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Review

Evaluating the Transition Towards Post-Carbon Cities: A Literature Review

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Abstract: To achieve the new European targets concerning CO₂ emission reduction, the concept of a post-carbon city has been promoted, which is focused on low-energy and low-emission buildings provided with intelligent heating and cooling systems, electric and hybrid cars, and better public transport. This paradigm entails the inclusion of aspects not strictly related to energy exploitation but referring to environmental, social, and economic domains, such as improvement in local energy security, people's opinion on different energy solutions, economic co-benefits for private users, environmental externalities, and so on. In this domain, it is of particular importance to provide the decision makers with evaluation tools able to consider the complexity of the impacts, thus leading to the choice of the most sustainable solutions. The paper aims to investigate the scientific literature in the context of evaluation frameworks for supporting decision problems related to the energy transition. The review is carried out through the scientific database SCOPUS. The analysis allows for systematizing the contributions according to the main families of evaluation methodologies, discussing to what extent they can be useful in real-world applications. The paper also proposes emerging trends and innovative research lines in the domain of energy planning and urban management. While the energy transition is an important trend, the analysis showed that few studies were conducted on the evaluation of projects, plans, and policies that aim to reach post-carbon targets. The scales of application refer mainly to global or national levels, while few studies have been developed at the district level. Life cycle thinking techniques, such as life cycle assessment and cost-benefit analysis, were widely used in this research field.

Keywords: energy investment; energy policy; economic evaluation; decision support system; life cycle analysis; cost-benefit analysis (CBA); multi-criteria decision analysis (MCDA); life cycle assessment (LCA); life cycle cost (LCC); sensitivity analysis



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1. Introduction

The new paradigm of the post-carbon city is becoming increasingly developed [1]. This new concept of urban space has led to a significant reconsideration of the fossil fuel-dependent city system, which aims at defining a new model of the sustainable city [2]. The European Commission defines a post-carbon city as a city characterized by a low-carbon system, where buildings are characterized by reduced energy consumption and limited production of climate-altering emissions, thanks to intelligent heating and cooling systems. Equally, the transport sector is influenced by this new concept through the use of electric and hybrid cars and a sustainable public transport system that makes cities less polluted. Taking into account all these challenges, the European Commission released a "Roadmap for moving to a competitive low-carbon economy in 2050", in which the way to achieve a low-carbon future is described [3]. The biggest challenges are the refurbishment of existing buildings because, in Europe, new buildings only comprise 1% of the total amount of building stocks and the expansion of new measures and interventions at the district and municipal level. Furthermore, since the percentage of the global population

living in the urban context will increase, reaching the percentage of 70% of people living in cities by 2050, the urban level will become fundamental to develop new sustainable models. In this perspective, all sectors can contribute to reducing emissions, and every possible action must be made from every side. The focus on the energy transition of cities was also underlined by the United Nations in the definition of the 17 Sustainable Development Goals (SDGs) within the 2030 Agenda [4]. Sustainable development to tackle climate change and build peaceful societies by the year 2030 is strongly reiterated by the SDG 11. In particular, the goal is to make cities and human settlements inclusive, safe, and durably built from a sustainable perspective. The main challenge is to keep urban centers as workplaces capable of producing income without damaging the environment and the territory and preserving natural resources by 2030. Energy is the central element of SDG 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy systems for all. SDGs 7 and 11 recognize the close link between cities and the energy sector, with the sole objective of guaranteeing human well-being by reducing energy poverty and preserving the environment by reducing the effects of climate change. Moreover, the goal of climate neutrality was evoked in December 2019 by the European Commission, which placed the environment at the center of its political action and launched the European Green Deal, which aims to base Europe on a green economy that can achieve carbon neutrality by 2050 [5]. The Green New Deal has assumed a leading role, especially during 2020 in the European panorama, passing from a strategy for growth to a strategy for relaunching the economy in the post-COVID-19 period [6].

With innovative and sustainable city models, new parameters come into play, intending to identify the best design profile to respond to new energy, environmental, and market policies. In this sense, evaluation tools able to support Decision Makers (DMs) and stakeholders in decision processes in the domain of the transformation of buildings/cities/regions are needed. A wide variety of tools for organizing and processing energy problems are available. The main evaluation methods could be clustered in three families; economic methods, multi-criteria approaches, and environmental evaluation techniques. Among the monetary methods, the most common standardized approaches used in the domain of energy decision-making problems are life thinking techniques, such as life cycle cost (LCC) [7] and cost-benefit analysis (CBA) [8]. In 2010, the Energy Performance of Buildings Directives recast (EBPD, 2010/31/EU) introduced the cost-optimal approach, which is determined by considering the overall costs related to the useful life of a building, such as investment costs for energy efficiency, costs of maintenance, operation, and replacement, and any disposal costs [9]. Over the past decade, multi-criteria decision analysis (MCDA) techniques have been widely used in this field [10]. These evaluation tools can support the decision problem in different ways and considering different evaluation principles. Unlike CBA, MCDA is inclined to involve decision-makers to capture a wide range of perspectives and verify the power of stakeholders' consent. Hybrid models that combine manual-based CBA with MCDA methods in the field of the district sustainability sector are being developed so that tangible and intangible criteria can be included in the assessment [11–13]. Moreover, several certification protocols based on qualitative assessment have been developed to assess the sustainability of buildings and neighborhoods, up to urban plans. These assessment tools define a project's performance score, analyzing all stages of the life cycle, from raw material purchase to demolition, and including the full range of economic, environmental, and social impacts [14–16]. The most widely used and recognized international certification schemes are the "Building Research Establishment Environmental Assessment Method" (BREEAM) [17], the "Leadership in Energy and Environmental Design" (LEED) [18], the "Green Star" in Australia [19], "Comprehensive Assessment System for Building Environmental Efficiency" (CASBEE) in Japan [20], and the "Green Mark" in Singapore [21].

In the context of the energy transition, review articles are limited. Most of the articles in the literature present in the most well-known and reliable bibliometric databases connect the concept of the energy transition to specific cases. Often, the energy transition is linked

to the concept of landscape transformation, land consumption, the use of renewable energy sources, and what benefits they bring but also what conflicts they have with the Sustainable Development Goals [22–26]. Papers have also been written about specific methods that can be used to examine the energy transition, such as system dynamics [27]. Other papers argue the issue from a regulatory point of view and how states can overcome the barriers that block a post-carbon vision and the reasons why it is necessary to do so [28,29]. Horschig and Thrän [30] examined several modeling approaches applicable to renewable energy policy planning and evaluation. However, the review is focused on quantitative and qualitative approaches, such as input/output modeling [31], computable general equilibrium modeling [32], system dynamics modeling [33], agent-based modeling [34], theory-based evaluation [35], multiple decision aiding analysis [36], and hybrid approaches. The authors do not take into consideration the monetary approaches that constitute the main tools required by national or international energy directives such as discounted cash flow (DCF), cost-benefit analysis (CBA) [8], and life cycle cost (LCC) [37].

The proposed paper, on the other hand, aims to have a broader view of the concept of energy transition and post-carbon vision. It proposes an innovative literature review that provides a systematic assessment of the energy transition, aiming to demonstrate the importance that the different evaluation methods acquire within the theme and the various fields of application that these methods are involved in. In addition, this review aims to highlight how different evaluation approaches can help to take into consideration the benefits and advantages for the development of society and future generations in a sustainable way [38,39].

This research aims to get a clear point of view on the issue of the energy transition, that is, the shift from the use of non-renewable energy sources to renewable sources. This change of direction is the basis for the formation of sustainable economies that are attentive to the use of renewable energy and sustainable development [40]. The study focuses, in particular, on the geographical areas that have shown a particular interest in this issue, but also the sector in which the topic is inserted, such as buildings, urban infrastructure, or, more generally, that of cities. The research also focuses on analyzing the role of different evaluation methods and approaches to support this goal. To achieve the purpose of the research, the literature analysis was carried out using the SCOPUS database. The paper is structured as follows: after the Introduction, a section dedicated to research methodology describes the method used to conduct the analysis of the literature and the different steps of the investigation. Next, the results section highlights the outcomes of the different steps taken during the analysis. Finally, in the Conclusions, the paper seeks to explain the overall view of the topic covered and the most interesting results present in the literature, but also the key points for future perspectives of the research.

2. Research Methodology

As previously mentioned, the purpose of this paper is to develop a bibliography analysis of literature regarding the context of energy transition and post-carbon vision, focusing in particular on decision-making processes and the role of evaluation tools. The aim is to highlight the more recent trends and key topics relevant to this issue, and obtain a current view of decision tools for supporting a sustainable economy and development. This overview can be useful as a guide for future research activities and for proving the central role that evaluation methods can play in this field of interest. The literature's bibliography analysis was conducted using the SCOPUS database, one of the most well-known and reliable online bibliography collection platforms. The analysis and all the data collected for the drafting of this paper are part of the period from May 2020 to October 2020. A multi-step approach was used in this research. Figure 1 shows the framework of the literature review performed in this research. The first step was selecting the keywords to use in the SCOPUS search. Specifically, given the large number of documents on the energy topic on SCOPUS, the analysis was conducted on three different and increasingly specific levels, adding keywords to the basic ones chosen to refine the research carried out. For the first

phase of the search, the most general one, it was decided to use the following keywords: (“*evaluation*” OR “*valuation*” OR “*assessment*”) AND (“*energy transition*” OR “*post-carbon*”). A total of 14,443 documents were found with an “all fields” search, while 699 documents were found by limiting the search to title, abstract, and keywords. The second phase of the research aimed at limiting the analysis to the territorial scale to which the documents found refer, and subsequently to the sector. For this purpose, specific keywords were added that focus on the scale of the application. The keywords used are the following:

- (“*evaluation*” OR “*valuation*” OR “*assessment*”) AND (“*energy transition*” OR “*post-carbon*”) AND (“*global*”) = 139 Documents;
- (“*evaluation*” OR “*valuation*” OR “*assessment*”) AND (“*energy transition*” OR “*post-carbon*”) AND (“*national*”) = 91 Documents;
- (“*evaluation*” OR “*valuation*” OR “*assessment*”) AND (“*energy transition*” OR “*post-carbon*”) AND (“*regional*”) = 63 Documents;
- (“*evaluation*” OR “*valuation*” OR “*assessment*”) AND (“*energy transition*” OR “*post-carbon*”) AND (“*urban*”) = 63 Documents;
- (“*evaluation*” OR “*valuation*” OR “*assessment*”) AND (“*energy transition*” OR “*post-carbon*”) AND (“*district*”) = 23 Documents.

Next, the analysis was narrowed based on the sector they refer to. Specifically, it was chosen to include the building sector, infrastructure sector, and, more generally, the city. The keywords used are the following:

- (“*evaluation*” OR “*valuation*” OR “*assessment*”) AND (“*energy transition*” OR “*post-carbon*”)) AND (“*building*”) = 86 Documents;
- (“*evaluation*” OR “*valuation*” OR “*assessment*”) AND (“*energy transition*” OR “*post-carbon*”)) AND (“*infrastructure*”) = 52 Documents;
- (“*evaluation*” OR “*valuation*” OR “*assessment*”) AND (“*energy transition*” OR “*post-carbon*”) AND (“*city*” OR “*cities*”) = 56 Documents.

For both searches in this second phase, the analysis was carried out considering only the results by title, abstract, and keywords. In the third phase of the analysis—the most interesting for the research—other keywords were added with the precise purpose of focusing on evaluation methods and approaches to identify, thanks to the analysis of the literature, what are the trends and use of these methods in the topic of energy. The new keywords used were partly suggested by SCOPUS as search filters, while others were manually entered into the database. The words that appeared as suggestions in the filters are the following:

“*Life Cycle Assessment (LCA)*” (28 document results); “*Cost-Benefit Analysis*” (22 document results); “*Sensitivity Analysis*” (16 document results); “*Environmental Impact Assessment*” (14 document results); “*Monte Carlo Methods*” (13 document results).

While the manually added words that reference evaluation methods are as follows:

“*Discounted Cash Flow*” OR “*DCF*” (0 results); “*Life Cycle Cost*” OR “*LCC*” (4 document results); “*Multicriteria*” OR “*MCDA*” OR “*MCA*” OR “*Multi-criteria*” OR “*Multiple Criteria Decision Analysis*” (13 Document Results); “*Neural network*” (2 document results); “*Regression Analysis*” OR “*Parametric Model*” (3 document results); “*Preference evaluation*” OR “*econometrics*” (5 document results); “*Geographical Information System*” OR “*GIS*” (12 document results); “*Quantitative Analysis*” (15 document results).

Those keywords were added to the string of keywords used in the first analysis phase. In the next paragraphs, these three phases will be named, respectively, Group A, Group B, and Group C. For each group, different analyses were conducted, which are titled *historical production analysis*, *country productivity analysis*, and *subject area analysis*. The first type of analysis (*historical production*) allows the comprehension of the productivity of the literature relating to these themes in the time frame indexed in SCOPUS. In this way, it is possible to understand the overall trend of the selected sample. The second analysis

(*country productivity*) shows how many documents published by the different countries were produced in the period indexed in SCOPUS, according to the authors' affiliation city. The third analysis (*subject area*) provides an overview of the sectors dealing with the issue of the energy transition and post-carbon issue. In addition, a cross-sectional comparison of the selected keywords for each group was provided to understand the relevance of specific words, approaches, and methods in this field. In particular, this comparison can support the identification of the gaps in literature production and of the most consolidated fields of research.

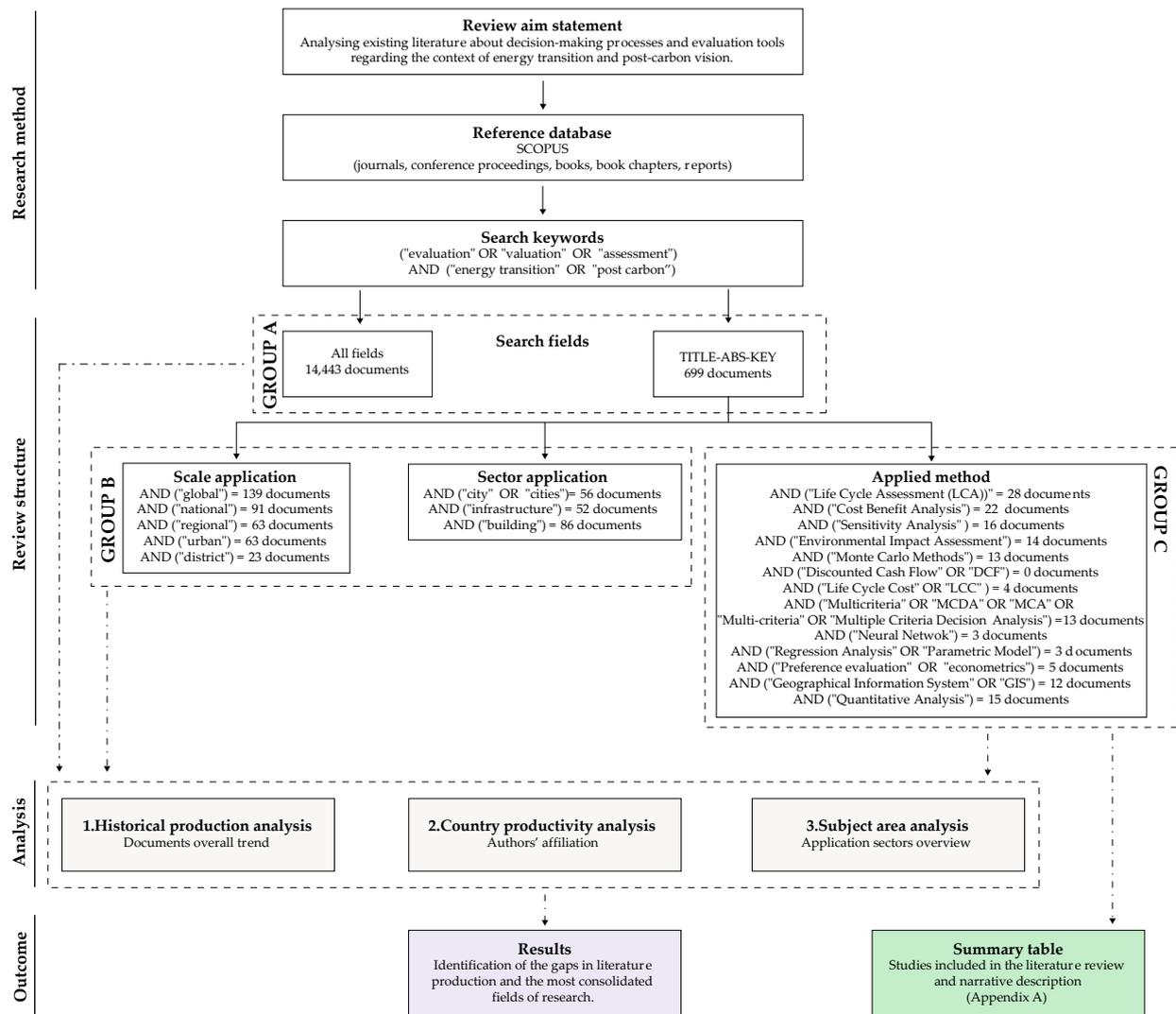


Figure 1. Literature review framework.

3. Results and Discussion

3.1. Group A: Analysis about Search Fields

The first analysis conducted on the topic of energy and post-carbon transition shows a large number of documents; 14,443 considering all with an "all fields" search, and 699 by limiting the search to title, abstract, and keywords. *Historical production* started in 1957, but only in the 1980s is the number of indexed documents over 10 per year. The intensive production of literature about the energy transition and post-carbon issue began after the 2000s. From 2000 to 2020, the number of documents is 14,138, equal to 97% of the entire literature production. In particular, in the last 10 years, the number documents

published is 13,359, which is 92% of the total. The second analysis, which focused on the research on title, abstract, and keywords (TITLE-ABS-KEY), shows similar results to the *historical production*. Additionally, in this case, the first document indexed in SCOPUS dates back to 1957, but only in 2005 is there a slight increase in production. From 2010 to 2020, the literature production increases significantly, with a total of 650 documents, equal to 93% of the entire production. Figure 2 reports the *historical production* of the literature for the research in “all fields” and limited to title, abstract, and keywords.

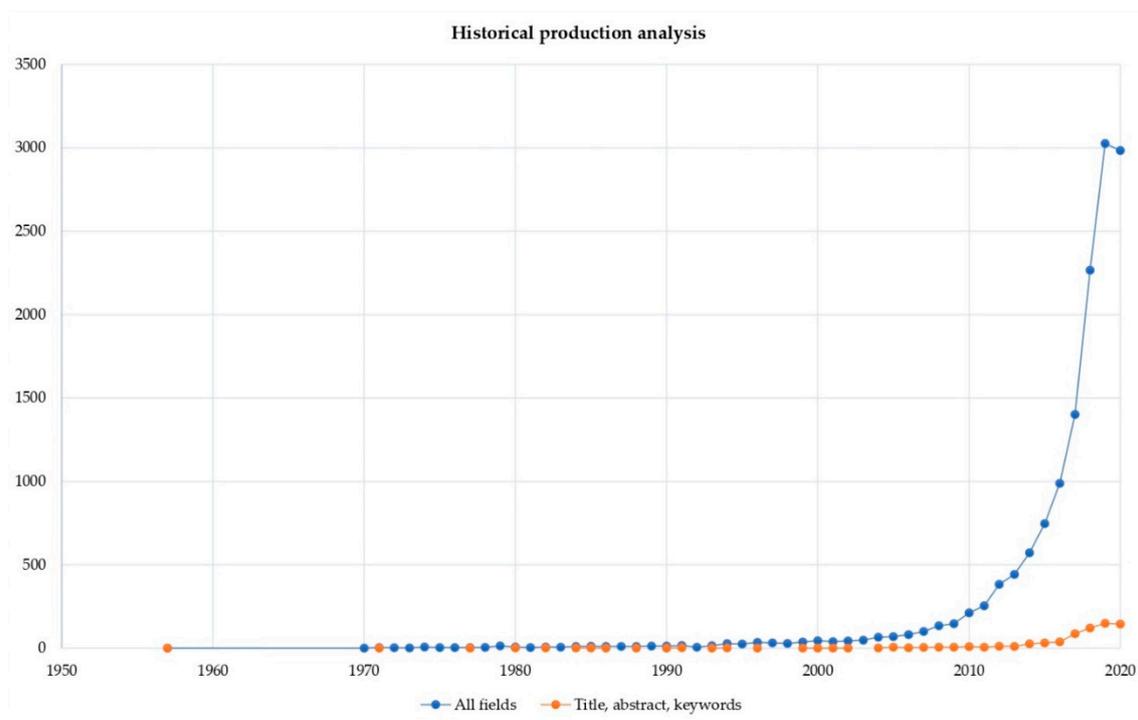


Figure 2. Historical production for “all fields” research and limited to title, abstract, and keywords.

The examination of the *subject areas* performed by SCOPUS is reported in Figures 3 and 4, and shows how many sectors deal with the topic of energy transition and post-carbon, including from energy to engineering, and from chemistry to mathematics, for a total of 27 subjects. Figure 3 shows the analysis of the 14,443 documents found on SCOPUS, and the main subjects involved in this topic are energy, environmental science, social science, and engineering. These four subjects alone account for 63% of the entire literature production.

In the same way, Figure 4 shows the analysis of sectors that have included this topic, taking into consideration only the 699 documents found by limiting to title, abstract, and keywords. In this case, energy, environmental science, and engineering represent the subjects with the largest number of documents. Social science is only equal to 9.4% of the total.

Comparing the weights of the two keywords *energy transition* and *post-carbon*, which are the keystones of this literature review, it can be seen that of the 699 documents found in SCOPUS, only 24 documents are related to the post-carbon keyword. Figures 5–8 show the results of the analysis of the comparison between the *energy transition* and *post-carbon* keywords. The largest proportion of documents related to *energy transition* was written in 2020 (172 documents). For the *energy transition* keyword, the production of literature has increased significantly in the last four years (Figure 5). While the contributions that use the *post-carbon* keyword record a constant trend, the production starts in 2005 to present, with a narrow difference throughout these fifteen years (Figure 6). Most of the documents with the *energy transition* keyword were involved in the fields of energy, environmental science, and engineering (Figure 7). The sector that used the *post-carbon* keyword the most is environmental science (Figure 8).

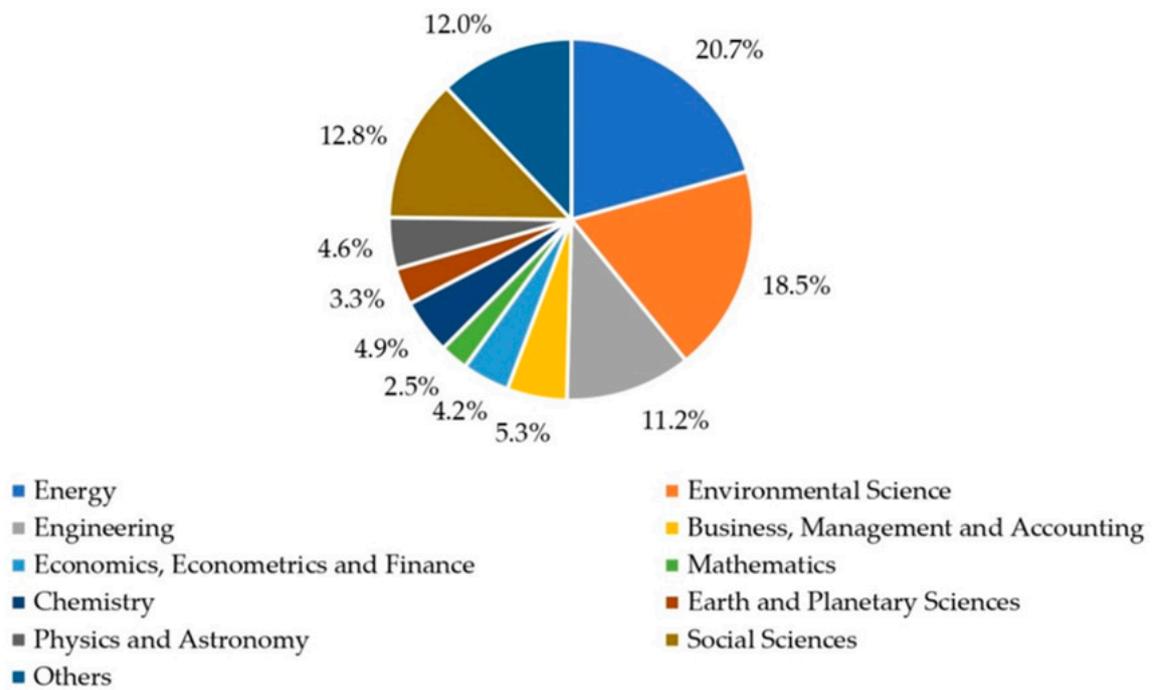


Figure 3. Subject area analysis for all fields of research.

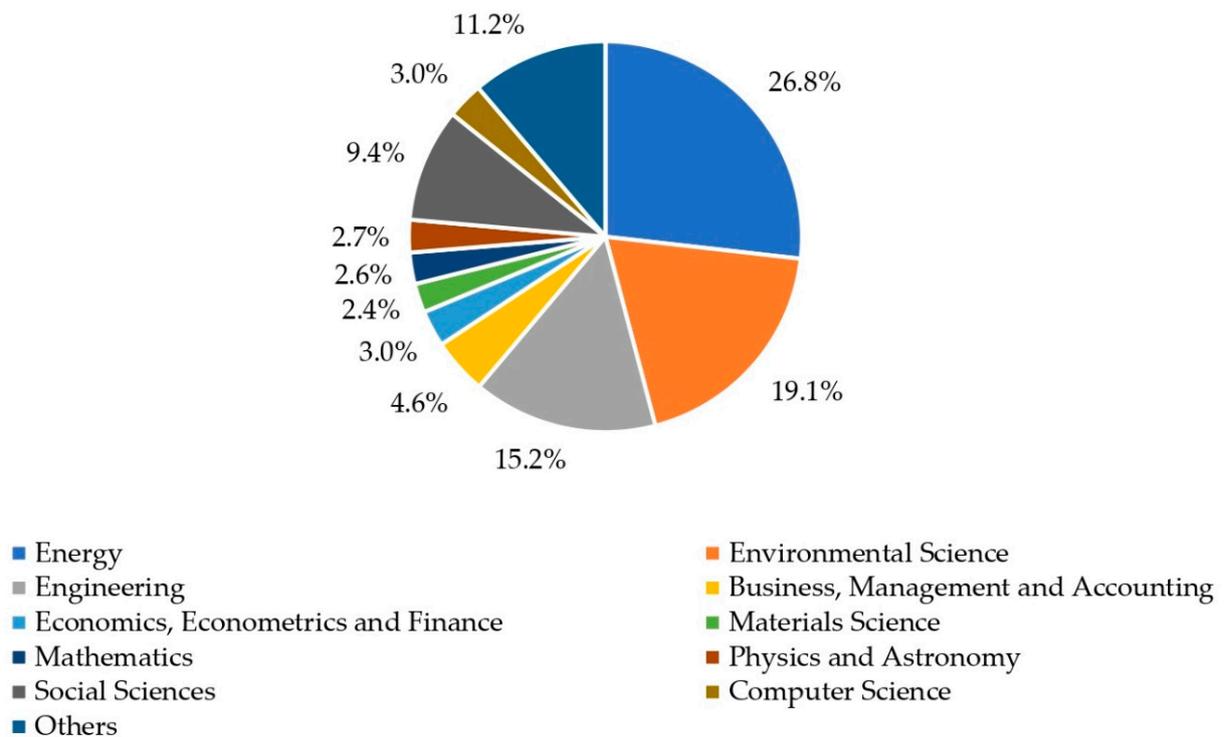
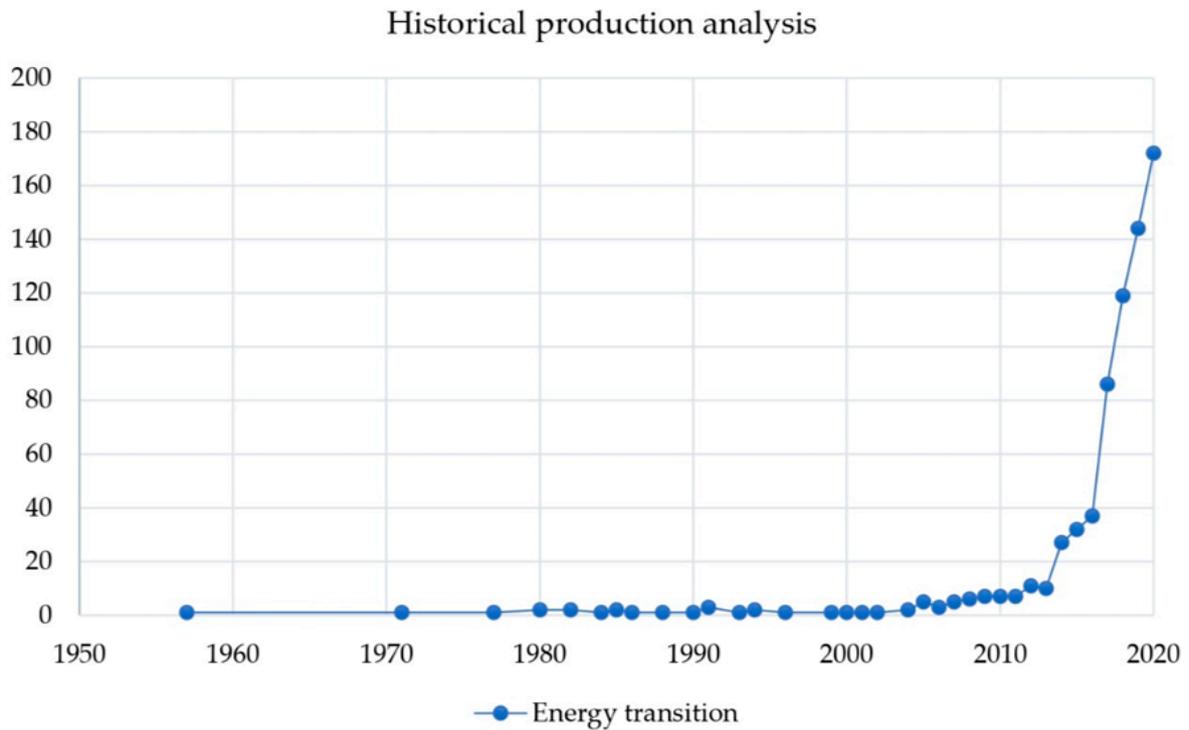


Figure 4. Subject area analysis limited to title, abstract, and keywords.



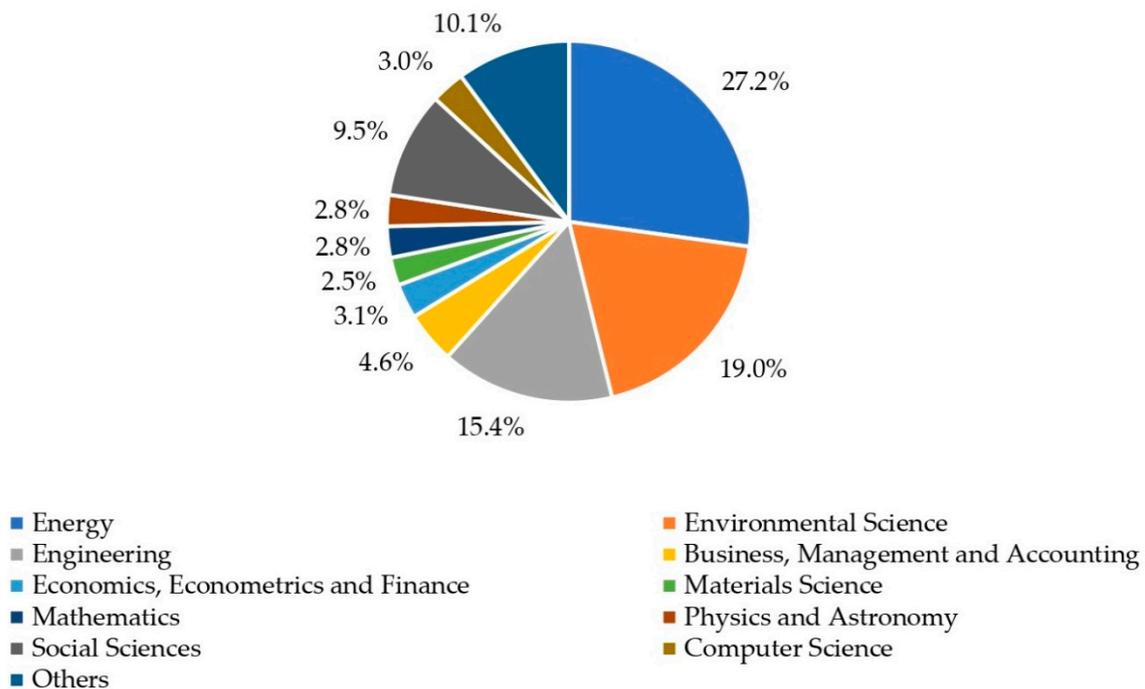


Figure 7. Subject area analysis for articles that used “energy transition” as a keyword.

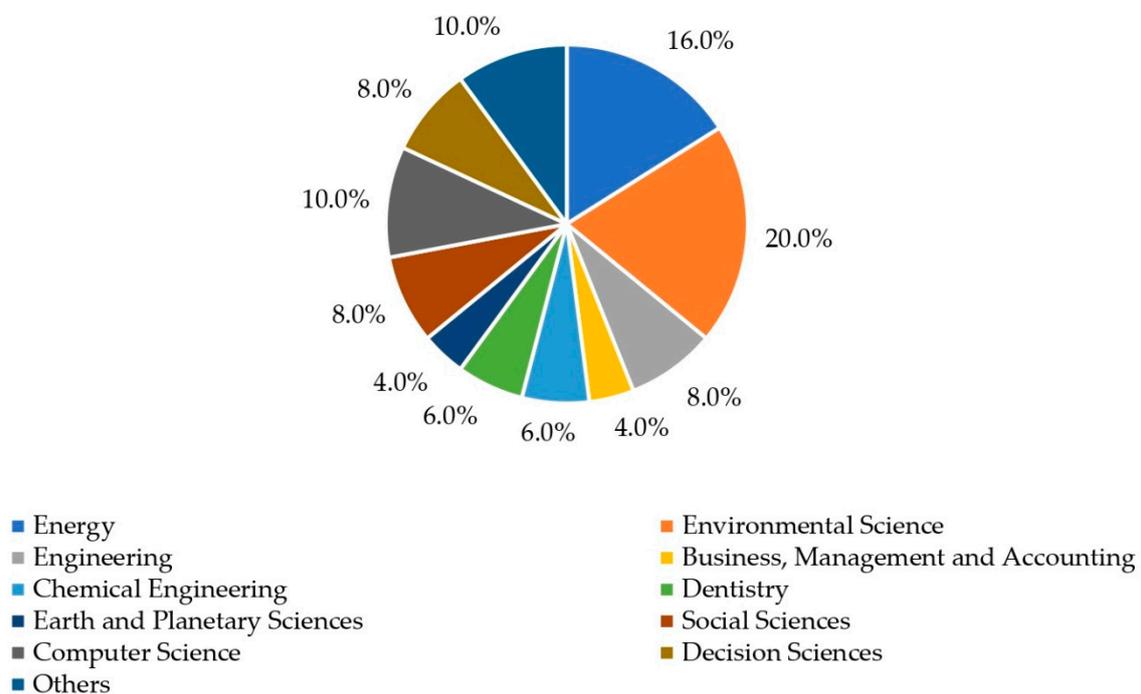


Figure 8. Subject area analysis for articles which used “post-carbon” as a keyword.

3.2. Group B: Energy Transition and Post-Carbon View at Territorial Scale and in Sector of Application

The second phase of analysis focused on the territorial scale in which the documents are inserted. The searches were conducted by limiting the research to title, abstract, and keywords. In particular, five searches were performed, each one using a specific

keyword that identifies a particular scale. The keywords used are the following: *global*, *national*, *regional*, *urban*, *district*. The results show that the *global* keyword has the largest number of documents (139 documents). Twenty-three documents are related to the *district* keyword which addresses the issue on a smaller and less used territorial scale. The *historical production* for the *national* keyword has been extensive since the 1970s. For the *district* keyword, instead, the first documents date back to 2015, with a slight increase in recent years. In each case, about 90% of documents relating to the different scales were written after 2015. Figure 9 reports the historical trends of literature for the different territorial analyses considered in this study.

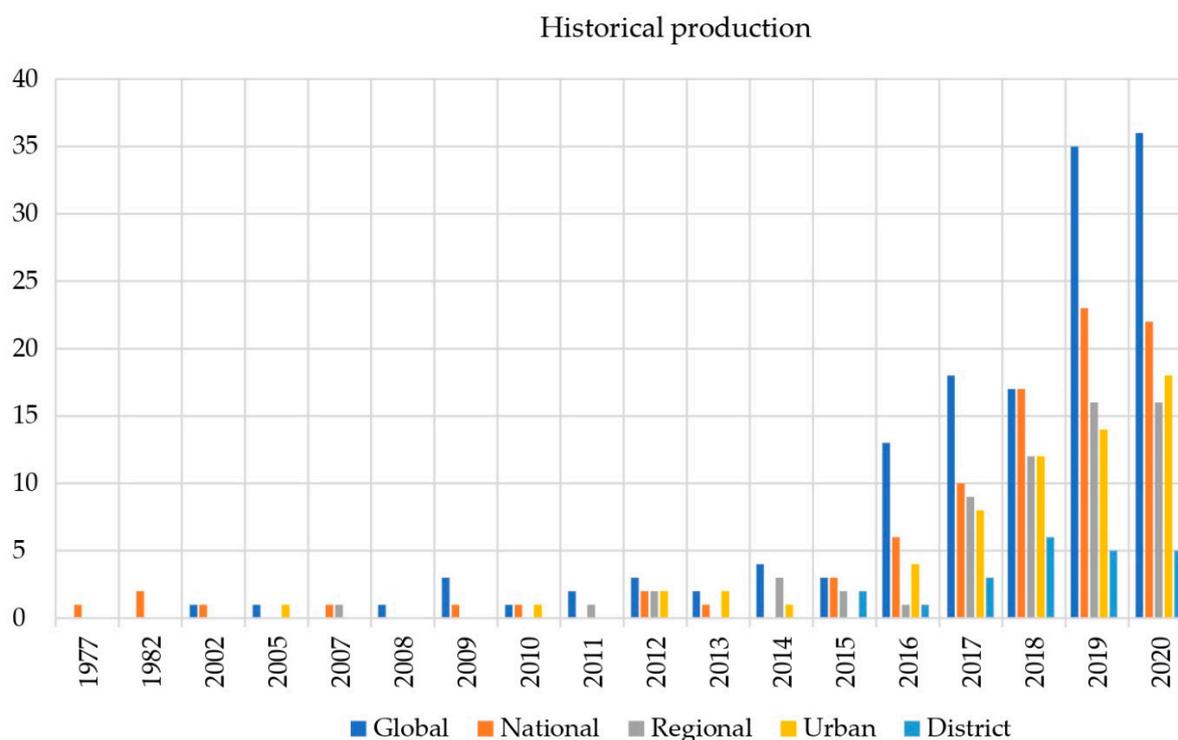


Figure 9. Historical production in different territorial scales.

Finally, as regards country productivity analysis, it is clear that the most of the documents were written in Germany. However, some slight differences can be observed between different countries. For example, with regard to the *global* territorial scale, the main producing countries are Germany and the United States, with 35 and 21 documents, respectively. On the *national* territorial scale, the UK is more productive than the United States. It is interesting to note that Italy is, together with Switzerland, the country with the highest production of documents linked to the *urban* territorial scale. At the same time, Italy and Germany are the countries with the greatest interest in writing documents about the *district* scale in the field of the energy transition and post-carbon issue. Figure 10 shows the number of publications produced by each country. Those with a lower incidence due to few publications are considered as “Others”.

As mentioned above, most of the documents that include the *district* keyword were written in Germany, Italy, and Spain since 2015. The main subjects of those 23 documents are energy, environmental science, and engineering. Furthermore, taking into consideration the analysis of documents for affiliations carried out by SCOPUS, the results conclude that the Politecnico di Torino is the institution with the highest number of affiliations, followed by the Technical University of Munich [41]. Figure 11 shows the result of the analysis on authors’ affiliations performed by SCOPUS.

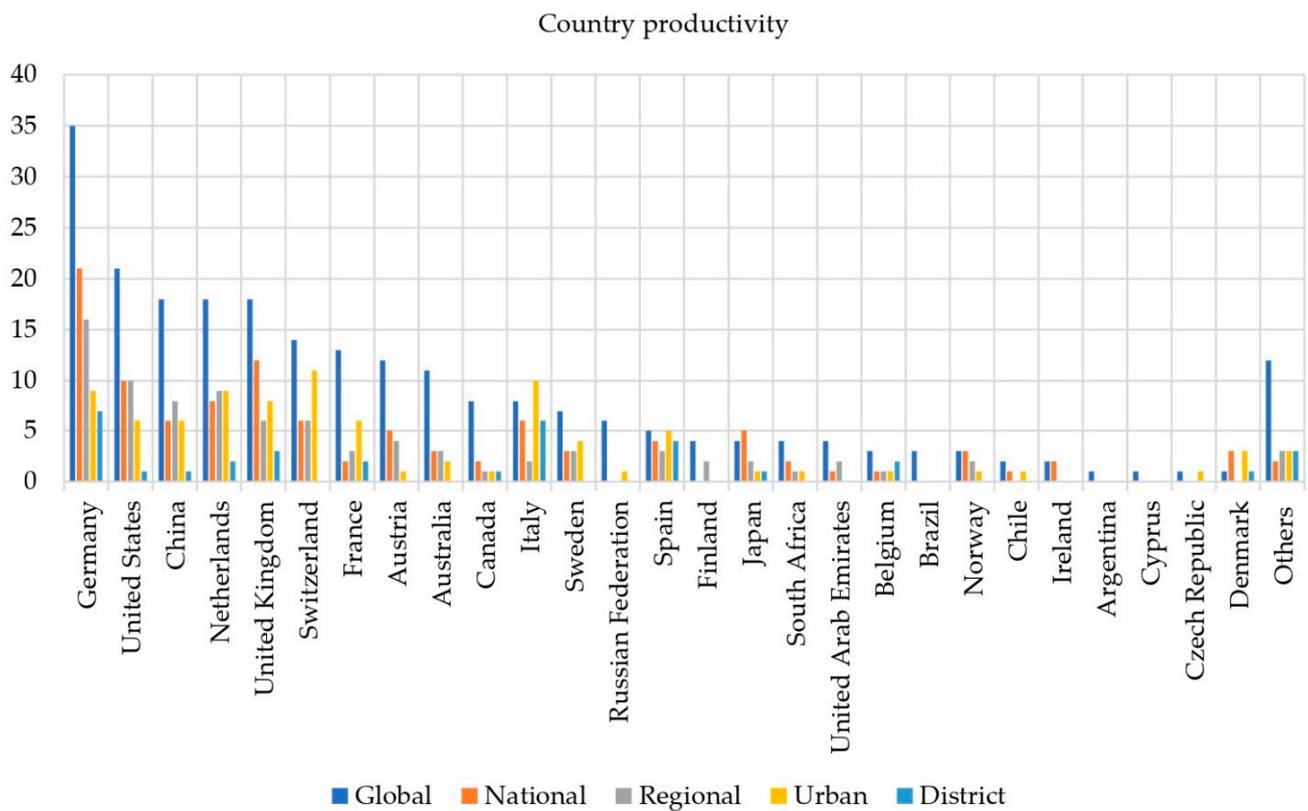


Figure 10. Number of publications per country.

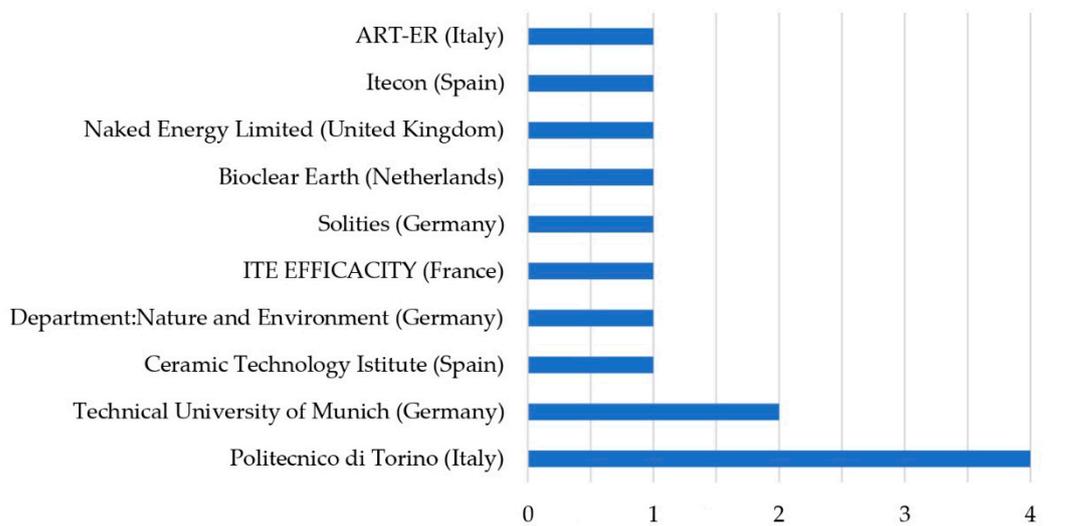


Figure 11. Number of documents by affiliations performed by SCOPUS.

The second search conducted in Group B narrows the analysis of the first group of documents found (699) based on the sector to which they refer. Specifically, three searches were carried out: one for the building sector, one for the infrastructure sector, and the last one, more generally, for the city environment. The results show that 86 documents deal with the building sector, 56 documents with city/cities, and 52 with the infrastructure sector.

3.3. Group C: Evaluation Approach and New Trends in Energy Transition and Post-Carbon View

The purpose of the third analysis—the most interesting for this literature review—is to focus on evaluation approaches, operational research, and new trends emerging about this topic. The search starts from the primary analysis (Group A). New keywords were introduced each time in each search, and in some cases derived from filter keywords suggested by SCOPUS in the primary search. Interestingly, words like life cycle assessment (LCA) and cost-benefit analysis (CBA) are among the first keywords suggested by SCOPUS. Other keywords are defined according to the authors' disciplinary field, to verify the possible gaps present in the literature production and highlight the importance of the specific approach and evaluation methods in the field of energy and post-carbon transition.

The results show different situations, as can be seen in Figure 12 and Table A1 in Appendix A. Discount cash flow (DCF) is absent in the literature production on this topic. On the contrary, LCA is the most used approach for the energy transition and post-carbon issue (28 documents). Another relevant result is given by the adoption of CBA (21 documents). Sensitivity analysis, environmental impact assessment, Monte Carlo methods, MCDA, GIS, and quantitative analysis have approximately the same number of documents, with more than 13 documents each. A greater number of documents with LCA and CBA could be explained by the relation that these methods have with the themes of the energy transition, what benefits come from the use of renewable sources, and the possibility to monitor and reuse each thing done with this type of energy approach [42–50]. Furthermore, LCA and CBA are manual-based analyses mostly used in practice to validate the economic feasibility of a large-scale project [8,51]. The absence of documents related to DCF can be partially explained by its use as an ex-ante approach to calculate the feasibility of new constructions or interventions, and is therefore more connected with the economic area.

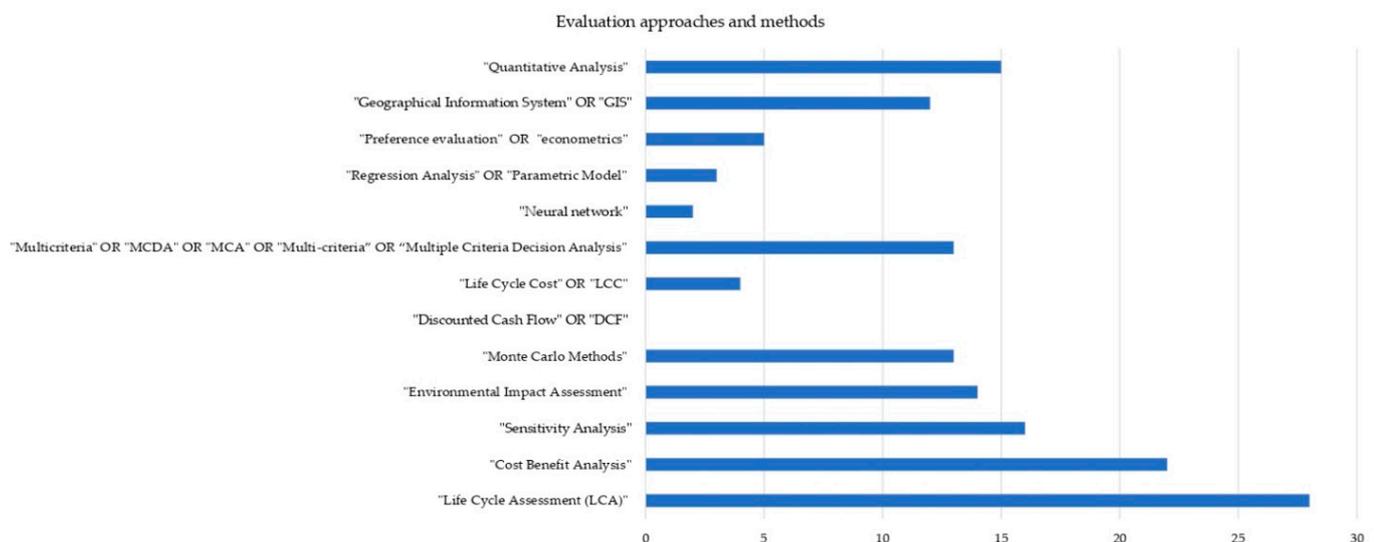


Figure 12. Number of documents in relation to evaluation approaches and methods.

Generally, the *historical production* in the context of evaluation approaches and methods to support the issue of energy transition and post-carbon target starts around 2005. In the last three years, the intensive production of documents begins, as it is possible to see in Figure 13. Most methods and approaches were involved in the energy sector only in recent years, but there are some exceptions. GIS and neural networks are the first two methods to appear in the articles between 2005 and 2006. However, these evaluation methods reappeared in the searches only in 2014, slightly increasing their presence in documents. Anyway, the increase in these evaluation methods within the documents only in recent years is caused by the modernity of the theme of the energy transition, but also because the evaluation methods are recent and not yet consolidated. As might

be expected, the results of the subject area analysis show an important production in the fields of energy, environmental science, and engineering in general for all evaluation approaches considered, as can be seen in Figure 14. It is interesting to notice that GIS and environmental impact assessment have the largest number of documents associated with social science, with seven and six documents, respectively.

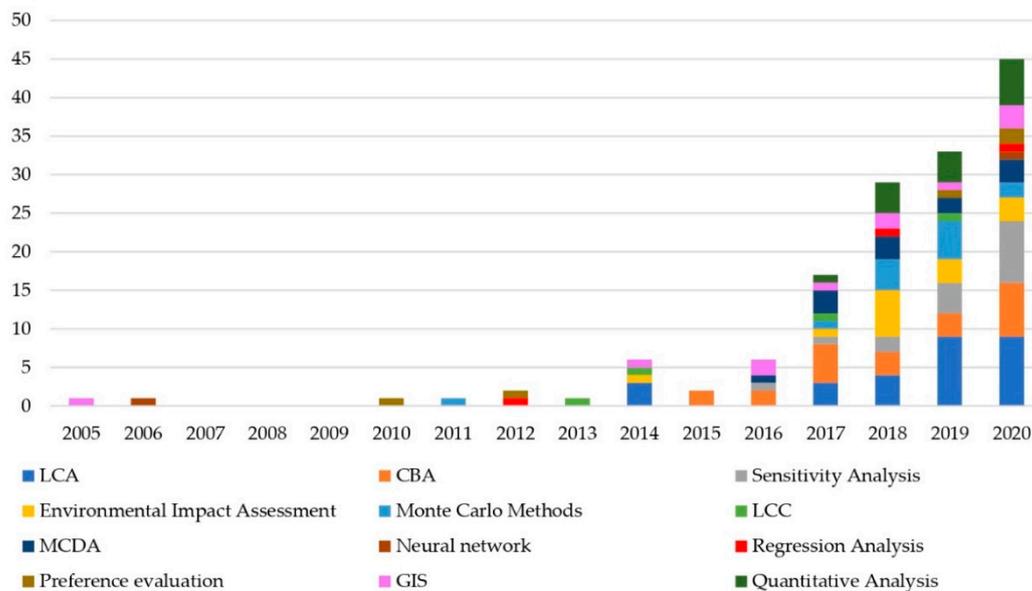


Figure 13. Historical production of literature per evaluation approach and method considered.

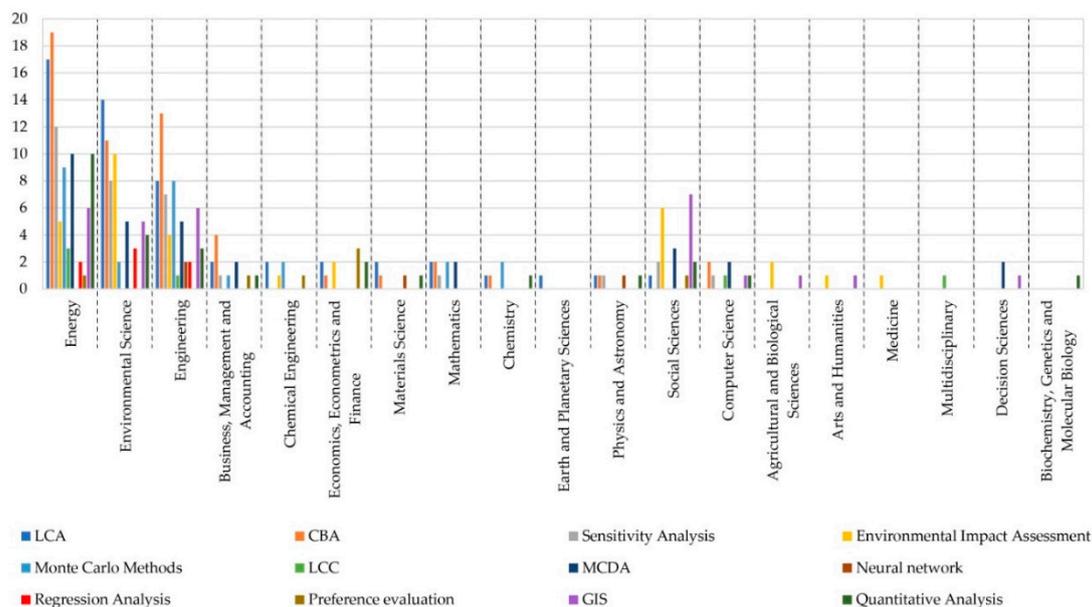


Figure 14. Subject areas per evaluation approach.

4. Conclusions and Future Implications

The present paper allowed us to understand the recent trends and the main issues related to the theme of energy transition and post-carbon targets. The energy transition and post-carbon view are currently the main trends because they are closely linked to the concept of sustainable development and the life cycle of products. This relationship

is also reflected in the recent number of documents adopting LCA and CBA approaches. The application of these two techniques by the academic literature in the energy sector is due to the fact that they represent the tools recognized at the European level in terms of project evaluation for all member states, regulated by standards capable of guaranteeing absolute transparency in the selection of projects to be carried out. In these documents, the topics range from the chemical to the food industry, and from the use of non-renewable resources to new renewable energy models, evaluating the realization costs and benefits brought about by some changes in the production methods.

Another aspect that emerges from this review is the growing interest in the field of energy transition and the natural environment to be preserved, with particular attention paid to the benefits and advantages for the development of society and future generations. These aspects are in fact in line with the aims suggested by the Sustainable Development Goals defined by the United Nations. In this context, life cycle analyses let to consider all the positive and negative impacts generated by a project, allowing us to obtain an overview of the performances and calculate the net benefit for society, and guarantee the achievement of economic and environmental sustainability goals.

It is clear that the interest in this topic involves all the world and will have positive repercussions on the environment on a planetary scale. From the territorial-scale analysis, the interest of different countries to study the impact of energy transition in a global vision is highlighted. The number of documents related to a global scale is greater with respect to the other territorial scales taken into consideration. Nevertheless, the interest in the district scale is deepened in different countries. The idea to operate on a small scale could probably guarantee the application of the post-carbon vision. Creating and making small areas of cities self-sufficient from an energy point of view, with a proactive character regarding the principles of eco-sustainability, are certainly easier. This is the beginning of a necessary change, which allows us to preserve natural resources and ensure a better quality of life for future generations.

It was interesting to discover that Italy, among the various European countries, is more interested in working and developing research on an urban and district scale, studying realistic solutions for cities and promoting their development with the purpose of guaranteeing the best quality of life. As previously mentioned, the Politecnico di Torino is the university with the majority of published documents and a high interest in developing studies in this field.

This preliminary search on SCOPUS has highlighted in recent years an increase in documents on this sector. Particularly interesting was the comparison between historical and country production and the subject areas, as well as the evaluation approaches and methods, to guide and understand the development of new trends in the research and which topics could be explored in the future.

The research provides a comprehensive view of the state of the art, which is useful for guiding future research and demonstrating the role of some evaluation approaches and methods in this field. At the same time, the research certainly shows some limitations. First of all, the analysis was conducted using a single database, even though SCOPUS is one of the most recognized and reliable bibliometric databases. Secondly, the search was implemented in a general way, because there is no in-depth analysis on individual documents, and the search, specifically, in the second and third stages, is limited to title, abstract, and keywords. Thirdly, the analyzed topic is very recent and there are not many applications of the evaluation methods in this area, so there are few documents to conduct an exhaustive analysis. Future investigations could consider the possibility of analyzing the individual documents in a more advanced way, to better understand the role and potentials of the single approach and methods applied in the view of energy changes. Since COP21, with the adoption of the Paris Agreement on Climate, and the new objectives set by the United Nations Economic Commission for Europe (UNECE), an increasing number of cities have committed themselves to concretely combat climate change and to pursue the common goal of carbon neutrality. The C40 cities established that the neutral city must

also take into consideration the urban sectors relevant to green spaces, waste, and water, and not only energy, mobility, and buildings, with the general objective of promoting sustainable development and ensuring green growth. In this comprehensive perspective, every single part of the city becomes a potential field of the experiment for new zero-carbon technologies. This vision involves a certain complexity in the definition of decisions. Multi-step evaluation procedures that investigate the economic, environmental, and social performance of city transition operations are necessary to define the milestones for actions in priority areas and create an organizational framework. Furthermore, hybrid models that facilitate dialogue between the different stakeholders involved can help define a decision-making process that is inclusive from a social point of view and sustainable from an economic and environmental point of view. In the future, it will be interesting to understand how the academic sector, researchers and scholars respond to the new rules that will emerge from these new models of sustainable cities and support public and private DMs.

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Appendix A

Table A1. Summary collection of studies by type of evaluation applied (Group C).

Authors	Years	Source Title	Evaluation Method	Objective and Application Context
Barnes et al. [52]	2005	The Urban Household Energy Transition: Social and Environmental Impacts in the Developing World	Geographical Information System	Analysis of the use of renewable energy and impacts on society
Shterenlikht and Howard [53]	2006	Fatigue and Fracture of Engineering Materials and Structures	Neural Network	Evaluation of the ductile to brittle transition behavior of ferritic steels.
Duke et al. [54]	2010	Frontiers of Chemical Engineering in China	Preference Evaluation OR Econometrics	Evaluation of the post-combustion sector and its involvement in energy production
Guasco et al. [55]	2011	Journal of Physical Chemistry A	Monte Carlo Methods	Study of the origin of anharmonic effects through Monte Carlo analysis
Arthur et al. [56]	2012	Energy Economics	Preference Evaluation OR Econometrics	Calculation of the elasticity of domestic energy demand at price and income in Mozambique
Heun and de Wit [57]	2012	Energy Policy	Regression Analysis OR Parametric Model	Analysis of the rise in the price of oil in relation to the energy transition

Table A1. Cont.

Authors	Years	Source Title	Evaluation Method	Objective and Application Context
Schaede et al. [58]	2013	Design and Assessment	Life Cycle Assessment, Life Cycle Cost	Evaluation and design of electric energy storage
Eising et al. [59]	2014	Applied Energy	Geographical Information System	Analysis of transport and supply chain integration
Evanno and Weinberger [60]	2014	Techniques-Sciences-Methodes	Environmental Impact Assessment	Analysis of specific feedback processes related to the biogas of accidents
King [61]	2014	Energy	Life Cycle Assessment	Comparison between the energy performance of systems in the energy transition
Nordman [62]	2014	Renewable Energy	Life Cycle Cost	Analysis of wind farms to power tea factories in Kenya
Zimmermann et al. [63]	2014	Metallurgical Research and Technology	Life Cycle Assessment	Importance of electric vehicles in the energy transition
Bachmann [64]	2015	Environmental Science and Technology	Cost–Benefit Analysis	Strengths and disadvantages of an approach to the environmental economy
Wesseh et al. [65]	2015	Journal of Cleaner Production	Cost–Benefit Analysis	Benefit analysis for renewable energy research and development programs in Liberia
Zimmermann et al. [66]	2015	Integrated Environmental Assessment and Management	Life Cycle Assessment	Study on the importance of electric vehicles for the energy transition
Calvert [67]	2016	Progress in Human Geography	Geographical Information System	Analysis of geographical contributions, study of energy and energy futures.
Cucchiella et al. [41]	2016	Energy Conversion and Management	Cost–Benefit Analysis, Sensitivity Analysis	Evaluation of small-scale photovoltaic systems and results
Herbert et al. [68]	2016	Sustainable Production and Consumption	Life Cycle Assessment	A proposal for types of greenhouse gas emissions
Lizana et al. [69]	2016	Energy and Buildings	Multiple Criteria Decision Analysis	Economic, environmental, and social assessment for a residential energy retrofit
Sager-Klauß [70]	2016	A+BE Architecture and the Built Environment	Geographical Information System	Support for sustainable energy transition planning in small and medium-sized communities
Sgouridis et al. [71]	2016	Renewable and Sustainable Energy Reviews	Cost–Benefit Analysis	Analysis of renewable energy costs in the United Arab Emirates
Carlier and Chardonnet [72]	2017	Environnement, Risques et Sante	Environmental Impact Assessment	Search for the path with the lowest environmental and health impact for the reconstruction of an power line
Kaltenegger et al. [73]	2017	Energy Policy	Cost–Benefit Analysis	Input–output and trend-based energy cost study in Germany and EU

Table A1. Cont.

Authors	Years	Source Title	Evaluation Method	Objective and Application Context
Ketzer et al. [74]	2017	Biomass and Bioenergy	Geographical Information System	Assessment of the sustainable potential of pasture biomass for energy supply
Kraan et al. [75]	2017	Advances in Intelligent Systems and Computing	Cost–Benefit Analysis	Models and studies for adaptation to climate change
Li and Trutnevyte [76]	2017	Applied Energy	Quantitative Analysis, Monte Carlo Methods	Analysis to reduce UK greenhouse gas emissions by 2050
Loßner et al. [77]	2017	Energy Economics	Cost–Benefit Analysis	Simulation of alternative scenarios on renewable energy
Muratori et al. [78]	2017	Renewable and Sustainable Energy Reviews	Cost–Benefit Analysis, Sensitivity Analysis	Assessment of the increase in the cost of building large energy plants in the US
Rakotoson and Praene [79]	2017	Journal of Cleaner Production	Life Cycle Assessment	Assessment of the environmental impacts of energy production in the French overseas territories
Scipioni et al. [80]	2017	Hydrogen Economy: Supply Chain, Life Cycle Analysis and Energy Transition for Sustainability	Multiple Criteria Decision Analysis	Analysis of the difficulties for a sustainable hydrogen economy
Serp et al. [81]	2017	Energies	Life Cycle Assessment	Evaluation of nuclear energy recycling
Wan Ahmad et al. [82]	2017	Journal of Cleaner Production	Multiple Criteria Decision Analysis	Quantitative assessment of the forces necessary for the sustainable management of the supply chain
Wang et al. [83]	2017	Energy Procedia	Life Cycle Cost, Multiple Criteria Decision Analysis	Resilience analysis for energy systems
Danielson et al. [84]	2018	Lecture Notes in Business Information Processing	Multiple Criteria Decision Analysis	Multi-policy analysis of sustainable choices in Jordan
Deakin and Reid [85]	2018	Journal of Cleaner Production	Cost–Benefit Analysis	Smart city analytics and behavior tips
Desthieux et al. [86]	2018	Frontiers in Built Environment	Geographical Information System	Presentation of a methodology for assessing solar radiation and energy production on building roofs and vertical facades in the city center
Ghannadzadeh [47]	2018	Chemical Engineering Research and Design	Life Cycle Assessment, Monte Carlo Methods	Assessment of the environmental impacts of the chemical components of vinyl chloride
Ghannadzadeh [48]	2018	Renewable Energy	Life Cycle Assessment, Environmental Impact Assessment, Monte Carlo Methods	Assessment of production process for rigid polyurethane synthesis
Huang et al. [87]	2018	Dianli Xitong Zidonghua/Automation of Electric Power Systems	Quantitative Analysis	Analysis and control of carbon market risk

Table A1. Cont.

Authors	Years	Source Title	Evaluation Method	Objective and Application Context
Li and Pye [88]	2018	Energy Research and Social Science	Quantitative Analysis	Experts assess uncertainties in UK energy transition
López Prol and Steininger [89]	2018	Progress in Photovoltaics: Research and Applications	Cost–Benefit Analysis	Calculation of the social profitability of the photovoltaic system in Germany
Maennel and Kim [90]	2018	Energies	Monte Carlo Methods	Assessment of the reduction of air pollutants produced by South Korea and Germany until 2030
Meschede et al. [91]	2018	Energy Conversion and Management	Cost–Benefit Analysis	Analysis of a 100% renewable subtropical island from the point of view of distribution
Meylan et al. [92]	2018	Waste Management	Life Cycle Assessment	Assessment of waste management systems
Mullally et al. [93]	2018	Environmental Science and Policy	Environmental Impact Assessment	Analysis of participation for the integration of environmental policy
Raoux et al. [25]	2018	Marine Policy	Environmental Impact Assessment	Analysis of alternative scenarios of how the ecosystem will be able to act in wind farms in Normandy
Shmelev and Shmeleva [94]	2018	Sustainable Development	Multiple Criteria Decision Analysis	Assessment of urban sustainability performance through indicators of 57 cities around the world
Skoczkowski et al. [95]	2018	Mitigation and Adaptation Strategies for Global Change	Environmental Impact Assessment	Estimation of the costs and benefits of power plants in Poland in the transition to a low-carbon economy
Torabi Moghadam et al. [96]	2018	Sustainable Cities and Society	Geographical Information System	Estimate of energy consumption of a large number of residential building stocks for space heating
Tronchin et al. [97]	2018	Energy	Regression Analysis OR Parametric Model	Test of an approach to link operational performance analytics with passive home design
Walker et al. [98]	2018	Applied Energy	Monte Carlo Methods, Sensitivity Analysis	Comparative analysis of solutions for aggregated residential prosumers in electricity markets
Wen et al. [99]	2018	Energy Procedia	Quantitative Analysis	Assessment of China’s energy sector transition strategy based on a dynamic simulation model
Zaman et al. [100]	2018	Energy Policy	Multiple Criteria Decision Analysis	Literature review of Bangladesh’s choices towards a sustainable policy
Zeyringer et al. [101]	2018	Renewable Energy	Quantitative Analysis, Sensitivity Analysis	Analysis of the potential contribution of marine energy in the UK from the point of view of energy systems
Zimmermann and Pye [102]	2018	Energy Policy	Environmental Impact Assessment	Assessing the impacts of decarbonization and what effects they have on UK energy and climate policies
Bódis et al. [103]	2019	Renewable and Sustainable Energy Reviews	Cost–Benefit Analysis	Geospatial methods to quantify the roof area to place photovoltaic systems

Table A1. Cont.

Authors	Years	Source Title	Evaluation Method	Objective and Application Context
Böing and Regett [104]	2019	Energies	Cost–Benefit Analysis	Analysis of CO ₂ emissions via multi-energy carriers
Burnley [105]	2019	Detritus	Life Cycle Assessment	Production of energy from waste
Camargo et al. [106]	2019	GeoScape	Geographical Information System	Estimation of the topology of Bavaria’s medium- and low-voltage networks
Cavalcanti et al. [107]	2019	Energy	Sensitivity Analysis	Analysis to quantify the environmental impacts associated with eucalyptus combustion
Coroiu [108]	2019	Proceedings of 2019 8th International Conference on Modern Power Systems, MPS 2019	Multiple Criteria Decision Analysis	Evaluation of the performance of energy efficiency solutions of service consumers
Correa-Florez et al. [109]	2019	Energies	Cost–Benefit Analysis, Monte Carlo Methods	Comparative analysis of solutions for aggregated residential prosumers in electricity markets
Costantini et al. [110]	2019	Eurasian Business Review	Preference Evaluation OR Econometrics	Evaluation of different sectors and their behavior in the introduction of new low-consumption technologies
Drouilles et al. [111]	2019	Energy Efficiency	Environmental Impact Assessment	Debate on the energy transition through residential areas in Switzerland
Ghannadzadeh and Meymivand [112]	2019	Clean Technologies and Environmental Policy	Life Cycle Assessment, Monte Carlo Methods	Evaluation of the ethylene oxide production process and solutions
Ghannadzadeh and Tarighaleslami [113]	2019	Environmental Progress and Sustainable Energy	Monte Carlo Methods, Life Cycle Assessment	Assessment of harmful materials in chlorine production
Jenniches and Worrell [114]	2019	Energy for Sustainable Development	Environmental Impact Assessment	Analysis of the benefits of photovoltaic systems in a German region
Jin et al. [115]	2019	Renewable and Sustainable Energy Reviews	Life Cycle Assessment	Estimation of water consumption of renewable energy
Leporini et al. [116]	2019	Renewable Energy	Life Cycle Assessment	A model for the reuse of oil and gas platforms
Marcucci et al. [117]	2019	Applied Energy	Monte Carlo Methods	Assessment of energy transition and climate change at the end of the century
Markov and Rajaković [118]	2019	Energy Conversion and Management	Sensitivity Analysis	Feasibility study in the direction of including significant impacts of the line rating and market conditions
Mohajeri et al. [119]	2019	Renewable Energy	Quantitative Analysis	Assessment of sustainable development scenarios for a Swiss village until 2050
Nitsch et al. [120]	2019	Energy, Sustainability and Society	Sensitivity Analysis	Estimation of land availability for wind energy

Table A1. Cont.

Authors	Years	Source Title	Evaluation Method	Objective and Application Context
Pedinotti-Castelle et al. [121]	2019	Renewable and Sustainable Energy Reviews	Life Cycle Cost	Cost efficiency assessment and sustainable technology solutions in the residential sector
Selvakkumaran and Ahlgren [122]	2019	Technology in Society	Quantitative Analysis	Study of the energy transition on household behavior
Stremke and Schöbel [123]	2019	Smart and Sustainable Built Environment	Environmental Impact Assessment, Multiple Criteria Decision Analysis	Presentation of a design method aimed at the energy transition
Thonemann and Maga [124]	2019	Sustainable Production, Life Cycle Engineering and Management	Life Cycle Assessment	Environmental analysis of different German energy scenarios
Watari et al. [125]	2019	Resources, Conservation and Recycling	Life Cycle Assessment	Saving mineral resources through the energy transition
Yang et al. [126]	2019	Nature Communications	Quantitative Analysis	Breakdown of energy transfer gap laws revealed by full-dimensional quantum scattering between hydrogen fluoride (HF) molecules
Yang et al. [127]	2019	Energy Procedia	Quantitative Analysis	Study of the average coal consumption rate in China and investments towards the energy transition
Yu et al. [128]	2019	Energy	Monte Carlo Methods, Sensitivity Analysis	Analysis of the reliability of the electrical system in Taiwan
Albers et al. [129]	2020	International Journal of Life Cycle Assessment	Life Cycle Assessment	Evaluation of the use of forest wood residues
Albers et al. [130]	2020	Science of the Total Environment	Sensitivity Analysis	Analysis of the impacts of organic carbon in the soil
Ameur et al. [39]	2020	Journal of Cleaner Production	Cost–Benefit Analysis	Evaluation of photovoltaic system performance
Atkins [131]	2020	Political Geography	Environmental Impact Assessment	Evaluation of the use and benefits of hydroelectric power against anti-dam movements
Banacloche et al. [44]	2020	Science of the Total Environment	Life Cycle Assessment	Sustainability assessment of a hybrid concentrated solar power and biomass plant
Braunholtz-Speight et al. [132]	2020	Nature Energy	Quantitative Analysis	Quantitative analysis of UK community energy project business models, funding mechanisms, and financial results
Brunet et al. [24]	2020	Sustainability (Switzerland)	Multiple Criteria Decision Analysis	Evaluation of a photovoltaic system in Madagascar
Cox et al. [46]	2020	Applied Energy	Life Cycle Assessment, Cost–Benefit Analysis, Sensitivity Analysis	Life cycle analysis and total costs of ownership of current and future vehicles
Dean et al. [133]	2020	International Journal of Greenhouse Gas Control	Cost–Benefit Analysis	Analysis of marine CO ₂ monitoring

Table A1. Cont.

Authors	Years	Source Title	Evaluation Method	Objective and Application Context
Ghannadzadeh and Tarighaleslami [42]	2020	Sustainable Energy Technologies and Assessments	Life Cycle Assessment	Assessment of sustainability in the production processes of glycerine
Harajli et al. [49]	2020	Energy Policy	Cost–Benefit Analysis	Integrated evaluation of hybrid solar–diesel systems for performance assessment
Höfer and Madlener [134]	2020	Energy Policy	Multiple Criteria Decision Analysis	Evaluation of the choices of different stakeholders on different energy transition scenarios
Hu et al. [135]	2020	Dianli Xitong Zidonghua/Automation of Electric Power Systems	Cost–Benefit Analysis, Sensitivity Analysis	Assessment of the effects of carbon on society and possible solutions
Jiang et al. [45]	2020	Renewable Energy	Life Cycle Assessment	Assessment of the benefits of pellet production in China
Kim et al. [136]	2020	Applied Energy	Regression Analysis OR Parametric Model	Analysis of public opinion change on the energy transition
Kokkinos et al. [137]	2020	Science of the Total Environment	Quantitative Analysis	Energy transition supported by Fuzzy cognitive map modeling
Middelhaue et al. [138]	2020	ECOS 2020—Proceedings of the 33rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems	Multiple Criteria Decision Analysis	Evaluation of key performance indicators on building energy system planning
Miranda et al. [139]	2020	Energies	Sensitivity Analysis	Evaluation of the development of geothermal energy in regions of North America
Muñoz et al. [140]	2020	Energy Strategy Reviews	Geographical Information System	Assessment of the energy performance of cities and future scenarios
Nechifor et al. [141]	2020	World Development	Environmental Impact Assessment	Assessment of steel reuse to support a circular economy in China
Paltsev [142]	2020	Economics of Energy and Environmental Policy	Quantitative Analysis	Quantitative analysis of the decision-making risks associated with different energy paths
Partidário et al. [143]	2020	International Journal of Hydrogen Energy	Life Cycle Assessment, Sensitivity Analysis	Analysis and cost assessments of the hydrogen economy approach
Patouillard et al. [144]	2020	International Journal of Life Cycle Assessment	Life Cycle Assessment, Sensitivity Analysis, Quantitative Analysis	Difference between Consequential Life Cycle Assessment (C-LCA) and LCA
Raugei et al. [145]	2020	Energies	Life Cycle Assessment	Assessment of greenhouse gas emissions and reduction of non-renewable energy through the use of home storage batteries in California

Table A1. Cont.

Authors	Years	Source Title	Evaluation Method	Objective and Application Context
Rohe [146]	2020	Environmental Innovation and Societal Transitions	Geographical Information System	Analysis of wind energy rooted in the national and global territory
Sareen and Grandin [147]	2020	Geografiska Annaler, Series B: Human Geography	Preference evaluation OR econometrics	Oslo 2019 and Lisbon 2020 European Green Capital (EGC) Winners Ratings
Saretta et al. [148]	2020	Sustainable Cities and Society	Geographical Information System	GIS integration for urban retrofit estimation
Seck et al. [149]	2020	Resources, Conservation and Recycling	Life Cycle Assessment	Assessment of the impact of copper availability on the energy transition
Sharma et al. [150]	2020	Environmental Innovation and Societal Transitions	Multiple Criteria Decision Analysis, Sensitivity Analysis	Analysis of decarbonization scenarios in Ireland
Shaw-Williams and Susilawati [151]	2020	Applied Energy	Monte Carlo Methods	Virtual network measurement assessment to address social equity in the energy transition for Australia's community housing sector
Taherahmadi et al. [152]	2020	International Journal of Sustainable Energy	Life Cycle Assessment	Comprehensive definition of zero energy building
Tarighaleslami et al. [43]	2020	Journal of Cleaner Production	Monte Carlo Methods, Life Cycle Assessment	Assessment for a cheese production plant
Vellini et al. [38]	2020	Journal of Cleaner Production	Cost–Benefit Analysis, Sensitivity Analysis	Quantification of the economic burden associated with the reduction of direct CO ₂ emissions
Wang et al. [153]	2020	Energy	Cost–Benefit Analysis, Environmental Impact Assessment	Cost–benefit analysis on different domestic energy use options
Wei et al. [154]	2020	China Economic Review	Preference Evaluation OR Econometrics, Quantitative Analysis	Presentation of energy demand progress in China
Wen et al. [155]	2020	International Journal of Electrical Power and Energy Systems	Quantitative Analysis	Quantitative analysis of the energy transition in China and future hypothetical scenarios
Wiehe et al. [156]	2020	International Journal of Energy Research	Geographical Information System	Presentation of a geospatial model that calculates the potential of renewable energies and their influence on society
Yan et al. [157]	2020	IEEE Sensors Journal	Neural Network	Proposal for an ultrasonic method for the inspection of gas pipelines

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