policymakers to support sustainable development and a low-carbon future. Similarly, Science of the Total Environment is an international journal that publishes interdisciplinary environmental research, emphasising the interconnection of multiple spheres such as the atmosphere, lithosphere, hydrosphere, biosphere, and anthroposphere. The Journal of Cleaner Production focuses on research and practice in Cleaner Production, environment, and sustainability, aiming to help societies become more sustainable.

Secondly, all these journals advocate for environmental sustainability. Renewable and Sustainable Energy Reviews aims to share innovative ideas and technologies to achieve emission targets set by international agreements. Science of the Total Environment invites contributions that significantly advance the understanding of environmental interactions. And, the Journal of Cleaner Production discusses both theoretical and practical aspects of cleaner production and sustainability. Finally, all journals recognise the importance of optimal and efficient resource utilisation, which includes energy, water, natural resources, and human capital.

Then we investigate the author keyword (see Fig. 4), employing a specifically developed thesaurus that helps us to aggregate synonymous, plural, and forms (e.g. "socio-technical" and "socio technical" or "Industry 4.0" and "I4.0" and "fourth industrial revolution"). This keyword map, generated using the VOSviewer software, offers a comprehensive visualization of the interconnected research themes within the field of energy transition models. Each node represents a distinct keyword, with its size reflecting the frequency or significance of the term within the sample of articles. The lines connecting these nodes denote co-occurrence relationships, where the thickness of the lines indicates the strength of these relationships. The colors of the nodes and lines, ranging from blue to yellow, signify the publication years of the keywords, spanning from 2018 to 2022.

At the heart of the map lies a central cluster predominantly colored in green, comprising crucial keywords such as "energy," "renewable energy," "sustainability," "energy transition," and "CO2 emissions." This cluster underscores the primary focus of contemporary research on transitioning to sustainable energy sources and mitigating carbon emissions. Surrounding this central cluster are several thematic groupings, each highlighting different aspects of the broader research landscape.

The top left cluster, shaded in green and blue, features keywords like

Table 1
Top ten sources of publications.

Journal	H-index	Total Cit.	#Papers
Renewable and Sustainable Energy Reviews	378	80	3
Science of the Total Environment	317	293	6
Journal of Cleaner Production	268	431	13
Applied Energy	264	168	7
Energy Policy	254	595	10
Ecological Economics	236	93	6
Energy	232	39	2
Journal of Environmental Management	218	22	2
Energy Economics	187	134	5
Environmental Science and Pollution Research	154	78	5

[4] The 2030 Agenda for Sustainable Development, https://sdgs.un.org/2030agenda

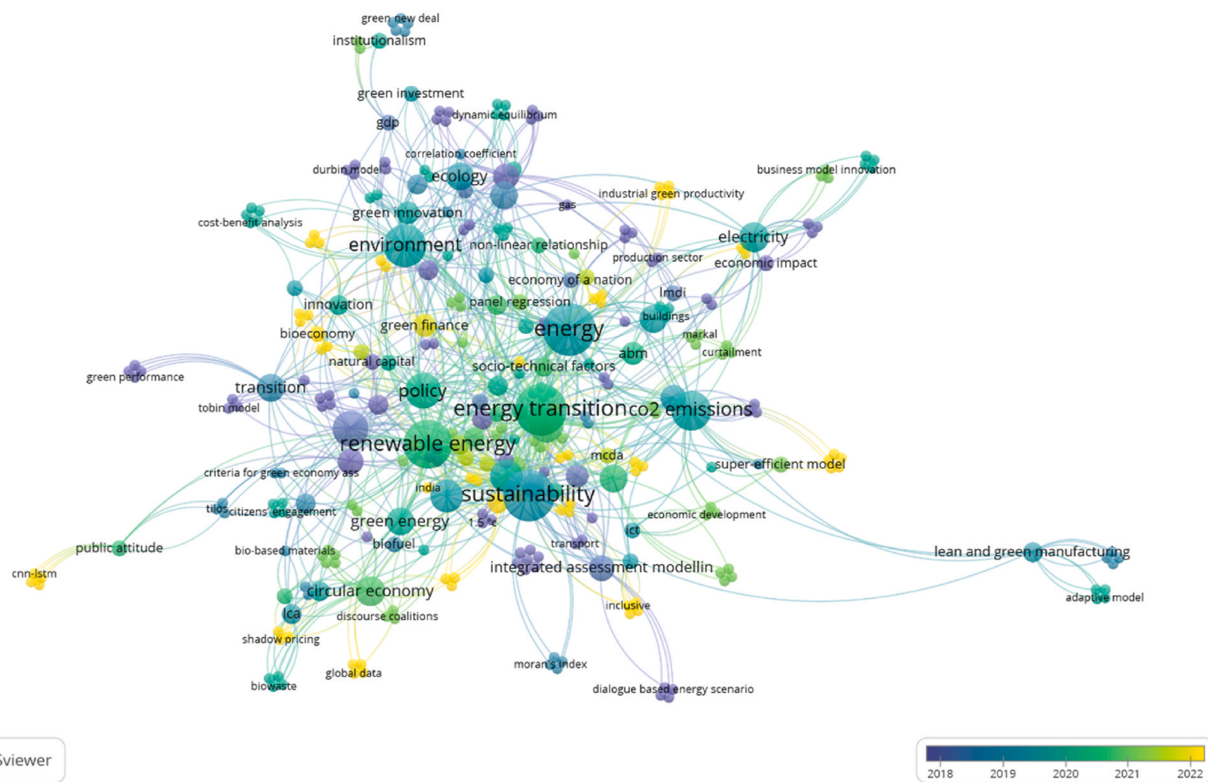

Fig. 4. Keyword's network map.

"environment," "ecology," "green innovation," and "policy." This grouping emphasizes the intersection of environmental science and policy, suggesting a strong research interest in regulatory frameworks and innovative solutions aimed at environmental sustainability. Adjacent to this, in the top right, is a cluster with keywords such as "electricity," "economic impact," "business model innovation," and "industrial green productivity." This cluster delves into the economic and industrial dimensions of sustainable energy, highlighting the importance of economic implications and business strategies in the transition to sustainable practices.

Towards the bottom left of the map, a yellow and green cluster focuses on the circular economy and public perception of sustainability. Key terms in this area include "circular economy," "bioeconomy," and "public attitude," reflecting research on integrating economic and environmental benefits through sustainable practices and the role of public opinion in driving these changes. Finally, the bottom right cluster, colored in green and yellow, emphasizes specific methodologies for achieving sustainability in manufacturing, with keywords like "lean and green manufacturing" and "adaptive model."

The high connectivity of central keywords such as "energy," "renewable energy," and "sustainability" underscores their pivotal role in the research landscape, showing extensive co-occurrence with other terms. The distinct thematic clusters reveal the diverse yet interconnected nature of research in this field, each contributing to the overarching goal of achieving sustainability.

A temporal analysis of the map, indicated by the color gradient, reveals the progression of research focus over time. In the earlier years (2018–2019), represented by blue and green nodes, there was a significant emphasis on foundational concepts like "environment," "ecology," "green innovation," and "policy." This period saw extensive exploration of regulatory frameworks and innovative solutions necessary for environmental sustainability. Moving towards more recent years (2020–2022), depicted by green to yellow nodes, research shifted towards practical applications and economic implications of sustainability. Keywords such as "business model innovation," "economic impact," "industrial green productivity," and "lean and green manufacturing" became more prominent, indicating a growing interest in integrating sustainable practices within industrial and economic frameworks. Recent trends (2021–2022), highlighted by yellow nodes, focus on the circular economy and public perception, reflecting the broader societal and economic focus on sustainability.

3.2. Content analysis

The 115 selected papers investigate different settings in which a transition from fossil fuels to renewable sources is in place, impacting the economic, environmental, and societal dimensions.

We first categorised the selected papers based on the type of impact assessed: economic, environmental, and societal.

As reported in Table 2, almost half of the articles (56) concurrently analyse the economic, environmental, and societal impacts. This result emphasizes the scientific community's recognition of the necessity to evaluate the effectiveness and sustainability of green energy transition models through a holistic perspective. On the other hand, 13 articles have dedicated their analysis solely to environmental impacts, demonstrating a significant interest in evaluating the effects of energy transitions on the environment, and, at the same time, the existence of a not-neglectable number of studies only limiting the attention to a single aspect considered still predominant with respect to others. It should be noted that the economic and societal impacts have been individually assessed in only 2 articles.

This suggests that literature, as expected in this specific context of investigation, tends to more frequently consider environmental impact in the case of single or double assessments. This phenomenon is explained by the emphasis placed on environmental impact by scholars aiming to achieve the goals set by the Paris Agreement (or others).

3.2.1. Methodological approaches

To address the research questions, we conducted an in-depth analysis of the methodological approaches used in the articles within our sample.

Table 2
Number of papers by type of impact and methodological approach assessed.

Dimensions	Impact	# Papers per Impact	Methodological Approach	# Papers per Methodological Approach	Framework
three	Environmental &Economic &Societal	56	ABM & Simulation	13	Coevolution model; Computable General Equilibrium (CGE) model; Dynamic Discrete Choice (DDC) model; Energy model; Environment–Energy–Economy (E3) model; Macroeconomic simulation model; Spatial Econometric model; Standard Vertical Product Differentation Duopoly model
			Case Study	10	Business Model Canvas; Circular Economy model; Directional Slacks-Based Inefficiency model; Life-Cycle Assessment (LCA); Multiple-Criteria Decision Analysis (MCDA); Super-Efficient SBM model
			Conceptual Model	5	Circular Economy Centric Quintuple-Helix model
			Statistical Model	12	Coupling Coordination Degree model (CCD), Spatial Econometric model, and Spatial Panel model; Dynamic model; Econometric model; Non-Linear Regression model; Non-Radial Directional Distance Function-Data Envelopment Analysis (DDF-DEA) Green Innovation Efficiency Evaluation model; Regression model; Simultaneous Equations model; Spatial Panel model and Mediating Effect model; Stochastic Frontier model
			Survey/Interview	1	n.a.
			Others	15	Conceptual Institutional Model; Data Envelope Analysis (DEA) model; Dynamics System model; Econometric model; Economic model; Energy model; Integrated Assessment Model (IAM); SWOT analysis + GAHP method + GTOPSIS; von Neumann model
two	Environmental &Economic	29	ABM & Simulation	10	Computable General Equilibrium (CGE) model; Energy Economic model; Energy Plan model; Generation Expansion Planning (GEP) model; Mixed-Integer Linear Programming model; Optimization model
			Case Study	2	Economic model; Energy model
			Conceptual Model	2	Fuzzy and Visual-Block model
			Statistical Model	10	Econometric model; Energy model; Mediation model; Panel Regression model; Slack Based Model (SBM); Spatial Autoregressive model
			Others	5	Energy Model; Hybrid model: "Kaya identity" and "IPAT model" with the Log-Mean Divisia Index Method (LMDI); Optimization model
	Economic &Societal	8	ABM & Simulation	3	Energy model; Evolutionary Game model; System Dynamics model
			Case Study	1	Cooperative Crowdfunding model
			Conceptual Model	1	Analytical model
			Statistical Model	1	Economic model
			Others	2	Econometric model; Mathematical model
	Environmental &Societal	5	ABM & Simulation	1	Energy model
			Case Study	1	Analytical model
			Survey/Interview	1	Cross-Paradigmatic model of public acceptance
			Others	2	Integrated Assessment Model (IAM); Mathematical model
one	Environmental	13	ABM & Simulation	3	Energy model
			Case Study	1	Life Cycle Assessment (LCA)
			Statistical Model	3	Autoregressive model; Computable General Equilibrium (CGE) model; Fixed Effect model
			Survey/Interview	1	Enabling model
			Others	5	Adaptive model; Economic model
	Economic	2	ABM & Simulation	1	Economic model
			Statistical Model	1	Mathematical Economic model
	Societal	2	Statistical Model	1	Regression model
			Others	1	Machine Learning model

This analysis allowed us to identify the following methodologies: ABM & Simulation, Case Study, Conceptual Model, Statistical Model, Survey/Interview, and Others. These categories are listed in the corresponding column of Table 2. We have dedicated the subsequent sections to each methodological approach.

3.2.1.1. ABM & simulation. Among the 115 selected papers, 27% (31 articles) employed the ABM & Simulation approach, as shown in Table 2. Most of these articles (13) comprehensively analysed economic, environmental, and societal impacts. Noteworthily, three of them employed agent-based models (Khansari and Hewitt, 2020a; Niamir et al., 2018; Xin-gang et al., 2022).

Niamir et al. (2018) demonstrate that societal interactions and the learning process influence individual energy choices in favour of the environment, leading to a significant reduction in energy consumption, private economic benefits, and a substantial decrease in CO_2 emissions.

Furthermore, some papers assess policy choices as valuable solutions to achieve the goals of the energy transition, such as the reduction of subsidies for fossil fuels, with the resulting proceeds used to subsidise green investments through fiscal policies (Monasterolo and Raberto, 2019), and an emissions trading system (Nong et al., 2017). On the other hand, Cassen et al. (2018), using the E3 (Economic, Environment, Energy) IMACLIM-R model, argue that carbon pricing policies serve as valuable guides for the transition but are insufficient to achieve the ambitious objective. An effective transition to low-carbon emissions requires substantial behavioural changes across all stakeholders, including businesses, consumers, and governments. The remaining papers within this group employ various types of simulation models to analyse the complex issues related to energy transition. These models include energy simulation models (Bolwig et al., 2020; Hafner et al., 2021; Kontochristopoulos et al., 2021), a computable general equilibrium model (Schütze et al., 2017), a macroeconomic simulation model (Jackson and Victor, 2020), a product differentiation duopoly model (Bougette and Charlier, 2015), and a spatial econometric model (Gao and Yuan, 2022). This variety in the adopted models and simulation approaches highlights the scientific community's commitment to exploring the broad and intricate phenomenon of energy transition from different perspectives and using more flexible methods.

Ten of the 31 papers focused their analysis on economic and environmental impacts. These studies have contributed to understanding the economic and environmental dynamics associated with transitions toward a more sustainable economy. Most of these papers pertain to the energy sector and employ various simulation models, such as the integrated assessment model (Capellán-Pérez et al., 2019) and energy planning models (Kim, 2018; Pfeifer et al., 2021). Others encompass multiple sectors, including the energy sector, utilising models such as the computable general equilibrium model (Pradhan and Ghosh, 2022) or the Tobin model (Kemp-Benedict, 2018).

The remaining papers jointly analyse the economic and societal impact, while fewer papers assess environmental and economic impacts.

Finally, simulation models, particularly ABM, seem well-suited to capturing multiple impacts due to their flexibility and ability to integrate diverse frameworks. These models effectively analyse the heterogeneity of actors involved, combining micro-level behavioral dynamics with macro-level policy effects in a single framework. Their increasing use reflects the need for methodologies that can handle the complexity of these processes by bridging micro-behavioral insights with macro dynamics.

3.2.1.2. Case study. As indicated in Table 2, 13% (15) of our sample exploited the Case Study's methodological approach. Ten out of 15 jointly analysed economic, environmental, and societal impacts.

The case studies in our sample use many different exploratory models, but they have a common desirable objective: the deep understanding and knowledge creation to support and advance a sustainable energy transition (Campos et al., 2022) in practical cases.

According to this type of methodological approach, the frameworks used to analyse the three impacts jointly include innovative business model strategies (Karami and Madlener, 2021), methodologies based on Life Cycle Analysis (LCA) and Life Cycle Costs (LCC) (Blanc et al., 2019; Ghafourian et al., 2022), and approaches proposed by the authors aiming to design a combination of drivers and policy instruments to promote the green energy transition by emphasising the effectiveness of the phenomenon of cooperation between companies, public organisations, and research institutes (Falcone et al., 2018). In conclusion, also the case study methodology is well adopted in the sample to cope with the assessment of joint impacts of complex transition processes, helping in bridging the gap between theory and practice. It is particularly useful in exploratory studies adopting mixed frameworks and investigation tools, allowing researchers taking into account the specificity of cases and the diversity of actors involved in the analysed processes.

3.2.1.3. Conceptual model. Only 8 papers (7%) employ a conceptual modelling approach. Among these, 5 papers perform a combined analysis of economic, environmental, and societal impacts, while 2 examine both the economic and environmental impacts, and 1 jointly addresses the economic and societal dimensions (see Table 1 in the Appendix). Conceptual models, although less frequently employed in our sample, are critical in advancing the theoretical and methodological foundations of the green economy. Some of the articles employing this approach aim to address the gaps in circular economy design. The work of Arsova et al. (2021), for instance, outlines the need to consider the multiplicity and variety of stakeholders in designing circular economy models, highlighting a recurring topic in the content of investigated sample. The article of Vukovic et al. (2019) has, instead, a methodological-related aim, and identifies fundamental criteria and useful indicators for assessing the green economy development status. Furthermore, Poltarykhin et al. (2018) explore potential scenarios and related indicators for green transition and sustainable development.

3.2.1.4. Statistical Model. Statistical models remain a cornerstone of green energy transition research, primarily due to their ability to uncover causal relationships between key economic, environmental, and societal variables. In fact, 24% of the papers in the sample (28) use a statistical methodological approach. 12 of these articles jointly analyse the economic, environmental, and societal impacts, 10 jointly analyse the economic and environmental impacts, while the remaining papers mainly analyse the impacts individually (refer to Table 1 in the Appendix for details).

As demonstrated by the articles of Fang et al. (2019) and Song et al. (2020), most of the works assessing the three impacts (economic, environmental, and social) cope with the relationships between environmental regulation, green innovation efficiency, and resource dependency. Regarding environmental regulation, Yang et al. (2020) argue that there is a need for more support for the energy transition through increased financial incentives from government authorities, such as green subsidies and carbon taxes, to promote innovative green technologies, especially in the early stage when the innovative technology is not yet mature.

The models used in this category are primarily regression models (Apostu et al., 2022; Ben Lahouel et al., 2020, 2021; Xie et al., 2021), econometric models (Capece et al., 2017; Denona Bogovic and Grdic, 2020; Yang et al., 2020; Ziegler, 2019), and hybrid models (Fang et al., 2019; Fu et al., 2018; Wang and Yang, 2019; K. Q. Zhang et al., 2022) such as the super energy efficiency and panel model used by Wang and Yang (2019).

One limitation of purely statistical approaches is their reliance on historical data, which may not always account for rapidly changing technological advancements or unforeseen societal shifts. Hybrid models that combine statistical methods and analytical models with dynamic simulations, such as those used by H. Zhang et al. (2022), offer a promising avenue for overcoming these limitations, suggesting a future research direction focused on methodological integration.

3.2.1.5. Survey/interview. As shown in Table 2, only 3% of the papers in the sample (3 papers) adopt a Survey/Interview methodological approach. Among these, 1 paper jointly analysed the economic, environmental, and societal impact, 1 paper jointly analysed the environmental and societal impact, and finally 1 analysed the environmental impact (Table 1 in Appendix). Despite the low representativeness in the sample of this kind of approach, the inclusion of qualitative methodologies such as interviews underscores the importance of understanding stakeholder perceptions and policy barriers in the energy transition. These methodologies provide insights often missed in purely quantitative models, such as public acceptance of new technologies (Stephanides et al., 2019), organizational resistance to change (Caldera et al., 2019), and characteristics of the political-administrative decision-making process in the context of green energy transition (Hoff et al., 2021).

3.2.1.6. Others. Finally, 30 of the collected papers adopt methodological approaches not classified in the previous categories. The diverse set of models classified as 'Others' illustrates the evolving nature of green energy transition research, where no single methodology can fully capture the complexity of the process. Among these, 15 papers jointly analyse the economic, environmental, and societal impacts, 5 papers jointly examine the economic and environmental impacts, 2 papers jointly analyse the economic and societal impacts, and the remaining studies individually analyse the impacts.

The models used in this category vary, including the multi-regional input-output model (Markandya et al., 2016), the conceptual institutional model (Droste et al., 2016), and the energy system model (Li et al., 2018). Despite the heterogeneity of these models, common concepts emerge from the works in this category. The energy transition process is complex, necessitating government interventions and policy tools to promote the development and adoption of green innovations. For example, Pyka et al. (2022) point out how emerging modelling techniques, such as agent-based modelling, can support policymaking and government authorities in managing the uncertainty and complexity of this process. On the other hand, B. Zhang et al. (2022) analyse how environmental legislation guides the green transition of businesses. This diversity of methods and the emergence of recurring topics (the complexities and uncertainties of green energy transition processes, the heterogeneity of involved stakeholders and actors, the role of legislation, etc.) outlines the need of the integration of models and the necessity to move toward interdisciplinary approaches drawing on insights from economics, environmental science, and governance studies.

3.2.2. Input-output investigated variables

The variables identified in the sample have been classified into six macro-categories: environmental, economic, societal, governance, knowledge, and technological. The variables were manually extracted during the content analysis of the papers in the sample. They were first identified as input or output variables and then, according to typologies of models adopting them or considering specific classifications provided directly by the authors of the papers, they were assigned to six main macro-categories.

Table 3 illustrates the taxonomy of variables examined in the 115 selected articles, categorised by macro-categories, type (Continue – C; Discrete – D), and measurement unit. As can be seen from Table 3, some variables are cross-categorised, i.e., they appear in two categories due to their relevance to both (e.g., Levelized Cost of Energy, Energy Price, Employment Rate). The variables marked with an asterisk (*) are those that appear with a frequency of two or more, and their occurrences will be detailed in the subsequent paragraph. The remaining variables appear only once. In designing energy transition models, the integration of variables across the environmental, economic, societal, governance, knowledge, and technological categories is fundamental for both companies and researchers. Each category provides distinct insights that inform strategies for transitioning to sustainable energy systems. *Economic* variables are crucial for understanding the financial dimensions of energy transitions. Continuous variables such as Average Enterprise Salary and Business Size allow researchers to evaluate the financial health and capacity of enterprises involved in energy transitions (B. Zhang et al., 2022). These variables, measured in currency, reflect the economic feasibility and implications of adopting renewable technologies. Capital Expenditures (CAPEX) and Operating Expenses (OPEX) are essential for assessing the initial investments and ongoing costs related to green technologies. Variables like Energy Price and Gross Domestic Product (GDP) further provide insights into market conditions and economic performance, influencing the viability and attractiveness of renewable energy investments (Nong et al., 2017). Additionally, variables such as Emission Price and Subsidies illustrate the impact of policy and market conditions on economic decisions. Measured in currency per metric ton of emissions or unit of energy, these metrics highlight financial incentives or disincentives for adopting low-carbon technologies (Bougette and Charlier, 2015). Understanding these factors is vital for companies to navigate the economic landscape of energy transitions and optimize their strategies according to financial and regulatory constraints. Environmental variables play a key role in assessing the effectiveness of energy transition strategies. Continuous variables such as CO_2 Emissions and Carbon Intensity of Electricity Generation provide critical data on environmental performance, measured in metric tons of CO_2 per unit of energy (van Vuuren et al., 2017). These metrics help quantify the environmental benefits of renewable energy technologies. Variables like Renewable Energy Production and Energy Efficiency also offer insights into the effectiveness of different energy systems. These are measured in MWh and percentage, respectively, facilitating a detailed evaluation of energy yield and resource utilisation efficiency. Furthermore, understanding Carbon Intensity Reduction and CO_2 Removal potential informs strategies aimed at reducing greenhouse gas emissions and enhancing carbon sequestration (van Vuuren et al., 2017). These variables, measured in metric tons of CO_2, reflect the outcomes of environmental policies and practices. *Societal* variables such as Labour Force and Labour Productivity provide insights into the

Table 3
Taxonomy of variables.

Category	Variables	Type C	Type D	Measurement Unit
Economic	Average Enterprise Salary	x		Currency
	Biofuel Sector Profitability	x		Currency
	Business Size		x	Categorical (small-medium-large)
	Capital*	x		Currency
	Capital Expenditures (CAPEX)	x		Currency
	Consumption goods	x		Currency
	Costs	x		Currency
	Crowdfunding Type		x	Categorical (Reward-Based Crowdfunding, Equity-Based Crowdfunding, Debt-Based Crowdfunding, Donation-Based Crowdfunding)
	Emission Price	x		Currency per metric ton of greenhouse gas emissions
	Emission Taxes	x		Currency per metric ton of greenhouse gas emissions
	Energy Demand	x		kWh
	Energy Price*	x		€/kWh
	Fiscal Subsidy	x		Currency
	Fuel Cost	x		Currency per unit of fuel quantity (e.g., USD per gallon, EUR per litre)
	Fuel Price	x		Currency per unit of fuel quantity (e.g., USD per gallon, EUR per litre)
	Gross Domestic Product (GDP)*	x		Currency
	Gross Regional Product (GRP)*	x		Currency
	Income*	x		Currency
	Inflation	x		Percentage (%)
	Investment*	x		Currency
	Labour Force*	x		Number of individuals or hours of work
	Labour Productivity	x		Units of output per unit of labour input (e.g., widgets per hour, revenue per employee)
	Levelized Cost of Energy (LCOE)*	x		€/MWh
	Net Present Value	x		Currency
	Normalised Price for Electricity	x		Currency per unit of electricity (e.g., USD per kWh, EUR per MWh).
	Operating Expense (OPEX)	x		Currency
	Price Volatility		x	Categorical (degree of variation of a trading price series over time)
	Profit	x		Currency
	Profit of Bioethanol Sales	x		Currency
	Raw Materials Price	x		Currency per unit of raw material (e.g., USD per ton, EUR per litre).
	Real Gross National Expenditure (GNE)	x		Currency
	Real Wage Rate	x		Currency per unit of time (e.g., USD per hour, EUR per year)
	Revenue*	x		Currency
	Selling Price of the Obtained Organic Bioethanol	x		Currency per unit of organic bioethanol (e.g., USD per litre, EUR per gallon)

(continued on next page)

Table 3 (*continued*)

Category	Variables	Type C	Type D	Measurement Unit
	Subsidies	x		Currency (e.g., USD, EUR)
	System Marginal Price	x		Currency per unit of energy (e.g., USD per MWh, EUR per kWh)
	Terms of trade	x		The ratio of the price of a country's exports to the price of its imports
	Time	x		Seconds, minutes, hours, days, etc., (depending on the context of the analysis)
	Value-Added*	x		Currency
Environmental	Annual Hydrogen Production	x		The unit depends on the volume measurement (e.g., cubic meters, litres)
	Building Type		x	Categorical variable, no specific measurement unit
	Carbon Productivity	x		Typically measured in output per unit of carbon input (e.g., kg of output per kg of carbon)
	CO2 Emissions*	x		Metric tons of CO_2
	CO2 Emissions Saving	x		Metric tons of CO_2
	Electrical Capacity Installed	x		The unit depends on the capacity measurement (e.g., kilowatts, megawatts)
	Energy Consumption*	x		kWh
	Energy Efficiency*	x		Percentage (%) or specific energy use metrics like kWh per output unit or metric tons of CO_2 equivalent per output unit
	Energy Generation Technology Type		x	Categorical variable, no specific measurement unit
	Energy Intensity	x		A measure of energy consumption per unit of another variable (e.g., kWh per square meter for buildings)
	Energy Label		x	Categorical variable, no specific measurement unit
	Energy Return on Energy Investment	x		Adimensional
	Energy Saving	x		Adimensional
	Energy Source*		x	Categorical variable indicating the type of energy source
	Energy Storage	x		Unit depends on the storage capacity measurement (e.g., kilowatt-hours, megawatt-hours)
	Energy Use*	x		kWh
	Environmental Burden Index (EBI)	x		Adimensional
	Environmental Pollution Level*	x		Metric tons of CO_2 equivalent
	Fuel Type		x	Categorical variable, no specific measurement unit
	Green Performance	x		Adimensional
	Green Production Self-Efficacy	x		Adimensional
	Green Technology Strategies		x	Categorical variable, no specific measurement unit
	Greenhouse Gases (GHG) Emissions*	x		Metric tons of CO_2 equivalent
	Heater Type		x	Categorical variable, no specific measurement unit
	Index of Resource Dependence	x		Adimensional
	Industrial Carbon Emissions Efficiency	x		Adimensional
	Land Use	x		The unit depends on the measurement (e.g., square meters, hectares)
	Mobility Satisfied by Personal Vehicles	x		Person-kilometres, a unit of distance travelled by personal vehicles
	Nuclear Installed Capacity	x		The unit depends on the capacity measurement (e.g., kilowatts, megawatts)
	Pollution Intensity	x		Adimensional
	Renewable Energy Profile Type		x	Categorical variable, no specific measurement unit
	Sustainable Prosperity Index (SPI)	x		Adimensional
	Total Factor Productivity (TFP)*	x		Adimensional
	Transport Sector Decarbonization Level	x		Adimensional
	Types of Bioethanol Produced		x	Categorical variable, no specific measurement unit
	Types of Plant Raw Materials Offered to Produce Bioethanol		x	Categorical variable, no specific measurement unit
	Wastewater Emissions*	x		Metric tons or square meters (m^2)
	Water Use*	x		Cubic meters (m^3) or litres
Societal	Acceptance Financial Support of Expansion of Electro-Mobility		x	Adimensional (Qualitative measure of acceptance)
	Acceptance Financial Support of Expansion of Renewable Energies		x	Adimensional (Qualitative measure of acceptance)
	Acceptance Financial Support of Saving Energy in Households and Industry		x	Adimensional (Qualitative measure of acceptance)
	Acceptance Nuclear Phase-Out		x	Adimensional (Qualitative measure of acceptance)
	Acceptance Power Grid Expansion		x	Adimensional (Qualitative measure of acceptance)
	Acceptance Support of Research to Improve Efficiency of Gas and Coal Power Plants		x	Adimensional (Qualitative measure of acceptance)
	Active Population	x		Number of individuals
	Consumer Preferences		x	Adimensional (Qualitative measure of preferences)
	Cooperation Level		x	Adimensional (Qualitative measure of cooperation)
	Employment generated by Energy Transition	x		Number of jobs
	Employment Rate*	x		Percentage (%)
	Entrepreneur Self-Esteem		x	Adimensional
	Green proactiveness orientation (GPO)		x	Adimensional (Qualitative measure of orientation)
	Household Type		x	Categorical variable, no specific measurement unit

(*continued on next page*)

Table 3 (*continued*)

Category	Variables	Type C	Type D	Measurement Unit
	Human Welfare		x	Adimensional (Qualitative measure of welfare)
	Income and Education levels for the human side	x		Currency for income, education level for education
	Learning Mechanism		x	Adimensional
	Lifestyle		x	Adimensional
	Non-poverty rate	x		Percentage (%)
	Number of Households	x		Count of households
	People's Preference Use Travel		x	Adimensional (Qualitative measure of preferences)
	Personal Outcome Expectation		x	Adimensional
	Population Density	x		Number of individuals per unit area
	Population Growth	x		Percentage (%)
	Probability of Collaboration		x	Adimensional
	Probability of Innovating		x	Adimensional
	Probability of Radicalness		x	Adimensional
	Propensity to Consume (APC)		x	Adimensional
	Psychological Factors (e.g. Awareness, Personal Norms, Feeling Guilt)		x	Adimensional
	Public Acceptance/ Opposition to a Sustainable Energy Transition		x	Adimensional (Qualitative measure of acceptance/opposition)
	Reputational Capital		x	Adimensional
	Resident Type		x	Categorical variable, no specific measurement unit
	Social Acceptance Type		x	Categorical variable, no specific measurement unit
	Social Factors (e.g. Subjective and Social Norms)		x	Adimensional
	Social Responsability		x	Adimensional
	Socio-demographic Factors (e.g. Education Level)	x		Education level for education, other socio-demographic factors adimensional
	Unemployment Rate*	x		Percentage (%)
	Urban Population Density	x		Number of individuals per unit area
Governance	CO2 Emissions Tax	x		Currency per unit of CO_2 emissions (e.g., USD per metric ton of CO_2)
	Domestic Reserves	x		Units depend on the specific type of reserves (e.g., barrels for oil, cubic meters for natural gas)
	Emission Price*	x		Currency per unit of emission (e.g., USD per metric ton of CO_2)
	Employment Rate*	x		Percentage (%)
	Energy Price*	x		Currency per unit of energy (e.g., USD per kWh)
	Environmental Regulation		x	Adimensional or qualitative scale
	Equity Concentration	x		Adimensional or percentage (%)
	Exchange Rate*	x		Currency per unit of another currency (e.g., USD per EUR)
	Fiscal Subsidy	x		Currency
	Fuel Cost	x		Currency per unit of fuel quantity (e.g., USD per gallon)
	Fuel Price	x		Currency per unit of fuel quantity (e.g., USD per gallon)
	Government Bonds	x		Currency
	Government Debt/Credit	x		Currency
	Government Deposits	x		Currency
	Government Intervention		x	Adimensional or qualitative scale
	Green Proactiveness Orientation (GPO)		x	Adimensional or qualitative scale
	Income Equality	x		Adimensional or percentage (%)
	Institutional Uncertainty		x	Adimensional or qualitative scale
	Interest Rate*	x		Percentage (%)
	Levelized Cost of Energy (LCOE)*	x		Currency per unit of energy (e.g., USD per MWh)
	Non-poverty rate	x		Percentage (%)
	Normalised Price for Electricity	x		Currency per unit of electricity (e.g., USD per kWh)
	Price Volatility	x		Adimensional or percentage (%)
	Public Policy Intervention Intensity		x	Adimensional or qualitative scale
	Rate of depreciation	x		Percentage (%)
	Raw Materials Price	x		Currency per unit of raw material (e.g., USD per ton)
	Real Wage Rate	x		Currency
	Regulation Level		x	Adimensional or qualitative scale
	Selling Price of the Obtained Organic Bioethanol	x		Currency per unit of bioethanol (e.g., USD per litre)
	Socio-demographic Factors (e.g. Education Level)		x	Education level or adimensional
	Subsidies	x		Currency
	Tax Intensity	x		Adimensional or percentage (%)
	Terms of trade		x	Adimensional or qualitative scale
	Trade Openness Level		x	Adimensional or percentage (%)
	Unemployment Rate*	x		Percentage (%)
	Volume of imports and exports	x		Units depend on the type of goods being measured (e.g., tons, barrels, currency)
Knowledge	Knowledge Capital		x	Adimensional
	Knowledge in Biofuel Sector		x	Adimensional
	Number of Invention Patents in Each Industry	x		Count of patents
Technological	Capacity Factor	x		Percentage (%)
	Energy Generation Technology Type		x	Categorical variable, no specific measurement unit
	Project Capability		x	Adimensional
	Quality of Renewable Energy Power Generation Equipment		x	Adimensional
	Technological Adoption Rate		x	Adimensional or percentage (%)
	Technological Innovation		x	Adimensional
	Technology Change		x	Adimensional

NB: *Indicate variables with an occurrence $\geq$2 in the sample of 115 papers.

human factors influencing the energy transition. Labour Force, measured in the number of individuals or hours worked, reflects the capacity and readiness of the workforce for new energy initiatives. Labour Productivity, measured in units of output per unit of labour input, assesses efficiency gains associated with new technologies and practices. These metrics are essential for understanding the social implications of energy transitions, including job creation, skills development, and productivity improvements (Niamir et al., 2018). *Governance* variables like Carbon Pricing Mechanisms and Renewable Energy Incentives are vital for shaping policy frameworks that drive the energy transition. These discrete variables, categorised into mechanisms such as cap-and-trade or carbon taxes, define the regulatory environment influencing economic and environmental decisions (B. Zhang et al., 2022). The effects of Environmental Legislation and Taxation Policies on energy transition models are significant, as these policies establish the parameters within which companies operate and make investment decisions. Measurement units for these variables are often categorical, indicating the type and scope of policies implemented. *Knowledge* variables provide insights into the intellectual and inventive resources available for advancing energy technologies. Knowledge Capital is an adimensional variable representing the accumulated intellectual assets and expertise within an organization or industry (Kamath et al., 2022). Knowledge in the Biofuel Sector, also adimensional, indicates the depth of specialized knowledge and research focused on biofuels, which can drive innovation and improve biofuel technologies (Falcone et al., 2018). The Number of Invention Patents in Each Industry is measured as a count of patents and serves as a tangible indicator of the level of innovation and technological advancement within specific sectors. A higher count of patents often correlates with greater innovation and competitiveness in the field. *Technological* variables are fundamental in assessing the efficiency and innovation of renewable energy systems. The Capacity Factor, measured as a percentage, quantifies the efficiency of energy generation technologies by comparing the actual energy output to the maximum possible output over time (Leporini et al., 2019). A higher Capacity Factor indicates greater reliability and efficiency of the technology. Energy Generation Technology Type serves as a categorical variable that classifies different technologies such as solar, wind, and hydro, without a specific measurement unit. Understanding the different types helps in comparing their effectiveness and suitability for various energy needs (Kim, 2018; Zhang et al., 2018). Project Capability and Quality of Renewable Energy Power Generation Equipment are adimensional variables that reflect the overall readiness and the quality of the technology used in projects. These factors can influence the performance and reliability of energy systems (Leporini et al., 2019; Markandya et al., 2016). Technological Adoption Rate can be measured either as a percentage or an adimensional value, representing how quickly new technologies are being adopted in the market (Huang and Liu, 2020; Khansari and Hewitt, 2020b). Technological Innovation and Technology Change are adimensional variables that reflect the level of advancement and the rate at which technological improvements are occurring, respectively (van Vuuren et al., 2017). In summary, understanding and integrating these diverse variables allows companies and researchers to develop more effective energy transition models. By analyzing economic, environmental, societal, governance, knowledge and technological factors, stakeholders can craft strategies that optimize resource use, minimize environmental impacts, and align with policy frameworks, thus facilitating a successful transition to sustainable energy systems.

Our content analysis has shown that about 50% of papers in the sample propose models, methodologies, and related variables to assess and understand the phenomenon of green energy transition in terms of joint impact on environmental, societal, and economic spheres. This analysis has also categorised variables mainly used as input and output variables of models and methodologies adopted. The thorough discussion and synthesis of the relationships among methodologies, variables, and typology of impacts assessed is performed below.

3.2.3. Methodological approaches and input-output variables

This section aims to discuss the results previously presented and mainly analyses relationships among methodologies, input, and output variables considering papers jointly analysing economic, environmental, and societal impacts. Here, two Sankey diagrams depicting variables with an occurrence greater than or equal to two (Figs. 5 and 6) are used to present our results. In Fig. 5, the Sankey diagram involves variables used as input for proposed models. Thus, it shows how the input variables are linked to the different research methodological approaches. A total of 16 input variables are highlighted: 8 economic (2 cross-categorised), 5 environmental, 5 governance variables (3 cross-categorised), and 1 societal variable (cross-categorised).

Variables exhibiting higher occurrences are mainly economic, such as Capital (occurring 10 times), Investment (9), Labour Force (8), and Costs (6). On the other hand, the input variable with the highest occurrence is the environmental variable, Energy Consumption (14).

Energy Consumption is a measure of energy utilisation, and authors delve into various facets of this variable. For instance, Li et al. (2022) scrutinise the total energy consumed from fossil sources, whereas K.Q. Zhang et al. (2022) analyse energy consumption from renewable sources. On a different note, Fang et al. (2019), Gao and Yuan (2022), and Jiang et al. (2022) focus on industrial energy consumption.

Furthermore, there is a group of 5 governance variables with a lower occurrence, including Energy Price (5), Exchange Rate (2), Interest Rate (2), and Levelized Cost of Energy (2). As mentioned above, some of these variables, such as Energy Price, Levelized Cost of Energy, and Employment Rate, are cross-categorised and specifically serve as both governance and economic or societal variables. For further details, refer to Table 3.

The only societal input variable considered is the Employment Rate, which has been examined in the studies by Falcone et al. (2018), Li et al. (2022), and Jiang et al. (2022).

Furthermore, by observing Fig. 5, it is interesting to note that most input variables —specifically, 13 out of 16 — are linked to ABM & Simulation models. This observation highlights the aptitude of such methodological approaches to deal with heterogeneous phenomena and issues, considering different layers of analysis (macro and micro). This is particularly felt and welcome in this field.

Fig. 6 below shows the Sankey Diagram linking the type of methodological approach of the research with the output variables with an occurrence greater than or equal to 2.

Fig. 6 shows 15 output variables, including 7 environmental variables, 6 economic variables, and 2 cross-categorised variables (societal and governance).

Differently from input variables, output variables are primarily represented by environmental indicators such as CO_2 Emissions (occurrence equal to 13 times), Greenhouse Gas (GHG) Emissions (3), Environmental Pollution Level (4), Energy Efficiency (4), Waste Water Emissions (2), Total Factor Productivity (TFP) (2), and Energy Use (2). It is interesting to note that the focus is primarily on quantitative variables related to CO2 and GHG emissions, and the level of environmental pollution. This observation highlights that the metrics used to assess environmental impact, though continually evolving, are strongly established. Thus, there exist common variables for evaluating environmental impact.

The second group, in terms of the number of variables, consists of economic variables such as GDP (8), Revenue (3), Value-Added (2), Investment (3), and GRP (2). It is observed that, as well as in the case of input variables, economic variables continue to maintain high relevance as outputs.

Finally, there is a subset of 2 variables, categorised both as societal and governance variables (see Table 3), namely Employment Rate (4) and Unemployment Rate (2).

Then, it is noteworthy that compared to the input variable case, the presence of societal variables increases (+1 because the variable of Unemployment Rate is added) in the output, as does the number of

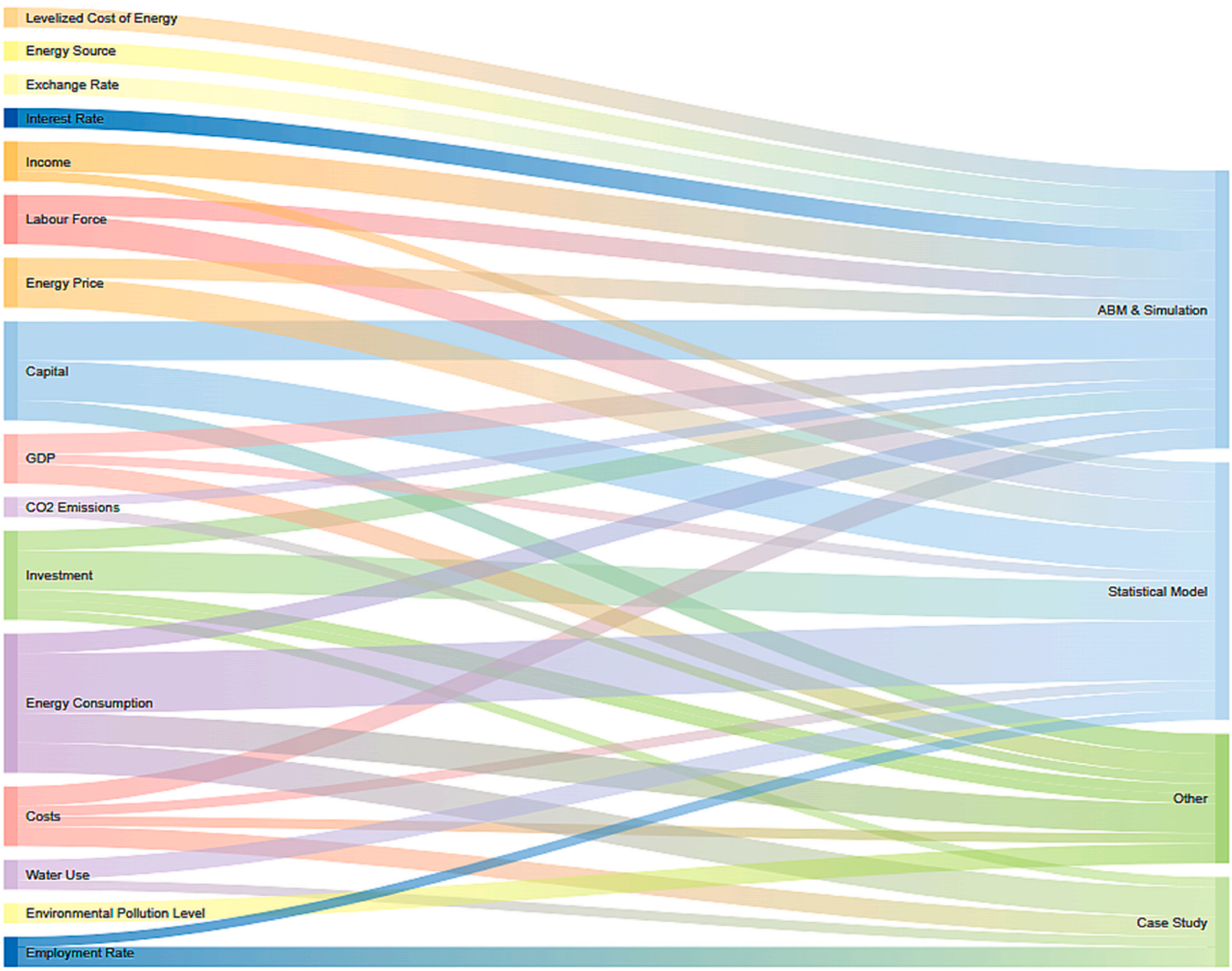

Fig. 5. Input variables and research methodological approaches - sankey diagram.[51].

articles evaluating them. Therefore, simultaneously with the economic and environmental aspects, the societal aspect is more prominently considered by authors in the output.

Furthermore, as shown in Table 3, various societal variables were analysed only once in our sample. The preceding statements suggest that while the societal aspect is gaining prominence within the scientific community, it remains in an early stage of development and, crucially, lacks standardisation. In other words, no common metrics allow for a standardised evaluation of the societal aspect associated with economic and environmental factors.

The future work of the scientific community in this direction will be crucial. However, the analysis suggests that developing ABM & Simulation models can be valuable tools for analysing complex phenomena such as the green energy transition due to their flexibility and methodological rigor.

Figs. 5 and 6 do not show the Conceptual Model and Survey/Interview approaches because papers adopting these approaches do not show an occurrence equal to or greater than 2 for the variables used as inputs. This aspect is certainly related to the fact that papers that belong to these two categories are numerically less frequent; at the same time, it could also be concluded that for research adopting a conceptual or a Survey/Interview approach, there is not sufficient convergence on a specific set of input variables. This last fact can also denote the lack of convergence in interpretative theoretical frameworks.

4. Discussion

The exploration of methodological approaches and their associated variables for assessing the transition to green energy represents a crucial endeavour within the academic community to unravel the intricacies of this multifaceted transition process. Our analysis aims to facilitate the development of new models, providing a springboard for identifying variables, methodologies, and impacts pertinent to the transition process. Thus, our results are a cornerstone for advancing innovative models tailored to capturing the nuanced dynamics of transitioning towards green energy. Further models, inspired by insights gleaned from our analysis, have the potential to incorporate a diverse array of economic, environmental, and social impacts, targeting policymakers who increasingly recognise the necessity for models—descriptive, predictive, and prescriptive—in comprehending the intricacies of the transition journey.

Input Variables and Methodological Approaches:

The association between input variables and research methodological approaches reveals that most involved variables relate to ABM & Simulation models. This suggests that ABM & Simulation methodologies are adept at handling the complexity and heterogeneity inherent in the green energy transition. These models enable researchers to incorporate diverse factors, including economic, environmental, and societal variables, and explore their interactions. Additionally, the prevalence of economic variables as input further underscores the importance of considering economic dimensions in the analysis of green energy

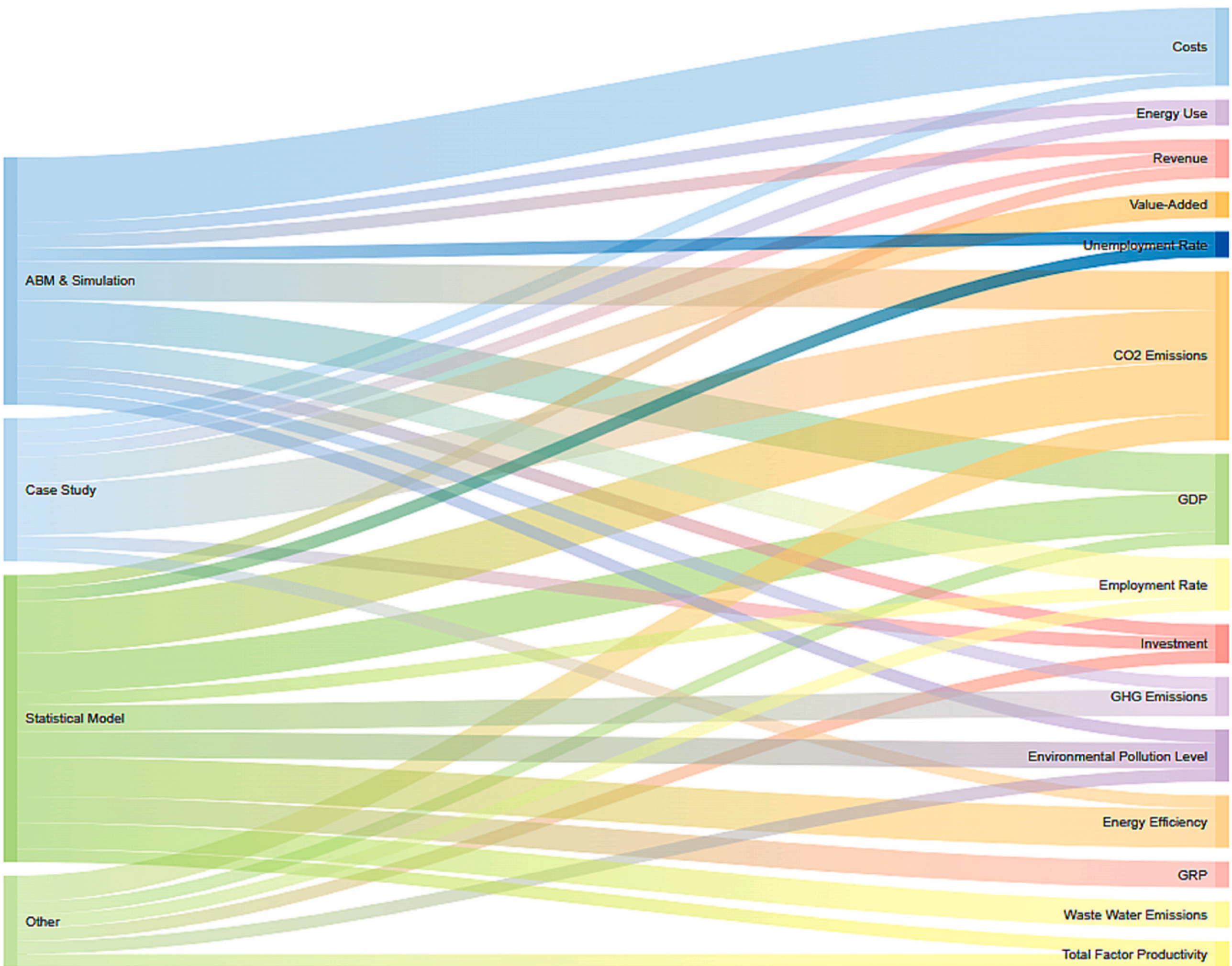

Fig. 6. Research methodology approaches and output variables - sankey diagram.

transition models.

Output Variables and Methodological Approaches:

The relationship between the methodological approach and output variables reveals that environmental indicators dominate the output variables, particularly CO_2 emissions and greenhouse gas emissions. This reflects the literature's emphasis on quantifying environmental impact, highlighting the significance of mitigating carbon emissions and pollution. Moreover, economic variables such as GDP and investment remain relevant as outputs, indicating the importance of assessing the economic implications of green energy transition efforts. Interestingly, there is a slight increase in the representation of societal variables in the output compared to the input, suggesting a growing recognition of the need to consider social aspects alongside economic and environmental factors. However, it is essential to note that societal variables remain less standardised and require further development in research methodologies.

Finally, to better present our results, the conceptual map in Fig. 7 summarises the primary outcomes of the SLR and reports results about all the articles (115) analysed and included in the sample. It is evident that economic variables are frequently used, more than other categories, as input variables, followed by environmental ones and those concerning governmental aspects. When we consider output variables, the most used ones are those related to environmental aspects. At the same time, we notice that societal variables gain increasing attention as output variables, thus reflecting an increasing interest in considering societal impacts as strictly related to other most common impacts usually evaluated in modelling and investigating green energy transition processes. As discussed above, the conceptual map highlights that methodologies increasingly adopted to investigate the phenomenon of energy transition in a more holistic and multidimensional way are those related not only to traditional statistical or econometric modelling but also to more flexible ones like ABM and other simulation approaches. This fact underscores the recognition, on behalf of the literature, of the complexity of the phenomenon under evaluation, the need to analyse multiple issues and aspects, and the necessity to dispose of flexible approaches to capture this complexity.

5. Conclusion

This research analysed the state of the art of green energy transition models to identify and categorize the adopted methodologies, input and output variables to study this phenomenon, and the relationships between variables and methodologies. In particular, we applied a SLR through the PRISMA approach to identify the most relevant articles in the field. The final sample of articles collected comprises 115 articles. First, we performed a descriptive analysis of the articles and found, as expected, a growing interest in green energy transition models with an increasing number of articles published over the years. However, we outlined the absence of consolidated modelling and methodological frameworks confirming the innovativeness of the theme, which still remains in a premature state. Second, we focused on the content of the articles. Specifically, we grouped articles according to the sustainable

Fig. 7. Conceptual map.

impact analysed, considering single, double, and triple impacts. Then, articles were categorised according to the methodology adopted: ABM & Simulation, Case Study, Conceptual Model, Statistical Model, and Survey/Interview, Others. As a result, most articles employed ABM & Simulation and Statistical Models. Finally, we defined a taxonomy of variables into different categories: environmental, economic, societal, governance, knowledge, and technological. Utilising the taxonomy of identified variables and methodological approaches as a foundation, we crafted Sankey diagrams to highlight the interconnected relationships between input-output variables and the methodologies employed in studying the green energy transition. The Sankey diagrams allowed us to emphasise the input-output variables currently adopted in studying how to move from traditional to green energy systems. Based on these results, as a final achievement, we developed a conceptual map that comprised input-output variables, methodological approaches, and environmental, economic, and societal impacts. The results of this study have both practical and theoretical implications.

From a theoretical perspective, the taxonomy of variables and the categorisation of methodologies identified can serve as a basis for researchers interested in developing models for green energy transition. Indeed, academics can exploit our taxonomy of variables to identify the crucial factors to be included in each energy transition model and then characterise the model in their specific setting. Furthermore, from this research emerged the absence of a structured theoretical framework to analyse the transition to green energy, which can represent a starting point for researchers to develop new theories. Concerning practical implications, the conceptual map provided in this study can support managers engaged in the energy transition in making informed decisions, optimising processes, and communicating effectively with stakeholders.

As an additional contribution of this paper, we report in Table 4 a schematisation of the research agenda as it emerges from the 115 papers selected as a sample in the present review. The research agenda was constructed based on an analysis of the open research questions identified from the articles included in our sample. We systematically examined the content of each article to identify future research directions. Once these research directions, previously reported by the authors, were identified, they were re-evaluated and analysed collectively to group them into thematic clusters (*open research themes*) based on their similarities or interconnectedness. Each thematic cluster is refined based on its relevance, potential impact, and feasibility for investigation within the researcher's context. This process ensures that the selected themes are not only academically relevant but also address practical challenges or contribute to policy development. Following the clustering process, we articulated clear research trajectories for each theme. These trajectories outline specific objectives, methodologies, expected outcomes, and potential applications of the research. They also help in defining the scope of each theme, ensuring that the research remains focused yet comprehensive.

Finally, a key limitation of this study is that the literature review was

Table 4
Research Agenda, open research themes, and possible research trajectories.

Open research theme	Research trajectories
1. Climate Policy Integration, Market, and Societal Goals	–Explore integration strategies aligning climate policy with social goals. –Investigate employment impacts due to technology investments, explore mechanisms for EU electricity market competitiveness, and assess green economy transitions.
2. Methodological Advancements in Modeling and Certification	–Address endogeneity issues in modelling distinguish between transient and persistent energy efficiency. – Study lean energy-saving and emission reduction strategy implementation through condition monitoring and develop evaluation standards and certification.
3. Enablers Testing, Lean Green Tools, and Model Enhancements	– Test enablers across sectors, and investigate lean and green tools for optimising sustainable business practices. – Address modelling limitations, apply recycling rates, and conduct a holistic analysis of the energy-economy-environment system.
4. Economic Model Accuracy, Regional Management, and Sustainable Development	– Enhance economic model accuracy, conduct region-specific analyses for green industry transition, and study global sustainable management. – Apply methodologies to larger samples covering various countries, and explore the relationship between green entrepreneurship, performance, and financial outcomes.
5. LCA, Impact Assessment, and Prosumer Models	– Improve impact assessment methods, focusing on compost benefits and decentralised biowaste management. – Conduct detailed surveys on heating technology preferences and examine causal relationships in emission reduction measures. Investigate prosumer business models, expand sample sizes, and analyse relations through multivariate approaches.
6. Temporal Variations, Real-time Data, and Foreign FIT Programs	– Explore temporal variations in low-carbon preferences and improve real-time data for carbon intensity estimations. – Investigate the impact of Feed in Tariff programs on foreign markets, address drawbacks, explore factors enabling deep decarbonization, and enhance databases.
7. Biofuel Development, Post-Funding Analysis, SME Decarbonization, and Startup Behavior	– Focus on expanding biomass for biofuels, consider land use – Study post-funding scenarios – Explore crowdfunding market limitations – Expand SME studies, analyse causal relations, and improve scenario designs for subdivided industries and technologies. – Extend startup studies, introduce mediators/moderators, and focus on the EU energy transition's impact on CO2 emissions.
8. Green Finance System, and Circular Economy Stakeholder Engagement	– Examine just transition implications, practical green finance applications, abatement policy interactions, and alternative policy scenarios. – Explore circular economy stakeholder engagement.
9. Integrated Energy Plan, Urban Agglomeration, and Interdisciplinary Research	– Develop an integrated energy plan for South America, considering mega infrastructures. – Explore urban agglomeration effects on carbon efficiency, conduct real-time urban logistics case studies, and address multi-criteria model limitations. – Focus on interdisciplinary research for sustainable energy systems.

conducted using publications available only up to December 2022. The exclusion of studies published in 2023 might limit the study's ability to reflect the most recent developments in the field. Therefore, future research should consider integrating the open issues identified in the research agenda with a selection of articles that includes the most recent studies, to provide an even more up-to-date and comprehensive analysis.

Finally, this research has highlighted the increasing need for academic institutions, corporate entities, and particularly policymakers to identify comprehensive models able to consider not only the three interrelated impacts of the green energy transition process (as also outlined by the portion of articles in the sample that cope with the issue of multiple assessments) but also the elements of the complexity characterizing it that involve heterogeneous stakeholders and multiple sources of uncertainties among the others ((Falcone et al., 2018; Pyka et al., 2022). Our findings serve as a wake-up call, demanding coordinated efforts toward creating comprehensive frameworks to understand and manage these complexities as the urgency grows.

CRediT authorship contribution statement

Vincenzo Del Duca: Writing – original draft, Methodology, Data curation. **Cristina Ponsiglione:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Conceptualization. **Simonetta Primario:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation. **Serena Strazzullo:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT 3.5 in order to check grammar and spelling of the work and to improve the language style. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Cristina Ponsiglione reports financial support and article publishing charges were provided by European Commission. Cristina Ponsiglione reports a relationship with European Commission that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table 1
List of 115 sample papers.

Methodological Approach	#Papers	Impact	#Papers per impact	Authors
ABM & Simulation	31	Economic, Environmental, and Societal	13	(Bolwig et al., 2020; Bougette and Charlier, 2015; Cassen et al., 2018; Gao and Yuan, 2022; Hafner et al., 2021; Jackson and Victor, 2020; Khansari and Hewitt, 2020a; Kontochristopoulos et al., 2021; Monasterolo and Raberto, 2019; Niamir et al., 2018; Nong et al., 2017; Schütze et al., 2017; Xin-gang et al., 2022)
		Economic, Environmental	10	(Bassi et al., 2021; Capellán-Pérez et al., 2019; Galván et al., 2022; Isik and Kaplan, 2020; Kemp-Benedict, 2018; Kim, 2018; Leporini et al., 2019; Pfeifer et al., 2021; Pradhan and Ghosh, 2022; Scott et al., 2020)
		Economic, Societal	3	(Gottschamer and Zhang, 2020; Jackson and Jackson, 2021; Li et al., 2021)
		Environmental, Societal	1	Komninos (2022)
		Economic	1	Wu et al. (2018)
		Environmental	3	(Bramstoft et al., 2018; Kougias et al., 2021; Lind and Espegren, 2017)
Case Study	15	Economic, Environmental, and Societal	10	(Blanc et al., 2019; Bobylev, 2015; Brunet et al., 2022; Campos et al., 2022; Falcone et al., 2018; Ghafourian et al., 2022; Jiang et al., 2022; Karami and Madlener, 2021; Resniova and Ponomarenko, 2021; Zhang et al., 2018)
		Economic, Environmental	2	(Quintás et al., 2018; Yushchenko and Patel, 2016)
		Economic, Societal	1	De Crescenzo et al. (2020)
		Environmental, Societal	1	Ortega Alvarado et al. (2021)
		Environmental	1	Zeller et al. (2020)
Conceptual Model	8	Economic, Environmental, and Societal	5	(Arsova et al., 2021; Ge et al., 2016; Hernández-Chea et al., 2021; Poltarykhin et al., 2018; Svartzman et al., 2019)
		Economic, Environmental	2	(Batrancea et al., 2021; Vukovic et al., 2019)
		Economic, Societal	1	Khan et al. (2021)
Other	30	Economic, Environmental, and Societal	15	(Al-Saleh and Mahroum, 2015; Andersen et al., 2020; Droste et al., 2016; Hao et al., 2019; Heikkinen, 2020; Ikram et al., 2021; Kamath et al., 2022; Lahcen et al., 2020; Li et al., 2018; Markandya et al., 2016; Nieto et al., 2020; Pamucar et al., 2022; Pyka et al., 2022; Yang et al., 2021; B. Zhang et al., 2022)
		Economic, Environmental	5	(Dinga and Wen, 2022; Dong et al., 2016; Huang and Liu, 2020; Stöckl et al., 2021; Townsend and Coroama, 2018)
		Economic, Societal	2	(Baran et al., 2020; Ghouse et al., 2022)
		Environmental, Societal	2	(Schlör et al., 2018; van Vuuren et al., 2017)
		Environmental	5	(Cai et al., 2019; Leong et al., 2020; Lin et al., 2022; Scarlat et al., 2022; Vieira et al., 2021)
		Societal	1	Huang et al. (2022)
Statistical Model	28	Economic, Environmental, and Societal	12	(Ben Lahouel et al., 2021; Denona Bogovic and Grdic, 2020; Fang et al., 2019; Fu et al., 2018; Li et al., 2022; Song et al., 2020; Sun et al., 2019; Vatalis et al., 2022; Yang et al., 2020; H. Zhang et al., 2022; K. Q. Zhang et al., 2022; Ziegler, 2019)
		Economic, Environmental	10	(Apostu et al., 2022; Baniya et al., 2021; Ben Lahouel et al., 2020; Capece et al., 2017; Feng and Chen, 2018; Lei et al., 2022; Magazzino et al., 2021; Wang and Yang, 2019; Xie et al., 2021; Zhu and Ye, 2018)
		Economic, Societal	1	Ronzon et al. (2022)
		Economic	1	Zhang and Lis (2020)
		Environmental	3	(Hong et al., 2022; Mao and He, 2018; Wang et al., 2020)
		Societal	1	Cai et al. (2022)
Survey/Interview	3	Economic, Environmental, and Societal	1	Hoff et al. (2021)
		Environmental, Societal	1	Stephanides et al. (2019)
		Environmental	1	Caldera et al. (2019)

Data availability

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

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