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# LIFE CYCLE ASSESSMENT OF RENEWABLE ENERGY SOURCES – KEY ISSUES. BIBLIOMETRIC ANALYSIS OF THE LITERATURE

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ABSTRACT: The aim of the analysis is to systematise scientific research related to the issue of environmental life cycle assessment (LCA) of renewable energy sources (RES) to identify key thematic areas and future research directions. A systematic literature review was applied based on bibliometric analysis of publications contained in scientific databases. The research request included records containing the term RES or the names of individual technologies in the titles in combination with the term LCA. A bibliometric analysis of over 1,000 publications identified four thematic clusters of research sub-areas and provided examples of publications referring to them. The result was a number of statistics, such as the structure of publication types, the productivity of authors by their nationality and the share of scientific disciplines. The analysis identified the most important publications in the thematic area. A review shows the interdisciplinarity of the research carried out and the relevance of the topic.

KEYWORDS: Life cycle assessment, renewable energy sources, research directions, bibliometric analysis

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## Introduction

In the face of the growing problem of environmental degradation, the transition to a climate-neutral economy is one of the most important challenges facing our and future generations (Montanarella & Panagos, 2021). Although much greener than conventional ones, renewable energy production technologies considered during their life cycle are not entirely 'clean'. In particular, they are responsible for the creation of waste and harmful emissions during their production and disposal phase.

When talking about environmental friendliness, it would be important to consider what this means today. In an age of continuous economic growth, it seems impossible to reduce the consumption of energy and natural resources. Top-down restrictions do not work perfectly, especially if only highly developed countries are obliged to follow them. Could new technologies such as renewable energy sources be the solution to this problem? Is technological development actually good for the environment, or are we once again caught in the progress trap (meaning that each improvement in our knowledge or in our technology will create new problems, which require new improvements)? LCA analyses of RES technologies are likely to answer these questions.

Researchers have analysed the life-cycle impact aspect of renewable energy technologies for more than 20 years. Despite this, the most recent review article (Motuzienė et al., 2022) addressing this topic highlights that although the Life Cycle Analysis (LCA) methodology is well-known and widely used, the problems encountered in its application often prevent the full use of LCA and the comparison of the results of many studies. Large differences were observed in the assessment of similar technologies due to different methodological assumptions.

Mapping the state of scientific research using a systematic approach to literature review makes it possible to assess the current scope of research on the one hand and to identify potentially new emerging research directions on the other (Szpilko & Ejdys, 2022). Bibliometric analysis, which is the research method of conducting a literature review, is mainly used at the initial stage of interest in a topic. By giving insight into a large number of publications, it allows the identification, synthesis, analysis and critical evaluation of their content (Montanarella & Panagos, 2021).

The aim of the study is to systematise, integrate, and evaluate scientific research related to the issue of environmental life cycle assessment (LCA) of renewable energy sources (RES) and to identify key thematic areas and future research directions.

## Materials and Methods

Quantitative techniques such as bibliographic analysis allow the identification of the current state of knowledge and development trends in a given research area. The results provide information on the main research directions in a given area, research trends and changes in the number of publications over a given period. They enable the creation of a range of statistics describing, for example, the structure of publication types, the share of scientific disciplines, the share of research funding organisations and funding programmes, as well as the construction of rankings of the most productive authors, journals, scientific units and countries in a given research area (Szum, 2021).

The analysis presented here is divided into 4 main stages: selection of scientific databases, selection of keywords and formulation of research queries, selection of inclusion criteria, and data compilation. The last stage, which is the actual analysis of the set of publications, includes data extraction, removal of duplicates, quantitative analysis and visualisation of the thematic area with the extraction of thematic clusters. The stages of the analysis are presented in Figure 1.

The selection of Scopus and Web of Science bibliographic databases, which are the leading databases for scientific papers, was the first stage of the analysis. The choice of databases was dictated by their availability and their coverage of papers from a wide range of scientific disciplines. The bibliometric analysis included publications containing the phrase "Life Cycle Assessment" together with the term Renewable Energy Sources or with the names of individual RES technologies (e.g. Photovoltaics, Heat Pump). The analysis did not include bio-based renewables such as biomass, biogas or other biofuels. Various notations and acronyms were included, such as LCA, life-cycle, RES, renewable, PV, etc. The search included publications containing the phrase in the titles only, as a preliminary analysis taking into account the occurrence of the phrase in titles, abstracts, and keywords qualified

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many publications that were not relevant to the research area under consideration. The selected inclusion criteria were then applied. Materials published between 2000 and 2023 were searched for. Research and review articles, conference proceedings, books, and book chapters were qualified for analysis. Publications not meeting the inclusion criteria were rejected. The results of the search are presented in Table 1.

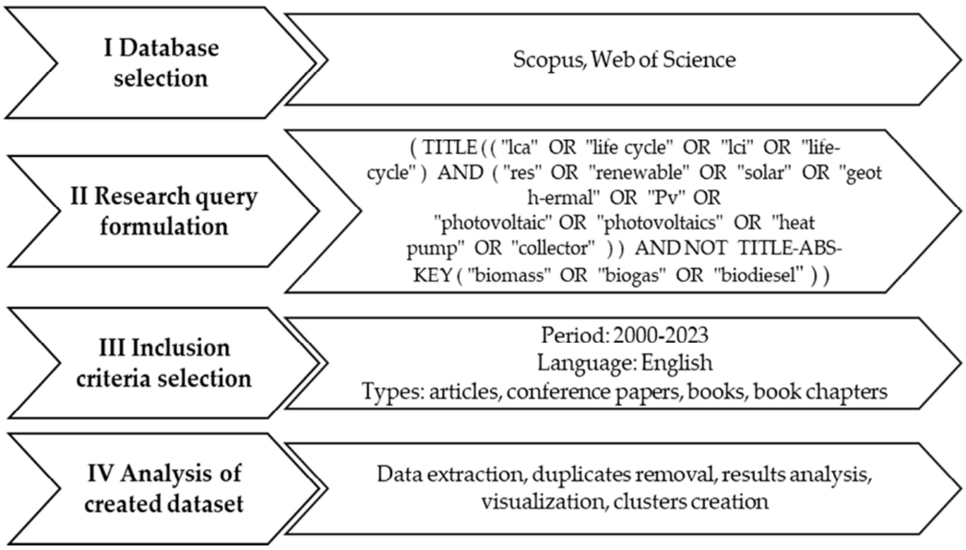


**Figure 1**. Stages of the bibliographic analysis study

**Table 1**. Results in subsequent search stages

| | Scopus | Web of Science |
|---|---|---|
| Number of articles found | 1 124 | 948 |
| Articles meeting the inclusion criteria | 1 069 | 900 |
| Number of articles after de-duplication | 1 082 | |

A search of the Scopus and Web of Science databases for compatibility with the research query generated 1124 and 948 records, respectively. In the next step, after discarding records that did not meet the inclusion criteria, 1069 papers from the Scopus database and 900 from WoS were qualified for analysis. Finally, after removing duplicates, a collection of 1082 scientific papers was obtained.

The collection of publications pertaining to the analysed subject area allowed the development of a number of statistics, such as the number of publications from the analysed subject area in particular years, the structure of publication types, the productivity of authors according to their nationality, and the share of scientific disciplines. The analysis indicated the most frequently occurring funding organisations and funding programmes and the most frequently cited publications. It also enabled a visual representation of the thematic area in the form of a map of the co-occurrence of keywords. Based on this, thematic clusters were created, representing the main research areas studied in the analysed publications. The VOSviewer software was used in the analysis.

## Results

As the result of the presented study, a compilation of the presence of the topic of environmental LCA of renewable energy technologies in the world literature was created. Interest in the issue has definitely increased over the period 2000-2023, selected for analysis. The number of publications in each year is shown in the graph in Figure 2.

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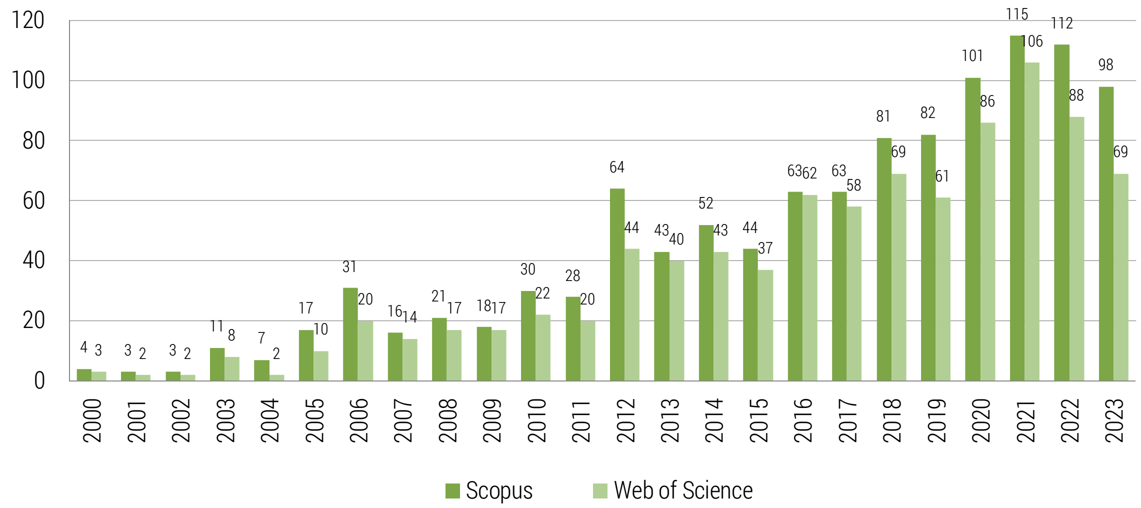


Figure 2. Number of publications in the subject area under study in the Scopus and Web of Science databases (indexed from January 2000 to November 2023)

The number of publications increased in both databases over the years, starting from a few per year to 115 in 2021 in the Scopus database, with a noticeable spike in interest in 2012. A similar trend was noted in the WoS database. Another summary obtained concerns the structure of publication types. The collection is dominated by research papers, followed by conference proceedings, review articles and book chapters. This structure is similar in both analysed databases. The diagram in Figure 3 shows the structure of publication types separately for the Scopus and WoS databases.

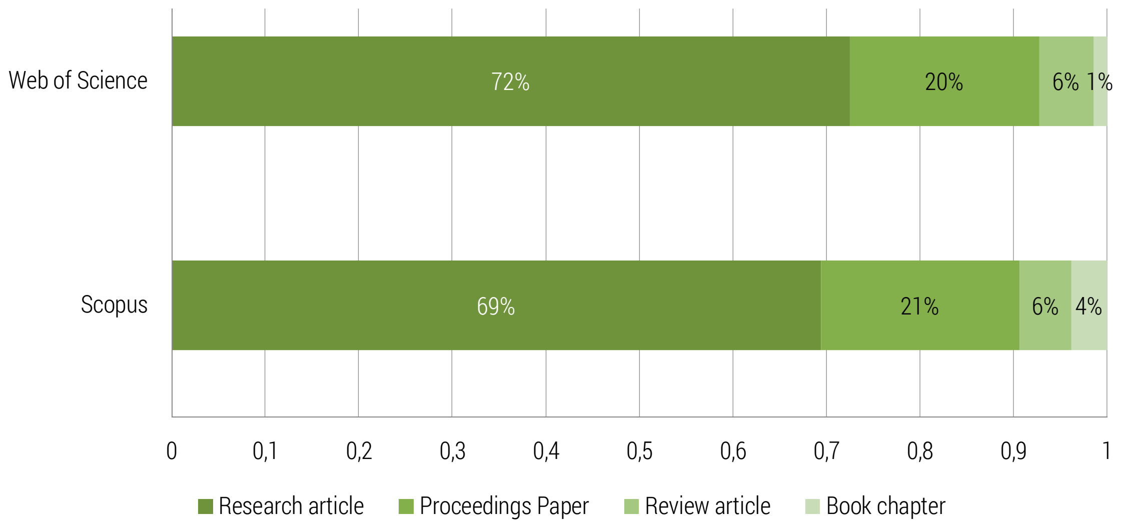


Figure 3. Structure of publication types in literature databases

Another statistic obtained was the proportion of individual scientific disciplines to which the authors classified their papers. The most frequently assigned disciplines are Energy (29%) and Engineering (22%). In total, articles assigned to these technical disciplines account for more than 50% of all articles published in this subject area. This is followed by Environmental Science (20%), Materials Science (6%), Economics and Management (5%), as well as Chemical Engineering (5%), Mathematics (4%) and Social Sciences (3%). The other scientific disciplines declared in this set of publications represent less than 3% of the total number. The share of disciplines is shown in Table 2. Table 2 also shows the number of papers belonging to the subject area under study, organised by funding organisation, country and author.

**Table 2.** Overview of contribution/quantities by disciplines, funding sponsors, countries and authors

| **Contribution of scientific disciplines [%]** | |
|---|---|
| Energy | 29% |
| Engineering | 22% |
| Environmental Science | 20% |
| Materials Science | 6% |
| Business, Management and Accounting | 5% |
| Chemical Engineering | 5% |
| Mathematics | 4% |
| Social Sciences | 3% |
| Computer Science | 2% |
| Other | 1% |
| **Documents by Funding sponsors/programmes [pcs.]** | |
| Horizon 2020 Framework Programme | 56 |
| National Natural Science Foundation of China | 51 |
| European Commission | 35 |
| National Science Foundation | 28 |
| U.S. Department of Energy | 20 |
| Ministerio de Economía y Competitividad | 13 |
| European Regional Development Fund | 13 |
| Engineering and Physical Sciences Research Council | 11 |
| Coordenação de Aperfeiçoamento de Pessoal de Nível Superior | 11 |
| National Key Research and Development Program of China | 11 |
| **Documents by Countries [pcs.]** | |
| USA | 219 |
| China | 115 |
| Italy | 111 |
| Spain | 95 |
| Great Britain | 79 |
| India | 70 |
| Germany | 66 |
| France | 48 |
| Australia | 45 |
| Canada | 38 |
| **Documents by Authors [pcs.]** | |
| Fthenakis, V. | 37 |
| Parisi, M. L. | 19 |
| Basosi, R. | 17 |
| Chemisana, D. | 16 |
| Kim, H. | 16 |
| Cellura, M. | 14 |
| Lamnatou, C. | 14 |
| Leccisi, E. | 14 |
| Tiwari, G. N. | 12 |
| Longo, S. | 11 |

Considering the country of origin of authors of publications related to LCA of RES technologies, the largest number of publications came from the United States. The number of US papers was more than double that of the next most frequently occurring country, China, but this number has only increased by about 12% in the last two years (2022-2023). China, on the other hand, proved to be a country very active recently in publishing papers in this research area, publishing as many as 44 papers between 2022-2023, an increase of more than 60% in the number of papers. Italy, Spain, and the UK were among the top publishing countries in this field, along with India and Germany. The Vosviewer tool allowed us to visualise the productivity of countries and the most popular international collaborations in the diagram in Figure 4.

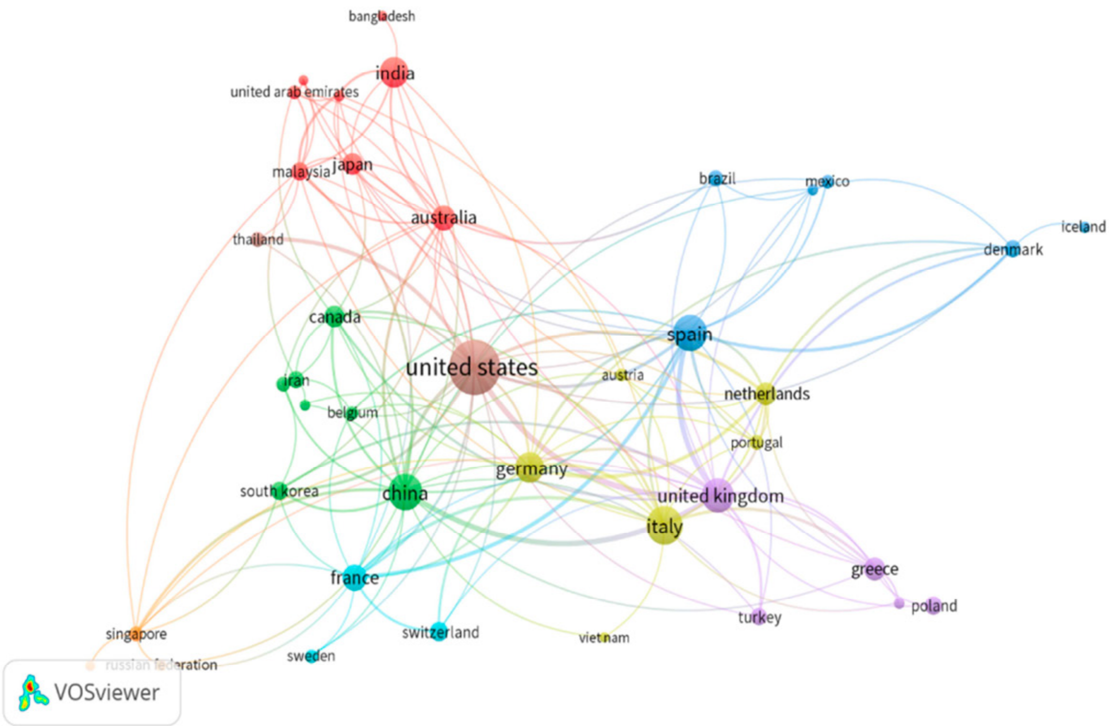


**Figure 4**. Visualisation of country productivity and international cooperation

The size of the circles indicates the number of publications, and the thickness of the line reflects the intensity of collaboration between authors from the countries concerned. The authors most likely to collaborate with authors from other countries are Americans, British, Spanish, Chinese, Germans and Italians. An interesting juxtaposition is that of organisations and programmes that fund research. Among these, the organisations with the highest number of funded studies in the area of LCA of RES technologies were government organisations and agencies, mainly from the European Union but also from China and the United States.

The author with the highest number of publications was Fthenakis, V. (37), whose co-authored publication "Emissions from photovoltaic life cycles" was ranked third most cited. This was followed, in order of authors, by Parisi, M. L. (19), Basosi, R. (17), Chemisana, D. (16) and Kim, H. (16), with the most publications on this topic. The analysis also produced a ranking of the most cited publications, which is presented in Table 3. Two of the five most cited were published in the Renewable and Sustainable Energy Reviews Journal. The most cited publication was the review article titled Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems by Peng, J., Lu, L., Yang, H. with more than 500 citations, published in the aforementioned journal.

The bibliometric analysis also extracted the most frequent keywords used by authors of publications related to the topic of Life Cycle Assessment of Renewable Energy Technologies. The VOSviewer programme was used for the analysis. The generated set contained a total of 100 words or phrases that appeared most frequently in the keywords included in the analysed articles. The keywords included words with the same meaning but with a different spelling, in a different grammatical form or abbreviated forms of expressions, as well as general expressions unrelated to the subject of the analysis (e.g. article, analysis). A text file (thesaurus) was prepared and used to organise the word set. Phrases directly denoting life cycle analysis were excluded from the set. The final set contained 90 keywords. The most frequent terms and the links between them are shown in Figure 5.

**Table 3.** The most cited articles on the subject area studied

| No. | Number of citations | | Title | Authors | Journal |
|---|---|---|---|---|---|
| | Scopus | WoS | | | |
| 1. | 512 | 440 | Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems | Peng et al. (2013) | Renewable and Sustainable Energy Reviews |
| 2. | 419 | 385 | Perovskite photovoltaics: Life-cycle assessment of energy and environmental impacts | Gong et al. (2015) | Energy and Environmental Science |
| 3. | 417 | 342 | Emissions from photovoltaic life cycles | Fthenakis et al. (2008) | Environmental Science and Technology |
| 4. | 412 | 318 | LCA of renewable energy for electricity generation systems – A review | Varun and Prakash (2009) | Renewable and Sustainable Energy Reviews |
| 5. | 381 | 334 | Multi-objective optimization minimizing cost and life cycle emissions of stand-alone PV-wind-diesel systems with batteries storage | Dufo-López et al. (2011) | Applied Energy |

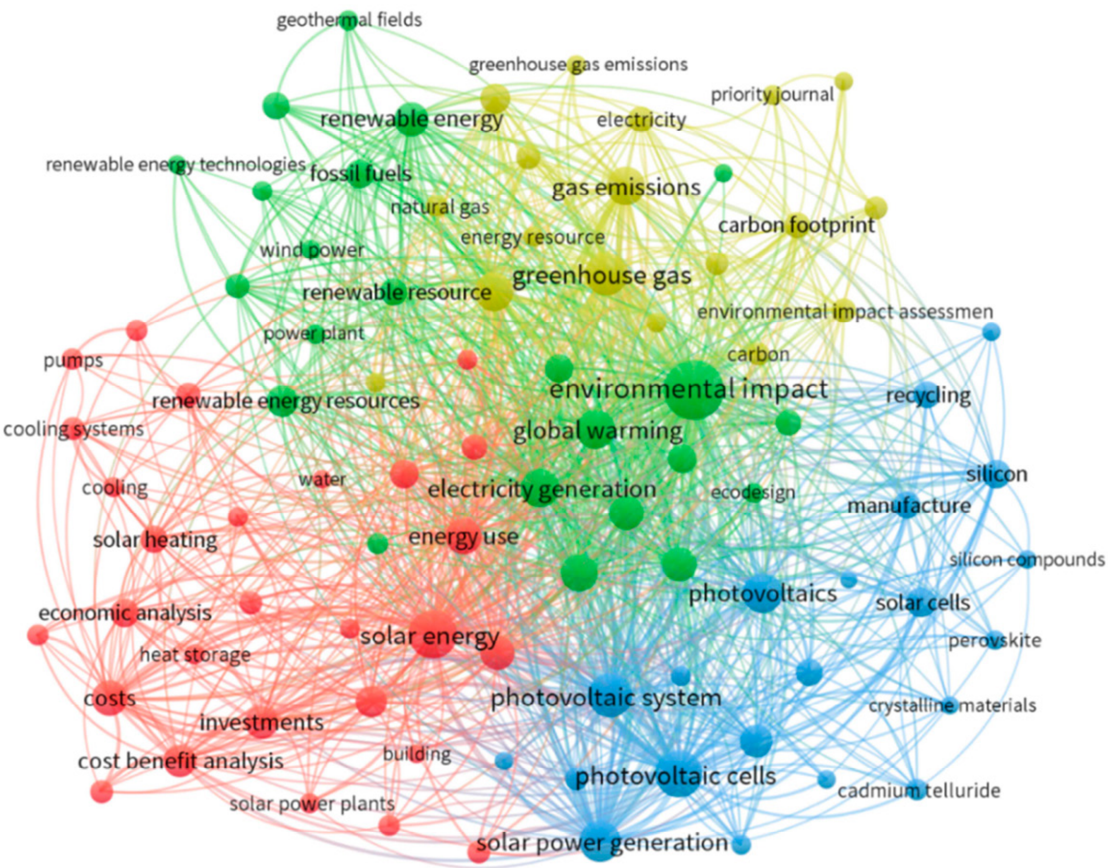


**Figure 5.** Keyword co-occurrence map

A keyword co-occurrence map provides information not only on how often a particular keyword occurred in the titles, abstracts and keywords but also which words occurred together in a single paper. The size of the circle indicates how often a given word occurs, while the thickness of the lines indicates the frequency of the words they combine together in a single paper. The diagram presented also provides a visualisation of the subject area under study.

The VoSviewer software, on the basis of the combining wordings, created four main thematic clusters, which are the main thematic areas that the authors dealt with in the LCA of renewable energy technologies. Table 4 shows the main thematic clusters and the keywords belonging to them, along with a breakdown by research sub-area.

**Table 4.** Identified thematic clusters

| No. | Research area | Keywords | Research sub-areas |
|---|---|---|---|
| 1. | LCA of RES in the building industry | *artificial life, building, comparative study, cooling, cooling systems, cost benefit analysis, costs, economic analysis, economics, energy efficiency, energy use, heat pump systems, heat storage, heating, investments, life cycle cost analysis, lifecycle costs, optimization, performance assessment, pumps, sensitivity analysis, solar energy, solar heating, solar power, solar power plants, solar radiation, uncertainty analysis, water* | RES technologies for buildings and integrated into the building |
| | | | Energy demand of buildings covered by RES and nearly zero-energy buildings |
| | | | Energy and economic efficiency |
| 2. | Renewable energy management | *Alternative energy, decision making, ecodesign, electricity generation, energy policy, environmental impact, environmental management, environmental performance, environmental technology, fossil fuels, geothermal energy, geothermal fields, global warming, global warming potential, lifecycle environmental impact, power plant, renewable energy, renewable energy resources, renewable energy technologies, renewable resource, sustainability, sustainable development* | Optimal selection of RES on the basis of their LCA |
| | | | Design aspects influencing RES LCA results |
| | | | Aspects of sustainable development |
| 3. | Life cycle assessment procedure for energy sources | *Cadmium telluride, crystalline materials, cumulative energy demand, energy management, energy payback time, manufacture, manufacturing, payback time, perovskite, photovoltaic cells, photovoltaic effects, photovoltaic panels, photovoltaic system, photovoltaics, recycling, silicon, silicon compounds, solar cells, solar concentrators, solar power generation, toxicity* | Devices manufacturing technologies |
| | | | Life cycle inventory of RES equipment |
| | | | End-of-life phase of RES devices |
| 4. | Life cycle environmental impact of RES | *Acidification, carbon, carbon dioxide, carbon emission, carbon footprint, climate change, electricity, emission control, energy, energy conservation, energy resource, environmental impact assessment, eutrophication, gas emissions, greenhouse gas, greenhouse gas emissions, natural gas* | Impact categories of RES technologies |
| | | | Comparison of RES versus conventional technologies |
| | | | RES development potential and dynamic LCA |

## Discussion

Research on the analysed problem has been conducted worldwide and has focused on a broad spectrum of aspects of the life cycle analysis of renewable energy sources. Table 5 contains examples of publications from the analysed set, which fit into the identified research areas and sub-areas.

**Table 5.** Research sub-areas of renewable energy life cycle assessment with publication examples

| No. | Research area | Research sub-areas | Selected publications |
|---|---|---|---|
| 1. | LCA of RES in the building industry | RES technologies for buildings and integrated into the building | Ardente et al. (2005); Fthenakis and Kim (2011); Gong et al. (2015); Kalogirou (2009); Koroneos and Tsarouhis (2012); Lamnatou et al. (2019); Ludin et al. (2018); Saner et al. (2010) |
| | | Energy demand of buildings covered by RES and nearly zero-energy buildings | Allouhi (2020); Gołębiowska and Żelazna (2018); Gouveia et al. (2020); Leccisi & Fthenakis (2021); Leckner and Zmeureanu (2011); Sajid and Bicer (2021); Silva et al. (2016) |
| | | Energy and economic efficiency | Burch et al. (2005); Hendrickson et al. (2013); Hin et al. (2014); Naves et al. (2019); Paiho et al. (2017); Zeiler et al. (2017) |
| 2. | Renewable energy management | Optimal selection of RES on the basis of their LCA | Allouhi (2020); Campos-Guzmán et al. (2019); Dufo-Lopez et al. (2011); Hin et al. (2014); Ko (2015); Symeonidou et al. (2021); Thapa et al. (2022) |
| | | Design aspects influencing RES LCA results | Battisti and Corrado (2005); Burkhardt III et al. (2011); Greening and Azapagic (2012); Hang et al. (2012); Laleman et al. (2011); Pacca et al. (2007); Uctug and Azapagic (2018) |
| | | Aspects of sustainable development | Brenner et al. (2018); Maceno et al. (2022); Peng et al. (2013); Zheng et al. (2023) |
| 3. | Life cycle assessment procedure for energy sources | Devices manufacturing technologies | Alberola-Borràs et al. (2018); De Wild-Scholten and Alsema (2006); Espinosa et al. (2011); Fthenakis (2004); Hong et al. (2016) |
| | | Life cycle inventory of RES equipment | Baharwani et al. (2014); Fthenakis et al. (2009); Martínez-Corona et al. (2017); Muller et al. (2021); Tosti et al. (2020) |
| | | End-of-life phase of RES devices | Ansanelli et al. (2021); Aryan et al. (2018); Ganesan and Valderrama (2022); Latunussa et al. (2016); Lim et al. (2022); Lunardi et al. (2018); Vellini et al. (2017) |
| 4. | Life-cycle environmental impact of RES | Impact categories of RES technologies | Bayer et al. (2013); Gong et al. (2015); Kaczmarczyk (2019); Pal and Kilby (2019); Tomasini-Montenegro et al. (2017) |
| | | Comparison of RES versus conventional technologies | Asdrubali et al. (2015); Fthenakis and Kim (2007); Varun et al. (2009) |
| | | RES development potential and dynamic LCA | Adedeji et al. (2020); Khanahmadi et al. (2021); Magrassi et al. (2017); Mousavi et al. (2022); Pehnt (2006); Raugei et al. (2021); Ren et al. (2020); Zhai and Williams (2010) |

The first highlighted area refers to aspects closely linking RES and buildings and the resulting implications for their life-cycle assessment. A keyword analysis of this area indicates three main research sub-areas: RES technologies for and integrated into buildings, the energy demand of buildings covered by RES together with near-zero energy buildings, and energy and economic efficiency. In each sub-area, the authors focused on different research questions. Much of the research on the life-cycle assessment of renewable energy sources focuses on the analysis of a single building technology (Fthenakis et al., 2008; Gong et al., 2015; Saner et al., 2010). Among photovoltaic technologies, the LCA results show that monocrystalline modules have the highest environmental impact in terms of energy consumption, energy payback time (EPBT) and greenhouse gas emission factor (Ludin et al., 2018). Analyses of the impact of geothermal systems, such as ground source heat pumps, point to the major role of the electricity used to power the unit in its life-cycle environmental impact (Saner et al., 2010). In turn, the study (Ardente et al., 2005) on solar thermal collector technologies once again emphasises the importance of clearly defining the boundaries of the study and describing the assumptions in detail. The results of this study indicate a 90% share of indirect emissions related to the production of raw materials. The studies on building-integrated photovoltaic (BIPVT) technologies highlight the differences in energy, exergy and economic efficiency of poly- and monocrystalline silicon and amorphous silicon modules, which affects their suitability for the requirements of different customer groups (Agrawal & Tiwari, 2010).

An important element of the analyses is the determination of the energy demand of the reference objects, which in the case of the analyses under consideration are residential buildings. Some of the studies concern real buildings; therefore, they are case studies (Saoud et al., 2021; Sim & Suh, 2021). In a number of studies, this is realised using building energy simulations. Simulation software such as TRNSYS, Energy Plus, Design Builder, and others are used. Another approach is to make assumptions about energy consumption based on statistical or literature data. A separate part of the research is studies with near-zero energy buildings as the reference object. A simulation study of a net zero energy house (NZEH), presented in the paper (Leckner & Zmeureanu, 2011), has shown that, even in cold climates, the use of solar technologies alone (photovoltaics and solar collectors) makes it possible to achieve such a high energy standard as a near-zero-energy building. However, this study only analyses the life-cycle costs and energy consumption of the technologies used without analysing the environmental impacts. Another highlighted sub-area concerns the energy and economic efficiency of RES use. Many studies combine the environmental aspects of life-cycle assessment with the economic aspects, as well as the energy efficiency of RES systems (Karlsdottir et al., 2010; Košičan et al., 2021). In this sub-area, life cycle cost analyses of renewable energy sources are a relevant group of analyses (Hendrickson et al., 2013; Pastore & Ignatova, 2010; Shonder et al., 2000; Zeiler et al., 2017).

Renewable energy management is another of the areas identified from the keywords, in which three further research sub-areas were identified: Optimal selection of RES based on their LCA, Design aspects influencing RES LCA results, and Sustainability aspects. The optimal selection of a RES system, or a single technology, from the growing number of available ones is one of the problems faced by researchers of renewable energy systems for residential buildings. This choice not only has to ensure the provision of sufficient energy, thus covering the energy needs of the building, but if LCA results are taken into account, the choice has to ensure the minimisation of environmental impacts. Two groups of methods are used for this: optimisation or multi-criteria decision support methods (MCDM). LCA optimisation studies of RES systems constitute a large group of studies in which technical quantities, e.g. the size of the systems, are optimised (Ko, 2015; Symeonidou et al., 2021), [values of individual impact categories, e.g. GWP, PEU (Hin et al., 2014) whether life cycle costs (Thapa et al., 2022)]. Many of these analyses are multi-criteria optimisations, where more than one objective function is specified. In the area of research into the application of multi-criteria methods to renewable energy issues, an important analysis was carried out by the authors of the publication (Campos-Guzmán et al., 2019). This was a detailed literature review on sustainable energy systems assessment. The study concludes that life cycle analysis (LCA) and multi-criteria decision-making (MCDM) techniques used in combination with the same methodological framework are the best tools for sustainable assessment of renewable energy sources. Some of the analyses refer to aspects of RES system design that significantly influence the results of their life cycle analysis. These aspects include the technological differences within the different technologies and the impact of design alternatives (Battisti & Corrado, 2005; Burkhardt III et al., 2011; Pacca et al., 2007) or the impact of location choice. In the literature, it is highlighted that the inappropriate choice of technology in a particular location can result in its high environmental impact, often exceeding that of fossil fuel-based technologies (Motuzienė et al., 2022).

Another identified sub-area relates to the concept of sustainability. The concept of sustainability and sustainable design is closely linked to environmental life cycle assessment. The advantage of LCA is that it prevents the transfer of environmental burdens and also enables the assessment of the potential for reuse of recycled materials from equipment, which is the basis of a circular economy (Brenner et al., 2018; Maceno et al., 2022).

Among single-technology studies, LCA studies of photovoltaic modules identify the EPBT factor as suitable for assessing the sustainability and environmental performance of this type of technology. It is emphasised that the study takes into account both the production technology and energy conversion efficiency, as well as the installation site (Peng et al., 2013).

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The third thematic cluster concerns the Life Cycle Assessment Procedure for Energy Sources. Three main research sub-areas have been distinguished: technologies for the production of devices, life-cycle inventories of RES devices, and end-of-life phase of RES devices. The first sub-area deals with the issue of production of equipment and components which are part of renewable energy source systems. This type of information is the basis for the life cycle inventory of equipment and thus constitutes an important element of the analysis of their environmental impact throughout their life cycle. For some technologies, such as photovoltaics, the impact of the production phase of the equipment is the impact causing the greatest environmental impact. In addition to the LCA of conventional manufacturing methods, the research area has included analysis of methods such as roll-to-roll for the production of polymer solar cells (Espinosa et al., 2011) whether analysis of cadmium production for the manufacture of CdTe-type modules (Fthenakis, 2004).

This research area also includes a sub-area on the disposal (end-of-life) phase of RES devices. When analysing appliance recycling processes, the authors, in addition to giving impact values of the whole process, try to identify the processing steps with the most significant impact on the outcome, highlighting the high contribution of transport, the plastic incineration process or the metal recovery processes from ash (Latunussa et al., 2016). Comparisons of different end-of-life scenarios (landfill, recycling) are also presented, which give differences in their environmental impacts. Depending on the technology, recycling impact values can result in an increase or decrease in the end-of-life impacts of the technology (Vellini et al., 2017). The most numerous group of studies and issues addressed by the authors of the studies within this thematic cluster are the life cycle inventories, which discuss all phases of the technology life cycle and describe the input (material and energy) and output flows (emissions) (Baharwani et al., 2014; Martínez-Corona et al., 2017; Tosti et al., 2020).

The last highlighted thematic cluster relates to the Environmental Impact of RES. Within it, research sub-areas such as Categories of Environmental Impacts of RES technologies, comparison of RES impacts with conventional technologies in their life cycle, and issues of RES development potential and their dynamic LCA are distinguished. Repeatedly, the research points to the multiplicity of RES impact categories assessed, where, in addition to GWP and EP, up to 18 impact categories commonly used in life cycle assessment are assessed (Tomasini-Montenegro et al., 2017). It has also been shown that, to date, only a few studies provide quantitative estimates of both the direct and indirect environmental impacts of the use of renewable sources, such as geothermal (Bayer et al., 2013). Studies comparing RES technologies with conventional energy production technologies show that for all renewable energy chains, the contribution of finite energy resources and greenhouse gas emissions is extremely low compared to conventional systems (Asdrubali et al., 2015). Further development of renewable technologies is an opportunity to reduce their already low environmental impact and meet increasingly stringent environmental regulations. Low-carbon technologies, such as nuclear power, are achieving similar results to renewables, such as photovoltaic modules (Fthenakis & Kim, 2007). In the study (Varun & Prakash, 2009) a review of existing life-cycle analyses of electricity generation systems based on renewable energy sources has been carried out. On the basis of one of those analyses, the extent of the carbon footprint of RES systems compared to conventional systems was identified to help rationalise the choice of energy supply systems.

## Future research directions

In addition to systematising research related to the issues addressed, the bibliometric analysis also aims to identify future research directions. The analysis of the available literature identified several main areas on which future research could focus. These include: life-cycle analysis of new types of RES devices, such as new types of batteries with unique capabilities or cogeneration systems, the role of artificial intelligence in data acquisition for LCI, machine learning for predicting the performance of RES installations and the efficiency of thermal energy storage, LCC-based optimisation using predictive models based on machine learning, the benefits of hybrid energy storage systems (HESS) in terms of LCA or estimating the degree of achievable energy self-sufficiency of buildings using GIS combined with LCA of their RES installations.

New technologies for the production of RES devices are one of the future research directions. One example is new technologies for the production of energy storage systems, which, as an important

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part of off-grid systems, make it possible to reduce the mismatch between the energy produced at the source and the energy demand. With the development of new types of batteries, the selection of a technically and economically suitable storage system, including its life, operating and maintenance costs, becomes an important part of life-cycle cost analyses of RES systems (Khanahmadi et al., 2021). Another example is new cogeneration systems, such as those using organic Rankine cycle (ORC) powered by solar energy, which can be successfully applied in areas where the distribution grid cannot or can only support the use of locally available and usable renewable energy sources (Mousavi et al., 2022). The life cycle inventory, on the other hand, as a key element of LCA analysis, is only as accurate as there is access to reliable data. The problem of data availability in terms of the set of inputs and outputs can be solved by using artificial intelligence techniques (Adedeji et al., 2020). This emphasises the need for cooperation between the public and private sectors. Another forward-looking research direction is the prediction of the performance of RES installations using machine learning (ML) models, potentially influencing an increase in the self-consumption of electricity from photovoltaic installations, which may have an impact on achieving better life-cycle cost optimisation results for these systems (Amini Toosi et al., 2023). Hybrid energy storage systems (HESS) are also playing an increasingly important role in LCA studies of RES systems, which, in Sweden, contribute to significant reductions in greenhouse gas emissions over the life cycle of systems powered by 100% renewable energy (Jiao & Månsson, 2023). Analyses using GIS (Geographic Information System) in combination with life cycle assessment analyses of RES equipment, e.g. photovoltaic installations, are also gaining popularity (Guillén-Lambea et al., 2023). This combination could represent a whole new line of research as a methodology for analysing urban renewable energy generation potential and its life-cycle environmental impact.

## Conclusions

The study aimed to identify current and future research directions related to the issue of Life Cycle Assessment of renewable energy technologies, mainly those used in residential buildings. Ever more stringent environmental requirements require an increasing share of renewable sources for electricity supply and heating. Achieving adequate energy efficiency in buildings already depends on the contribution of RES to their energy needs. In many countries, investments in RES are publicly subsidised and, therefore, widespread. However, there is still little public debate about their overall environmental impact, namely the impacts they cause throughout their life cycle.

The research carried out has allowed scientific and practical conclusions to be drawn and future research directions to be identified. The systematic review of the literature made it possible to identify the most important studies related to the chosen research area. It also allowed to monitor the appearance of new articles appearing in scientific databases. A review of the LCA articles of renewable energy sources shows the interdisciplinarity of the research carried out in this subject area and the relevance of the topic. The field is a priority area of interest for government institutions as well as the European Union. Among the trends for future research, new tools such as Artificial Intelligence and Machine Learning deserve special attention. The exclusion of terms related to biofuels, i.e. biogas, biomass and biodiesel, from the research query can be pointed out as limitations of this study. Also, the classification of thematic clusters as research areas, which were formed on the basis of the most frequent keywords in a number chosen arbitrarily by the author, may be considered subjective and constitute a limitation of the study.

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# OCENA CYKLU ŻYCIA ODNAWIALNYCH ŹRÓDEŁ ENERGII – KLUCZOWE ZAGADNIENIA. ANALIZA BIBLIOMETRYCZNA LITERATURY

STRESZCZENIE: Celem analizy jest usystematyzowanie badań naukowych związanych z zagadnieniem środowiskowej oceny cyklu życia (LCA) odnawialnych źródeł energii (OZE), identyfikacja kluczowych obszarów tematycznych oraz przyszłych kierunków badań. Zastosowano systematyczny przegląd literatury oparty na analizie bibliometrycznej publikacji zawartych w naukowych bazach danych. Zapytanie badawcze obejmowało rekordy zawierające w tytułach termin OZE lub nazwy poszczególnych technologii w połączeniu z terminem LCA. Analiza bibliometryczna ponad 1000 publikacji pozwoliła zidentyfikować cztery klastry tematyczne, podobszary badawcze oraz podać przykłady publikacji odnoszących się do nich. W rezultacie uzyskano szereg statystyk, takich jak struktura typów publikacji, produktywność autorów według ich narodowości czy udział dyscyplin naukowych. Analiza pozwoliła zidentyfikować najważniejsze publikacje w danym obszarze tematycznym. Przegląd wskazuje na interdyscyplinarność prowadzonych badań i istotność tematu.

SŁOWA KLUCZOWE: ocena cyklu życia, odnawialne źródła energii, kierunki badań, analiza biblio metryczna

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