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# Economic evaluation methodologies for Renewable Energy Communities and the architectural heritage. A literature review

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**Abstract**

This review aims to provide a general framework of the literature on economic sustainability and financial feasibility for RECs, focusing on the challenges related to the building stock and architectural heritage energy retrofit with the purpose of reducing running costs.
In particular, this review analysed 95 research papers, focusing on the main used economic evaluation approaches and indicators for the assessment of a new or an existing REC.
Results showed that the implementation of RECs deserves to be examined with a combination of complementary approaches able to guarantee a balance between economically sustainable and renewable energy systems and the buildings' cultural, architectural and historical values. The articles data sample of the present research highlighted the presence of numerous methodologies and approaches that need to be combined to evaluate all the aspects of the RECs.
Future research could develop a comprehensive methodological approach to evaluate the RECs' economic sustainability by considering economic, energy and social benefits and preserving the buildings' cultural value.
This review draws a state-of-the-art of economic approaches and indicators for RECs to support the future developments of a standardized evaluation procedure in the context of the currently evolving regulatory framework.

## 1. Introduction

Renewable Energy Communities (RECs) have gained prominence, aiming to empower citizens and communities to actively participate in the transition to clean energy sources (Sikora, 2021). These communities - also known as "energy cooperatives", "smart energies communities" or "green energy communities" - are grassroots initiatives (community-based approaches created to address localized problems) that emancipate residents to take an active role in producing, consuming, and managing renewable energy resources (Bovera & Lo Schiavo, 2022; Cirrincione et al., 2020).

RECs aim to promote clean, sustainable, and decentralized energy production and consumption. They encourage individuals, companies, and public and private subjects to collaborate and invest in generating electricity.  Energy is typically generated from sources such as solar, wind, hydro, geothermal, or biomass. within a specific geographic area. RECs could provide a pathway toward sustainable energy systems by actively involving individuals and communities in transitioning to clean energy sources.

In fact, by fostering energy self-sufficiency, RECs contribute to reduce carbon emissions, enhance energy security, and foster local economic development (Italian Government Resolution n. 727/2022/R/eel).

Energy communities are driving EU's energy transition since 2019 through the recognition of the important role of local actors and citizens in producing renewable energy; according to European Commission RECs could take diverse legal entities (association, cooperative, non-profit organization or a limited liability company) (Energy Community Repository, 2023) to jointly invest in energy assets. By increasing the number of RECs, the decarbonization of the built heritage could be more accessible and easier for private citizens.

In 2020, Italy introduced the initial transitional regulations for RECs through Article 42-bis of Act n°8/2020 (revised with Legislative Decree n. 199/2021). The regulatory framework establishes rights and enabling structures, with current support schemes exclusively reserved for RECs. Despite the established regulatory framework, the development of energy communities has been relatively limited in Italy until 2021 when the number of grants and fundings has supported the constitution of new RECs in the Italian territory.

Establishing a REC goes beyond merely deploying renewable energy as it should imply, as an essential step, a deep evaluation to assess the REC's economic feasibility, cost-effectiveness, long-term viability, and social benefits. In this regard, besides environmental advantages, RECs are able to produce both social and economic benefits (Ceglia, Marrasso, Samanta, et al., 2022) as they could create local jobs, boost regional economies, and provide affordable and sustainable energy options for community members (Kaiser et al., 2022).
However, their successful implementation necessitates to face the challenge of the building stock energy retrofit and to demonstrate the economic sustainability by ensuring long-term viability from a life cycle perspective (Fregonara & Ferrando, 2018, 2020).

Besides, in some contexts RECs can play a significant role in improving the energy performance of the building stock and the architectural heritage by integrating renewable energy sources, reducing reliance on fossil fuels and fostering energy transition as well as new opportunities for the enhancement of the abandoned heritage (Mazzarella, 2015).

The call for Positive Energy Districts (PEDs) (Joint Call for Proposals / MICall 21: Positive Energy Districts and Neighbourhoods for Climate Neutrality, 2021) has boosted the sustainable urbanization by highlighting the importance of a collective energy transition process that is not limited the single building but it is aimed at transforming the neighborhoods. From 2018 PEDs try to involve a large number of stakeholders to cooperate and co-product knowledge and energy as key actions towards climate neutrality.

Moreover, the Agenda 2050 calls for sustainable urban planning that integrates and protects the architectural heritage within cities (COM, 2022; European Commission, 2022; Silander, 2022). Historic buildings and architectural heritage are essential components of a nation's identity and cultural heritage as they reflect past generations' history, traditions, and craftsmanship (CENGİZ & YANMAZ, 2019; Presidente della Repubblica, 2004). Therefore, preserving and enhancing these assets should be a priority to maintain a sense of continuity and cultural identity. This involves striking a balance between urban development and preserving architectural heritage to create sustainable, more liveable and vibrant urban environments (Barreca et al., 2020; Rolando et al., 2022).

In this regard, the implementation of renewable energy systems must be carefully considered to ensure a harmonious coexistence (Pane, 2008) between sustainable new interventions and the preservation of architectural heritage by adopting innovative and tailored design and engineering solutions (Baggio et al., 2017; Gremmelspacher et al., 2021).

Currently, the absence of mandatory procedures for the economic and financial assessment of RECs has given rise to of different multidisciplinary methods conceived by professionals and researchers.

This review aims to provide a general framework of the literature on RECs' economic sustainability and financial feasibility, focusing on the challenges related to the building stock and architectural heritage energy retrofit. Therefore, the economic evaluation discipline could suggest approaches and methods related to RECs capable of considering various components, including the initial investment required for infrastructure development, ongoing operational costs, potential revenue streams from energy sales, potential savings in energy cost, financial risks, and the overall economic (positive or negative) impacts on the community (Felice et al., 2021).

The present review presents the data sampling process in Section 2. The results are illustrated in Section 3 and highlight the publications typology and the applied economic evaluation methods, focusing on the architectural heritage issues; lastly, Section 4 draws the conclusions.

## 2. Methodological approach

The methodological approach was based on a systematic data sampling process, based on the leading international databases shared by scientific communities (Scopus, Web of Science), accessed from November 2022 to April 2024. Articles, books, and other types of non-indexed publications were selected to set a complete analysis of the assessment methods published and researched.
At the start of the research, the review intends to evaluate economic sustainability to support REC's feasibility with particular attention to historic buildings and architectural heritage. For this reason, three main topics were considered for the initial set of queries: economic feasibility, economic assessment, and heritage.

The search algorithm (and selection criteria) used to construct the initial set of papers consisted of a combination of 9 differentiated terms (see Query Strings in Fig. 1) connected by the Boolean operators AND and OR. Additionally, the results were further refined by selecting articles falling under the categories "Engineering", "Mathematics", "Business, Financial and Management" and "Decision Process" thus achieving the initial set of papers of 236 articles. Different queries were built by integrating the primary topic of interest («*renewable energy communit**») with economic evaluation and financial issues ("*assess**", "*benefit**", "*enhance**", "cash*", "income*"); at the same time the query "*renewable energy communit* AND "heritage*" did not yield any results highlighting a huge gap in the literature. To further ensure the relevance and quality of the dataset, only peer-reviewed journal articles written in English and explicitly addressing economic or financial aspects of RECs were retained. Contributions not aligned with the defined scope, as well as duplicates and non-academic sources, were systematically excluded during the filtering process.

To ensure the quality and reliability of the data, specific exclusion criteria (like the relevance to the review's scope and the articles' aim) were implemented to filter the results, and only peer-reviewed articles were included in the preliminary set of manuscripts. For example, several articles were found on the use of renewable energy sources in fields unrelated to architecture (such as electric vehicles, biofuels, etc.), which were excluded as they were not relevant to the research topic. A final reading and critical analysis of the dataset was conducted on the 149 filtered articles to define the review's focus better and confirm the ultimate database.

At the end of the filtering procedure, some new fields were added (Type, Cases Country, Author Country, Energy Source, Econometric method, Applied indicators) to analyze the different trends of the research.The critical analysis of the bibliography through VosViewer software (VOSviewer - Visualizing Scientific Landscapes, release 1.6.18, https://www.vosviewer.com//) has allowed to find authors' keywords clusters to implement the categorisation and the organisation of the final dataset.

Lastly, the review has provided a final database of 95 articles highlighting insights into economic assessment methods relevant to RECs, shedding light on their application in different contexts.

## 3. Results

### 3.1 Overview of the results

The final data sample (Appendix, Table A1) consisted of 95 research papers concerning different topics (Fig. 2) related the economic sustainability of RECs. Table A1 provides a detailed overview

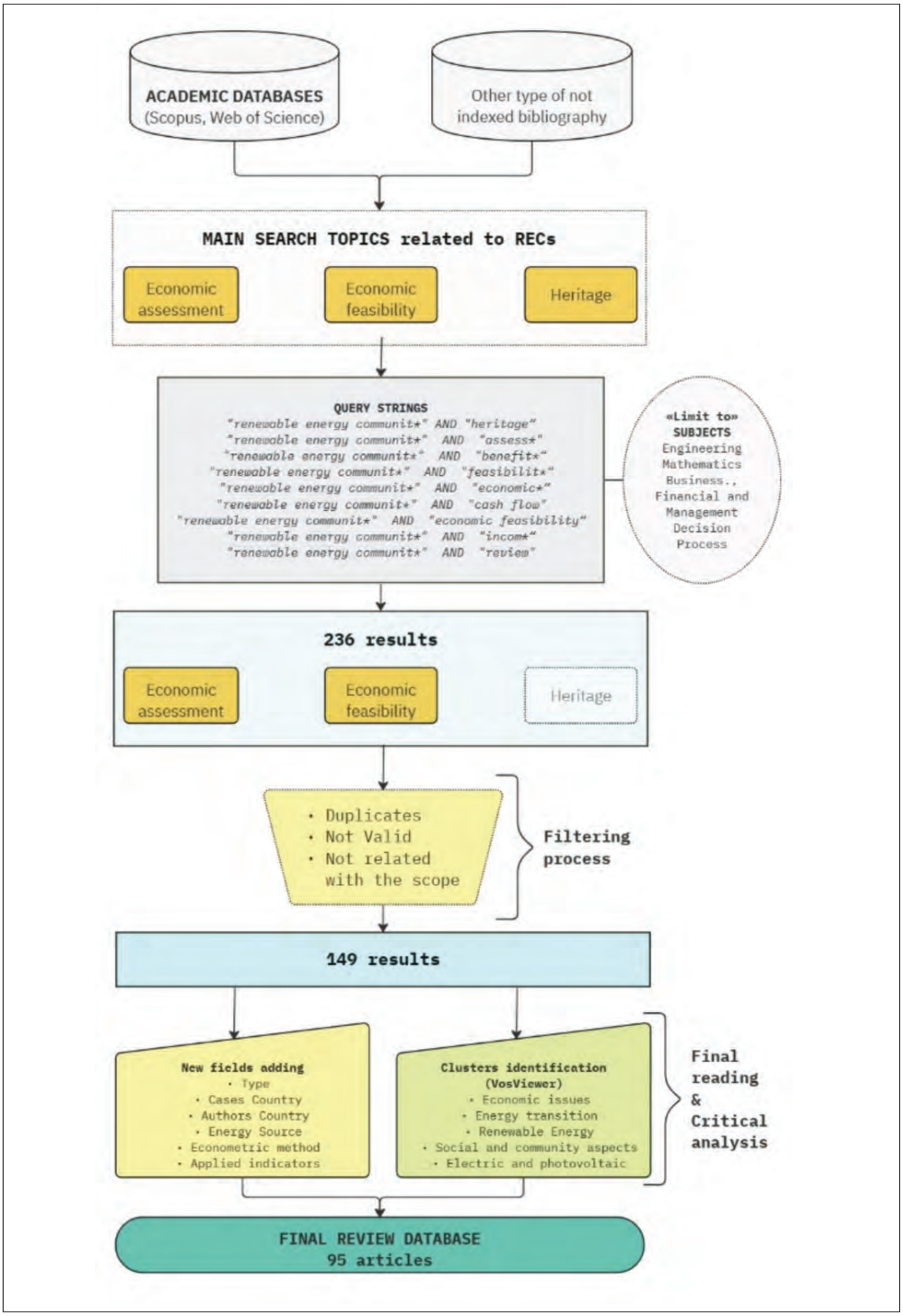


**Figure 1.** Flowchart of the methodological approach. (Source: Authors' elaboration).

of selected scientific contributions, classified according to key criteria for the analysis of RECs, including: study typology, main objective, indicators used, energy source, geographic context, economic methodology adopted, and year of publication. From a chronological perspective, a significant increase in publications over the past five years can be observed, indicating a growing interest in RECs as key instruments for sustainable energy transition. However, the methodological fragmentation identified—particularly in economic and evaluation approaches—points to the urgent need for more integrated analytical frameworks that combine economic, social, and environmental dimensions.

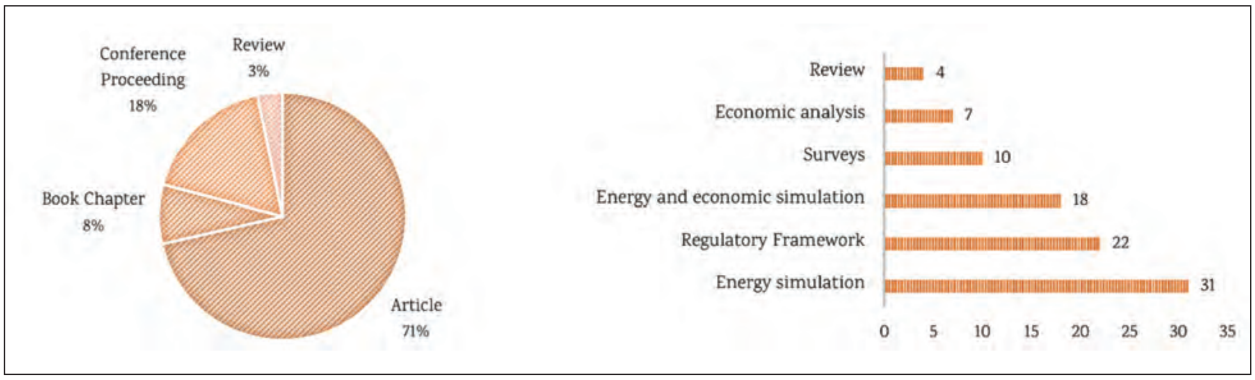


**Figure 2.** Articles types (a) and main topics (b) in the data sample. (Source: Authors' elaboration).

The distribution indicates a strong interest in energy simulation and frameworks for analysis, while social aspects are less represented in the present research overview.

Many articles (22) dealt with "Regulatory framework" since the main focus is related to legislative issues, regulations and standards (see for example Adu-Kankam & Camarinha-Matos, 2022; Biresselioglu et al., 2021; D'Alpaos & Andreolli, 2021; Spasova & Braungardt, 2021, 2022; Trevisan et al., 2023). Only four papers are literature reviews, where authors summarize and critically analyze existing researches.

Many papers (18) implied energy and economic simulation techniques to explore the interactions between energy-related factors and their economic implications, such as incentives (see for example Caramanico et al., 2021). The majority of articles (31) were focused on energy simulation, which represents a prominent area of research investigating energy systems, technologies, processes, and energy simulation models and software (see for example Khosravi et al., 2018; Liobikienė & Dagiliūtė, 2021; Lowitzsch, 2019; Qu et al., 2021; Spigliantini et al., 2017; Tomin et al., 2022).

Other papers (7) were specifically focused on the analysis of economic aspects, such as costs (Afzali et al., 2023; Ceglia et al., 2023; Robertson et al., 2020), benefits, market trends, and financial impacts (Fina, Monsberger, et al., 2022; Kyriakopoulos, 2022). On the other hand, researchers seem partially interested in examining the broader impacts of projects, policies, or technologies by considering both social and economic factors (see for example Dóci, 2021; Dóci & Gotchev, 2016; Kaiser et al., 2022; Ubelmesser et al., 2022).

Lastly, only one paper explored the social implications and impacts of energy-sustainable behaviour or policies by performing a sociological analysis (Wuebben & Peters, 2022), while three papers were based on survey research aimed at investigating insights and opinions on specific topics from population involved into a REC (Coenen & Hoppe, 2022; Gomez et al., 2022; Rakowska et al., 2022).

Contextually with the preliminary analyses of the data sample, some elaborations with VOSviewer software (accessed April-July 2023) were performed in order to check the presence of possible theme clusters by the association of authors' keywords. Despite the great polarity of the keyword "Renewable Energy Communit*," which is the main focus of all publications.

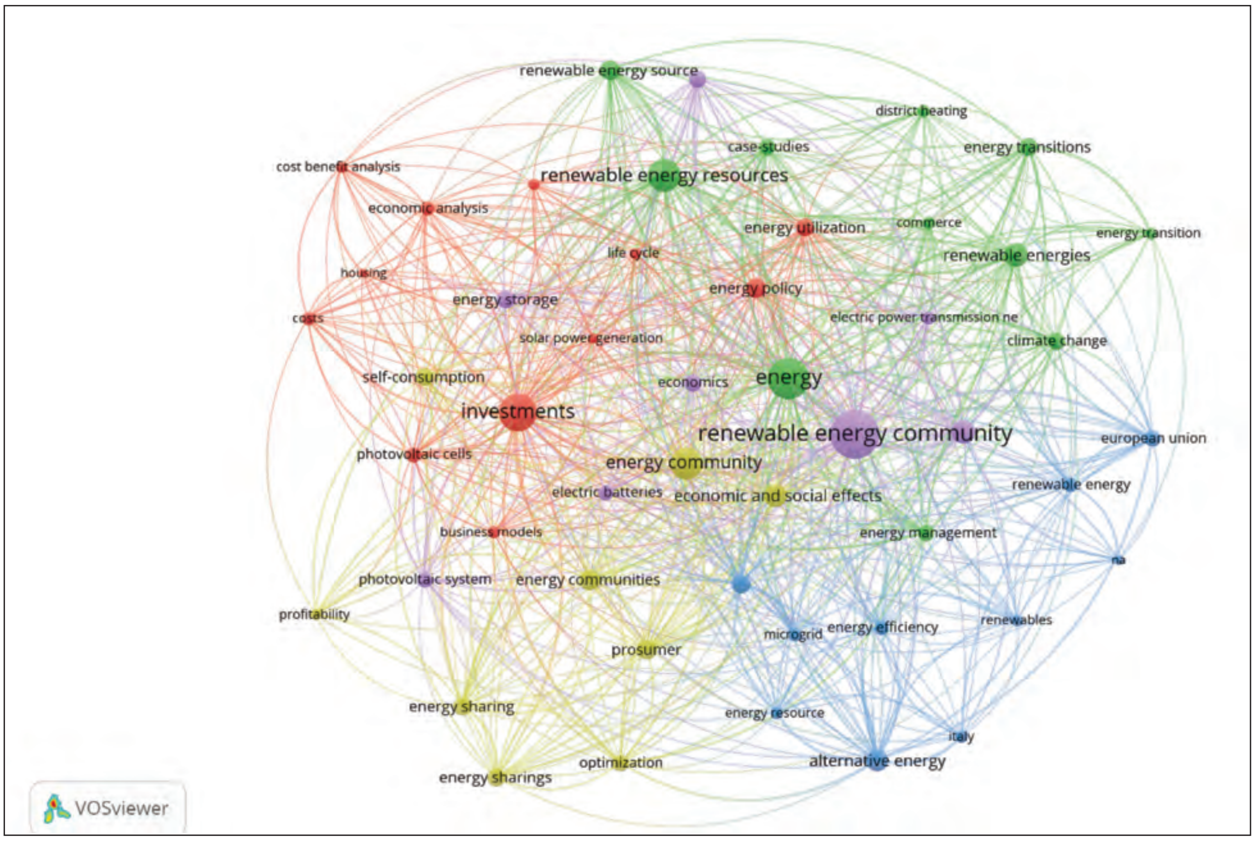


**Figure 3.** Bibliography map of the data sample (95 items). (Source: Authors' elaboration on VosViewer software).

The result of the bibliography map (Fig. 3) showed five potential clusters connecting the authors' keywords of 50 papers (of the total sample of 95):

1. The first cluster (RED "Economic issues", 12 items) connected research papers or publications that primarily delved into economic aspects of energy and other relevant topics, such as cost analysis, economic implications of energy policies, and financial impacts of energy projects (Carreras & Steinmaurer, 2022; Ceglia et al., 2023; Ceglia, Marrasso, Roselli, et al., 2022; Felice et al., 2021; Fina, Schwebler, et al., 2022; Fina & Auer, 2020; Gomez et al., 2022; Kyriakopoulos, 2022; Mutani et al., 2021; Napoli et al., 2022; Petrichenko et al., 2022; Viti et al., 2020).
2. The second cluster (GREEN – "Energy transition", 11 items) dealt with researches related to the transition from conventional energy sources to more sustainable and renewable alternatives. It covered topics such as the integration of clean energy technologies, policy frameworks for energy transition, and the challenges of transitioning to a low-carbon economy (Adu-Kankam & Camarinha-Matos, 2022; Carreras & Steinmaurer, 2022; D'Alpaos & Andreolli, 2021; Fina, Schwebler, et al., 2022; Kyriakopoulos, 2022).
3. The third cluster (BLUE "Renewable energy", 10 items), focused on research papers concerning various aspects of renewable energy sources, such as solar, wind, hydro, geothermal, and other renewable energy technologies, their implementation, efficiency, and potential environmental impacts (Khan, 2016; Moncecchi et al., 2020).
4. The fourth cluster (YELLOW "Social and community aspects", 9 items) highlighted researches that examined social and community implications of energy-related activities, policies and topics such as community engagement in energy projects, social acceptance of renewable energy technologies, and the impact of energy policies on vulnerable populations(Dóci, 2021; Dóci & Gotchev, 2016; Gjorgievski et al., 2021; Kaiser et al., 2022;

Liobikienė & Dagiliūtė, 2021; Ubelmesser et al., 2022; Wicki et al., 2022).

5. The fifth cluster (PURPLE "Electric and photovoltaic", 8 items) focused on researches related to electric power systems, photovoltaic (solar energy) technologies and issues related to power grid integration, photovoltaic efficiency, energy storage solutions, and advancements in solar energy generation (Barbour et al., 2018; Conte et al., 2022; Pitt & Nolden, 2020; Secchi et al., 2021; Wicki et al., 2022).

It should be noted that the bibliographic analysis through VosViewer has not identified clusters related to architectural heritage; this fact confirms the absence of interest in the buildings in the context of RECs' research.

Furthermore, the analysis of the renewable energy sources dealt with in the articles (Fig. 4) highlighted that more than half of the researches considered solar energy (53%). This fact could also be explained by the localization of the case studies in the Mediterranean area. However, it should be noted that solar energy technologies have advanced significantly over the years, making it an increasingly viable and cost-effective option to meet different energy needs.

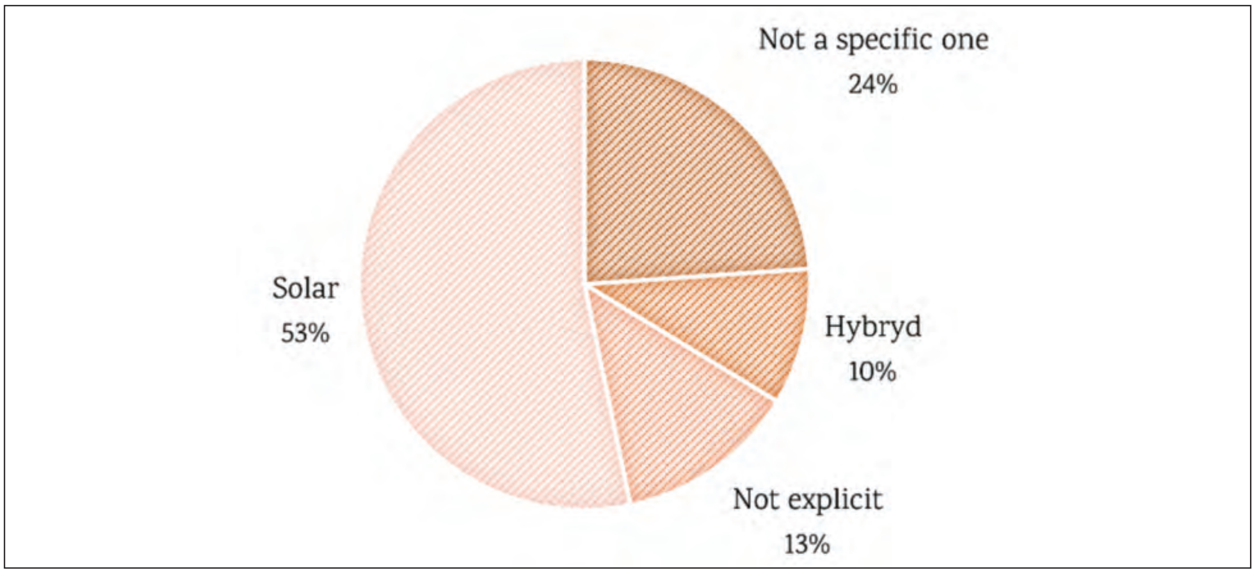


**Figure 4.** Renewable energy source the data sample. (Source: Authors' elaboration).

A particular attention was paid to studies focused on hybrid systems (10%), based on the combination of two or more renewable sources such as wind and solar energy or hydrogen and solar. This energy mix helps to reduce dependency on a single energy source, making the community more resilient to fluctuations in weather conditions or resource availability. In very few cases (1%), hybrid systems refer to heat pumps and biomass production(Ceglia, Marrasso, Roselli, et al., 2022).

It is relevant to note that many not-applicative papers do not specify the renewable energy source (24%) as some simulations of fictitious cases do not make explicit the energy source (13%) (Conte et al., 2022; Pastore et al., 2022).

### 3.2 Economic approaches and their applications

The present paragraph presents an overview of different approaches that have been applied to evaluate the economic sustainability and feasibility for RECs projects. It is worth mentioning that some classic economic evaluation methods - like Discounted Cash Flow Analysis (Benaroch & Kauffman, 1999; Majd & Pindyck, 1987) and Life Cycle Costing (Fregonara, 2017; Fregonara et al., 2017, 2018) were only partially applied in the researches on the topic.

Figure 5a shows that in only 45 articles an economic approach was applied; the different economic approaches applied in the paper's data sample are specified in Figure 5b.

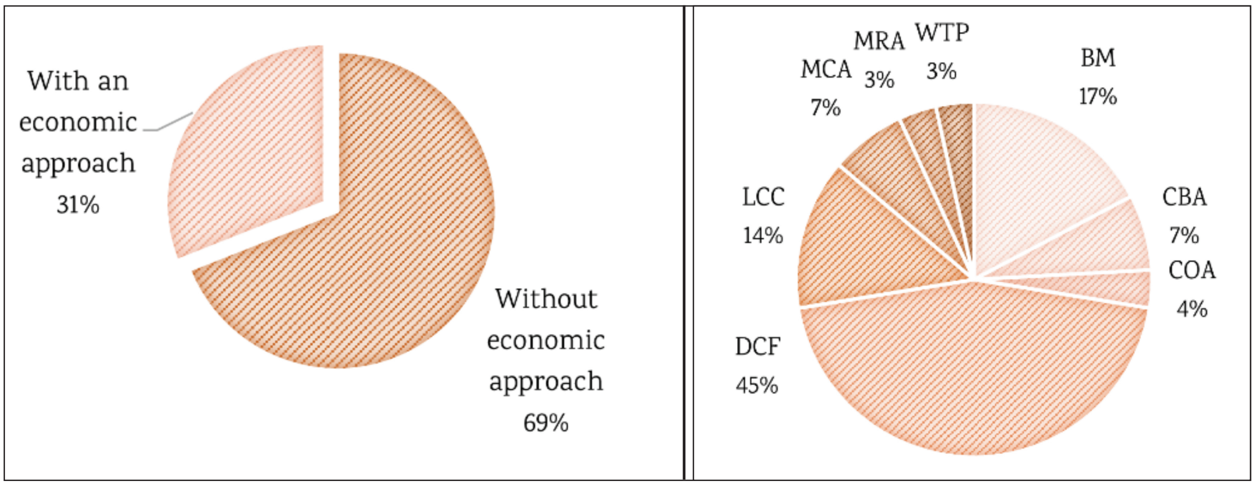


**Figure 5.** Economic approaches applied in the analysed papers. Source: authors' elaboration.

*3.2.1 Discounted Cash Flow Analysis*

The most commonly applied approach to evaluate the economic feasibility of RECs was the Discounted Cash Flow Analysis (DCFA, 45%) applied by performing the calculation of Net Present Value (NPV) and the Internal Rate of Revenues (IRR).

(Mutani et al., 2021) evaluated the energy performance of the REC by using two key indexes: self-consumption and self-sufficiency, with the addition of a cost-optimal analysis (Becchio et al., 2016) to assess the economic feasibility of the REC by considering investment costs and economic incentives to compare and analyze potential REC scenarios. The proposed flexible methodology was applied during the design phase of RECs, to identify the optimal configuration that maximizes revenue from incentives and enhances energy independence. The results of the study demonstrated that REC initiatives offer advantages by keeping stakeholders together, as well as ensuring both economic benefits and positive environmental impacts.

In recent research (Ceglia, Marrasso, Roselli, et al., 2022) presented a model for analyzing and optimizing energy systems to assess the economic feasibility of a REC in Tirano (Northern Italy). The study identified the technical features of energy conversion systems and explored different scenarios by considering the economic value of cogeneration operating modes, photovoltaic penetration, and thermal energy. The economic analysis showed a simple Payback Time (PBT) of... and the NPV of around 12 and 13 million Euros for cogeneration operating at full power, suggesting the economic viability of wood-biomass-based energy systems. Another case in Italy is studied by (Moncecchi et al., 2020) who powered a methodology to optimize the production of a REC portfolio by taking into account the various energy sources available to its members, their unique energy requirements, and associated tariffs to introduce a model for the assessment of energy flows among members to understand optimal investments. The best solution that maximizes the NPV of the investment was achieved using a genetic algorithm.

The NPV calculation was also performed by Viti et al. (2020), who simulated various economic scenarios to understand which scheme would best facilitate the integration of REC into the National energy market. The results demonstrated that collective prosumer behaviour can lead to more rapid adoption of building-integrated renewable energy sources (RES); moreover, the self-consumption of electricity within the REC can generate significant savings on energy bills, resulting in positive economic performance indicators across all analyzed scenarios.

Another application in the Italian context was performed by Napoli et al. (2022), who applied a methodology designed to assess the economic viability of various green areas as passive energy measures for both public and private stakeholders. The multidisciplinary approach integrated microclimatic and comfort level analysis and evaluated the energy needs of a house sample. The economic feasibility was verified across different scenarios and from the various public and private investors viewpoint, highlighting that the economic viability for specific stakeholders can be achieved during the management phase if suitable incentives, equivalent to the planting cost, are provided.

The NPV calculation was also included in both theoretical and empirical studies by Chaudhry et al. (2022b, 2022a) which aimed to analyze the technical aspects of collective prosumership by examining energy flow through consumption and generation profiles. The economic impacts, from both consumers' and investors' perspectives, were calculated considering the annual cost of energy consumption and the NPV of the investment, that is enclosed in the proposed key performance indicators (KPIs), was introduced to interpret and compare simulation results, aligning them with the objectives of stakeholders within the REC.

### *3.2.2 Business model*

Several papers that face economic feasibility in the context of REC applied business models (Casalicchio et al., 2022; Lowitzsch, 2019; Moreno et al., 2022; Pitt & Nolden, 2020).
Lowitzsch (2019) presented consumer stock ownership plans (CSOPs) as a business model for RECs. This research analysed 67 cases from 18 countries by highlighting the need for flexible business models to attract diverse co-investors. CSOPs promote scalable investments in utilities, attracting different kinds of stakeholders (municipalities, small and medium-sized enterprises, plant engineers, and energy suppliers as co-investors) to ensure RECs' acceptance in energy markets.

An alternative use of the business model was proposed by Casalicchio et al. (2022) who applied this approach as a tool to fairly allocate benefits among the participants in a REC in Bolzano (Italy). Additionally, a Fairness Index was introduced to compare different business models based on their distribution of benefits. The results of this approach led to a more appropriate and fair distribution of benefits, ensuring that all participants could receive the fairest economic return for their involvement.

### *3.2.3 Life Cycle Costing and Life Cycle Assessment*

In the context of this research, the core economic approach to evaluate the financial viability of renewable energy projects undertaken to establish RECs is the Life Cycle Costing (LCC), which was adopted in several researches ("Assessment of the Cost of Various Renewable Energy Systems to Provide Power for a Small Community: Case of Bukha, Oman," 2018; Caramanico et al., 2021; Mohseni & Brent, 2022; Nguyen et al., 2017; Shadmand et al., 2011). LCC supports the analysis of total costs and benefits (Fregonara, 2020) associated with renewable energy projects over its lifespan, helping community members to be aware of their investment and ensuring the long-term sustainability and economic viability of the community-led initiatives.

Caramanico et al. (2021) focused on a comprehensive study that combined a Life Cycle Assessment (LCA) of a fuel cell-photovoltaic hybrid micro-cogeneration system for residential buildings with a detailed economic analysis. The investigation employed simple financial indicators, namely Net Present Cost and Payback Period, to assess the viability of two investment options based on different energy sources that have in common a base scenario from the perspective of a homeowner. The proposed model was aimed to optimize the energy mix by minimizing life cycle impacts and costs while maximizing renewable contributions and energy savings; the model was applied by using binary integer and continuous variables in a CPLEX environment. Results showed its effectiveness in identifying the best strategies with minimal deviations from desired goals.

Another kind of LCC model was presented by (Shadmand et al., 2011) who performed an optimization tool for analyzing the feasibility of a hybrid wind-photovoltaic power system to meet the load requirements in a grid-tied apartment complex. A techno-economic approach was applied to identify the most reliable energy supply with the lowest investment. Results indicated that the optimal solution consists of most of the load covered by photovoltaic panels and the remaining by wind turbines. The indicators for the analysis were Payback Time, Levelized Cost of Energy (LCOE) with net metering, and considerations of federal incentives to assess comprehensive costs for owners.

The most recent research with life cycle implications is carried out by Elomari et al. (2024) for a residential REC in Terragona (Spain) including 100 buildings. Through a programming language that includes a machine learning algorithm, the application of LCC and LCA is performed to maximize the green energy use: the final scenario is achieved by the fulfilment of a multi-criteria decision-making approach to choose the best configuration for the REC.

### *3.2.4 Multi-Criteria Decision Analysis*

Other papers applied Multi-Criteria Decision Analysis (MCDA) to RECs to compare different economic indicators and to evaluate targets' preferences (Tomin et al., 2022; Torabi Moghadam et al., 2020).

To implement the Community-Scale Optimization (CSOP) model, (Torabi Moghadam et al., 2020) applied a methodological approach that comprises three main phases: the identification and description of selected buildings, then the preliminary feasibility analysis and lastly the target group involvement. The CSOP model was first applied in two pilot regions (Czech Republic and Poland) and then it was applied on a case study in Susa Valley (Italy). The best scenario was identified with the preference ranking organization method for enrichment evaluation (PROMETHEE) methodology by comparing KPIs and sensitivity analysis.

### *3.2.5 Cost-Benefit Analysis*

Wuebben and Peters (2022) used Cost-Benefit Analysis (CBA) to assess the environmental, economic and social worth of RECs in promoting "solar prosumerism" through a mixed methods approach. First, seven home solar installers' installation proposals were analyzed using multimodal discourse analysis and they revealed accurate financial advantages but inappropriate social as well as environmental benefits. Furthermore, the study compared the computed efficiencies of proposed solar installations with four different PVSC solar arrays by employing actual load and generation profiles. Findings showed that the high fluctuation in household demand has a significant impact on self-consumption rate and profitability. It was shown that minute-by-minute time series can reveal hidden added value as well as social profits that are often overlooked when estimating homes solar potentials.

A classical application of the CBA was proposed by (Mutani et al., 2021) in the context of Villar Pellice (Italy) by investigating the hourly energy consumption and local renewable energy production. Some indexes (like self-sufficiency and self-consumption index) were proposed to facilitate the evaluation; a cost-optimal analysis was performed in parallel to evaluate the economic feasibility through investment costs and economic incentives. Results showed the assurance of different kinds of benefits for RECs like cooperation between stakeholders, economic and environmental advantages, and social implications.

### *3.2.6 Multiple Regression Analyses*

Multiple Regression Analyses (MRAs) are statistical methods that were applied with forecasting purposes in the 3% of the analysed papers. (Cabarcos et al., 2020) measured the predisposition to participate or invest in RECs in a survey conducted in Galicia, considering factors such as gender, income capital, and trust and cooperation. Authors used MRA and Principal Component Analysis (PCA) to evaluate demographic indicators (gender, age, education level) and socio-psychological characteristics to determine Willingness To Pay (WTP) and potential involvement in RECs.

Similarly, the WTP was combined with MRA by Liobikienė & Dagiliūtė (2021) by examining the influence of three key factors for green energy in Lithuania: environmental outcomes, the country's development level, and social pressure. The MRA's results indicated that environmental concern had a negative and insignificant direct impact on the WTP more for green energy.

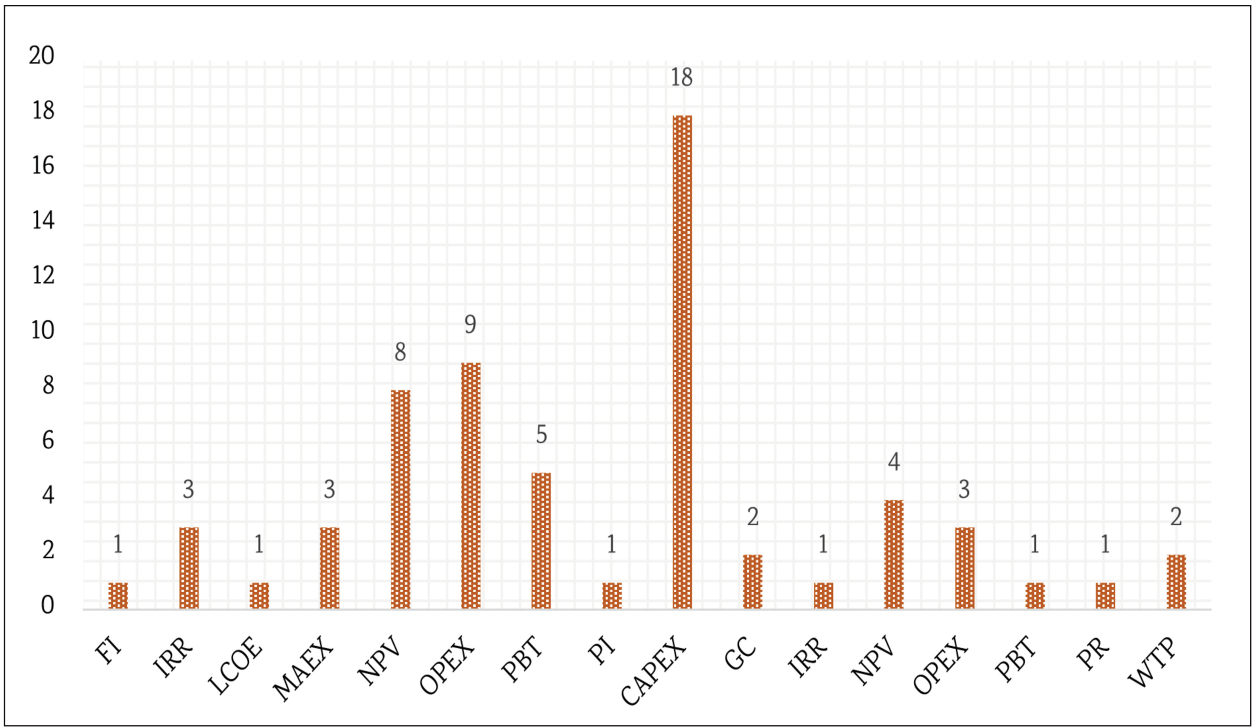


**Figure 6.** Economic indicators used in the analysed papers (Source: Authors' elaboration).

### 3.2.7 *Economic indicator-based analyses*

The principal economic indicators used in the analysed papers are illustrated in Fig. 6.

In many energy simulations the Capital Expenditures (CAPEX) and Operating Expenditures (OPEX) indicators were widely analysed; the CAPEX indicator represents the initial investment in a project, and it was used in 18 researches, as the most popular indicator (Chaudhry et al., 2022b, 2022a; Khosravi et al., 2018; Pastore et al., 2022; Tomin et al., 2022). Besides, the OPEX refers to the ongoing costs of operating and maintaining an energy project, and it was used in 9 researches ((Ancona et al., 2022; Caramanico et al., 2021; Casalicchio et al., 2022; Cielo et al., 2021; Cutore et al., 2023; Ji et al., 2022; Khosravi et al., 2018; Li & Okur, 2023; Viti et al., 2020)), even combined with the Capital and Maintenance Expenditures (MAEX) indicator.

The three classical indicators for the assessment of an investment's profitability were used in several researchers: NPV (Net Present Value) appeared in 8 papers, IRR (Internal Rate of return) in 3 papers, while PBP (PayBack Period) in 8 papers. NPV represents the present value of future cash flows minus the initial investment. IRR is the discount rate at which the net present value becomes zero, while NPV represents the necessary time period for an investment to recoup its initial cost through the generated cash flows or savings.

Moreover, the WTP was applied in 2 papers to understand how much individuals were willing to pay for green energy: two applications are found in the papers (Ceglia, Marrasso, Samanta, et al., 2022; Liobikienė & Dagiliūtė, 2021).

The GC (Generation Cost) indicator was used in other 2 researches to measure the cost of generating energy (Mutani et al., 2021; Mutani & Usta, 2022).

Casalicchio et al. (2022) used the FI (Fairness Index) for benefit and investments assessment to equally redistribute the benefits obtained from the REC. Another indicator, LCOE (Levelized Cost of Energy), FI was used by Tomin et al. (2022) to calculate the average cost of producing each unit of energy over the lifetime of a project.

It is worth mentioning other two indicators: the PI (Profitability Index), that was used by Moncecchi et al. (2020) to calculate the ratio between the present value benefits and the present value costs; and the PR (Perceived Risk), that was used by Dóci & Gotchev (2016) to assess the time required for an investment to recover its initial costs.

**Table 1.** Synthetic overview of the main economic approaches (Source: Author's elaboration based on the literature review database)

| | Application Domains | Advantages | Limitations |
|---|---|---|---|
| Discounted Cash Flow Analysis (DCFA) | Economic feasibility studies; investment analysis; optimization of REC configurations | Widely recognized; enables clear evaluation of NPV, IRR, and payback time; supports cost-optimal REC configuration | May oversimplify complex scenarios; sensitive to input assumptions; lacks social dimension |
| Business Model | Fairness assessment; stakeholder engagement; investment structure definition | Allows fair benefit distribution; supports investment strategies; flexible for stakeholders | Requires clear governance and stakeholder involvement; fairness subjective |
| Life Cycle Costing (LCC) & Life Cycle Assessment (LCA) | Techno-economic studies; hybrid system evaluation; long-term sustainability planning | Captures total costs and benefits across project lifecycle; supports sustainability analysis; useful for long-term planning | Data intensive; complex implementation; requires long-term projections |
| Multi-Criteria Decision Analysis (MCDA) | Scenario analysis; stakeholder preference integration; pilot studies | Considers multiple objectives and stakeholder preferences; helps in ranking alternatives and making strategic decisions | Requires subjective judgment for weighting; complexity increases with criteria |
| Cost-Benefit Analysis (CBA) | Prosumer models; social-environmental impact evaluations; incentive assessment | Includes environmental, economic and social benefits; facilitates in-depth, holistic assessments | Relies on accurate valuation of non-monetary benefits; often context-dependent |
| Multiple Regression Analysis (MRA) | Willingness to pay studies; socio-demographic influence evaluations | Captures behavioral and demographic factors; helps in estimating WTP and participation likelihood | Correlation does not imply causation; requires robust data for reliability |
| Economic Indicator-based Analysis | Financial performance tracking; comparative project analysis; cost modeling | Standardized and versatile; facilitates comparison across projects; captures key financial metrics like CAPEX, OPEX, NPV | May not reflect intangible benefits or stakeholder preferences; requires comprehensive data |

Table 1 provides a synthetic overview of the principal economic approaches used to assess the feasibility and sustainability of RECs. DCFA emerges as the most widely applied approach, primarily due to its ability to quantify investment profitability through standard financial indicators such as NPV and IRR. However, it often lacks integration with social and environmental dimensions. In contrast, Business Model approaches prioritize equitable benefit distribution and stakeholder engagement, facilitating co-investment and long-term collaboration. LCA and LCC extend the analytical scope by capturing both economic and environmental impacts over a project's lifespan, making them particularly suitable for long-term strategic planning.

MCDA introduces a more holistic evaluation by incorporating stakeholder preferences and qualitative factors, although it may be constrained by methodological complexity and subjectivity. CBA adds value by integrating social and environmental externalities, yet its outcomes often depend heavily on context-specific assumptions.

Meanwhile, statistical techniques such as MRA contribute insights into socio-behavioral factors affecting REC participation, offering a more granular understanding of user engagement. Lastly, indicator-based analyses provide a versatile framework for comparing project performances through standardized economic metrics, though they may overlook non-financial drivers of success.

### 3.3 REC and architectural heritage: opportunity or risk?

In the context of RECs, architectural heritage and renewable sources have the potential to create a harmonious blend (Rosa, 2020b, 2020a) of sustainable energy practices and cultural preservation. By integrating renewable energy technologies into historic buildings and architectural heritage, it is possible to achieve a dual purpose: reducing carbon emissions and preserving buildings' cultural, architectural and historical values. This integration requires a delicate balance between the functional requirements of renewable energy systems, the architectural heritage's aesthetic and the structural integrity protection (Castellani et al., 2018; Franco et al., 2015; Rosa, 2020a).

One of the key challenges in incorporating renewable sources into architectural heritage is ensuring minimal visual impact (Rosa, 2020a). Historic buildings often have unique architectural features, shapes and technological elements that contribute to their cultural significance and forms landscapes that define national cultural identity (Presidente della Repubblica, 2004). Any modifications or additions, such as solar panels or wind turbines, must be carefully designed and integrated to be compatible with the existing aesthetics and not compromise the buildings' architectural value. As Mazzarella, (2015) promoted, the most effective approach to harmonize the relationship between energy retrofit and architectural heritage protection is closely monitoring the development and implementation of legal acts by informing administrations (like the Italian Superintendency) and sharing information with them.

Solar energy is one of the most used renewable sources for the architectural heritage retrofit: panels can be integrated into rooftops or façades, allowing the building to generate clean electricity (Rosa, 2020a). Other innovative design techniques, such as building-integrated photovoltaics (BIPV), enable solar panels to be seamlessly incorporated into building materials such as glass or tiles (Biyik et al., 2017; Kuhn et al., 2021; Martín-Chivelet et al., 2022; Polo et al., 2022). This approach not only harnesses solar energy but also preserves the structure's architectural integrity.

Similarly, wind energy can be harnessed in areas with sufficient wind resources without compromising architectural heritage (Xydis et al., 2022). Hydroelectric power also offers opportunities particularly for structures near rivers or bodies of water (Filho & Feitosa, 2022; Hommes, 2019; Punys et al., 2019). Moreover, geothermal energy systems can be discreetly installed beneath the ground: geothermal heat pumps can provide efficient heating and cooling while reducing the reliance on traditional fossil fuel-based systems (Miller, 2020; Pisello et al., 2014).

The European Commission has implemented various measures to decrease the buildings energy consumption: three significant directives, namely Directive 2002/91/EC, Directive 2010/31/EU and Directive 2018/844/EU (EPBD I, II, III), have played key roles in this effort.

The initial directive primarily emphasized methodologies for new buildings, while the second placed greater emphasis on existing buildings and the third introduced the concept of "high efficiency alternative systems" and the respect of the building heritage. Also in relation with the Green Deal the focus includes not only significant renovations but also retrofitting or replacement of existing building technical elements and systems in a long life-span (Ciulla et al., 2016; Galatioto et al., 2017; Mazzarella, 2015; Piselli et al., 2020). The main concern lies in the preservation and protection of historic buildings that are not yet listed in the official protection registry and so in case of total renovation and energy retrofit are at risk of total transformation and loss of their identity characteristics.

## 4. Conclusion

The path towards the implementation of RECs able to guarantee a economically sustainable energy retrofit of architectural heritage represents the current challenge of balancing the requirements of renewable energy systems with the buildings' cultural, architectural and historical values.

This paper explored the relationship between renewable energy technologies, architectural heritage, and economic sustainability by analysing 95 papers.

The first results showed poor literature with few case studies related to historic buildings, hence the present review draws an overview of the economic methods linked to the designing and modelling a REC with the integration of papers related to architectural heritage and energy efficiency measures to enhance and preserve it.

Another important focus is dedicated to energy and economic simulations that are present in the majority of publications related to RECs: in the most of cases the energy simulation is related to an economic analysis to calculate the cost of initial investment and the possible incentives and impacts due to the REC. The analysed literature confirms that DCF is the most applied approach to evaluate the economic feasibility of a REC, despite some assessment use only few single indicators to streamline the analyses.

A critical comparison of the economic approaches reviewed reveals that no single method can fully capture the complexity of RECs, especially when heritage buildings are involved. While DCFA offers clear, quantitative insights, it may overlook fairness, environmental impacts, and social dynamics. Conversely, business models and MCDA allow for more inclusive, stakeholder-driven strategies but require high levels of coordination and methodological clarity. LCC and LCA demonstrate strong potential for holistic evaluation but demand extensive data and long-term forecasting. This diversity suggests that future methodologies should strive toward hybrid and adaptive frameworks, capable of combining technical rigor, economic robustness, and cultural sensitivity. Future research should aim to develop integrated, adaptable economic evaluation models that align with conservation constraints and support inclusive stakeholder participation. Furthermore, the findings presented in this review offer practical insights for policymakers and sector professionals, providing a comparative foundation to develop more effective regulatory strategies, financial instruments, and operational models tailored to the integration of RECs in heritage contexts.

Findings revealed that RECs have emerged as a viable pathway to foster buildings' energy retrofit without compromising the irreplaceable cultural value of architectural heritage. Integrating renewable energy technologies into historical buildings requires careful consideration of architectural preservation, aesthetics, and societal significance (Mazzarella, 2015). Successful case (Baggio et al., 2017; CENGİZ & YANMAZ, 2019; Gremmelspacher et al., 2021) demonstrated that with meticulous planning, innovative solutions, and community engagement, the implementation of renewable energy projects can not only retain the charm of historical structures but also serve as beacons of sustainable progress.

Economic evaluation emerges as a critical aspect in realizing the potential of RECs in historical areas (Franco et al., 2015). By establishing robust methodologies to assess financial feasibility, return on investment, and long-term benefits, stakeholders can confidently pursue renewable energy projects with a holistic understanding of their economic implications (Nguyen et al., 2017; Qu et al., 2021). A plenty of advanced data-driven techniques have been applied to provide more accurate cost and risk assessments, facilitating more informed decision-making processes. Moreover, this review highlighted the need of public policies, regulatory frameworks, and financial incentives to foster the adoption of renewable energy solutions while safeguarding architectural heritage (Mazzarella, 2015). Robust public-private partnerships could be instrumental in driving RECs forward, bringing together diverse expertise to manage the complex interaction between economic, cultural, and environmental factors.

In conclusion, preserving architectural heritage and integrating renewable energy sources requires collaboration between architects, conservationists, engineers, and local communities (Battista et al., 2022; Guo et al., 2021); it involves conducting thorough assessments of the site's energy needs, exploring suitable renewable technologies, and ensuring compliance with heritage conservation guidelines and regulations (Ascione et al., 2011; Jaggs & Palmer, 2000; Pane, 2008).

**Authors' constribution**

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## Appendix

**Table A1.** Final data sample (Authors' elaboration).

| ID | Authors | Typology | Category | Indicators | Energy Source | Country | Economic Methods | Year |
|---|---|---|---|---|---|---|---|---|
| 1 | Dóci G., Gotchev B. | Socio-economic analysis | Social | PR | Solar | Netherlands | NO | 2016 |
| 2 | Khan S.S. | Framework | Energy | NO | Solar | NO | NO | 2016 |
| 3 | Kirchhoff H., Kebir N., Neumann K., Heller P.W., Strunz K. | Energy simulation | Energy | NO | Solar | Germany | NO | 2016 |
| 4 | Barbour E., Parra D., Awwad Z., González M.C. | Energy simulation | Energy | NO | Solar | United States | NO | 2018 |
| 5 | Boretti A., Al-Zubaidy S. | Energy simulation | Energy | NO | Solar | Spain | NO | 2018 |
| 6 | Khosravi A., Koury R.N.N., Machado L., Pabon J.J.G. | Energy and economic simulation | Economic | CAPEX, OPEX | Hybrid | Iran | LCC | 2018 |
| 7 | Azarova V., Cohen J., Friedl C., Reichl J. | Economic analysis | Economic | WTP | ALL | Various | NO | 2019 |
| 8 | Boulaire F., Narimani A., Bell J., Drogemuller R., Vine D., Buys L., Walker G. | Energy simulation | Energy | NO | Solar | Australia | NO | 2019 |
| 9 | Lowitzsch J. | Economic analysis | Economic | NO | ALL | NO | BM | 2019 |
| 10 | Svetec E., Nad L., Pasicko R., Pavlin B. | Framework | Energy | NO | NO | Croatia | NO | 2019 |
| 11 | Balashova S., Ratner S., Gomonov K., Berezin A. | Energy simulation | Energy | NO | Solar | Russia | NO | 2020 |
| 12 | Cabarcos M.Á.L., Castro N.R., Viña V.M. | Economic analysis | Economic | WTP | Solar | Spain | MRA | 2020 |
| 13 | Hanke F., Lowitzsch J. | Framework | Energy | NO | NO | NO | NO | 2020 |
| 14 | He W., Wang G., Pan C. | Energy simulation | Energy | NPV, IRR | Solar | China | NO | 2020 |
| 15 | Lowitzsch J., Hoicka C.E., van Tulder F.J. | Framework | Energy | NO | ALL | NO | NO | 2020 |
| 16 | Moncecchi M., Meneghello S., Merlo M. | Energy and economic simulation | Economic | CAPEX, OPEX, NPV, PBT, PI | Solar | Italy | DCF | 2020 |
| 17 | Pitt J., Nolden C. | Economic analysis | Economic | NO | Solar | UK | BM | 2020 |
| 18 | Rocha R., Collado J.V., Soares T., Retorta F. | Framework | Energy | NO | NO | NO | NO | 2020 |
| 19 | Torabi Moghadam S., Di Nicoli M.V., Manzo S., Lombardi P. | Energy and economic simulation | Economic | CAPEX, OPEX, PBT | Solar | Italy | MCA | 2020 |
| 20 | Ugwoke B., Adeleke A., Corgnati S.P., Pearce J.M., Leone P. | Energy simulation | Energy | NO | Solar | Nigeria | NO | 2020 |
| 21 | Viti S., Lanzini A., Minuto F.D., Caldera M., Borchiellini R. | Framework | Economic | NPV,IRR | Solar | Italy | DCF | 2020 |

Follow **Table A1.** Final data sample (Authors' elaboration)

| ID | Authors | Typology | Category | Indicators | Energy Source | Country | Economic Methods | Year |
|---|---|---|---|---|---|---|---|---|
| 22 | Xue Y., Temeljotov-Salaj A., Engebø A., Lohne J. | Review | Energy | NO | NO | Various | NO | 2020 |
| 23 | Yüksel S., Dinçer H., Uluer G.S. | Framework | Energy | NO | ALL | Various | NO | 2020 |
| 24 | Biresselioglu M.E., Limoncuoglu S.A., Demir M.H., Reichl J., Burgstaller K., Sciullo A., Ferrero E. | Framework | Energy | NO | ALL | Various | NO | 2021 |
| 25 | Boulanger S.O.M., Massari M., Longo D., Turillazzi B., Nucci C.A. | Framework | Energy | NO | NO | No | NO | 2021 |
| 26 | Caramanico N., Di Florio G., Baratto M.C., Cigolotti V., Basosi R., Busi E. | Economic analysis | Economic | CAPEX, OPEX, NPV, PBT | Hybrid | Italy | DCF | 2021 |
| 27 | Ceglia F., Marrasso E., Roselli C., Sasso M. | Energy simulation | Energy | NO | Solar | Italy | NO | 2021 |
| 28 | Cielo A., Margiaria P., Lazzeroni P., Mariuzzo I., Repetto M. | Energy and economic simulation | Economic | OPEX, CAPEX, MAEX, NPV, IRR | Solar | Italy | DCF | 2021 |
| 29 | D'Alpaos C., Andreolli F. | Framework | | NO | NO | NO | NO | 2021 |
| 30 | Dawoud S.M. | Energy simulation | Energy | NO | Hybrid | Egypt | NO | 2021 |
| 31 | Dóci G. | Socio-economic analysis | | NO | ALL | Germany, Netherlands | NO | 2021 |
| 32 | Felice A., Rakocevic L., Peeters L., Messagie M., Coosemans T., Camargo L.R. | Energy simulation | Energy | NO | Solar | Belgium | DCF | 2021 |
| 33 | Fina B., Roberts M.B., Auer H., Bruce A., MacGill I. | Energy simulation | | NO | Solar | Austria | NO | 2021 |
| 34 | Grignani A., Gozzellino M., Sciullo A., Padovan D. | Framework | | NO | NO | Italy | NO | 2021 |
| 35 | Koirala B., Hers S., Morales-España G., Özdemir Ö., Sijm J., Weeda M. | Framework | | NO | ALL | Germany | NO | 2021 |
| 36 | Kojonsaari A.-R., Palm J. | Framework | | NO | ALL | NO | NO | 2021 |
| 37 | Koltunov M., Bisello A. | Framework | | NO | ALL | NO | NO | 2021 |
| 38 | Kumar A., Singh A.R., Meena N.K., Deng Y., He X., Kumar P., Bansal R.C. | Framework | | NO | Solar | NO | NO | 2021 |
| 39 | Liobikienė G., Dagiliūtė R. | Socio-economic analysis | Social | NO | ALL | Lithuania | WTP | 2021 |
| 40 | Mutani G., Santantonio S., Beltramino S. | Energy and economic simulation | Economic | GC | Solar | Italy | CBA | 2021 |

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| ID | Authors | Typology | Category | Indicators | Energy Source | Country | Economic Methods | Year |
|---|---|---|---|---|---|---|---|---|
| 41 | Mutani G., Todeschi V. | Energy and economic simulation | Economic | GC | Solar | Italy | COA | 2021 |
| 42 | Rossi F., Heleno M., Basosi R., Sinicropi A. | Energy simulation | Energy | NO | Solar | Italy | NO | 2021 |
| 43 | Secchi M., Barchi G., Macii D., Moser D., Petri D. | Energy simulation | Energy | NO | Solar | Italy | NO | 2021 |
| 44 | Sforzini M., Nicita G., Pastore L., Lo Basso G., de Santoli L. | Energy Simulation | Energy | NO | Hybrid | Italy | NO | 2021 |
| 45 | Spasova D., Braungardt S. | Framework | Energy | NO | ALL | Germany | NO | 2021 |
| 46 | Todeschi V., Marocco P., Mutani G., Lanzini A., Santarelli M. | Energy simulation | Energy | NO | Solar | Italy | NO | 2021 |
| 47 | Adu-Kankam K.O., Camarinha-Matos L.M. | Framework | Energy | NO | ALL | NO | NO | 2022 |
| 48 | Agostinelli S., Neshat M., Majidi Nezhad M., Piras G., Astiaso Garcia D. | Energy simulation | Energy | NO | Hybrid | Italy | NO | 2022 |
| 49 | Ali A., Fakhar M.S., Kashif S.A.R., Abbas G., Khan I.A., Rasool A., Ullah N. | Energy and economic simulation | Economic | CAPEX, PBT | Hybrid | Pakistan | DCF | 2022 |
| 50 | Ancona M.A., Baldi F., Branchini L., De Pascale A., Gianaroli F., Melino F., Ricci M. | Energy simulation | Economic | CAPEX, OPEX, NPV | Solar | Italy | DCF | 2022 |
| 51 | Barberi A., Dio V.D., Pietra B.D., Favuzza S., Galluzzo M., Massaro F., Musca R., Zizzo G. | Energy simulation | Energy | NO | Solar | Italy | NO | 2022 |
| 52 | Boche A., Foucher C., Villa L.F.L. | Review | Energy | NO | NO | NO | NO | 2022 |
| 53 | Bula I., Syla F., Kopacek P., Hajrizi E., Bula E. | Energy simulation | Energy | NO | Solar | Kosovo | NO | 2022 |
| 54 | Casalicchio V., Manzolini G., Prina M.G., Moser D. | Energy and economic simulation | Economic | OPEX, CAPEX, FI | Solar | Italy | BM | 2022 |
| 55 | Ceglia F., Marrasso E., Samanta S., Sasso M. | Energy simulation | Energy | NO | Solar | Italy | NO | 2022 |
| 56 | Chaudhry S., Surmann A., Kühnbach M., Pierie F. | Energy and economic simulation | Economic | CAPEX, NPV | Solar | NO | DCF | 2022 |
| 57 | Chaudhry S., Surmann A., Kühnbach M., Pierie F. | Energy and economic simulation | Economic | CAPEX, NPV | Solar | Germany | DCF | 2022 |
| 58 | Coenen F.H.J.M., Hoppe T. | Survey | Energy | NO | NO | NO | NO | 2022 |
| 59 | Conte F., Mosaico G., Natrella G., Saviozzi M., Bianchi F.R. | Energy simulation | Energy | NO | Solar | Fictitious/Not Specified | NO | 2022 |

Follow **Table A1.** Final data sample (Authors' elaboration)

| ID | Authors | Typology | Category | Indicators | Energy Source | Country | Economic Methods | Year |
|---|---|---|---|---|---|---|---|---|
| 60 | De Lotto R., Micciché C., Venco E.M., Bonaiti A., De Napoli R. | Framework | | NO | NO | Italy | NO | 2022 |
| 61 | Eichman J., Torrecillas Castelló M., Corchero C. | Review | | NO | ALL | Spain | NO | 2022 |
| 62 | Fina B., Monsberger C., Auer H. | Energy simulation | Energy | NO | Solar | Fictitious/Not Specified | DCF | 2022 |
| 63 | Fina B., Monsberger C., Auer H. | Energy simulation | Energy | NO | Solar | Austria | NO | 2022 |
| 64 | Fouladvand J., Ghorbani A., Sarı Y., Hoppe T., Kunneke R., Herder P. | Energy simulation | | NO | Solar | NO | NO | 2022 |
| 65 | Gomez A., Tyl B., Pottier A. | Survey | | NO | ALL | France | NO | 2022 |
| 66 | Ji L., Wu Y., Liu Y., Sun L., Xie Y., Huang G. | Energy and economic simulation | Economic | CAPEX, OPEX, MAEX | Hybrid | China | LCC | 2022 |
| 67 | Kaiser S., Oliveira M., Vassillo C., Orlandini G., Zucaro A. | Socio-economic analysis | Social | NO | Solar | Italy | NO | 2022 |
| 68 | Lage M., Castro R. | Review | Energy | NO | Solar | Portugal | NO | 2022 |
| 69 | Lo Basso G., Pastore L.M., de Santoli L. | Energy and economic simulation | Economic | CAPEX | Hybrid | Italy | LCC | 2022 |
| 70 | Macarthur J.L., Hoicka C.E., Das R.R. | Framework | | NO | ALL | NO | NO | 2022 |
| 71 | Maione A., Massarotti N., Santagata R., Vanoli L. | Energy simulation | | NO | ALL | Italy | NO | 2022 |
| 72 | Marić L.L., Keko H., Delimar M. | Energy simulation | | NO | Solar | Croatia | NO | 2022 |
| 73 | Minai A.F., Usmani T., Alotaibi M.A., Malik H., Nassar M.E. | Energy simulation | | NO | | NO | NO | 2022 |
| 74 | Minuto F.D., Lanzini A. | Energy and economic simulation | Economic | CAPEX,OPEX, NPV | Solar | Fictitious/Not Specified | BM | 2022 |
| 75 | Moreno A., Villar J., Gouveia C.S., Mello J., Rocha R. | Economic analysis | Economic | NO | ALL | Spain | BM | 2022 |
| 76 | Napoli G., Corrao R., Scaccianoce G., Barbaro S., Cirrincione L. | Energy and economic simulation | Economic | NPV, IRR | Solar | Italy | DCF | 2022 |
| 77 | Pastore L.M., Lo Basso G., Quarta M.N., de Santoli L. | Energy simulation | | NO | ALL | Fictitious/Not Specified | NO | 2022 |
| 78 | Popescu M.-F., Constantin M., Chiripuci B.C. | Framework | Energy | NO | ALL | Various | NO | 2022 |
| 79 | Queiroz H., Amaral Lopes R., Martins J., Fialho L., Bravo Dias J., Bilo N. | Energy simulation | Energy | NO | Solar | Portugal | NO | 2022 |
| 80 | Quirosa G., Torres M., Soltero V.M., Chacartegui R. | Energy simulation | | NO | Solar | Spain | NO | 2022 |

Follow **Table A1.** Final data sample (Authors' elaboration)

| ID | Authors | Typology | Category | Indicators | Energy Source | Country | Economic Methods | Year |
|---|---|---|---|---|---|---|---|---|
| 81 | Rakowska J., Maciejczak M., Batyk I.M., Farelnik E. | Survey | Social | NO | Solar | Poland | NO | 2022 |
| 82 | Robinson D., del Guayo I. | Framework | | NO | ALL | Spain | NO | 2022 |
| 83 | Spasova D., Braungardt S. | Framework | | NO | NO | NO | NO | 2022 |
| 84 | Teske F., Funk F., Fehrle A., Franke J. | Energy simulation | | NO | NO | NO | NO | 2022 |
| 85 | Tomin N., Shakirov V., Kurbatsky V., Muzychuk R., Popova E., Sidorov D., Kozlov A., Yang D. | Energy and economic simulation | Economic | CAPEX, LCOE | Hybrid | Japan | MCA | 2022 |
| 86 | Ubelmesser L., Klingert S., Becker C. | Socio-economic analysis | Social | NO | ALL | NO | NO | 2022 |
| 87 | Wicki L., Pietrzykowski R., Kusz D. | Socio-economic analysis | Social | NO | Solar | Poland | NO | 2022 |
| 88 | Wuebben D., Peters J.F. | Energy and economic simulation | Economic | NPV | Solar | Spain | CBA | 2022 |
| 89 | Zwickl-Bernhard S., Auer H., Golab A. | Energy and economic simulation | Economic | CAPEX, OPEX, NPV | Solar | Austria | DCF | 2022 |
| 90 | Cutore E., Volpe R., Sgroi R., Fichera A. | Energy and economic simulation | Economic | CAPEX, OPEX, Total installation | Solar | Italy | DCF | 2023 |
| 91 | Li N., Okur Ö. | Economic analysis | Economic | CAPEX, OPEX, | Solar | Fictitious/Not Specified | LCC | 2023 |
| 92 | Roy A., Olivier J.-C., Auger F., Auvity B., Bourguet S., Schaeffer E. | Social and energy analysis | Energy | PBT | ALL | France | NO | 2023 |
| 93 | Battaglia V.; Vanoli L.; Zagni M. | Energy and economic simulation | Energy | NPV | Geothermal | Italy | DCF | 2023 |
| 94 | Elomari Y.; Mateu C.; Marín-Genescà M.; Boer D. | Energy and economic simulation | Economic | NPV | Solar | Spain | LCC | 2024 |
| 95 | Buonomano A.; Giuzio G.F.; Maka R.; Palombo A.; Russo G. | Energy simulation | Economic | PBP | Other | Fictitious/Not Specified | LCC | 2024 |

# Metodologie di valutazione economica per le Comunità Energetiche Rinnovabili e il patrimonio architettonico. Una review della letteratura

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**Parole chiave**

Valutazione economica, sostenibilità economica, comunità energetiche rinnovabili, patrimonio edilizio, patrimonio architettonico

**Abstract**

La presente review mira a fornire un quadro generale della letteratura sulla sostenibilità economica e sulla fattibilità finanziaria nell'ambito delle Comunità Energetiche Rinnovabili (CER), concentrandosi sulle sfide relative alla riqualificazione energetica del patrimonio edilizio e architettonico con l'obiettivo di ridurre i costi di gestione.

In particolare, sono stati analizzati 95 articoli scientifici, esaminando i principali approcci e indicatori di valutazione economica utilizzati per l'analisi di una CER, nuova o esistente.

I risultati hanno mostrato che l'attuazione delle CER merita di essere esaminata attraverso una combinazione di approcci complementari, in grado di garantire un equilibrio tra sistemi energetici rinnovabili ed economicamente sostenibili e i valori culturali, architettonici e storici degli edifici. Il campione degli articoli selezionati evidenzia la presenza di numerose metodologie e approcci che necessitano di essere integrati per valutare tutti gli aspetti delle CER.

Le future ricerche potrebbero sviluppare un approccio metodologico completo per valutare la sostenibilità economica delle CER, considerando benefici economici, energetici e sociali e al contempo preservando il valore culturale degli edifici.

La review propone quindi uno stato dell'arte degli approcci economici e degli indicatori utilizzati per le CER, al fine di supportare lo sviluppo futuro di una procedura di valutazione standardizzata nel contesto del quadro regolamentativo attualmente in evoluzione.

## 1. Introduzione

Le Comunità Energetiche Rinnovabili (CER) hanno acquisito crescente rilevanza, con l'obiettivo di responsabilizzare cittadini e comunità affinché partecipino attivamente alla transizione verso fonti energetiche pulite (Sikora, 2021). Queste comunità – note anche come «cooperative energetiche», «comunità energetiche intelligenti» o «comunità energetiche verdi» – rappresentano iniziative dal basso (approcci basati sulla comunità creati per affrontare problematiche locali), che consentono ai residenti di assumere un ruolo attivo nella produzione, nel consumo e nella gestione delle risorse energetiche rinnovabili (Bovera & Lo Schiavo, 2022; Cirrincione et al., 2020).

Le CER mirano a promuovere una produzione e un consumo energetico pulito, sostenibile e decentralizzato. Esse incentivano individui, aziende, soggetti pubblici e privati a collaborare e investire nella generazione di elettricità. L'energia viene tipicamente prodotta da fonti quali solare, eolica, idroelettrica, geotermica o biomassa, all'interno di un'area geografica specifica. Le CER possono costituire un percorso verso sistemi energetici sostenibili, coinvolgendo attivamente individui e comunità nella transizione verso fonti rinnovabili.

In effetti, promuovendo l'autosufficienza energetica, le CER contribuiscono a ridurre le emissioni di carbonio, aumentare la sicurezza energetica e favorire lo sviluppo economico locale (Delibera del Governo Italiano n. 727/2022/R/eel).

Dal 2019, le comunità energetiche stanno guidando la transizione energetica dell'UE, grazie al riconoscimento dell'importante ruolo degli attori locali e dei cittadini nella produzione di energia rinnovabile; secondo la Commissione Europea, le CER possono assumere diverse forme giuridiche (associazione, cooperativa, organizzazione senza scopo di lucro o società a responsabilità limitata) (Energy Community Repository, 2023) per investire congiuntamente in asset energetici. L'aumento del numero delle CER potrebbe rendere più accessibile e semplice per i cittadini privati la decarbonizzazione del patrimonio edilizio.

Nel 2020, l'Italia ha introdotto la normativa transitoria iniziale per le CER tramite l'articolo 42-bis della Legge n°8/2020 (modificato successivamente con il Decreto Legislativo n. 199/2021). Il quadro normativo definisce diritti e strumenti abilitanti, con regimi di sostegno attualmente riservati esclusivamente alle CER. Nonostante ciò, fino al 2021 lo sviluppo delle comunità energetiche in Italia è stato piuttosto limitato, finché l'erogazione di finanziamenti e contributi non ha favorito la costituzione di nuove CER sul territorio nazionale.

Costituire una CER non significa semplicemente implementare energia rinnovabile: richiede un'attenta valutazione della fattibilità economica, dell'efficacia dei costi, della sostenibilità a lungo termine e dei benefici sociali. In questo senso, oltre ai vantaggi ambientali, le CER possono generare benefici economici e sociali (Ceglia, Marrasso, Samanta, et al., 2022), creando occupazione locale, stimolando le economie regionali e fornendo energia sostenibile e a costi accessibili per i membri della comunità (Kaiser et al., 2022).

Tuttavia, per una loro efficace implementazione, è necessario affrontare la sfida della riqualificazione energetica del patrimonio edilizio e dimostrare la sostenibilità economica, garantendo la fattibilità a lungo termine secondo una prospettiva di ciclo di vita (Fregonara & Ferrando, 2018, 2020).

Inoltre, in determinati contesti, le CER possono svolgere un ruolo significativo nel migliorare la prestazione energetica del patrimonio edilizio e architettonico, integrando fonti di energia rinnovabile, riducendo la dipendenza dai combustibili fossili e favorendo la transizione energetica, oltre a rappresentare nuove opportunità per la valorizzazione del patrimonio abbandonato (Mazzarella, 2015).

Il bando per i *Positive Energy Districts* (PEDs) (*Joint Call for Proposals* / MICall 21: Positive Energy Districts and Neighbourhoods for Climate Neutrality, 2021) ha incentivato l'urbanizzazione sostenibile, sottolineando l'importanza di un processo collettivo di transizione energetica che superi la scala del singolo edificio e trasformi interi quartieri. A partire dal 2018, i PEDs cercano di coinvolgere un ampio numero di stakeholder per cooperare e co-produrre conoscenza ed energia, come azioni fondamentali verso la neutralità climatica.

Inoltre, l'Agenda 2050 promuove una pianificazione urbana sostenibile che integri e tuteli il patrimonio architettonico all'interno delle città (COM, 2022; European Commission, 2022; Silander, 2022). Gli edifici storici e il patrimonio architettonico costituiscono componenti essenziali dell'identità e del patrimonio culturale di una nazione, riflettendo la storia, le tradizioni e la maestria delle generazioni passate (CENGİZ & YANMAZ, 2019; Presidente della Repubblica, 2004). Pertanto, la conservazione e la valorizzazione di tali beni dovrebbero essere una priorità, per mantenere un senso di continuità e identità culturale. Ciò implica trovare un equilibrio tra sviluppo urbano e tutela del patrimonio architettonico, per creare ambienti urbani sostenibili, vivibili e dinamici (Barreca et al., 2020; Rolando et al., 2022).

In quest'ottica, l'implementazione di sistemi energetici rinnovabili deve essere attentamente valutata per garantire una coesistenza armoniosa (Pane, 2008) tra interventi sostenibili e salvaguardia del patrimonio architettonico, adottando soluzioni progettuali e ingegneristiche innovative e su misura (Baggio et al., 2017; Gremmelspacher et al., 2021).

Attualmente, l'assenza di procedure obbligatorie per la valutazione economica e finanziaria delle CER ha portato allo sviluppo di metodi multidisciplinari differenti, elaborati da professionisti e ricercatori.

Questa *review* intende quindi fornire un quadro generale della letteratura sulla sostenibilità economica e sulla fattibilità finanziaria delle CER, con particolare attenzione alle sfide legate alla riqualificazione energetica del patrimonio edilizio e architettonico. In tal senso, la disciplina della valutazione economica può suggerire approcci e metodi capaci di considerare vari elementi, tra cui l'investimento iniziale per lo sviluppo delle infrastrutture, i costi operativi ricorrenti, i potenziali ricavi derivanti dalla vendita dell'energia, i risparmi ottenibili, i rischi finanziari e gli impatti economici complessivi (positivi o negativi) sulla comunità (Felice et al., 2021).

La presente *review* descrive il processo di campionamento dei dati nella Sezione 2. I risultati sono illustrati nella Sezione 3, con riferimento alla tipologia delle pubblicazioni e ai metodi di valutazione economica applicati, con un focus sulle tematiche del patrimonio architettonico; infine, la Sezione 4 propone le conclusioni.

## 2. Approccio metodologico

L'approccio metodologico adottato si è basato su un processo sistematico di campionamento dei dati, utilizzando le principali banche dati internazionali condivise dalla comunità scientifica (Scopus, Web of Science), consultate tra novembre 2022 e aprile 2024. Sono stati selezionati articoli, libri e altre tipologie di pubblicazioni non indicizzate al fine di impostare un'analisi completa dei metodi valutativi pubblicati e studiati.

All'inizio della ricerca, l'obiettivo della *review* era valutare la sostenibilità economica per supportare la fattibilità delle CER, con particolare attenzione agli edifici storici e al patrimonio architettonico. Per questo motivo, sono stati considerati tre macro-temi per l'impostazione iniziale delle query: fattibilità economica, valutazione economica e patrimonio.

L'algoritmo di ricerca (e i criteri di selezione) impiegati per costruire il set iniziale di articoli si sono basati sulla combinazione di 9 termini differenziati (vedi *Query Strings* in Figura 1), connessi tramite operatori booleani AND e OR. Inoltre, i risultati sono stati ulteriormente affinati selezionando gli articoli appartenenti alle categorie "Ingegneria", "Matematica", "Economia, Finanza e Management" e "Processi decisionali", ottenendo così un set iniziale di 236 articoli. Sono state formulate diverse query integrando il tema centrale («*renewable energy communit**») con aspetti economici e finanziari ("assess*", "*benefit**", "*enhance**", "*cash**", "*income**"); la query "*renewable energy communit** AND *heritage*" non ha prodotto risultati, mettendo in evidenza una significativa lacuna nella letteratura. Per garantire la pertinenza e la qualità del dataset, sono stati mantenuti solo articoli scientifici *peer-reviewed* in lingua inglese che affrontassero esplicitamente aspetti economici o finanziari delle CER. Sono stati sistematicamente esclusi contributi non allineati con l'obiettivo della ricerca, così come duplicati e fonti non accademiche.

Per assicurare la qualità e l'affidabilità dei dati, sono stati implementati criteri specifici di esclusione (come la rilevanza rispetto all'obiettivo della *review* e la coerenza con le finalità degli articoli), mantenendo solo articoli *peer-reviewed* nella selezione preliminare. Ad esempio, sono stati esclusi numerosi articoli sull'uso di fonti energetiche rinnovabili in campi non attinenti all'architettura (come i veicoli elettrici o i biocarburanti). Una lettura finale e un'analisi critica del dataset è stata condotta sui 149 articoli filtrati per definire meglio il focus della review e confermare la base dati definitiva.

Al termine del processo di filtraggio, sono stati aggiunti alcuni nuovi campi (tipologia, paese del caso studio, paese degli autori, fonte energetica, metodo econometrico, indicatori applicati) per analizzare le tendenze della ricerca. L'analisi bibliografica critica, attraverso il software *VosViewer* (*VOSviewer - Visualizing Scientific Landscapes*, versione 1.6.18, https://www.vosviewer.com//), ha permesso di individuare cluster di parole chiave degli autori, contribuendo alla categorizzazione e organizzazione del dataset finale. Infine, la *review* ha prodotto un database conclusivo di 95 articoli, offrendo spunti rilevanti sui metodi di valutazione economica applicabili alle CER e mettendo in luce il loro utilizzo in contesti differenti.

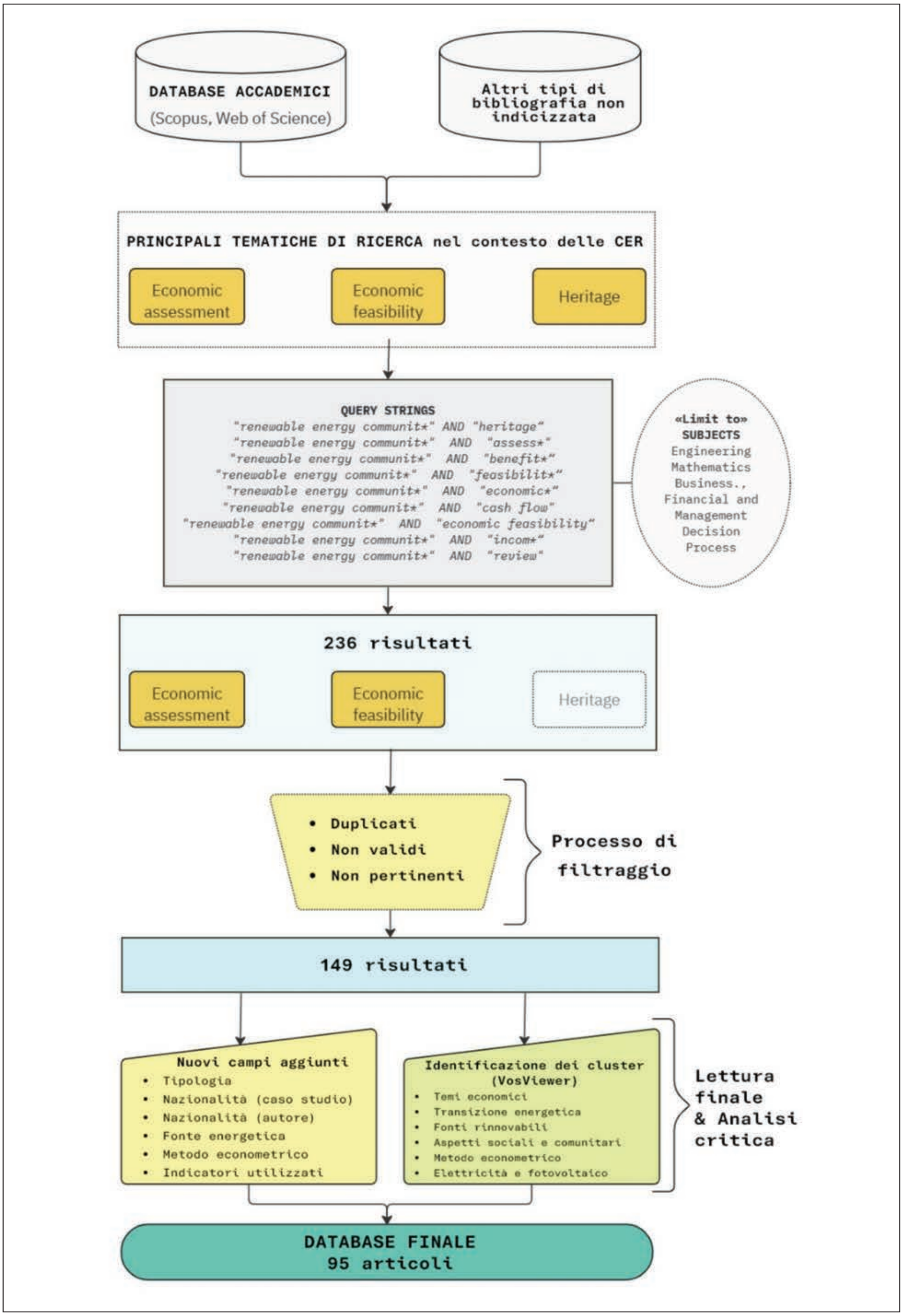


**Figura 1.** Diagramma di flusso dell'approccio metodologico. (Fonte: Elaborazione delle autrici).

## 3. Risultati

### 3.1 Panoramica dei risultati

Il campione finale (Appendice, Tabella A1) è composto da 95 articoli scientifici, riguardanti diversi temi connessi alla sostenibilità economica delle CER. La Tabella A1 fornisce una panoramica dettagliata dei contributi selezionati, classificati secondo criteri chiave per l'analisi delle CER, tra cui: tipologia dello studio, obiettivo principale, indicatori utilizzati, fonte energetica, contesto geografico, metodologia economica adottata e anno di pubblicazione.

Dal punto di vista cronologico, si osserva un significativo incremento delle pubblicazioni negli ultimi cinque anni, segno del crescente interesse verso le CER come strumenti chiave per la transizione energetica sostenibile. Tuttavia, la frammentazione metodologica riscontrata – in particolare negli approcci economici e valutativi – evidenzia la necessità urgente di sviluppare quadri analitici più integrati, in grado di combinare dimensioni economiche, sociali e ambientali.

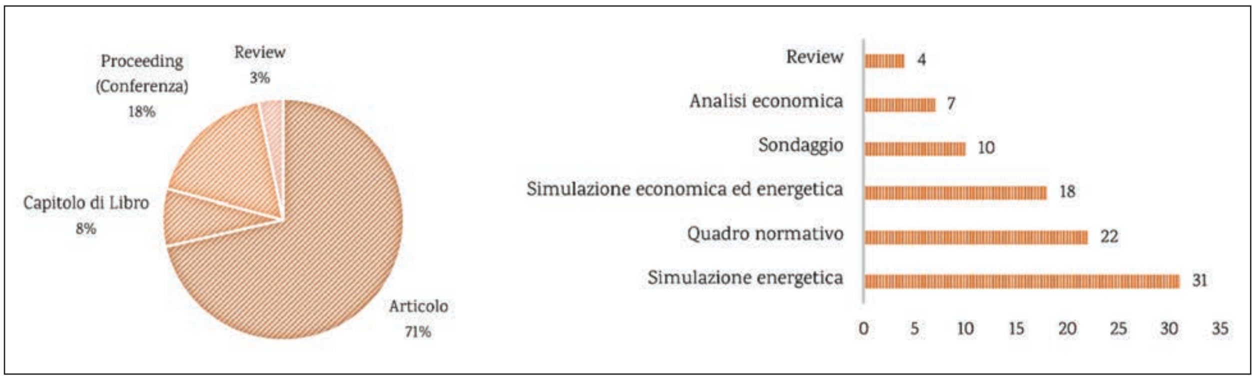


**Figura 2.** Tipologie di articoli (a) e principali argomenti (b) nel campione analizzato. (Fonte: Elaborazione delle autrici).

La distribuzione tematica indica un forte interesse per la simulazione energetica e per i quadri analitici, mentre gli aspetti sociali risultano meno rappresentati nel panorama della ricerca attuale.

Numerosi articoli (22) si concentrano sul "quadro normativo", affrontando tematiche legislative, regolamenti e standard (si vedano ad esempio: Adu-Kankam & Camarinha-Matos, 2022; Biresselioglu et al., 2021; D'Alpaos & Andreolli, 2021; Spasova & Braungardt, 2021, 2022; Trevisan et al., 2023). Solo quattro contributi sono revisioni della letteratura, in cui gli autori sintetizzano e analizzano criticamente le ricerche esistenti.

Diversi articoli (18) adottano tecniche di simulazione energetica ed economica, volte ad esplorare le interazioni tra fattori energetici e implicazioni economiche, come gli incentivi (ad esempio, Caramanico et al., 2021). La maggioranza degli articoli (31) si concentra invece sulla simulazione energetica, un ambito di ricerca predominante che analizza sistemi, tecnologie e modelli di simulazione energetica (ad es. Khosravi et al., 2018; Liobikienė & Dagiliūtė, 2021; Lowitzsch, 2019; Qu et al., 2021; Spigliantini et al., 2017; Tomin et al., 2022).

Altri articoli (7) analizzano in modo specifico gli aspetti economici, come i costi (Afzali et al., 2023; Ceglia et al., 2023; Robertson et al., 2020), i benefici, le tendenze di mercato e gli impatti finanziari (Fina, Monsberger, et al., 2022; Kyriakopoulos, 2022). Più limitato appare invece l'interesse verso una valutazione multidimensionale (economica e sociale) dei progetti, delle politiche o delle tecnologie (ad esempio: Dóci, 2021; Dóci & Gotchev, 2016; Kaiser et al., 2022; Ubelmesser et al., 2022).

Solo un articolo ha esplorato le implicazioni sociali dei comportamenti o delle politiche energetiche sostenibili attraverso un'analisi sociologica (Wuebben & Peters, 2022), mentre tre articoli si basano su indagini tramite questionari, per raccogliere opinioni e percezioni delle comunità coinvolte in una CER (Coenen & Hoppe, 2022; Gomez et al., 2022; Rakowska et al., 2022).

In parallelo all'analisi preliminare del campione, è stata effettuata un'elaborazione con il software VOSviewer (consultato tra aprile e luglio 2023) per verificare la presenza di eventuali cluster tematici attraverso l'associazione delle parole chiave degli autori.

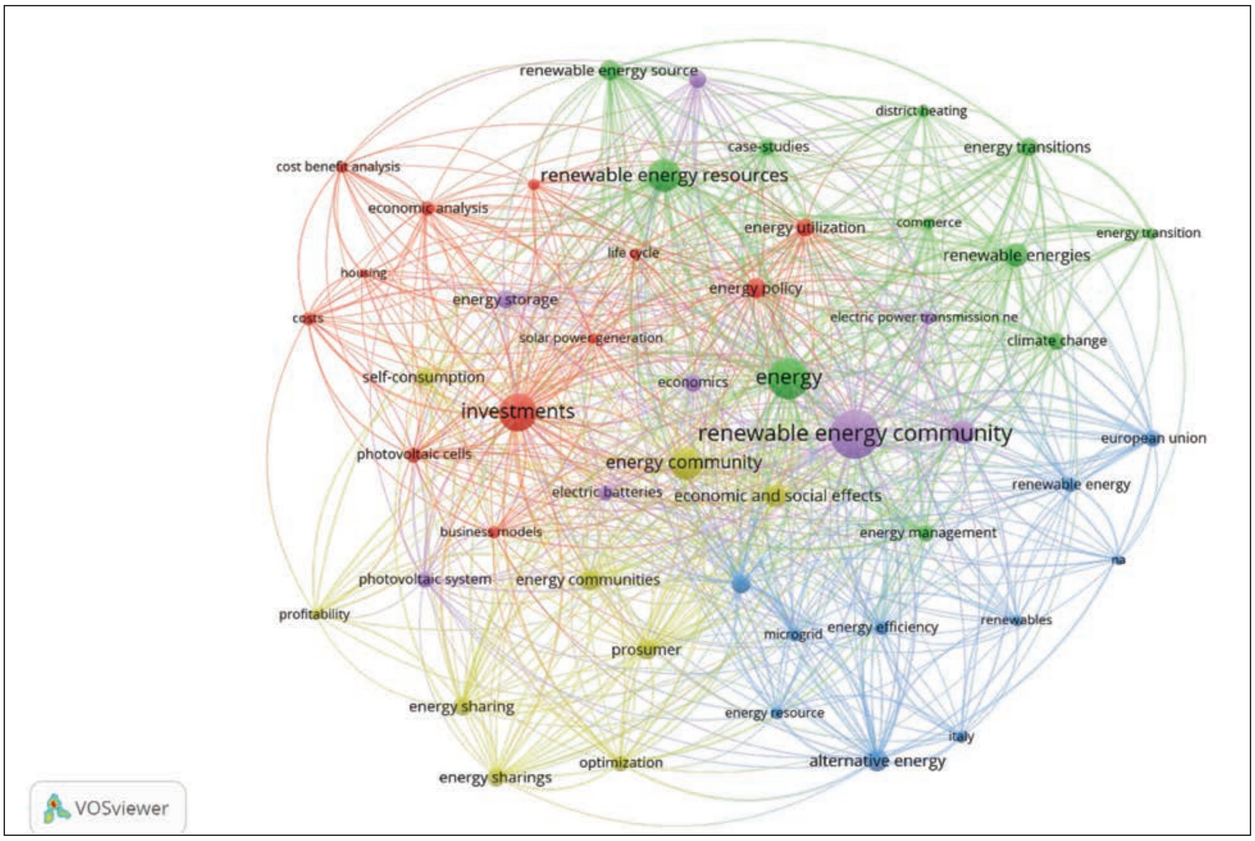


**Figura 3.** Mappa bibliografica del campione di dati (95 articoli). (Fonte: Elaborazione delle autrici).

Nonostante la forte polarità della keyword "*Renewable Energy Communit**", risultata centrale in tutte le pubblicazioni, la mappa bibliografica (Figura 3) ha evidenziato cinque cluster tematici rilevanti (su 50 articoli del totale):

1. Primo cluster (ROSSO – "Temi economici", 12 articoli). Collega articoli e pubblicazioni che si sono concentrati principalmente su aspetti economici dell'energia e su tematiche affini, quali l'analisi dei costi, le implicazioni economiche delle politiche energetiche e gli impatti finanziari dei progetti energetici (Carreras & Steinmaurer, 2022; Ceglia et al., 2023; Ceglia, Marrasso, Roselli, et al., 2022; Felice et al., 2021; Fina, Schwebler, et al., 2022; Fina & Auer, 2020; Gomez et al., 2022; Kyriakopoulos, 2022; Mutani et al., 2021; Napoli et al., 2022; Petrichenko et al., 2022; Viti et al., 2020).
2. Secondo cluster (VERDE – "Transizione energetica", 11 articoli). Ha riguardato ricerche inerenti alla transizione da fonti energetiche convenzionali verso alternative più sostenibili e rinnovabili. Ha incluso tematiche quali l'integrazione delle tecnologie per l'energia pulita, i quadri normativi per la transizione e le sfide legate alla trasformazione verso un'economia a basse emissioni di carbonio (Adu-Kankam & Camarinha-Matos, 2022; Carreras & Steinmaurer, 2022; D'Alpaos & Andreolli, 2021; Fina, Schwebler, et al., 2022; Kyriakopoulos, 2022).
3. Terzo cluster (BLU – "Fonti rinnovabili", 10 articoli). Ha incluso articoli che trattano vari aspetti delle fonti energetiche rinnovabili, come solare, eolico, idroelettrico, geotermico e altre tecnologie, la loro implementazione, efficienza e i potenziali impatti ambientali (Khan, 2016; Moncecchi et al., 2020).
4. Quarto cluster (GIALLO – "Aspetti sociali e comunitari", 9 articoli). Ha evidenziato ricerche che hanno esaminato le implicazioni sociali e comunitarie delle attività e delle politiche energetiche, nonché tematiche come il coinvolgimento delle comunità nei progetti energetici, l'accettazione sociale delle tecnologie per l'energia rinnovabile e l'impatto delle politiche energetiche sulle popolazioni vulnerabili (Dóci, 2021; Dóci & Gotchev, 2016; Gjorgievski et al.,

2021; Kaiser et al., 2022; Liobikienė & Dagiliūtė, 2021; Ubelmesser et al., 2022; Wicki et al., 2022).

5. Quinto cluster (VIOLA – "Elettricità e fotovoltaico", 8 articoli). Ha incluso ricerche relative ai sistemi di energia elettrica, alle tecnologie fotovoltaiche (energia solare) e a problematiche connesse all'integrazione in rete, all'efficienza del fotovoltaico, alle soluzioni di accumulo dell'energia e ai progressi nella generazione da fonte solare (Barbour et al., 2018; Conte et al., 2022; Pitt & Nolden, 2020; Secchi et al., 2021; Wicki et al., 2022).

È importante sottolineare che l'analisi bibliografica effettuata non ha individuato alcun cluster riconducibile al tema del patrimonio architettonico: ciò conferma una scarsa attenzione della letteratura scientifica verso l'edilizia storica nel contesto delle CER.
Infine, l'analisi delle fonti energetiche trattate negli articoli (Figura 4) ha rivelato che oltre la metà delle ricerche considera l'energia solare (53%), probabilmente a causa della localizzazione dei casi studio nell'area mediterranea. Tuttavia, va anche considerato il progresso delle tecnologie solari, che le ha rese un'opzione sempre più accessibile e conveniente per soddisfare diversi fabbisogni energetici.

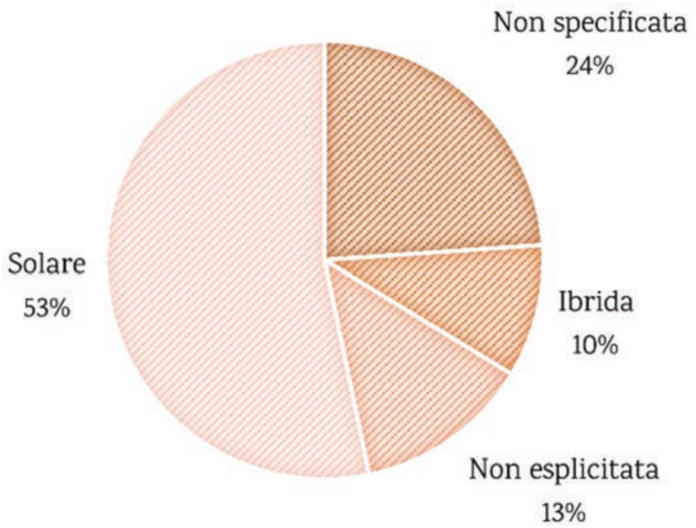


**Figura 4.** Indicatori economici utilizzati negli articoli analizzati. (Fonte: Elaborazione delle autrici).

Un'attenzione particolare è stata riservata agli studi su sistemi ibridi (10%), che combinano due o più fonti, come eolico e solare o idrogeno e solare. Questo mix energetico consente di ridurre la dipendenza da una singola fonte, aumentando la resilienza della comunità rispetto a variazioni climatiche o alla disponibilità delle risorse. In pochissimi casi (1%) si fa riferimento a sistemi ibridi basati su pompe di calore e produzione da biomassa (Ceglia, Marrasso, Roselli, et al., 2022).

È infine rilevante osservare che molti articoli non applicativi non specificano la fonte energetica utilizzata (24%) e in alcuni casi (13%) si tratta di simulazioni fittizie in cui la fonte non è esplicitata (Conte et al., 2022; Pastore et al., 2022).

### 3.2 Approcci economici e loro applicazioni

Il presente paragrafo offre una panoramica dei diversi approcci adottati per valutare la sostenibilità economica e la fattibilità dei progetti di CER. È opportuno osservare che alcuni metodi classici di valutazione economica – come l'Analisi dei Flussi di Cassa Scontati (Benaroch & Kauffman, 1999; Majd & Pindyck, 1987) e il Life Cycle Costing (Fregonara, 2017; Fregonara et al., 2017, 2018) – sono stati applicati solo parzialmente nelle ricerche sull'argomento.

Come mostrato in Figura 5a, solo 45 articoli del campione analizzato hanno applicato un approccio economico. Le diverse metodologie adottate sono riportate in dettaglio in Figura 5b.

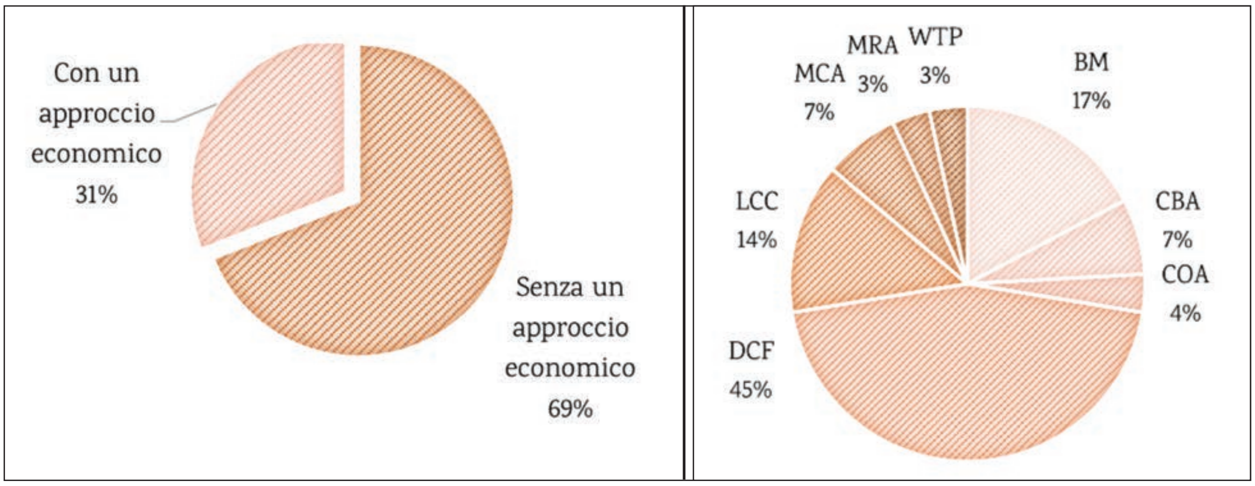


**Figura 5.** Approcci economici applicati negli articoli analizzati. (Fonte: Elaborazione delle autrici).

### *3.2.1 Analisi dei Flussi di Cassa Scontati (DCFA)*

L'approccio più comunemente applicato per valutare la fattibilità economica delle CER è stato l'Analisi dei Flussi di Cassa Scontati (Discounted Cash Flow Analysis, DCFA), utilizzata nel 45% dei casi, attraverso il calcolo del Valore Attuale Netto (VAN-NPV) e del Tasso Interno di Rendimento (TIR-IRR).

Ad esempio, Mutani et al. (2021) hanno valutato le prestazioni energetiche della CER utilizzando due indicatori chiave: autoconsumo e autosufficienza, aggiungendo un'analisi di costo ottimale (Becchio et al., 2016) per valutare la fattibilità economica in relazione a costi di investimento e incentivi economici. La metodologia proposta, applicata nella fase progettuale della CER, consente di individuare la configurazione ottimale che massimizzi i ricavi dagli incentivi e l'indipendenza energetica. I risultati hanno dimostrato che le CER offrono vantaggi ambientali ed economici, favorendo la coesione tra gli stakeholder.

In un'altra ricerca recente, Ceglia, Marrasso, Roselli, et al. (2022) hanno presentato un modello per analizzare e ottimizzare i sistemi energetici in funzione della fattibilità economica di una CER nel comune di Tirano (Italia settentrionale). Sono state considerate diverse configurazioni tecniche e scenari operativi della cogenerazione, penetrazione fotovoltaica ed energia termica. L'analisi economica ha mostrato un Pay-Back Time (PBT) contenuto e un NPV tra i 12 e i 13 milioni di euro, nel caso di cogenerazione a pieno regime, confermando la sostenibilità economica di sistemi energetici basati su biomassa legnosa.

Un altro studio italiano è quello di Moncecchi et al. (2020), che ha sviluppato una metodologia per ottimizzare la produzione di un portafoglio di CER, considerando la disponibilità di fonti energetiche, i fabbisogni specifici e le tariffe. È stato introdotto un modello per analizzare i flussi energetici tra i membri e identificare gli investimenti ottimali, massimizzando il NPV grazie a un algoritmo genetico.

Anche Viti et al. (2020) hanno calcolato il NPV simulando diversi scenari economici per valutare i modelli più efficaci per l'integrazione delle CER nel mercato energetico nazionale. I risultati hanno evidenziato che il comportamento collettivo dei prosumer può favorire l'adozione rapida di fonti rinnovabili integrate negli edifici, con risparmi in bolletta significativi e indicatori economici positivi in tutti gli scenari analizzati.

Nel contesto italiano, Napoli et al. (2022) hanno proposto una metodologia per valutare la fattibilità economica di aree verdi come misure passive per stakeholder pubblici e privati. L'approccio multidisciplinare integra analisi microclimatiche e dei livelli di comfort, valutando i fabbisogni energetici di un'abitazione tipo. La sostenibilità economica è stata verificata da diverse prospettive, dimostrando che la redditività può essere raggiunta in fase di gestione, se supportata da incentivi equivalenti ai costi di impianto.

Infine, Chaudhry et al. (2022a; 2022b) hanno incluso il calcolo del NPV in studi teorici ed empirici, per analizzare la prosumerizzazione collettiva attraverso i profili di consumo e produzione. L'impatto economico è stato valutato sia dal punto di vista dei consumatori che degli investitori, con indicatori di performance (KPI) costruiti per confrontare i risultati delle simulazioni con gli obiettivi degli stakeholder della CER.

### *3.2.2 Business model*

Diversi articoli che trattano la fattibilità economica nel contesto delle CER hanno applicato il *business model* (Casalicchio et al., 2022; Lowitzsch, 2019; Moreno et al., 2022; Pitt & Nolden, 2020).

Lowitzsch (2019) ha presentato i Consumer Stock Ownership Plans (CSOPs) come modello di business per le CER. Lo studio ha analizzato 67 casi in 18 paesi, evidenziando la necessità di modelli flessibili per attrarre co-investitori diversificati. I CSOPs favoriscono investimenti scalabili nei servizi energetici, attirando vari stakeholder (municipalità, piccole e medie imprese, impiantisti e fornitori energetici), promuovendo l'accettazione delle CER nel mercato.

Un uso alternativo del *business model* è stato proposto da Casalicchio et al. (2022), che hanno applicato tale approccio come strumento per distribuire equamente i benefici tra i partecipanti di una CER a Bolzano (Italia). È stato introdotto anche un Indice di Equità (Fairness Index) per confrontare diversi modelli di business in base alla redistribuzione dei benefici. I risultati hanno mostrato una ripartizione più giusta e bilanciata dei vantaggi, assicurando che tutti i partecipanti potessero ottenere un ritorno economico equo per il loro coinvolgimento.

### *3.2.3 Life Cycle Costing e Life Cycle Assessment*

Nel contesto di questa review, l'approccio economico centrale per valutare la sostenibilità finanziaria dei progetti rinnovabili destinati alla costituzione delle CER è il *Life Cycle Costing* (LCC), adottato in diverse ricerche (Okedu and Al-Hashmi, 2018; Caramanico et al., 2021; Mohseni & Brent, 2022; Nguyen et al., 2017; Shadmand et al., 2011). L'approccio LCC consente di analizzare i costi e benefici totali associati ad un progetto energetico rinnovabile lungo il suo intero ciclo di vita, permettendo ai membri della comunità di avere consapevolezza dell'investimento e di garantire la sostenibilità a lungo termine.

Caramanico et al. (2021) hanno condotto uno studio completo combinando l'LCA di un sistema ibrido micro-cogenerativo a celle a combustibile e fotovoltaico per edifici residenziali, con un'analisi economica dettagliata. Sono stati impiegati indicatori finanziari semplici come il *Net Present Cost* e il *Payback Period* per valutare la validità di due opzioni d'investimento, basate su differenti fonti energetiche. Il modello ha mirato a ottimizzare il mix energetico minimizzando gli impatti ambientali e i costi nel ciclo di vita, massimizzando al contempo i contributi rinnovabili e i risparmi. L'applicazione è stata condotta tramite variabili intere binarie e continue in ambiente CPLEX, mostrando l'efficacia della metodologia per l'identificazione di strategie ottimali.

Shadmand et al. (2011) hanno presentato un modello LCC per analizzare la fattibilità di un sistema ibrido eolico-fotovoltaico in un complesso residenziale collegato alla rete. È stato adottato un approccio tecnico-economico per individuare la soluzione più affidabile con il minor investimento. L'analisi ha mostrato che la configurazione ottimale copre il carico principalmente con pannelli fotovoltaici e in misura minore con turbine eoliche. Gli indicatori utilizzati sono stati il *Pay Back Time* (PBT), il *Levelized Cost Of Energy* (LCOE).

Una ricerca più recente con implicazioni al ciclo di vita è stata condotta da Elomari et al. (2024) su una CER residenziale a Terragona (Spagna), comprendente 100 edifici. Tramite un linguaggio di programmazione e un algoritmo di apprendimento automatico, sono stati applicati LCC e LCA per massimizzare l'uso di energia verde. Lo scenario finale è stato definito attraverso un approccio multi-criterio per la scelta della configurazione ottimale della CER.

### 3.2.4 *Analisi Multi-Criteria*

Alcuni articoli hanno applicato l'Analisi Multi-Criteria (*Multi-Criteria Decision Analysis*, MCDA) alle CER per confrontare diversi indicatori economici e valutare le preferenze dei soggetti coinvolti (Tomin et al., 2022; Torabi Moghadam et al., 2020).

Per implementare il modello *Community-Scale Optimization* (CSOP), Torabi Moghadam et al. (2020) hanno applicato un approccio metodologico articolato in tre fasi principali: identificazione e descrizione degli edifici selezionati, analisi preliminare di fattibilità e coinvolgimento del gruppo target. Il modello è stato applicato inizialmente in due aree pilota (Repubblica Ceca e Polonia), per poi essere sperimentato in un caso studio nella Val di Susa (Italia). Lo scenario migliore è stato individuato utilizzando la metodologia *PROMETHEE* (*Preference Ranking Organization Method for Enrichment Evaluation*), attraverso il confronto degli indicatori di *performance* (KPI) e l'analisi di sensitività.

### 3.2.5 *Analisi costi-benefici*

Wuebben e Peters (2022) hanno utilizzato l'Analisi Costi-Benefici (*Cost-Benefit Analysis*, CBA) per valutare il valore ambientale, economico e sociale delle CER nella promozione del "prosumerismo solare", attraverso un approccio a metodi misti. Nella prima fase, sette proposte di installazione di impianti solari domestici sono state analizzate mediante analisi discorsiva multimodale, rivelando vantaggi finanziari realistici, ma benefici sociali e ambientali descritti in modo inadeguato. Nella seconda fase, l'efficienza delle installazioni proposte è stata confrontata con quattro impianti fotovoltaici reali, utilizzando i profili effettivi di consumo e generazione. I risultati hanno mostrato che l'elevata variabilità della domanda domestica incide fortemente sull'autoconsumo e sulla redditività. È stato evidenziato che serie temporali ad alta risoluzione (minuto per minuto) possono rivelare valore aggiunto e benefici sociali spesso trascurati nelle stime del potenziale solare domestico.

Un'applicazione più classica della CBA è stata proposta da Mutani et al. (2021) nel caso di Villar Pellice (Italia), analizzando il consumo orario di energia e la produzione locale da fonti rinnovabili. Sono stati introdotti alcuni indici (come autoconsumo e autosufficienza) per facilitare la valutazione. Parallelamente, è stata condotta un'analisi di costo ottimale per valutare la fattibilità economica in relazione a costi di investimento e incentivi economici. I risultati hanno evidenziato il potenziale delle CER nel generare benefici multipli, quali cooperazione tra stakeholder, vantaggi economici e ambientali, e ricadute sociali.

### 3.2.6 *Analisi di regressione multipla*

Le Analisi di Regressione Multipla (*Multiple Regression Analyses*, MRA) sono metodi statistici applicati in funzione previsionale nel 3% degli articoli analizzati.

Cabarcos et al. (2020) hanno misurato la predisposizione a partecipare o investire in una CER tramite un sondaggio svolto in Galizia, prendendo in considerazione fattori come genere, capitale di reddito, fiducia e cooperazione. Gli autori hanno utilizzato MRA e Analisi delle Componenti Principali (PCA) per valutare indicatori demografici (genere, età, livello di istruzione) e caratteristiche socio-psicologiche, al fine di determinare la Disponibilità a Pagare (*Willingness to Pay*, WTP) e il potenziale coinvolgimento nella CER.

Analogamente, la WTP è stata combinata con la MRA da Liobikienė e Dagiliūtė (2021) per analizzare l'influenza di tre fattori chiave sull'energia verde in Lituania: risultati ambientali, livello di sviluppo del paese e pressione sociale. I risultati dell'analisi di regressione hanno indicato che la preoccupazione ambientale ha avuto un impatto negativo e non significativo sulla WTP per l'energia rinnovabile.

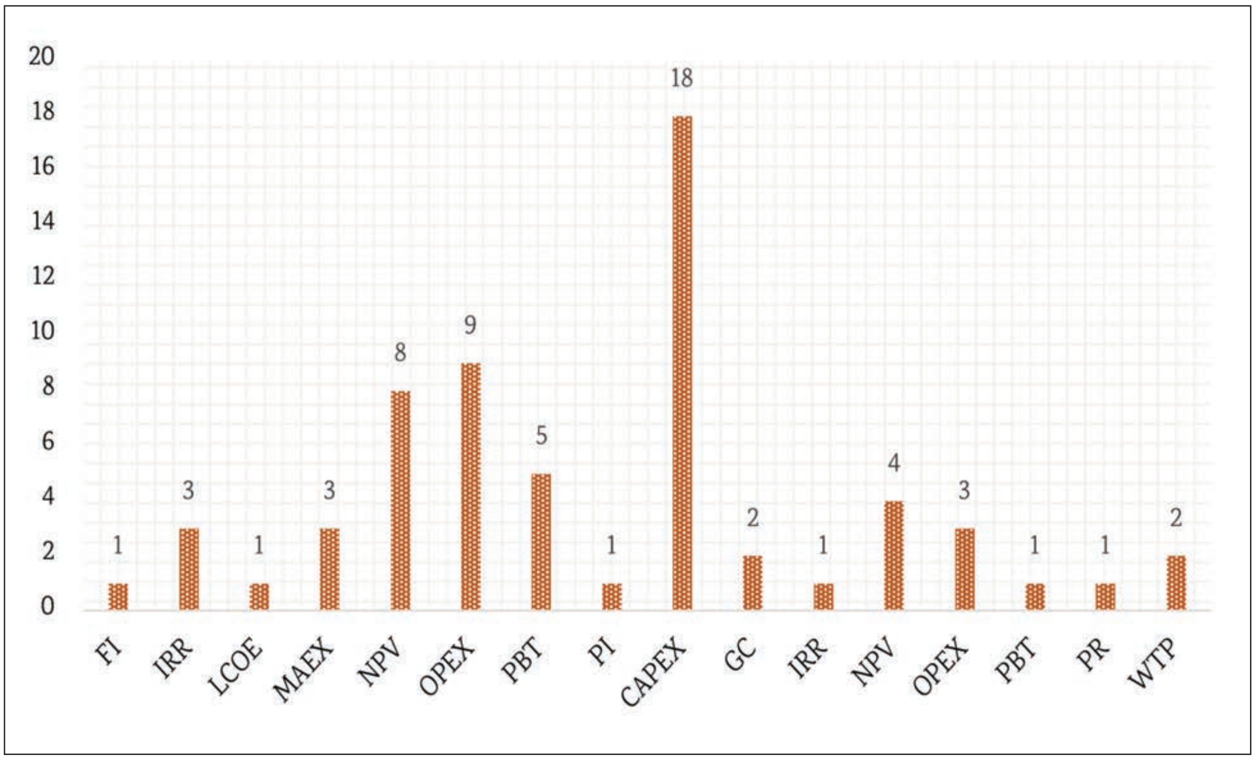


**Figura 6.** Fonte di energia rinnovabile nel campione di dati. (Fonte: Elaborazione delle autrici).

*3.2.7 Economic indicator-based analyses*

I principali indicatori economici utilizzati negli articoli analizzati sono illustrati nella Figura 6.

In molte simulazioni energetiche sono stati ampiamente analizzati gli indicatori CAPEX (spese in conto capitale) e OPEX (spese operative). Il CAPEX rappresenta l'investimento iniziale di un progetto ed è stato impiegato in 18 articoli, risultando l'indicatore più diffuso (Chaudhry et al., 2022a, 2022b; Khosravi et al., 2018; Pastore et al., 2022; Tomin et al., 2022). L'OPEX, che rappresenta i costi di gestione e manutenzione, è stato utilizzato in 9 articoli (Ancona et al., 2022; Caramanico et al., 2021; Casalicchio et al., 2022; Cielo et al., 2021; Cutore et al., 2023; Ji et al., 2022; Khosravi et al., 2018; Li & Okur, 2023; Viti et al., 2020), talvolta in combinazione con l'indicatore MAEX (spese di manutenzione).

I tre indicatori classici per la valutazione della redditività di un investimento – NPV (Net Present Value), IRR (Internal Rate of Return) e PBP *(Payback Period*) – sono stati impiegati in più articoli: NPV in 8 studi, IRR in 3, e PBP in 8.

La WTP (*Willingness to Pay*) è stata applicata in 2 articoli per comprendere quanto i cittadini siano disposti a pagare per l'energia verde (Ceglia, Marrasso, Samanta, et al., 2022; Liobikienė & Dagiliūtė, 2021).

L'indicatore GC (Generation Cost), che misura il costo di produzione dell'energia, è stato utilizzato in 2 studi (Mutani et al., 2021; Mutani & Usta, 2022).

Casalicchio et al. (2022) hanno applicato l'indicatore FI (*Fairness Index*) per valutare benefici e investimenti, al fine di redistribuire equamente i profitti ottenuti all'interno della CER. Un altro indicatore, LCOE (*Levelized Cost of Energy*), è stato utilizzato da Tomin et al. (2022) per calcolare il costo medio di produzione per unità di energia durante l'intero ciclo di vita del progetto.
Altri due indicatori menzionati sono: PI (*Profitability Index*), impiegato da Moncecchi et al. (2020) per calcolare il rapporto tra benefici attualizzati e costi attualizzati; PR (*Perceived Risk*), usato da Dóci & Gotchev (2016) per valutare il tempo necessario affinché un investimento recuperi i costi iniziali.

**Tabella 1.** Panoramica sintetica dei principali approcci economici (Fonte: Elaborazione dell'autore basata sul database della *literature review*)

| Approccio | Domini di applicazione | Vantaggi | Limiti |
|---|---|---|---|
| Analisi dei Flussi di Cassa Scontati (DCFA) | Studi di fattibilità economica; analisi d'investimento; ottimizzazione delle configurazioni delle CER | Ampiamente riconosciuto; consente la valutazione chiara di NPV, IRR, e PBT; supporta configurazioni ottimali | Può semplificare scenari complessi; sensibile alle ipotesi iniziali; privo di dimensione sociale |
| Modello di Business | Valutazione dell'equità; coinvolgimento degli stakeholder; definizione della struttura d'investimento | Consente una distribuzione equa dei benefici; supporta strategie d'investimento; flessibile per gli stakeholder | Richiede una governance chiara e partecipazione; l'equità può essere soggettiva |
| Life Cycle Costing (LCC) & Life Cycle Assessment (LCA) | Studi tecnico-economici; valutazione di sistemi ibridi; pianificazione sostenibile a lungo termine | Considera costi e benefici lungo l'intero ciclo di vita; supporta analisi di sostenibilità; utile per pianificazione strategica | Richiede molti dati; complesso da implementare; necessita di proiezioni a lungo termine |
| Analisi Multi-Criterio (MCDA) | Analisi di scenari; integrazione delle preferenze degli stakeholder; studi pilota | Considera più obiettivi e le preferenze dei soggetti coinvolti; aiuta a ordinare le alternative strategiche | Necessita di giudizi soggettivi per la ponderazione; complessità crescente con l'aumentare dei criteri |
| Analisi Costi-Benefici (CBA) | Modelli prosumer; valutazione degli impatti sociali-ambientali; analisi degli incentivi | Include benefici ambientali, economici e sociali; facilita valutazioni approfondite e olistiche | Dipende da valutazioni accurate di benefici non monetari; spesso legata al contesto specifico |
| Analisi di Regressione Multipla (MRA) | Studi sulla disponibilità a pagare; valutazione delle influenze socio-demografiche | Cattura fattori comportamentali e demografici; utile per stimare la partecipazione potenziale | La correlazione non implica causalità; richiede dati robusti per affidabilità |
| Analisi basata su indicatori economici | Monitoraggio delle performance finanziarie; confronto tra progetti; modellazione dei costi | Standardizzata e versatile; consente confronti tra progetti; individua parametri economici chiave | Può trascurare benefici intangibili o preferenze degli stakeholder; richiede dati completi |

La Tabella 1 offre una sintesi comparativa dei principali approcci economici applicati per valutare la sostenibilità delle CER. La DCFA si conferma il metodo più diffuso grazie alla capacità di quantificare la redditività degli investimenti attraverso indicatori standard come NPV e IRR, ma risulta spesso limitato per quanto riguarda le dimensioni sociale e ambientale. Al contrario, i modelli di business e l'MCDA pongono maggiore enfasi sulla partecipazione e sull'equità tra stakeholder, pur richiedendo una notevole strutturazione e chiarezza metodologica. Gli approcci basati su LCC/LCA offrono una visione olistica, ma richiedono molte informazioni e una pianificazione a lungo termine. La CBA è utile per includere esternalità sociali e ambientali, mentre le analisi statistiche (MRA) forniscono spunti comportamentali e sociali. Infine, l'uso di indicatori economici facilita confronti diretti tra casi studio, ma rischia di ignorare variabili qualitative rilevanti.

### 3.3 CER e patrimonio architettonico: opportunità o rischio?

Nel contesto delle CER, il patrimonio architettonico e le fonti energetiche rinnovabili presentano il potenziale per dar vita a una sintesi armoniosa tra pratiche energetiche sostenibili e tutela culturale (Rosa, 2020b, 2020a). L'integrazione delle tecnologie per l'energia rinnovabile all'interno di edifici storici e del patrimonio architettonico consente il raggiungimento di un duplice obiettivo: la riduzione delle emissioni di carbonio e la salvaguardia dei valori culturali, architettonici e storici degli edifici. Tale integrazione richiede un equilibrio delicato tra le esigenze funzionali dei sistemi energetici rinnovabili, l'estetica del bene architettonico e la protezione della sua integrità strutturale (Castellani et al., 2018; Franco et al., 2015; Rosa, 2020a).

Una delle principali sfide nell'integrazione delle fonti rinnovabili nel patrimonio architettonico risiede nell'assicurare un impatto visivo minimo (Rosa, 2020a). Gli edifici storici presentano spesso caratteristiche architettoniche uniche, forme e soluzioni tecnologiche che ne determinano la rilevanza culturale e che, nel loro insieme, contribuiscono a delineare quei paesaggi che definiscono l'identità culturale nazionale (Presidente della Repubblica, 2004). Qualsiasi modifica o aggiunta – come pannelli solari o turbine eoliche – deve pertanto essere progettata e integrata con estrema attenzione, in modo da risultare compatibile con l'estetica esistente e non comprometterne il valore architettonico. Come sostenuto da Mazzarella (2015), l'approccio più efficace per armonizzare il rapporto tra riqualificazione energetica e tutela del patrimonio architettonico consiste in un monitoraggio attento dell'evoluzione normativa, accompagnato da un dialogo costante con le amministrazioni competenti (quali le Soprintendenze italiane), finalizzato alla condivisione delle informazioni e alla costruzione di consapevolezza tecnica e culturale.

Tra le fonti rinnovabili più comunemente impiegate negli interventi di riqualificazione del patrimonio architettonico, l'energia solare occupa un ruolo centrale: i pannelli possono essere integrati nelle coperture o sulle facciate, consentendo la produzione di energia elettrica pulita (Rosa, 2020a). Ulteriori soluzioni progettuali innovative, come il fotovoltaico integrato negli edifici (BIPV), permettono l'inserimento dei moduli solari all'interno dei materiali da costruzione — ad esempio vetro o tegole — rendendo l'intervento ancora più discreto e compatibile con l'involucro edilizio (Biyik et al., 2017; Kuhn et al., 2021; Martín-Chivelet et al., 2022; Polo et al., 2022). Questo approccio consente non solo di sfruttare l'energia solare, ma anche di preservare l'integrità architettonica del manufatto.

In modo analogo, l'energia eolica può essere sfruttata in aree caratterizzate da adeguate risorse anemometriche, senza compromettere il valore del patrimonio architettonico (Xydis et al., 2022). Anche l'energia idroelettrica rappresenta un'opportunità, in particolare per strutture situate in prossimità di corsi d'acqua o bacini naturali (Filho & Feitosa, 2022; Hommes, 2019; Punys et al., 2019). Inoltre, i sistemi geotermici possono essere installati in maniera non invasiva al di sotto del suolo: le pompe di calore geotermiche garantiscono un riscaldamento e raffrescamento efficienti, riducendo al contempo la dipendenza dai tradizionali sistemi alimentati da combustibili fossili (Miller, 2020; Pisello et al., 2014).

La Commissione Europea ha introdotto diverse misure volte alla riduzione dei consumi energetici nel settore edilizio, tra cui tre direttive fondamentali: la Direttiva 2002/91/CE, la Direttiva 2010/31/UE e la Direttiva 2018/844/UE (EPBD I, II, III). La prima direttiva si è concentrata principalmente sui metodi di valutazione per gli edifici di nuova costruzione, la seconda ha posto maggiore enfasi sul patrimonio edilizio esistente, mentre la terza ha introdotto il concetto di "sistemi alternativi ad alta efficienza" e il rispetto per il patrimonio architettonico.

In linea con il Green Deal, l'attenzione si è estesa non solo agli interventi di riqualificazione profonda, ma anche alla sostituzione o all'adeguamento di elementi tecnici esistenti negli edifici a lungo ciclo di vita (Ciulla et al., 2016; Galatioto et al., 2017; Mazzarella, 2015; Piselli et al., 2020). Una delle preoccupazioni principali riguarda la conservazione e la protezione degli edifici storici non ancora formalmente tutelati, i quali, in caso di interventi integrali di riqualificazione energetica, sono a rischio di trasformazioni radicali e perdita delle caratteristiche identitarie.

## 4. Conclusioni

Il percorso verso l'implementazione di Comunità Energetiche Rinnovabili capaci di garantire una riqualificazione energetica economicamente sostenibile del patrimonio architettonico rappresenta la sfida attuale nel conciliare i requisiti tecnici dei sistemi da fonte rinnovabile con i valori culturali, architettonici e storici degli edifici.

Il presente studio ha esplorato la relazione tra tecnologie per l'energia rinnovabile, patrimonio architettonico e sostenibilità economica attraverso l'analisi di 95 articoli scientifici. I primi risultati evidenziano una letteratura carente, con pochi casi studio dedicati a edifici storici. Per questo motivo, la *review* della letteratura propone una sintesi dei metodi economici utilizzabili nella progettazione e modellazione di una CER, integrando contributi relativi al patrimonio architettonico e agli interventi di efficientamento energetico volti alla sua valorizzazione e conservazione.

Un ulteriore focus è dedicato alle simulazioni energetiche ed economiche, presenti nella maggior parte delle pubblicazioni relative alle CER. Nella maggioranza dei casi, la simulazione energetica è affiancata da un'analisi economica volta a calcolare il costo dell'investimento iniziale, i possibili incentivi e gli impatti derivanti dall'implementazione della CER. La letteratura analizzata conferma che l'approccio più adottato per valutare la fattibilità economica è rappresentato dall'Analisi dei Flussi di Cassa Scontati, sebbene alcune valutazioni si limitino all'uso di indicatori singoli per semplificare l'analisi.

Un confronto critico tra gli approcci economici esaminati mostra che nessun metodo singolo è in grado di cogliere appieno la complessità delle CER, specialmente quando coinvolgono edifici storici. Se da un lato la DCFA fornisce una valutazione quantitativa chiara, dall'altro può trascurare aspetti di equità, impatti ambientali e dinamiche sociali. Al contrario, i modelli di business e le analisi multicriteri offrono strategie più inclusive e partecipate, ma richiedono alti livelli di coordinamento e rigore metodologico. Gli approcci *Life Cycle Costing* e *Life Cycle Assessment* dimostrano un grande potenziale per valutazioni olistiche, ma necessitano di dati complessi e previsioni di lungo periodo. Tale varietà metodologica suggerisce che le future ricerche dovrebbero orientarsi verso framework ibridi e adattivi, capaci di integrare rigore tecnico, solidità economica e sensibilità culturale.

Le ricerche future dovrebbero dunque sviluppare modelli di valutazione economica integrati e flessibili, coerenti con i vincoli conservativi e in grado di supportare un'effettiva partecipazione degli stakeholder. I risultati presentati in questa *review* offrono indicazioni operative utili per i decisori pubblici e i professionisti del settore, fornendo una base comparativa per elaborare strategie normative, strumenti finanziari e modelli operativi più efficaci, specificamente orientati all'integrazione delle CER nei contesti patrimoniali.

Le evidenze emerse confermano che le CER si configurano come una via percorribile per promuovere la riqualificazione energetica degli edifici, senza compromettere il valore culturale insostituibile del patrimonio architettonico. L'integrazione delle tecnologie rinnovabili negli edifici storici richiede una valutazione attenta degli aspetti legati alla conservazione architettonica, all'estetica e alla rilevanza sociale (Mazzarella, 2015). Casi di successo (Baggio et al., 2017; Cengiz & Yanmaz, 2019; Gremmelspacher et al., 2021) hanno dimostrato che, attraverso una pianificazione accurata, soluzioni progettuali innovative e il coinvolgimento attivo della comunità, l'implementazione di interventi a base rinnovabile può non solo preservare il fascino delle architetture storiche, ma anche renderle simboli del progresso sostenibile.

La valutazione economica emerge come aspetto centrale per valorizzare il potenziale delle CER nei contesti storici (Franco et al., 2015). L'adozione di metodologie solide per analizzare la fattibilità finanziaria, il ritorno dell'investimento e i benefici di lungo termine consente agli stakeholder di affrontare i progetti in maniera consapevole e informata (Nguyen et al., 2017; Qu et al., 2021). Numerose analisi avanzate basate su dati sono state impiegate per ottenere stime più accurate sui costi e sui rischi, facilitando processi decisionali più efficaci. Inoltre, la *review* sottolinea la necessità di politiche pubbliche, quadri normativi e incentivi finanziari in grado di favorire l'adozione di soluzioni energetiche rinnovabili, garantendo al contempo la tutela del patrimonio architettonico (Mazzarella, 2015). In tale direzione, partenariati pubblico-privati solidi potrebbero giocare un ruolo decisivo nella promozione delle CER, riunendo competenze eterogenee per gestire l'interazione complessa tra aspetti economici, culturali e ambientali.

In conclusione, la tutela del patrimonio architettonico e l'integrazione delle fonti energetiche rinnovabili richiedono un'efficace collaborazione tra architetti, restauratori, ingegneri e comunità locali (Battista et al., 2022; Guo et al., 2021); ciò implica l'esecuzione di valutazioni approfondite sui fabbisogni energetici del sito, la selezione delle tecnologie rinnovabili più idonee e il rispetto delle normative e linee guida per la conservazione del patrimonio (Ascione et al., 2011; Jaggs & Palmer, 2000; Pane, 2008).

### Contributo degli autori

Questo articolo presenta i primi risultati della revisione della letteratura della ricerca di dottorato «Valorizzazione economica del patrimonio architettonico e Comunità Energetiche Rinnovabili (CER): opportunità, scenari e strumenti di valutazione» a cura di Giorgia Malavasi (conclusa in data 24/04/2025). Concettualizzazione: G.M. A.B. E.F., D.R.; cura dei dati: G.M.; analisi formale: G.M.; indagine: G.M.; metodologia: G.M. A.B. E.F., D.R.; supervisione: A.B. E.F., D.R.; stesura originale: G.M.; revisione e editing: G.M. A.B. E.F., D.R. Tutti gli autori hanno letto e approvato la versione pubblicata del manoscritto.

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## Appendice

**Tabella A1.** Il campione finale. (Fonte: Elaborazione delle autrici)

| ID | Autori | Tipologia | Categoria | Indicatori | Fonte energetica | Nazione | Metodi economici | Anno |
|---|---|---|---|---|---|---|---|---|
| 1 | Dóci G., Gotchev B. | Socio-economic analysis | Social | PR | Solar | Netherlands | NO | 2016 |
| 2 | Khan S.S. | Framework | Energy | NO | Solar | NO | NO | 2016 |
| 3 | Kirchhoff H., Kebir N., Neumann K., Heller P.W., Strunz K. | Energy simulation | Energy | NO | Solar | Germany | NO | 2016 |
| 4 | Barbour E., Parra D., Awwad Z., González M.C. | Energy simulation | Energy | NO | Solar | United States | NO | 2018 |
| 5 | Boretti A., Al-Zubaidy S. | Energy simulation | Energy | NO | Solar | Spain | NO | 2018 |
| 6 | Khosravi A., Koury R.N.N., Machado L., Pabon J.J.G. | Energy and economic simulation | Economic | CAPEX, OPEX | Hybrid | Iran | LCC | 2018 |
| 7 | Azarova V., Cohen J., Friedl C., Reichl J. | Economic analysis | Economic | WTP | ALL | Various | NO | 2019 |
| 8 | Boulaire F., Narimani A., Bell J., Drogemuller R., Vine D., Buys L., Walker G. | Energy simulation | Energy | NO | Solar | Australia | NO | 2019 |
| 9 | Lowitzsch J. | Economic analysis | Economic | NO | ALL | NO | BM | 2019 |
| 10 | Svetec E., Nad L., Pasicko R., Pavlin B. | Framework | Energy | NO | NO | Croatia | NO | 2019 |
| 11 | Balashova S., Ratner S., Gomonov K., Berezin A. | Energy simulation | Energy | NO | Solar | Russia | NO | 2020 |
| 12 | Cabarcos M.Á.L., Castro N.R., Viña V.M. | Economic analysis | Economic | WTP | Solar | Spain | MRA | 2020 |
| 13 | Hanke F., Lowitzsch J. | Framework | Energy | NO | NO | NO | NO | 2020 |
| 14 | He W., Wang G., Pan C. | Energy simulation | Energy | NPV, IRR | Solar | China | NO | 2020 |
| 15 | Lowitzsch J., Hoicka C.E., van Tulder F.J. | Framework | Energy | NO | ALL | NO | NO | 2020 |
| 16 | Moncecchi M., Meneghello S., Merlo M. | Energy and economic simulation | Economic | CAPEX, OPEX, NPV, PBT, PI | Solar | Italy | DCF | 2020 |
| 17 | Pitt J., Nolden C. | Economic analysis | Economic | NO | Solar | UK | BM | 2020 |
| 18 | Rocha R., Collado J.V., Soares T., Retorta F. | Framework | Energy | NO | NO | NO | NO | 2020 |
| 19 | Torabi Moghadam S., Di Nicoli M.V., Manzo S., Lombardi P. | Energy and economic simulation | Economic | CAPEX, OPEX, PBT | Solar | Italy | MCA | 2020 |
| 20 | Ugwoke B., Adeleke A., Corgnati S.P., Pearce J.M., Leone P. | Energy simulation | Energy | NO | Solar | Nigeria | NO | 2020 |
| 21 | Viti S., Lanzini A., Minuto F.D., Caldera M., Borchiellini R. | Framework | Economic | NPV,IRR | Solar | Italy | DCF | 2020 |

Segue **Tabella A1.** Il campione finale. (Fonte: Elaborazione delle autrici)

| ID | Autori | Tipologia | Categoria | Indicatori | Fonte energetica | Nazione | Metodi economici | Anno |
|---|---|---|---|---|---|---|---|---|
| 22 | Xue Y., Temeljotov-Salaj A., Engebø A., Lohne J. | Review | Energy | NO | NO | Various | NO | 2020 |
| 23 | Yüksel S., Dinçer H., Uluer G.S. | Framework | Energy | NO | ALL | Various | NO | 2020 |
| 24 | Biresselioglu M.E., Limoncuoglu S.A., Demir M.H., Reichl J., Burgstaller K., Sciullo A., Ferrero E. | Framework | Energy | NO | ALL | Various | NO | 2021 |
| 25 | Boulanger S.O.M., Massari M., Longo D., Turillazzi B., Nucci C.A. | Framework | Energy | NO | NO | No | NO | 2021 |
| 26 | Caramanico N., Di Florio G., Baratto M.C., Cigolotti V., Basosi R., Busi E. | Economic analysis | Economic | CAPEX, OPEX, NPV, PBT | Hybrid | Italy | DCF | 2021 |
| 27 | Ceglia F., Marrasso E., Roselli C., Sasso M. | Energy simulation | Energy | NO | Solar | Italy | NO | 2021 |
| 28 | Cielo A., Margiaria P., Lazzeroni P., Mariuzzo I., Repetto M. | Energy and economic simulation | Economic | OPEX, CAPEX, MAEX, NPV, IRR | Solar | Italy | DCF | 2021 |
| 29 | D'Alpaos C., Andreolli F. | Framework | | NO | NO | NO | NO | 2021 |
| 30 | Dawoud S.M. | Energy simulation | Energy | NO | Hybrid | Egypt | NO | 2021 |
| 31 | Dóci G. | Socio-economic analysis | | NO | ALL | Germany, Netherlands | NO | 2021 |
| 32 | Felice A., Rakocevic L., Peeters L., Messagie M., Coosemans T., Camargo L.R. | Energy simulation | Energy | NO | Solar | Belgium | DCF | 2021 |
| 33 | Fina B., Roberts M.B., Auer H., Bruce A., MacGill I. | Energy simulation | | NO | Solar | Austria | NO | 2021 |
| 34 | Grignani A., Gozzellino M., Sciullo A., Padovan D. | Framework | | NO | NO | Italy | NO | 2021 |
| 35 | Koirala B., Hers S., Morales-España G., Özdemir Ö., Sijm J., Weeda M. | Framework | | NO | ALL | Germany | NO | 2021 |
| 36 | Kojonsaari A.-R., Palm J. | Framework | | NO | ALL | NO | NO | 2021 |
| 37 | Koltunov M., Bisello A. | Framework | | NO | ALL | NO | NO | 2021 |
| 38 | Kumar A., Singh A.R., Meena N.K., Deng Y., He X., Kumar P., Bansal R.C. | Framework | | NO | Solar | NO | NO | 2021 |
| 39 | Liobikienė G., Dagiliūtė R. | Socio-economic analysis | Social | NO | ALL | Lithuania | WTP | 2021 |
| 40 | Mutani G., Santantonio S., Beltramino S. | Energy and economic simulation | Economic | GC | Solar | Italy | CBA | 2021 |

Segue **Tabella A1.** Il campione finale. (Fonte: Elaborazione delle autrici)

| ID | Autori | Tipologia | Categoria | Indicatori | Fonte energetica | Nazione | Metodi economici | Anno |
|---|---|---|---|---|---|---|---|---|
| 41 | Mutani G., Todeschi V. | Energy and economic simulation | Economic | GC | Solar | Italy | COA | 2021 |
| 42 | Rossi F., Heleno M., Basosi R., Sinicropi A. | Energy simulation | Energy | NO | Solar | Italy | NO | 2021 |
| 43 | Secchi M., Barchi G., Macii D., Moser D., Petri D. | Energy simulation | Energy | NO | Solar | Italy | NO | 2021 |
| 44 | Sforzini M., Nicita G., Pastore L., Lo Basso G., de Santoli L. | Energy Simulation | Energy | NO | Hybrid | Italy | NO | 2021 |
| 45 | Spasova D., Braungardt S. | Framework | Energy | NO | ALL | Germany | NO | 2021 |
| 46 | Todeschi V., Marocco P., Mutani G., Lanzini A., Santarelli M. | Energy simulation | Energy | NO | Solar | Italy | NO | 2021 |
| 47 | Adu-Kankam K.O., Camarinha-Matos L.M. | Framework | Energy | NO | ALL | NO | NO | 2022 |
| 48 | Agostinelli S., Neshat M., Majidi Nezhad M., Piras G., Astiaso Garcia D. | Energy simulation | Energy | NO | Hybrid | Italy | NO | 2022 |
| 49 | Ali A., Fakhar M.S., Kashif S.A.R., Abbas G., Khan I.A., Rasool A., Ullah N. | Energy and economic simulation | Economic | CAPEX, PBT | Hybrid | Pakistan | DCF | 2022 |
| 50 | Ancona M.A., Baldi F., Branchini L., De Pascale A., Gianaroli F., Melino F., Ricci M. | Energy simulation | Economic | CAPEX, OPEX, NPV | Solar | Italy | DCF | 2022 |
| 51 | Barberi A., Dio V.D., Pietra B.D., Favuzza S., Galluzzo M., Massaro F., Musca R., Zizzo G. | Energy simulation | Energy | NO | Solar | Italy | NO | 2022 |
| 52 | Boche A., Foucher C., Villa L.F.L. | Review | Energy | NO | NO | NO | NO | 2022 |
| 53 | Bula I., Syla F., Kopacek P., Hajrizi E., Bula E. | Energy simulation | Energy | NO | Solar | Kosovo | NO | 2022 |
| 54 | Casalicchio V., Manzolini G., Prina M.G., Moser D. | Energy and economic simulation | Economic | OPEX, CAPEX, FI | Solar | Italy | BM | 2022 |
| 55 | Ceglia F., Marrasso E., Samanta S., Sasso M. | Energy simulation | Energy | NO | Solar | Italy | NO | 2022 |
| 56 | Chaudhry S., Surmann A., Kühnbach M., Pierie F. | Energy and economic simulation | Economic | CAPEX, NPV | Solar | NO | DCF | 2022 |
| 57 | Chaudhry S., Surmann A., Kühnbach M., Pierie F. | Energy and economic simulation | Economic | CAPEX, NPV | Solar | Germany | DCF | 2022 |
| 58 | Coenen F.H.J.M., Hoppe T. | Survey | Energy | NO | NO | NO | NO | 2022 |
| 59 | Conte F., Mosaico G., Natrella G., Saviozzi M., Bianchi F.R. | Energy simulation | Energy | NO | Solar | Fictitious/Not Specified | NO | 2022 |

Segue **Tabella A1.** Il campione finale. (Fonte: Elaborazione delle autrici)

| ID | Autori | Tipologia | Categoria | Indicatori | Fonte energetica | Nazione | Metodi economici | Anno |
|---|---|---|---|---|---|---|---|---|
| 60 | De Lotto R., Micciché C., Venco E.M., Bonaiti A., De Napoli R. | Framework | | NO | NO | Italy | NO | 2022 |
| 61 | Eichman J., Torrecillas Castelló M., Corchero C. | Review | | NO | ALL | Spain | NO | 2022 |
| 62 | Fina B., Monsberger C., Auer H. | Energy simulation | Energy | NO | Solar | Fictitious/Not Specified | DCF | 2022 |
| 63 | Fina B., Monsberger C., Auer H. | Energy simulation | Energy | NO | Solar | Austria | NO | 2022 |
| 64 | Fouladvand J., Ghorbani A., Sarı Y., Hoppe T., Kunneke R., Herder P. | Energy simulation | | NO | Solar | NO | NO | 2022 |
| 65 | Gomez A., Tyl B., Pottier A. | Survey | | NO | ALL | France | NO | 2022 |
| 66 | Ji L., Wu Y., Liu Y., Sun L., Xie Y., Huang G. | Energy and economic simulation | Economic | CAPEX, OPEX, MAEX | Hybrid | China | LCC | 2022 |
| 67 | Kaiser S., Oliveira M., Vassillo C., Orlandini G., Zucaro A. | Socio-economic analysis | Social | NO | Solar | Italy | NO | 2022 |
| 68 | Lage M., Castro R. | Review | Energy | NO | Solar | Portugal | NO | 2022 |
| 69 | Lo Basso G., Pastore L.M., de Santoli L. | Energy and economic simulation | Economic | CAPEX | Hybrid | Italy | LCC | 2022 |
| 70 | Macarthur J.L., Hoicka C.E., Das R.R. | Framework | | NO | ALL | NO | NO | 2022 |
| 71 | Maione A., Massarotti N., Santagata R., Vanoli L. | Energy simulation | | NO | ALL | Italy | NO | 2022 |
| 72 | Marić L.L., Keko H., Delimar M. | Energy simulation | | NO | Solar | Croatia | NO | 2022 |
| 73 | Minai A.F., Usmani T., Alotaibi M.A., Malik H., Nassar M.E. | Energy simulation | | NO | | NO | NO | 2022 |
| 74 | Minuto F.D., Lanzini A. | Energy and economic simulation | Economic | CAPEX,OPEX, NPV | Solar | Fictitious/Not Specified | BM | 2022 |
| 75 | Moreno A., Villar J., Gouveia C.S., Mello J., Rocha R. | Economic analysis | Economic | NO | ALL | Spain | BM | 2022 |
| 76 | Napoli G., Corrao R., Scaccianoce G., Barbaro S., Cirrincione L. | Energy and economic simulation | Economic | NPV, IRR | Solar | Italy | DCF | 2022 |
| 77 | Pastore L.M., Lo Basso G., Quarta M.N., de Santoli L. | Energy simulation | | NO | ALL | Fictitious/Not Specified | NO | 2022 |
| 78 | Popescu M.-F., Constantin M., Chiripuci B.C. | Framework | Energy | NO | ALL | Various | NO | 2022 |
| 79 | Queiroz H., Amaral Lopes R., Martins J., Fialho L., Bravo Dias J., Bilo N. | Energy simulation | Energy | NO | Solar | Portugal | NO | 2022 |
| 80 | Quirosa G., Torres M., Soltero V.M., Chacartegui R. | Energy simulation | | NO | Solar | Spain | NO | 2022 |

Segue **Tabella A1.** Il campione finale. (Fonte: Elaborazione delle autrici)

| ID | Autori | Tipologia | Categoria | Indicatori | Fonte energetica | Nazione | Metodi economici | Anno |
|---|---|---|---|---|---|---|---|---|
| 81 | Rakowska J., Maciejczak M., Batyk I.M., Farelnik E. | Survey | Social | NO | Solar | Poland | NO | 2022 |
| 82 | Robinson D., del Guayo I. | Framework | | NO | ALL | Spain | NO | 2022 |
| 83 | Spasova D., Braungardt S. | Framework | | NO | NO | NO | NO | 2022 |
| 84 | Teske F., Funk F., Fehrle A., Franke J. | Energy simulation | | NO | NO | NO | NO | 2022 |
| 85 | Tomin N., Shakirov V., Kurbatsky V., Muzychuk R., Popova E., Sidorov D., Kozlov A., Yang D. | Energy and economic simulation | Economic | CAPEX, LCOE | Hybrid | Japan | MCA | 2022 |
| 86 | Ubelmesser L., Klingert S., Becker C. | Socio-economic analysis | Social | NO | ALL | NO | NO | 2022 |
| 87 | Wicki L., Pietrzykowski R., Kusz D. | Socio-economic analysis | Social | NO | Solar | Poland | NO | 2022 |
| 88 | Wuebben D., Peters J.F. | Energy and economic simulation | Economic | NPV | Solar | Spain | CBA | 2022 |
| 89 | Zwickl-Bernhard S., Auer H., Golab A. | Energy and economic simulation | Economic | CAPEX, OPEX, NPV | Solar | Austria | DCF | 2022 |
| 90 | Cutore E., Volpe R., Sgroi R., Fichera A. | Energy and economic simulation | Economic | CAPEX, OPEX, Total installation | Solar | Italy | DCF | 2023 |
| 91 | Li N., Okur Ö. | Economic analysis | Economic | CAPEX, OPEX, | Solar | Fictitious/Not Specified | LCC | 2023 |
| 92 | Roy A., Olivier J.-C., Auger F., Auvity B., Bourguet S., Schaeffer E. | Social and energy analysis | Energy | PBT | ALL | France | NO | 2023 |
| 93 | Battaglia V.; Vanoli L.; Zagni M. | Energy and economic simulation | Energy | NPV | Geothermal | Italy | DCF | 2023 |
| 94 | Elomari Y.; Mateu C.; Marín-Genescà M.; Boer D. | Energy and economic simulation | Economic | NPV | Solar | Spain | LCC | 2024 |
| 95 | Buonomano A.; Giuzio G.F.; Maka R.; Palombo A.; Russo G. | Energy simulation | Economic | PBP | Other | Fictitious/Not Specified | LCC | 2024 |