

Green and Renewable Energy Innovations

Subjects: **Economics**

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Taking into account factors such as unfavorable climate changes, shrinking fossil fuel resources, low energy efficiency, and the pace of population growth, the transformation towards green and renewable energy is one of the most important goals and challenges facing the world. The energy sector is the source of about 75% of global greenhouse gas emissions and energy-related emissions are reaching new record levels. For the energy transition to succeed, innovation at the level of technology, business processes and policies (local, national, and international) are necessary.

green energy

renewable energy

innovation

1. Introduction

Population growth and the accompanying socio-economic development increase the demand for energy and energy-related services, as all societies need such services to meet basic human needs and improve human well-being, and to develop and support production processes ^[1]. In 2014, the total global consumption of primary energy amounted to approximately 160,310 million MWh, and it was predicted that this value would increase to 240,318 million MWh in 2040 ^[2]. Global reserves of fossil fuels are depleting very quickly: based on average global usage forecasts, it is assumed that oil and gas may last for 50 more years, and coal and uranium for about 100 more years ^[3]. Due to the long-term and very intensive use of non-renewable energy sources, there are also harmful effects on the environment, such as air pollution, climate change, and irreversible loss of natural resources.

The UN states that to keep global warming below 1.5 °C, emissions must be reduced by 45% until 2030 and to net zero by 2050 ^[4]. It is estimated that the energy sector is the source of about three-quarters of global greenhouse gas emissions ^[5]. Thus, the energy sector plays a fundamental and growing role in achieving the decarbonization of the economy ^[6]. Therefore, in May 2021, the International Energy Agency (IEA) published its monumental Net Zero by 2050 report, which assumes that the electricity sector must move from being the highest emitting sector in 2020 to the first sector to achieve net zero emissions by 2040 in the world ^[7]. At the same time, the IEA emphasizes that achieving this goal requires unprecedented efforts by all actors.

Decarbonization of the electricity sector is at the heart of the response to the threat of climate change. Therefore, the Paris Agreement underlines the urgent need for action in this area—in particular, the shift from fossil fuels to renewable energy and increasing energy efficiency ^[8]. This problem has also been included in the UN Sustainable Development Goals ^[9]. Goal 7 is to achieve universal access to affordable, reliable, and modern energy and to significantly increase the share of renewable energy in the energy mix. People's dependence on energy has

increased significantly, but energy poverty remains an international development challenge. As energy is a prerequisite for many aspects of modern life, lack of access reflects social and economic inequalities. However, it must be based on low-emission technological solutions that reduce greenhouse gas emissions, and thus improve living and health conditions and ensure sustainable development of life on the planet ^[9].

However, as the International Renewable Energy Agency (IRENA) highlights in its 2022 Tracking Report on Sustainable Development Goal 7 ^[10], the latest available data and selected energy scenarios show that at the current pace of progress, the world does not stand much chance of achieving any of the goals and metrics under SDG 7. This is especially true for the most vulnerable groups of countries, which from the beginning have been significantly lagging behind in this area. Worldwide, 91% of the population had access to electricity in 2020, still leaving 733 million people without access to electricity. According to forecasts, the problem of lack of access to electricity in 2030 will still affect 630 million people ^{[11][12]}.

Renewable energy is defined by the IPCC ^[13] as:

'(...) any form of energy from solar, geophysical, or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. Renewable energy is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes low carbon technologies such as solar energy, hydropower, wind, tide and waves and ocean thermal energy, as well as renewable fuels such as biomass'.

In many cases, the terms *renewable energy* and *green energy* are used interchangeably, but there are important differences between the terms. Green energy is a subset of renewable energy and includes resources that provide more environmental benefits as they come from natural sources such as the sun, water, and wind ^[14].

The International Energy Agency (IEA) proposes the following classification of renewable energy technologies based on their stage of development:

- First generation technologies, i.e., hydropower, biomass combustion, geothermal energy and heat;
- Second generation technologies, i.e., solar heating and cooling, wind energy, bioenergy, solar photovoltaics;
- Third generation technologies, i.e., thermal solar energy, ocean energy, geothermal energy, integrated bioenergy systems ^[15].

Globally, it is estimated that in 2008 renewable energy accounted for 12.9% of the total 492 exajoules (EJ) of primary energy supply ^[14]. Moreover, as the WHO report ^[16] shows, in 2010–2019 the share of renewable energy sources in total final energy consumption increased by only 2.7%. It was a good sign that although the COVID-19 pandemic had a bad effect on the energy transformation and stopped many green energy projects, in 2020 the use of renewable energy sources continued to grow and accounted for over 80% of all new electricity capacity added that year ^[17]. However, in 2021, the share of renewable energy sources in global electricity production reached only 28.7% (after a slight increase of 0.4%) resulting from the global electricity demand reaching its all-time high,

the slowdown in economic activity caused by COVID-19, and drought in several regions that reduced hydropower production [18].

2. Research Trends

As already signaled in the Introduction, innovation is one of the key elements of achieving SDG 7 and accelerating the development of green and renewable energy. Both from the perspective of science and practice, an in-depth understanding of scientific achievements in the field of green and renewable energy is of key importance [19].

The basic criterion for assessing the interest of researchers in a given scientific area and the dynamics of this interest is the number of publications and its distribution over the years [20][21][22][23][24]. **Figure 1** shows the number of published documents on green and renewable energy and innovation in 2012–2022. It is worth noting that there is an increasing trend in the number of scientists researching the topic of innovation in the field of green and renewable energy. This increase is particularly noticeable in the last three years, i.e., during the period of intensified discussions on the climate and energy crisis and the green transformation. As the problem of climate change and dwindling fossil resources becomes more urgent, the authors predict that this trend will continue into the future.

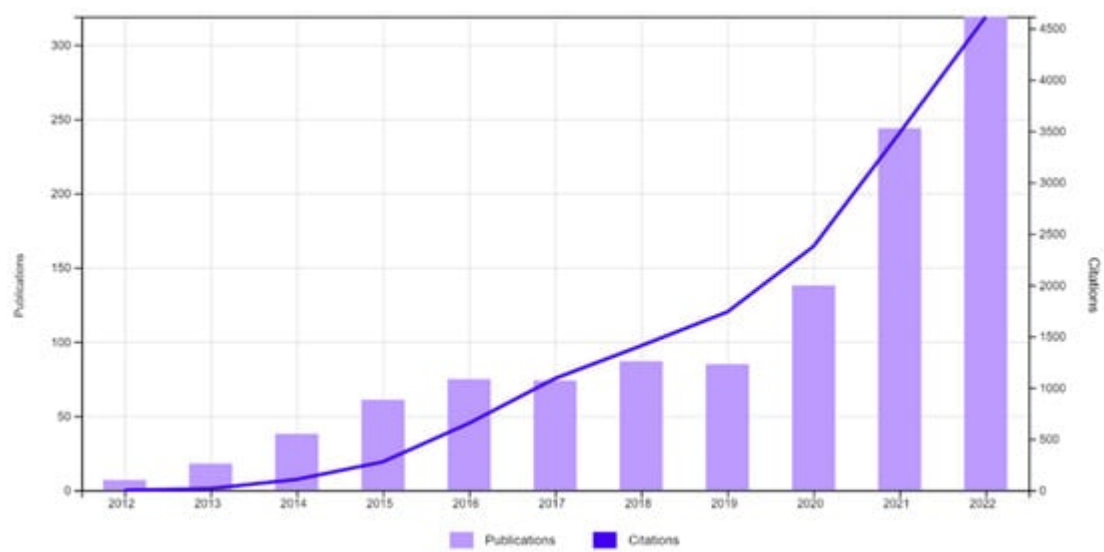


Figure 1. The number of documents on green and renewable energy and innovation and the number of citations of documents (2012–2022).

Table 1 presents the researchers who published at least four papers on green and renewable energy and innovation. The most productive authors in this rating with six articles are Jahid (University of Ottawa, Canada), Anser (Super Univ, Pakistan), and Alsharif (Sejong University, North Korea), followed by Cabeza (University of Lleida, Spain), Ahmad (Shandong University of Technology, China), Dincer (Istanbul Medipol University, Turkey), and Yüksel (Istanbul Medipol University, Turkey) with five papers on green and renewable energy innovation. Meanwhile, twelve authors each published four studies.

Table 1. The leading authors of documents on green and renewable energy and innovation.

Authors	No. of Papers	% of 1144	Citations
Jahid, Abu	6	0.5245	56
Anser, Muhammad Khalid	6	0.5245	32
Alsharif, Mohammed H.	6	0.5245	27
Cabeza, Luisa F.	5	0.4371	390
Ahmad, Mahmood	5	0.4371	20
Dincer, Hasan	5	0.4371	11
Yuksel, Serhat	5	0.4371	11
Coma, Julia	4	0.3497	361
Perez, Gabriel	4	0.3497	361
Stucki, Tobias	4	0.3497	156
Sarkodie, Samuel Asumadu	4	0.3497	121
Asif, Muhammad	4	0.3497	119
Kharel, Rupak	4	0.3497	109
Zgid, Dominika	4	0.3497	106
Kaiwartya, Omprakash	4	0.3497	94
Sun, Huaping	4	0.3497	42
Olah, Judit	4	0.3497	26
Nassani, Abdelmohsen A.	4	0.3497	7
Zaman, Khalid	4	0.3497	7

As **Table 2** shows, the most popular journals in the field of green and renewable energy and innovation are *Energies* (MDPI, IF: 3.252) with 19 publications and 961 citations, *Sustainability* (MDPI, IF: 3.889) with 91 publications and 650 citations, and *IEEE Access* (IEEE, IF: 3.476) with 40 published articles and 551 citations. They are followed by the *Environmental Science and Pollution Research* (Springer Heidelberg, IF: 5.19) with 36 articles and 281 citations and the *Frontiers in Environmental Science* (Frontiers Media SA, IF: 5.411) with 31 papers and 83 citations.

Table 2. Top 20 journals with articles on green and renewable energy and innovation.

Journal	No. of Papers % of 1144 Citations		
Energies	119	10.402	961
Sustainability	91	7.955	650
IEEE Access	40	3.497	551
Environmental Science and Pollution Research	36	3.147	281
Frontiers in Environmental Science	31	2.710	83
Energy Reports	26	2.273	79
Energy Policy	19	1.661	739
Economic Research-Ekonomska Istrazivanja	16	1.399	80
Frontiers in Energy Research	16	1.399	48
Applied Energy	15	1.311	845
Applied Sciences-Basel	11	0.962	73
IEEE Journal on Selected Areas in Communications	9	0.787	444
Renewable Energy	9	0.787	305
Journal of Cleaner Production	9	0.787	262
Energy Economics	7	0.612	290
International Journal of Environmental Research and Public Health	7	0.612	47
Renewable and Sustainable Energy Reviews	6	0.524	147
Energy Strategy Reviews	6	0.524	58
Mathematical Problems in Engineering	6	0.524	21
Heliyon	5	0.437	27

[25][26][27]. **Table 3**
renewable

energy innovations. The most productive authors in this area are from the People's Republic of China with 363 papers (which is 31% of all papers on green and renewable energy innovations). Moreover, important study in this area has been carried out in the USA and England (approximately 10% and 8% of review articles, respectively). **Figure 3** shows a geographical map of 93 countries in accordance with the number of published articles.

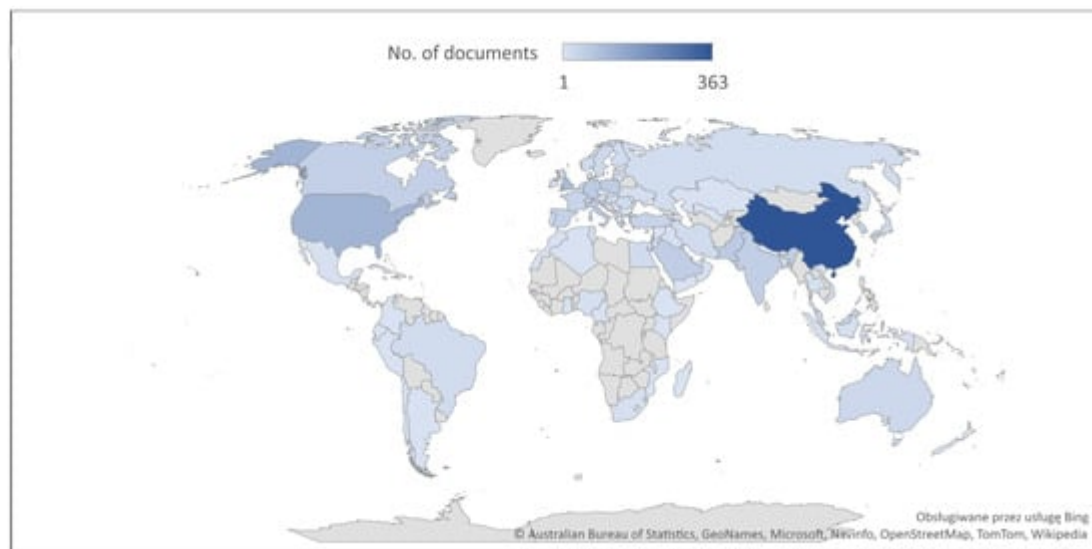


Figure 3. A map of countries in accordance with the number of published articles on green and renewable energy and innovation.

Table 3. Documents on green and renewable energy and innovation by country.

Country	No. of Papers	% of 1144	Citations
Peoples Republic of China	363	31.731	4182
USA	118	10.315	3009
England	102	8.916	2619
Italy	71	6.206	867
Pakistan	63	5.507	814
Germany	60	5.245	1607
Poland	55	4.808	343
Saudi Arabia	54	4.720	970
India	51	4.458	525
Canada	49	4.283	1197
Spain	45	3.934	937
South Korea	41	3.584	667
Turkey	40	3.497	643
Malaysia	38	3.322	425

Country	No. of Papers	% of 1144	Citations
France	36	3.147	603
Taiwan	33	2.885	190
Netherlands	29	2.535	658
Australia	28	2.448	365
Sweden	27	2.360	357
Switzerland	23	2.010	921

the results of the citation analysis of authors, institutions, and countries. **Figure 4** shows data with a minimum of three documents and 100 institutions meeting the thresholds.

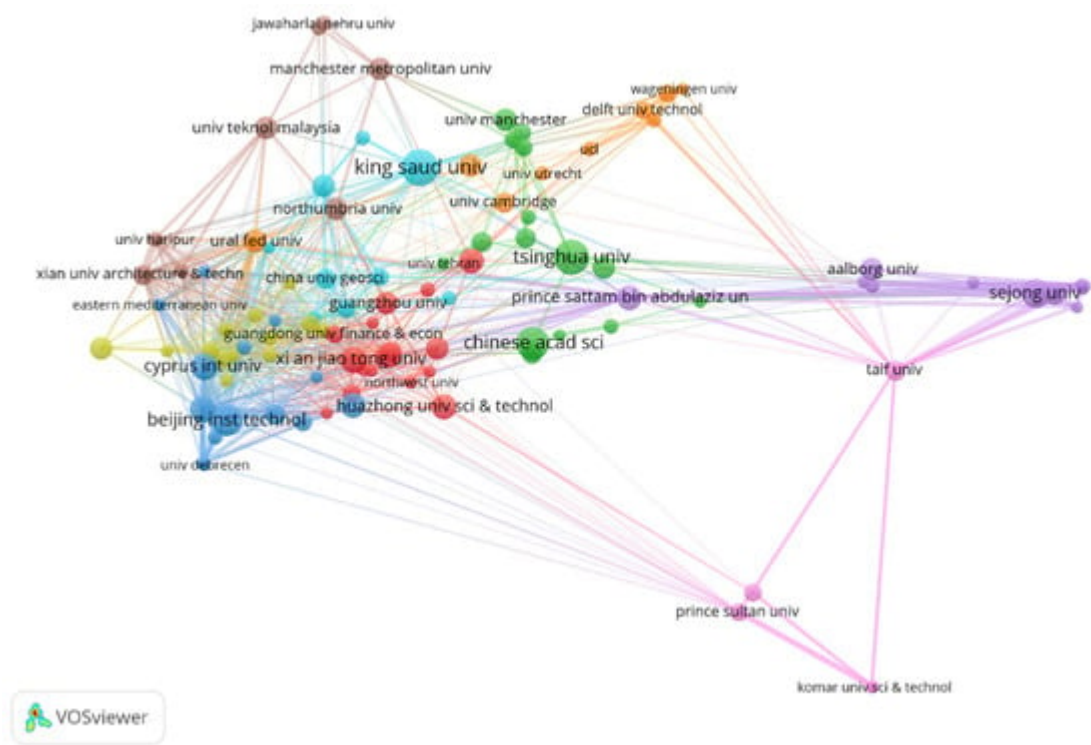


Figure 4. Bibliographic coupling of organizations.

Table 4 presents the most frequently cited articles from the research area under study. It is worth noting that there is a very good representativeness of studies published in the last decade (2012–2022) [28][29][30][31][32][33][34][35][36][37]. This is confirmed by the fact that the topic of innovation in the field of green and renewable energy is a development topic. Moreover, the importance of some studies, such as Richter [35] and Lehr et al. [36], indicate that this topic began to appear in the 2000s, but a particularly dynamic increase in the number of studies in this field could be observed from 2015.

Table 4. Most cited articles.

Article	Year	Author(s)	Citations	Citations per Year
Green preparation of reduced graphene oxide for sensing and energy storage applications	2014	Bo et al.	390	48.75
Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm	2017	van Vuuren et al.	324	64.80
Tailoring the energy landscape in quasi-2D halide perovskites enables efficient green-light emission	2017	Quan et al.	316	63.2
Energy-efficient base-stations sleep-mode techniques in green cellular networks: A survey	2015	Wu et al.	260	37.14
Tubular graphitic-C3N4: A prospective material for energy storage and green photocatalysis	2013	Tahir et al.	207	23.00
Renewable energy-driven innovative energy-efficient desalination technologies	2014	Ghaffour et al.	191	23.87
Green scheduling of a two-machine flowshop: Trade-off between makespan and energy consumption	2016	Mansouri et al.	175	29.16
Business model innovation for sustainable energy: German utilities and renewable energy	2013	Richter	168	18.67
Green jobs? Economic impacts of renewable energy in Germany	2012	Lehr et al.	166	16.60
Vertical greenery systems for energy savings in buildings: A comparative study between green walls and green facades	2017	Coma et al.	159	31.80

technique, as reported by Albort-Morant et al. [20] describes the key authors, often cited with other authors. **Figure 5** shows a citation map where each circle represents a document, and the size of the circle corresponds to the number of citations [38].

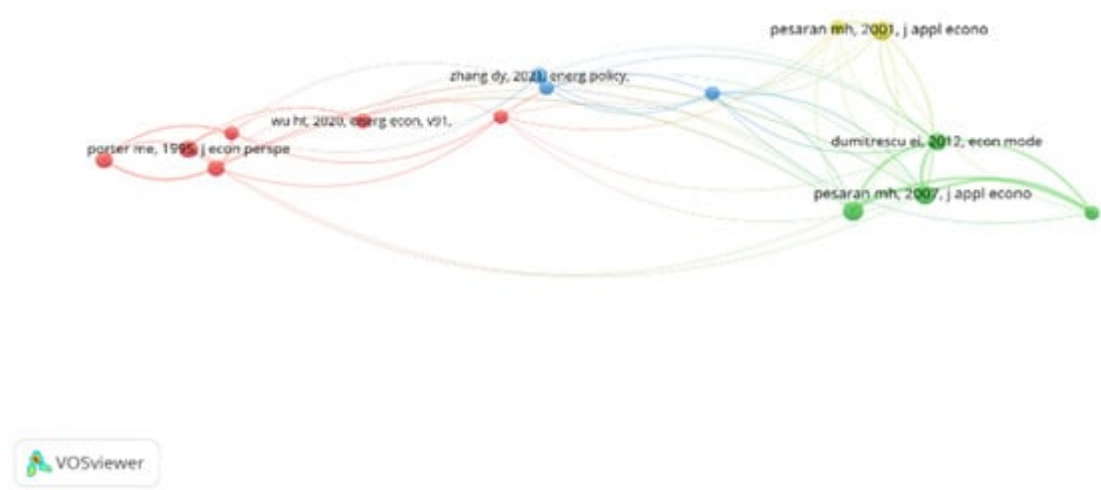


Figure 5. Co-citation of references map.

The analysis defined four clusters of papers that cited each other. The red cluster shows research that mainly concerns the environment–competitiveness relationship [39], renewable energy and technological innovations [40], and energy-saving innovations [41]. The green cluster shows studies that relate to the panel unit root test, as described in [42], and diagnostic tests for cross-sectional relationships in panels, as in [43]. The blue cluster covers the topics of green public finance and sustainable green finance [44], CO₂ emissions in the context of economic growth and renewable energy production [45] and energy poverty and energy efficiency [46]. The yellow cluster focuses on research methods [47][48].

In the next step, the technique of bibliographic coupling of authors was employed to identify active researchers in the field and provides a view of the research structure of the front of the field. Of the 4194 authors, researchers selected those with a minimum of three publications and 10 citations. Only 44 authors met the threshold. **Figure 6a** presents the authors bibliographic coupling map. To make the map more readable researchers created two more showing the four defined clusters more precisely. **Figure 6b** presents the first three clusters, and **Figure 6c** presents the fourth cluster, namely:

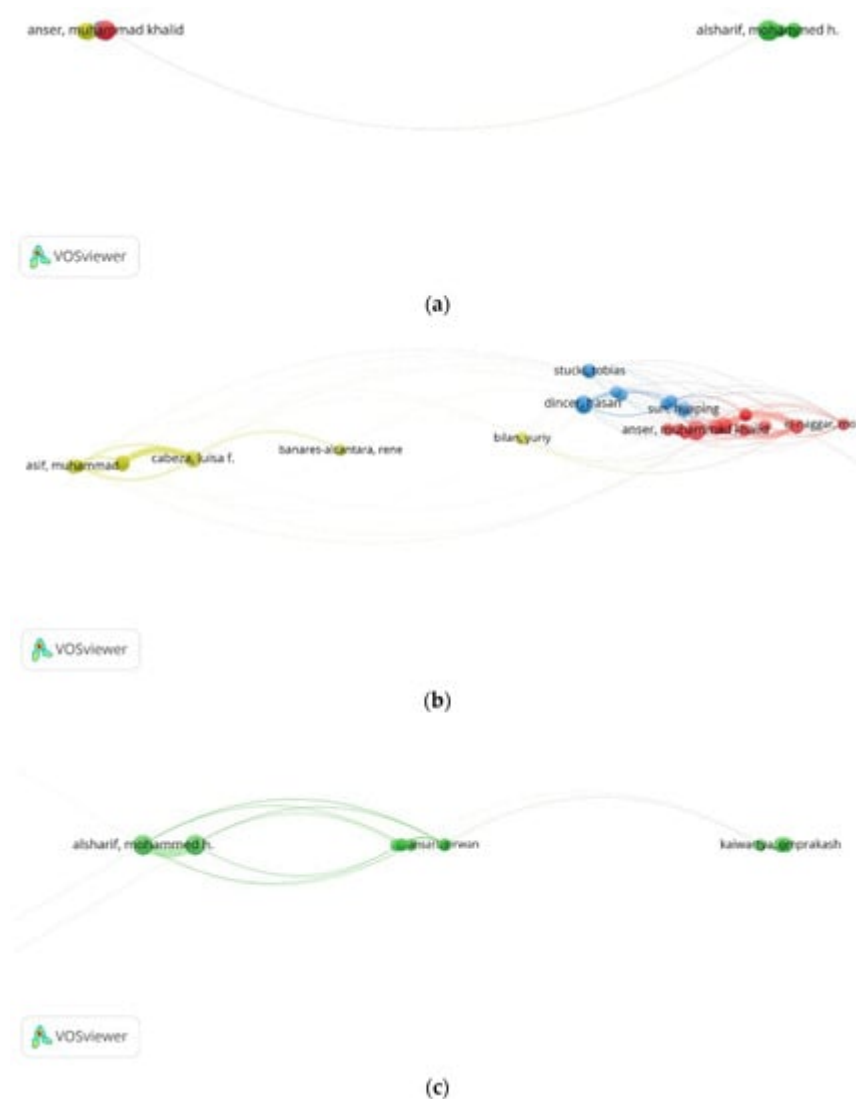


Figure 6. (a) Authors bibliographic coupling map. (b) Authors bibliographic coupling map—clusters 1–3. (c) Authors bibliographic coupling map—cluster 4.

- The red cluster with 12 authors led by Anser M.K. (Shandong University of Technology, China), Ahmad M. (Super Univ, Pakistan), and Olah J. (University of Johannesburg, South Africa) focuses on financial, technological, and social aspects of green transformation.
- The blue cluster represented by nine authors, such as Dincer H. (Istanbul Mediapol University, Turkey), Stucki T. (Bern University of Applied Sciences, Switzerland), and Sun H. (Tianjin University of Commerce, China), focuses research on green and renewable energy policy and economics.
- The yellow cluster covers eight authors including Asif M. (Glasgow Caledonian University, UK), Cabez L.F. (University of Lleida, Spain), and Coma J. (University of Lleida, Spain), whose research focuses on energy aspects of sustainable and green buildings as well as technological aspects of the green transformation.
- The green cluster includes 11 authors led by Ansharif MA (Sejong University, South Korea), Ansari N. (New Jersey Institute of Technology, US), and Kaiwartya O (Nottingham Trent University, UK), who focus their research on such themes as mobile and cellular networks or sensors for green computing.

Following Phillips et al. [48], in order to illustrate the geographic allocation of knowledge, bibliographic coupling of countries was used. **Figure 7** shows three clusters in relation to the network of countries defined as a result of the analysis. The green cluster includes Asian countries under the strong leadership of the People's Republic of China supported by Latin America (Mexico and Brazil), South Africa, and Canada. Another cluster, red, combines research from the United States and European Union (mostly Italy, Germany, Poland, and France) with contribution from Israel and Egypt. In the blue cluster, the most productive countries are England, Saudi Arabia, Spain, Malaysia, and Australia.

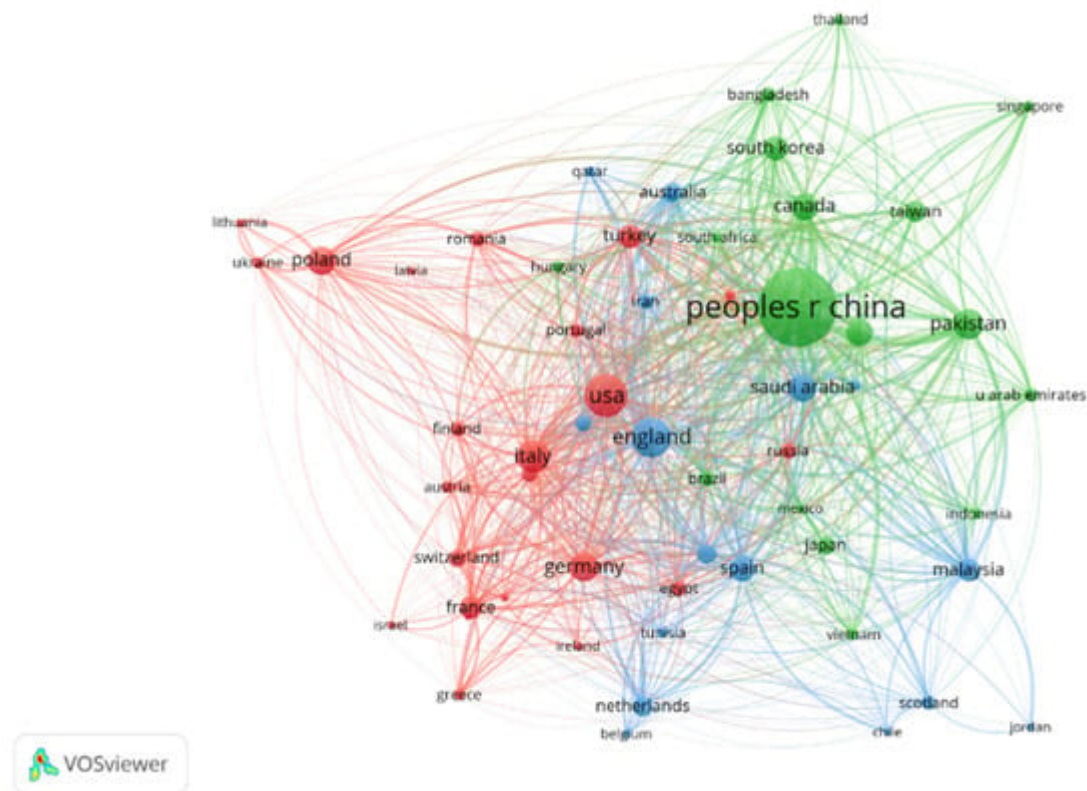


Figure 7. Bibliographic coupling of countries.

The analysis of the author's keywords is also very important due to the fact that the keywords correspond to the context of the publication and thus define the main topics and research trends [\[49\]](#).

Figure 8 shows the most common author keywords and the author keyword network in articles. The minimum number of author keywords for a co-occurrence map is five and the minimum cluster size is specified as 12. The author's most popular keywords are *renewable energy* (131), *energy efficiency* (90), *green energy* (57), *energy consumption* (40), and *sustainable development* (34). The identified 92 author's keywords were classified into four clusters.

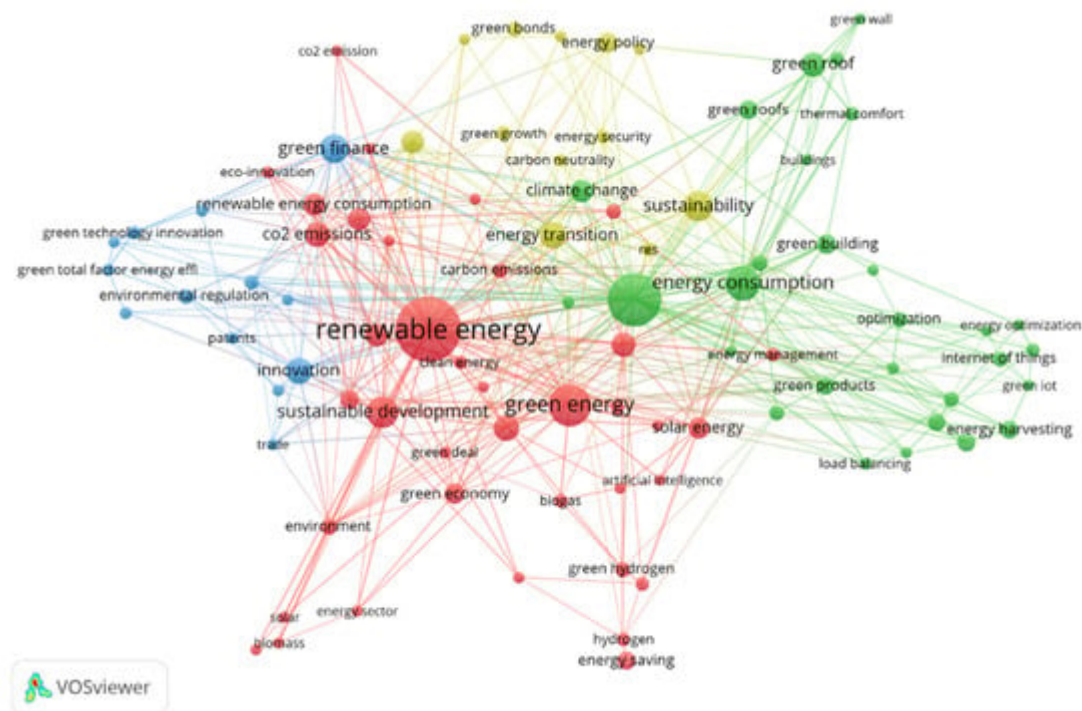


Figure 8. Co-occurrence map (keywords network).

- The red cluster (38 keywords) encapsulates such terms as *renewable energy* and *green energy* followed by *sustainable development*, *CO₂ emissions*, *solar energy*, *green economy*, *environmental sustainability*, *green innovation*, *renewable energy sources*, and *technological innovation*, which led to the naming of this cluster as “renewable technology innovations”.
- The green cluster (29 keywords) revolves around the terms *energy efficiency* and *energy consumption*, followed by *the green roof*, *green products*, *climate change*, *green building*, *energy harvesting*, *smart grid*, *green communication*, and *optimization*, which led to the naming of this cluster as “energy consumption efficiency and sustainability”.
- The blue cluster (13 keywords) revolves around the terms *green finance*, *innovation*, and *environmental regulation*, followed by *patents*, *green technology innovation*, *financial development*, *energy intensity*, and *environmental policy*, which led to the naming of this cluster as “renewable energy innovations ecosystem”.
- The yellow cluster (12 keywords) revolves around the terms *sustainability*, *energy transition*, and *economic growth*, followed by *energy policy*, *green bonds*, *green growth*, *energy security*, and *carbon neutrality*, which led to the naming of this cluster as “renewable energy innovation investments”.

Using the same map, **Figure 9** shows the chronological evolution of research topics. Thanks to this, it is possible to identify the most current topics in the researched area, which turn out to be green finance, green innovations, renewable energy consumption, CO₂ emission, and carbon neutrality, while energy efficiency related to green construction or energy harvesting have been the main topics of interest in the previous decade.



Figure 10 presents the most cited journals. The best three journals in the researched area are *Energies*, *Sustainability*, and *IEEE Access*. These journals appear as the most important sources in green and renewable energy research (in the innovation context) and can be helpful for further research and also to the identification of consistent journals on green energy and renewable energy.



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