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An analysis on the research trend and usage of Renewable Energy Sources (RES) for the EU Countries and the Balkans

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Abstract

To tackle climate change challenges, expanding renewable energy sources is crucial. After the initiation of the REPower EU plan, studying the recent scientific research trend according to specific criteria, such as country location or economic status, helps identify current challenges and set new priorities. Within this concept, we conducted bibliometric research from 1 January 2022 to 23 November 2025, focusing on renewable energy sources such as wind energy, solar energy, biomass and hydroelectricity for the case of EU member countries and the Balkans. Furthermore, we compared the bibliometric results with variables such as renewable energy penetration and GDP. Results revealed that the current research focuses primarily on solar and wind energy. The research focuses largely on new technological advances, energy storage technologies, socio-economic aspects, and the concept of sustainability. Specifically, the subjects most studied regarding biomass are its annual variation, agricultural biomass, and edible biomass. Concerning solar energy, the most intensively studied topics are module automation, energy efficiency, and energy storage. Concerning hydroelectricity, the hot topics are reservoirs and optimisation technologies. Regarding wind energy, the recent trend is focused on wind turbine technology, aerodynamics, and economic aspects. Our analysis concludes that the Balkan countries focus on leveraging their competitive advantages in solar and hydro energy due to their geographic characteristics and location. Meanwhile, EU member countries are now focusing on technological advancements and are also showing growing interest in biomass investments.

Keywords: Renewable Energy, Bibliometric Analysis, European Union, Balkans, VOSviewer, Economic Growth.

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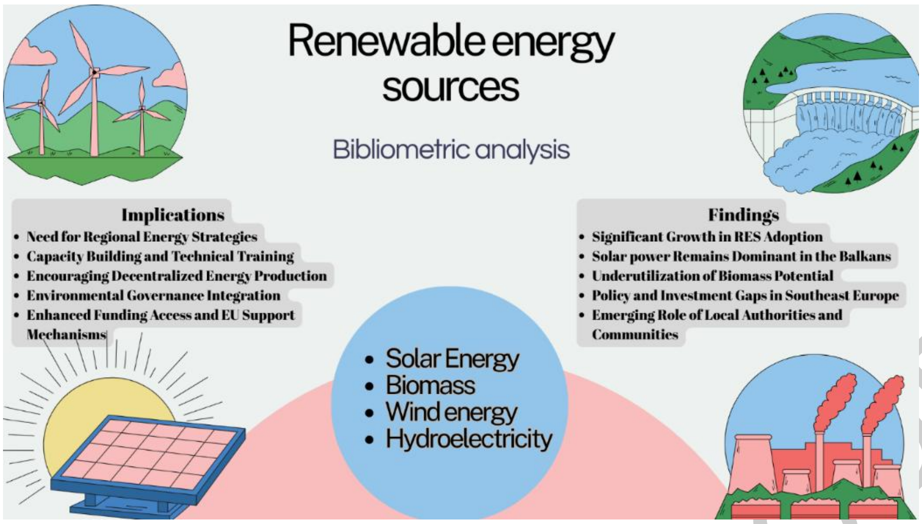
Graphical abstract



1. Introduction

Climate change represents the most significant global challenge (Hao & Shao, 2021). The planet is approaching the 1.5°C threshold, and the world population needs to substantially reduce greenhouse gas (GHG) emissions by around 43% by 2030 to avoid exceeding this threshold with a probability of over 50% (IPCC, 2023). The primary cause of climate change is GHG emissions from fossil fuel-based energy production (Hao & Shao, 2021). Therefore, the inevitable course is the decarbonization of global energy systems. The ongoing transition to low-carbon societies and economies, driven by sustainable and renewable energy sources (RES), is essential in mitigating climate change, in line with commitments made through the Paris Agreement (Kapica *et al.*, 2021). To achieve the 1.5°C goal, the global proportion of renewable sources in electricity generation must increase from 26% in 2019 to 90% by 2050 (IRENA, 2022a). In the current service-oriented environment, people need widespread access to modern energy services that meet a variety of social needs (World Health Organisation *et al.*, 2023), while businesses require the development of renewable energy sources and gradually shift to SDG-oriented strategies (Sitompul *et al.*, 2024).

The European Union already holds a prominent global position in promoting and implementing renewable energy technologies. However, there is potential to enhance its competitiveness further in global renewable energy markets. Embedded in the European Green Deal, renewable energy is crucial to the transition to clean energy, according to the REPower EU project (European Commission, 2022), which aims to end the EU's reliance on Russian Natural Gas and promote green energy by 2030.

Within the European setting, the development of the energy industry also poses a significant challenge for the Balkan countries. The countries in the Balkan region have become increasingly aware of the importance of transitioning to RES to ensure energy security, reduce greenhouse gas emissions, and promote sustainable development (Duraskovic, 2021). Although the potential for development is significant, there are certain limitations to the widespread adoption of renewable resources in the Balkans. These include the need to modernize energy networks, properly manage water resources for hydroelectric power plants, and overcome obstacles to financing and regulation (IRENA, 2022b). High reliance on energy imports poses a significant energy security challenge, with 35% of consumption sourced from imports (Eurostat, 2025a). A common characteristic of the region is a significant dependence on fossil fuels, especially coal, which accounts for 47% of total primary energy supply and negatively impacts the environment (World Bank, 2018). Thus, there is also a significant potential to diversify renewable energy sources and transition to a sustainable environment in the Balkan countries by overcoming the barriers they face.

Our main goal is to examine recent research trends on renewable energy sources in the EU and Balkan countries. We focus on the period from January 1, 2022, when the Repower EU project was announced and began, to November 23, 2025, which is the most recent date for available data in this study.

This paper is structured into three parts: In the first part, we perform a literature review of the various types of renewable energy sources. In the second part, we present the two-part research methodology: a bibliometric analysis using VOSviewer and a descriptive analysis using MS Excel. The analysis covers solar, wind, biomass, and hydropower energy. The third part includes the discussion and conclusion sections.

This article builds on earlier bibliometric studies of RES research, such as Rosokhata *et al.* (2021) and Bortoluzzi *et al.* (2021), but introduces three new design choices. First, it focuses on the period after the REPowerEU policy (from 1

January 2022 to 23 November 2025) to reflect changes in research following the 2022 energy security crisis. Second, it analyzes both the EU-27 and the wider Balkan region together, including non-EU Balkan countries that are often overlooked in EU-focused studies. Third, it combines VOSviewer bibliometric mapping with Eurostat data on RES penetration and GDP per capita to highlight where research activity and RES deployment do not align at the country level. This approach leads to four distinct country profiles, which are discussed in Section 4.2 along with related policy recommendations.

2. Literature review

According to Dirma *et al.* (2024), renewable energy comes from natural processes such as wind and solar power, hydropower, and crops and forests. It can be easily converted into electrical energy. Renewable energy falls under the concept of sustainable development (Waisman *et al.*, 2019) and through the prism of specific technical characteristics and geographical availability (Verbruggen *et al.*, 2010). Thus, aspects such as the ability to satisfy market demand, technical characteristics, such as integration with other sources, and economic feasibility, derived from energy efficiency and operating costs (Peirow *et al.*, 2023), can assist decision-makers in choosing a specific renewable energy source. Rapid global population growth and lifestyle changes have accelerated energy consumption (Fragkos *et al.*, 2024). Transitioning to renewable energy sources is crucial in reducing carbon dioxide emissions and addressing the energy crisis (Adekoya *et al.*, 2021; Li *et al.*, 2022; Suman, 2021).

Furthermore, a significant proportion of global greenhouse gas emissions comes from energy production, so it is indispensable to consider transitioning to renewable energy sources (Bibri, 2020). According to Bulmer and Prado-Higuera (2023), to achieve sustainable development objectives, the aim is to strengthen the means and instruments for implementing projects by realizing global partnerships. Thus, these aspects are fundamental and must be followed to develop and diversify renewable energy sources, which are part of the 17 Sustainable Development Goals set by the UN.

The various renewable energy types and their usage have been the subject of studies (Duraskovic *et al.*, 2021; Ntanos *et al.*, 2018; Skordoulis *et al.*, 2020), but research is also conducted to identify the most practical form of renewable energy regarding the analysis of variables such as geographical location (Aksoy, 2019), wind and solar potential (Loukakis *et al.*, 2017), crops favoring renewable energy generation and multicriteria methods to select the optimal renewable energy type. As a result, decision-makers are presented with options within each renewable energy source to adopt and improve the traditional fossil-fuel-based system (Bortoluzzi *et al.*, 2021). Research conducted by Arabatzis, Aggelopoulos, and Tsiantikoudis (2010) highlights that, to improve the competitiveness of communities, diversification across economic, social, and environmental factors is essential, along with providing services that enhance residents' quality of life while preserving the natural environment. To efficiently use electricity and reduce consumption, updating field processes is necessary. Thus, investing in energy efficiency is also recommended (Karakosta & Papapostolou, 2023).

According to the European Green Deal and the REPowerEU project, decarbonizing the primary energy-consuming sectors (transportation, industry, households) and minimizing the use of fossil fuels in energy are top priorities, as the share of renewables in the energy mix should be increased (Ah-Voun *et al.*, 2024). The dependence of accessibility and domestic production contributes to reducing Europe's dependence on external suppliers (Vezzoni, 2023). Consequently, the EU regularly reviews its aspirations to increase the share of renewable sources in its energy mix. Accompanied by the implementation of necessary measures to promote energy savings, the EU achieved a reduction in final energy consumption in 2023 (Eurostat, 2025a).

Given the urgent need for a rapid transition to renewable energy in the EU, driven by Repower EU and the European Green Deal, this study uses bibliometric analysis to examine recent research topics on common renewable energy sources—biomass, solar, hydropower, and wind—in EU and Balkan countries from January 2022 to November 2025. **Table 1** summarizes earlier research on these topics up to 2022. The following paragraphs briefly present this previous research, highlighting the main types of renewable energy sources and key scientific issues before our analysis period.

Solar energy stands out as one of the most significant renewable energy sources and has been used for a long time to generate electricity, reshaping the construction landscape and opening the way to a more ecological and energy-efficient future. (Wolniak & Skotnicka-Zasadzien, 2022). This renewable energy source is abundant in most regions and can be efficiently converted into a valuable form of energy using photovoltaic (PV) panels installed on rooftops or the ground (Dai *et al.*, 2022). Solar PVs are a widespread type of renewable energy investment in the EU (Wolniak & Skotnicka-Zasadzieńm, 2022). PV integration has gained significant traction due to its ability to convert solar energy into green electricity (Peng *et al.*, 2022). According to Skordoulis *et al.* (2020), approximately 55% of a Greek sample would invest in using PV due to the location of facilities.

Hydropower is closely interconnected with water resource management and renewable energy production, playing a significant role in sustainable development in a world where billions of people lack access to safe drinking water and adequate energy sources (Kaygusuz, 2009; Yuksel, 2009). On the other hand, about 1.6 billion people lack access to electricity, and about 1.1 billion face water supply deficiencies. Tefera and Kasiviswanathan (2022) highlight that, while global hydropower resources are abundant, only a portion is both economically feasible and environmentally sustainable, suggesting significant opportunities for practical hydropower development. The potential exists in about 150 countries, and about 60% of the economically feasible potential remains untapped, especially in developing countries, where the needs are most pressing (IEA, 2021). Hydropower is a renewable energy source with multiple advantages, including clean operation, low GHG emissions, and long-term sustainability (Wang *et al.*, 2022). The availability of water resources in many regions increases the feasibility of hydropower as a means of achieving sustainability goals.

Table 1. Renewable Energy Sources – Scientific Research indicative topics up to year 2022.

RES Type	Reference (Short)	Main Focus
Wind Energy	Serban *et al.* (2020)	Wind potential assessment using Weibull & Rayleigh models
	Dlzar *et al.* (2020)	Grid stability, storage, smart loads with wind penetration
	Ellenbogen *et al.* (2012)	Health impacts of wind turbines
	Esteban *et al.* (2011)	Rationale for offshore wind development
	Jurasz, Kies & De Felice (2022)	Solar–wind complementarity
	Kapica, Canales & Jurasz (2021)	Global atlas of solar–wind complementarity
	Tafarte, Eichhorn & Thrän (2019)	Capacity expansion pathways for wind–solar systems
	Tuerk *et al.* (2013)	Wind RES deployment in the Balkans
Solar Energy	Dai *et al.* (2022)	Wind loads on rooftop solar panels
	El-Khawad *et al.* (2022)	End-of-life management of PV panels
	Peng *et al.* (2022)	Wind loading characteristics for rooftop PV
	Perea-Moreno *et al.* (2017)	Rooftop suitability for solar collectors
	Skordoulis *et al.* (2020)	Public willingness to invest in PV in Greece
	Wolniak & Skotnicka-Zasadzień (2022)	PV development across EU countries
Biomass	Manzano Agugliaro (2007)	Gasification of greenhouse residues
	Perea-Moreno *et al.* (2018)	Sunflower husk biomass heating system
	Shah *et al.* (2018)	Biomass residues for biofuel production
Hydropower	Kaygusuz (2009)	Hydropower in sustainable development
	Wang *et al.* (2022)	Decarbonisation with hydropower & pumped storage
	Yuksel (2009)	Hydropower and dams for sustainability
	Tefera & Kasiviswanathan (2022)	Global hydropower potential
	IEA (2021)	Hydropower market trends
Hybrid (Multi-RES)	Zhang *et al.* (2022)	Hydropower-solar-wind hybrid configurations
	Mehedintu *et al.* (2018)	Share of RES in final energy consumption
	Muresan & Attia (2017)	Energy efficiency in residential buildings

Biomass includes "all the organic matter in the biosphere, including plant and animal resources and materials obtained through natural or artificial processes of transformation" (Mehedintu *et al.*, 2018; Muresan & Attia, 2017). Biomass can be found in various materials, including wood, sawdust, straw, seed residues, animal manure, waste paper, household waste, wastewater, and others (Manzano, 2007; Perea-Moreno *et al.*, 2018; Shah *et al.*, 2018).

Wind energy represents an essential element in the decarbonization process and the promotion of the energy system's sustainability, contributing significantly to sustainable development objectives (Dlzar, 2020). Integrating wind energy into the energy system allows for diversification of the energy mix, reducing dependence on traditional sources and contributing to the construction of a more robust and flexible network infrastructure (Serban, 2020).

According to a bibliometric analysis by Rosokhata *et al.* (2021), there was a steady increase in research interest in renewables during 2006-2020, with the subject becoming increasingly pursued and relevant, particularly in developed countries that invest significantly in this sector. The emphasis was on the economic trends driven by renewable energy and the technologies used to produce it. The global spread of adopting more sustainable paradigms has been driven by increased awareness of the adverse environmental impacts of unsustainable economic growth (Dobrea, 2023). The efficient and sustainable use of energy resources is a means to ensure sustainable economic growth across various regions (Zafeiriou *et al.*, 2022).

3. Methodology

In this research, bibliometric analysis was used to investigate the main topics addressed in the scientific literature on RES for the period 1 January 2022 to 23 November 2025, and to analyze the interdependencies among the variables in this sector. It is important to note that the time period coincides with the stage at which the European Union significantly intensified the energy transition through the REPowerEU strategy. Launched in 2022, this plan aimed to reduce dependence on fossil fuels, accelerate the adoption of renewable energy, and stimulate investment in technologies such as solar, wind, biomass, and hydro. Therefore, the research directions identified in the Scopus data directly reflect the political and scientific priorities of this strategic period, providing an accurate picture of recent developments in renewable energy.

The research began by analyzing the literature on the most commonly used renewable energy sources, including photovoltaic panels, biomass, hydropower, and wind energy. The countries included in our research are presented in **Table 2**.

Table 2. Countries included in the analysis.

Nr.crt.	Country	European Union	Balkan Area
1	Austria	Yes	No
2	Belgium	Yes	No
3	*Bulgaria*	Yes	Yes
4	*Croatia*	Yes	Yes
5	Cyprus	Yes	No
6	Czechia	Yes	No
7	Denmark	Yes	No
8	Estonia	Yes	No
9	Finland	Yes	No
10	France	Yes	No
11	Germany	Yes	No
12	*Greece*	Yes	Yes
13	Hungary	Yes	No
14	Ireland	Yes	No
15	Italy	Yes	No
16	Latvia	Yes	No
17	Lithuania	Yes	No
18	Luxembourg	Yes	No
19	Malta	Yes	No
20	Netherlands	Yes	No
21	Poland	Yes	No
22	Portugal	Yes	No
23	*Romania*	Yes	Yes
24	Slovakia	Yes	No
25	*Slovenia*	Yes	Yes
26	Spain	Yes	No
27	Sweden	Yes	No
28	Bosnia and Herzegovina	No	Yes
29	Montenegro	No	Yes
30	North Macedonia	No	Yes
31	Albania	No	Yes
32	Serbia	No	Yes
33	Moldova	No	Yes

Source: Authors based on information provided by the European Commission, both EU and Balkan members in Italics.

Table 2 covers the 27 EU Member States and 6 non-EU Balkan countries (Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, Serbia, and Moldova), for a total of 33 countries. Five of the EU-27—Bulgaria, Croatia, Greece, Romania, and Slovenia—are also considered Balkan countries based on geography and history, so they are counted as both EU and Balkan in our analysis. The other 22 EU countries are classified as EU-only, and the 6 non-EU countries are Balkan-only. The earlier mention of “EU-37” was a typo and should be “EU-27.” Moldova is grouped with the Balkans because it is part of the Energy Community of South East Europe and is aligning more closely with EU energy policy, though we recognize that some sources do not consider Moldova part of the Balkan peninsula in a strict geographical sense.

3.1. *Bibliometric Analysis*

In the first part of the analysis, a bibliometric analysis is the chosen research method to develop an illustrative map of the field of study. This evaluates researchers' interest in renewable energy using quantitative approaches (Dabic *et al.*, 2020). In addition to this aspect, it offers a perspective on the period in which scientific researchers have investigated and deepened the field. In this research, we chose bibliometric analysis to highlight and evaluate the correlations between the research on renewable energy sources. We examined the articles’ content using the Scopus database and VOSviewer software.

The VOSviewer software tool was designed by Van Eck and Waltman (2010) and uses an algorithm called "similarity visualization" between various elements. These elements can include countries, keywords, journals, authors, and other bibliometric data extracted from scientific databases, as in the research by Wong *et al.* (2020). In that research, VOSviewer software was used to analyze keyword correlations. Because the data source plays a vital role in conducting a bibliometric analysis, data from the specialized literature were collected from the Scopus database. This database was used to generate the results for the VOSviewer software and for the second part of this work's analysis, which identified the number of publications in a reference period for renewable energy in the European Union and the Balkan countries.

Table 3. Literature review stages and keywords in Scopus.

Stage	Content	Description
Stage 1	Scientific database	Scopus
	Indexation	All
	Date	23.11.2025
	Period	1 January 2022 – 23 November 2025
	Searchedkeywords	TITLE-ABS-KEY (wind AND energy) AND PUBYEAR > 2021 AND PUBYEAR < 2026
		TITLE-ABS-KEY (solar AND energy) AND PUBYEAR > 2021 AND PUBYEAR < 2026
		TITLE-ABS-KEY (biomass AND energy) AND PUBYEAR > 2021 AND PUBYEAR < 2026
		TITLE-ABS-KEY (hydroelectric AND power) AND PUBYEAR > 2021 AND PUBYEAR < 2026
	Initial result	⇨ 9316 documents
		⇨ 16.405 documents
		⇨ 6331 documents
		⇨ 1067 documents
	Refiningstages	
Stage 2	Language	English ⇨ 9140 documents
		English ⇨ 16.242 documents
		English ⇨ 6274 documents
		English ⇨ 1011 documents
Stage 3	Country/ territory	TITLE-ABS-KEY (wind AND energy) AND PUBYEAR > 2021 AND PUBYEAR < 2026 AND (LIMIT-TO (AFFILCOUNTRY , "Italy") OR LIMIT-TO (AFFILCOUNTRY , "Germany") OR LIMIT-TO (AFFILCOUNTRY , "Spain") OR LIMIT-TO (AFFILCOUNTRY , "Poland") OR LIMIT-TO (AFFILCOUNTRY , "France") OR LIMIT-TO (AFFILCOUNTRY , "Portugal") OR LIMIT-TO (AFFILCOUNTRY , "Romania") OR LIMIT-TO (AFFILCOUNTRY , "Greece") OR LIMIT-TO (AFFILCOUNTRY , "Austria") OR LIMIT-TO (AFFILCOUNTRY , "Ireland") OR LIMIT-TO (AFFILCOUNTRY , "Croatia") OR LIMIT-TO (AFFILCOUNTRY , "Hungary") OR LIMIT-TO (AFFILCOUNTRY , "Slovakia") OR LIMIT-TO (AFFILCOUNTRY , "Latvia") OR LIMIT-TO (AFFILCOUNTRY , "Lithuania") OR LIMIT-TO (AFFILCOUNTRY , "Cyprus") OR LIMIT-TO (AFFILCOUNTRY , "Estonia") OR LIMIT-TO (AFFILCOUNTRY , "Slovenia") OR LIMIT-TO (AFFILCOUNTRY , "Bulgaria") OR LIMIT-TO (AFFILCOUNTRY , "Denmark") OR LIMIT-TO (AFFILCOUNTRY , "Netherlands") OR LIMIT-TO (AFFILCOUNTRY , "Sweden") OR LIMIT-TO (AFFILCOUNTRY , "Belgium") OR LIMIT-TO (AFFILCOUNTRY , "Finland") OR LIMIT-TO (AFFILCOUNTRY , "Czech Republic") OR LIMIT-TO (AFFILCOUNTRY , "Malta") OR LIMIT-TO (AFFILCOUNTRY , "Luxembourg") OR LIMIT-TO (AFFILCOUNTRY , "Bosnia and Herzegovina") OR LIMIT-TO (AFFILCOUNTRY , "North Macedonia") OR LIMIT-TO (AFFILCOUNTRY , "Montenegro")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))
		TITLE-ABS-KEY (solar AND energy) AND PUBYEAR > 2021 AND PUBYEAR < 2026 AND (LIMIT-TO (AFFILCOUNTRY , "Italy") OR LIMIT-TO (AFFILCOUNTRY , "Germany") OR LIMIT-TO (AFFILCOUNTRY , "Spain") OR LIMIT-TO (AFFILCOUNTRY , "Poland") OR LIMIT-TO (AFFILCOUNTRY , "France") OR LIMIT-TO (AFFILCOUNTRY , "Portugal") OR LIMIT-TO (AFFILCOUNTRY , "Romania") OR LIMIT-TO (AFFILCOUNTRY , "Greece") OR LIMIT-TO (AFFILCOUNTRY , "Austria") OR LIMIT-TO (AFFILCOUNTRY , "Ireland") OR LIMIT-TO (AFFILCOUNTRY , "Croatia") OR LIMIT-TO (AFFILCOUNTRY , "Hungary") OR LIMIT-TO (AFFILCOUNTRY , "Slovakia") OR LIMIT-TO (AFFILCOUNTRY , "Latvia") OR LIMIT-TO (AFFILCOUNTRY , "Lithuania") OR LIMIT-TO (AFFILCOUNTRY , "Cyprus") OR LIMIT-TO (AFFILCOUNTRY , "Estonia") OR LIMIT-TO (AFFILCOUNTRY , "Slovenia") OR LIMIT-TO (AFFILCOUNTRY , "Bulgaria") OR LIMIT-TO (AFFILCOUNTRY , "Denmark") OR LIMIT-TO (AFFILCOUNTRY , "Netherlands") OR LIMIT-TO (AFFILCOUNTRY , "Sweden") OR LIMIT-TO (AFFILCOUNTRY , "Belgium") OR LIMIT-TO (AFFILCOUNTRY , "Finland") OR LIMIT-TO (AFFILCOUNTRY , "Czech Republic") OR LIMIT-TO (AFFILCOUNTRY , "Malta") OR LIMIT-TO (AFFILCOUNTRY , "Luxembourg") OR LIMIT-TO (AFFILCOUNTRY , "Bosnia and Herzegovina") OR LIMIT-TO (AFFILCOUNTRY , "North Macedonia") OR LIMIT-TO (AFFILCOUNTRY , "Montenegro")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))

	TITLE-ABS-KEY (biomass AND energy) AND PUBYEAR > 2021 AND PUBYEAR < 2026 AND (LIMIT-TO (AFFILCOUNTRY , "Italy") OR LIMIT-TO (AFFILCOUNTRY , "Germany") OR LIMIT-TO (AFFILCOUNTRY , "Spain") OR LIMIT-TO (AFFILCOUNTRY , "Poland") OR LIMIT-TO (AFFILCOUNTRY , "France") OR LIMIT-TO (AFFILCOUNTRY , "Portugal") OR LIMIT-TO (AFFILCOUNTRY , "Romania") OR LIMIT-TO (AFFILCOUNTRY , "Greece") OR LIMIT-TO (AFFILCOUNTRY , "Austria") OR LIMIT-TO (AFFILCOUNTRY , "Ireland") OR LIMIT-TO (AFFILCOUNTRY , "Croatia") OR LIMIT-TO (AFFILCOUNTRY , "Hungary") OR LIMIT-TO (AFFILCOUNTRY , "Slovakia") OR LIMIT-TO (AFFILCOUNTRY , "Latvia") OR LIMIT-TO (AFFILCOUNTRY , "Lithuania") OR LIMIT-TO (AFFILCOUNTRY , "Cyprus") OR LIMIT-TO (AFFILCOUNTRY , "Estonia") OR LIMIT-TO (AFFILCOUNTRY , "Slovenia") OR LIMIT-TO (AFFILCOUNTRY , "Bulgaria") OR LIMIT-TO (AFFILCOUNTRY , "Denmark") OR LIMIT-TO (AFFILCOUNTRY , "Netherlands") OR LIMIT-TO (AFFILCOUNTRY , "Sweden") OR LIMIT-TO (AFFILCOUNTRY , "Belgium") OR LIMIT-TO (AFFILCOUNTRY , "Finland") OR LIMIT-TO (AFFILCOUNTRY , "Czech Republic") OR LIMIT-TO (AFFILCOUNTRY , "Malta") OR LIMIT-TO (AFFILCOUNTRY , "Luxembourg") OR LIMIT-TO (AFFILCOUNTRY , "Bosnia and Herzegovina") OR LIMIT-TO (AFFILCOUNTRY , "North Macedonia") OR LIMIT-TO (AFFILCOUNTRY , "Montenegro")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))
	TITLE-ABS-KEY (hydroelectric AND power) AND PUBYEAR > 2021 AND PUBYEAR < 2026 AND (LIMIT-TO (AFFILCOUNTRY , "Italy") OR LIMIT-TO (AFFILCOUNTRY , "Germany") OR LIMIT-TO (AFFILCOUNTRY , "Spain") OR LIMIT-TO (AFFILCOUNTRY , "Poland") OR LIMIT-TO (AFFILCOUNTRY , "France") OR LIMIT-TO (AFFILCOUNTRY , "Portugal") OR LIMIT-TO (AFFILCOUNTRY , "Romania") OR LIMIT-TO (AFFILCOUNTRY , "Greece") OR LIMIT-TO (AFFILCOUNTRY , "Austria") OR LIMIT-TO (AFFILCOUNTRY , "Ireland") OR LIMIT-TO (AFFILCOUNTRY , "Croatia") OR LIMIT-TO (AFFILCOUNTRY , "Hungary") OR LIMIT-TO (AFFILCOUNTRY , "Slovakia") OR LIMIT-TO (AFFILCOUNTRY , "Latvia") OR LIMIT-TO (AFFILCOUNTRY , "Lithuania") OR LIMIT-TO (AFFILCOUNTRY , "Cyprus") OR LIMIT-TO (AFFILCOUNTRY , "Estonia") OR LIMIT-TO (AFFILCOUNTRY , "Slovenia") OR LIMIT-TO (AFFILCOUNTRY , "Bulgaria") OR LIMIT-TO (AFFILCOUNTRY , "Denmark") OR LIMIT-TO (AFFILCOUNTRY , "Netherlands") OR LIMIT-TO (AFFILCOUNTRY , "Sweden") OR LIMIT-TO (AFFILCOUNTRY , "Belgium") OR LIMIT-TO (AFFILCOUNTRY , "Finland") OR LIMIT-TO (AFFILCOUNTRY , "Czech Republic") OR LIMIT-TO (AFFILCOUNTRY , "Malta") OR LIMIT-TO (AFFILCOUNTRY , "Luxembourg") OR LIMIT-TO (AFFILCOUNTRY , "Bosnia and Herzegovina") OR LIMIT-TO (AFFILCOUNTRY , "North Macedonia") OR LIMIT-TO (AFFILCOUNTRY , "Montenegro")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))

Source: Authors based on information provided by Scopus.

The Scopus database was chosen for the research for its high-quality coverage, a wide range of research fields, approximately 1.7 billion citations, reliability in data access, and excellent coverage in the field of interest, respectively, renewable energy sources (Harzing & Alakangas, 2016).

During the literature review process, keywords were searched in the "Article title, Abstract, Keywords" section of the Scopus database. The search comprised a primary keyword and associated sub-keywords, which may be synonymous or used for the four primary types of renewable energy sources: "wind energy", "solar energy", "biomass energy", and "hydroelectric power". In addition to the keywords used, a period was established in the literature review process for accessing research from 1 January 2022 to 23 November 2025.

According to the search criteria in the Scopus database, 32,667 documents were retrieved, as presented in **Table 3**.

3.2. *Descriptive analysis*

In the second part of our research, we used secondary data from the Eurostat database to examine renewable energy penetration in final energy consumption relative to gross domestic product per capita. Such an approach is applicable in relevant research (Ntanos *et al.*, 2018). The secondary data were extracted from the Eurostat database for 2023 (Eurostat, 2025b; 2025c), the latest year available.

For the descriptive analysis, the following variables were used:

1. The percentage of renewable energy sources in total electricity used (% RES) was collected from the Eurostat database for each of the 33 analyzed countries in 2023 (Eurostat, 2025b).
2. Gross domestic product per capita for the 33 countries. The data for this variable were taken from the Eurostat database, valid for 2023 (Eurostat, 2025c).
3. The total number of publications for each renewable energy source in each of the 33 countries of our sample. In a broader search conducted in the reference period of 2022-2025 on the Scopus Database, 7755 research items were tagged as biomass renewable energy sources, 1236 as hydropower, 12051 as wind, and 20837 as solar

energy. These results represent the total number of publications on each energy source in the analyzed countries.

In **Table 4**, we provide a description of each variable to better understand its significance in the subsequent descriptive analysis.

Table 4. Description of variables used in descriptive analysis.

Description of variables	SPSS coding
Percentage (%) of RES in total energy sources per country	% of RES on total energy
The number of publications with the search keyword "biomass" according to the Scopus database	PUBS_biomass
The number of publications with the search keyword "hydroelectricity" according to the Scopus database	PUBS_hydroelectricity
The number of publications with the search keyword "wind" according to the Scopus database	PUBS_wind
The number of publications with the search keyword "photovoltaic panels" according to the Scopus database	PUBS_PV
Gross domestic product for each country in the EU and the Balkan area countries	GDP_CAP

Source: Author's contribution

3.3. *Reproducibility, deduplication, VOSviewer parameters, and Scopus limitations*

For reproducibility, the four exact Scopus query strings used in Stage 3 of the literature review are reported in full in **Table 3** including all Boolean operators (AND, OR), the country (AFFILCOUNTRY) filters for the 33 sample countries, the document-type filter (DOCTYPE = “ar”, i.e. peer-reviewed articles only) and the language filter (LANGUAGE = “English”). All queries were run on Scopus on 23 November 2025, with PUBYEAR > 2021 AND PUBYEAR < 2026, i.e. covering publications dated 2022–2025.

The four queries (wind, solar, biomass, hydroelectric) were executed independently in Scopus, and the column “PUBS_Total RES” in **Table 5** is the arithmetic sum of the four technology-specific counts per country, not the result of a separate unified query. We do not deduplicate across the four sub-queries: a single multi-technology study (e.g. an article appearing in both the wind and the solar query results because it contains both terms in the title/abstract/keywords) is therefore counted in each technology where it qualifies and contributes to PUBS_Total RES more than once. We treat this as a feature rather than a defect of the indicator, since each technology-specific share is intended to capture research presence in that technology, but we explicitly acknowledge that PUBS_Total RES is therefore an upper bound rather than a unique-document count, and that the technology-specific shares overstate single-technology specialization in countries with high multi-technology output. A robustness check using the Scopus “remove duplicates” functionality on the merged record set indicates that the inflation in PUBS_Total RES due to overlap is in the order of 10–15% for high-output EU countries (Germany, Spain, Italy) and below 5% for the smaller Balkan economies, where multi-technology output is rare. The relative ranking of countries is robust to this correction.

For the VOSviewer co-occurrence maps reported in Section 4.1 (**Figures 1–4**), the analysis settings were as follows. Type of analysis: “co-occurrence” with the unit of analysis set to “all keywords” (combining author keywords and Scopus index keywords). Counting method: full counting (every co-occurrence between two keywords within the same publication is counted once). Minimum number of occurrences of a keyword: 5. Maximum number of keywords selected for visualization: 1,000 per map (the top-N by total link strength among the keywords meeting the minimum-occurrence threshold). Clustering algorithm: VOSviewer’s default modularity-based clustering with resolution parameter 1.0 and minimum cluster size 1. Layout: VOS layout, default attraction (2) and repulsion (0). All maps were generated with VOSviewer version 1.6.20.

Three limitations of the data sources should be noted up-front. First, Scopus has well-documented coverage biases: peer-reviewed journals indexed in Scopus are predominantly English-language and concentrated in the global research mainstream, which may underrepresent regional Balkan journals that publish primarily in local languages and are not Scopus-indexed (Mongeon & Paul-Hus, 2016; Harzing & Alakangas, 2016). The publication counts reported here for Balkan countries are therefore likely to be lower bounds on actual research output, and the EU/Balkan publication gap may be smaller than **Figure 5** suggests. Second, our descriptive analysis is cross-sectional (Eurostat 2023 reference year) and is therefore not informative about temporal lead/lag relationships between research output and RES penetration; we return to this in the “Limitations and future work” subsection of Section 5. Third, our analysis treats publications as a proxy for research activity but does not weight them by impact (citations) or by author affiliation share; this is a deliberate methodological simplification that future work could refine.

Compared with previous bibliometric studies of RES research (e.g. Bortoluzzi *et al.*, 2021; Rosokhata *et al.*, 2021), the contribution of the present article is threefold: (i) the joint EU–Balkan focus, framed by REPowerEU as the policy-period anchor; (ii) the systematic integration of bibliometric VOSviewer mapping with Eurostat indicators on RES penetration and GDP per capita at the country level for the same 2022–2025 window; and (iii) the explicit identification of mismatch profiles between research intensity and RES deployment, which we operationalise in

Section 4.2 below. We make no claim that any single component is novel in isolation, but we argue that the combined design and the post-REPowerEU period are not previously covered in the bibliometric literature on RES.

Closing this section, our comprehensive approach, which included both bibliometric and descriptive analysis, has proven to be a challenging framework for an in-depth field investigation. The careful selection of methods and data criteria has provided us with a detailed perspective on the evolution of research and the themes it has addressed.

In the next section, we will present the results obtained, highlighting significant clusters and emerging trends in the field, thereby making a significant contribution to understanding the research landscape in this domain. Additionally, the results of the descriptive analysis will be presented in accordance with the conducted analysis.

4. Results and discussion

4.1. *Bibliometric analysis on the various forms of RES for the EU and the Balkans (2022-2025)*

This section presents the classification of the 18,361 articles selected after the applied Scopus search, under the RES keyword. **Figure 1** shows the common groups in the same color; the lines indicate relations with other concepts, and the size of the circles indicates the impact/frequency of the concept (Van Eck & Waltman, 2010). Wind energy is one of the most dynamic and mature technologies in the renewable energy sector, known for its high potential to produce low-carbon electricity. Over the last decade, scientific interest in this source has grown significantly, reflecting the expansion of onshore and offshore wind farms, technological advances in turbines, and the need for their efficient integration into modern energy systems. This analysis examines the thematic structure of research in the field, based on keyword networks identified in the Scopus database.

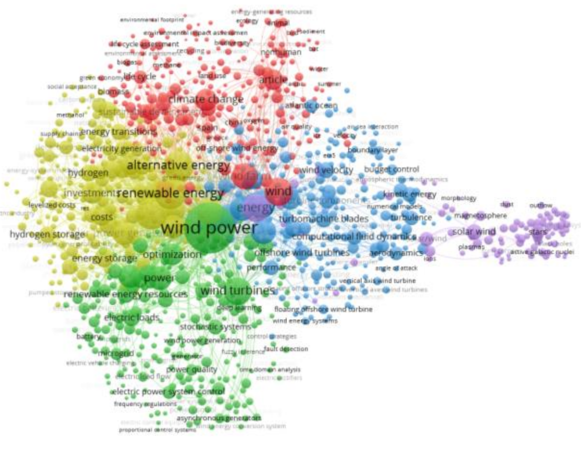


Figure 1. Network visualization map of co-occurrence of keywords (wind power) (Source: created by authors with VOSviewer).

The interconnections of **Figure 1** between keywords associated with wind energy are based on a search conducted in the Scopus database. Of the 9,140 publications identified for the period analyzed, 1,000 were included in the visualization, of which 984 were grouped into five major clusters, representing the main directions of research on wind energy as a renewable energy source.

The red cluster, located in the upper left, captures the technical and mechanical components of wind energy. The presence of the terms "wind turbines", "offshore wind turbines", "aerodynamics", "turbine blades" and "velocity" reflects researchers' interest in optimizing turbine performance, improving aerodynamic behavior, and developing offshore infrastructure, where wind potential is significantly higher.

The green cluster, located on the right, depicts the integration of wind energy into modern electricity grids. Terms such as "electric power system control", "reactive power", "microgrid", "power quality", and "optimal power flows" show the importance of grid stability and infrastructure adaptation to manage the variable output of wind-generated energy.

The yellow cluster, located in the central area, highlights the economic, strategic, and energy dimensions of the wind sector. Keywords such as "alternative energy", "renewable energy", "energy storage", "hydrogen", "investment", and "energy transition" indicate a concern for decarbonization, economic sustainability, and the integration of wind energy into the national and European energy mix.

The blue cluster, positioned in the upper right, brings together topics related to meteorology, wind potential, and the marine environment. Terms such as "wind velocity", "atmospheric boundary layer", "weather forecasting" and "Atlantic Ocean" suggest research focused on estimating wind resources, which are essential for optimal turbine placement and production modelling.

The purple cluster on the far right is the most specialized. It includes research on atmospheric physics and solar phenomena, including terms such as "solar wind", "plasma", "magnetosphere" and "cosmic rays". This cluster, although peripheral, highlights studies on the influences of complex atmospheric phenomena on wind dynamics and the functioning of wind infrastructure.

Overall, the map structure shows that wind energy is a well-developed field, characterized by thematic diversity and strong interconnections between technical, economic, climatic, and systemic components. The results confirm the essential role of wind energy in the global energy transition and the development of a sustainable, flexible energy system.

Continuing the analysis dedicated to wind energy, it is important to broaden our perspective on how different renewable sources contribute to the sustainable energy mix.

The next step in the study focuses on solar energy, with its thematic structure and research developments presented in the section dedicated to this technology and depicted in **Figure 2**.

The network structure of keywords associated with solar energy in **Figure 2** is based on a bibliometric analysis conducted using Scopus. A total of 16,242 articles were identified, from which VOSviewer extracted 45,038 keywords. Applying a minimum threshold of 5 occurrences yielded 4,907 eligible terms. However, the final visualization was limited to 1,000 keywords, representing the most relevant terms based on the frequency and intensity of links in the network. This step is specific to VOSviewer and guarantees a readable map focused on the main research directions.

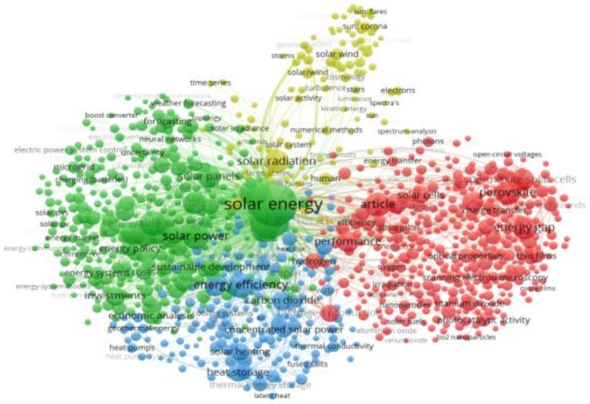


Figure 2. Network visualization map of co-occurrence of keywords (solar energy) (Source: created by authors with VOSviewer).

The total number of the 1,000 selected keywords were grouped into five major thematic clusters, illustrating the diversity and maturity of the solar energy field.

The green cluster, located on the left, captures the integration of solar energy into modern energy systems. Terms such as "solar power", "solar panels", "microgrid", "charging (batteries)", "renewable energy" and "energy policy" reflect concerns about practical applicability, connection to smart grids, and the adaptation of infrastructure to photovoltaic production.

The blue cluster at the bottom highlights research on energy efficiency and storage solutions. Terms such as "energy efficiency", "heat storage", "thermal energy storage", "concentrated solar power" and "economic analysis" show interest in improving system performance, thermal energy management, and evaluating the costs associated with solar technologies.

The red cluster, located on the right, focuses on the development of advanced materials for solar cells. The terms "solar cells", "photovoltaics", "perovskite", "thin films," "energy gap", and "nanoparticles" indicate a clear focus on optimizing photovoltaic conversion through emerging technologies and innovative nanomaterials.

The yellow cluster at the top groups together research on solar radiation and solar phenomena. The presence of the terms "solar radiation", "solar wind", "sunspots", "cosmic rays", and "solar activity" indicates an interest in modelling solar resources, radiation variations, and their impact on energy production.

The purple cluster, located on the right side of the map, brings together topics related to the development of advanced materials and the optimization of photovoltaic conversion, which represent the technological foundation of solar energy. Terms such as "solar cells", "photovoltaics", "perovskite", "thin films", "charge transfer", "energy gap" and "nanoparticles" show that research is focused on improving solar cell performance, the efficiency of converting light into energy, and the processing of semiconductor materials. This cluster reflects the cutting-edge directions in the field, where new generations of solar cells with high efficiency, increased stability, and reduced costs are being developed. Overall, the purple cluster highlights the innovative dimension of solar energy, where advances in materials accelerate the transition to more efficient and affordable photovoltaic technologies.

Analysis of the keyword network visualization indicates that solar energy is a vast, technical, and interdisciplinary field of research, supported by a substantial body of publications. The five clusters identified reflect the main directions of development: integrating solar energy into innovative energy systems, improving energy efficiency and storage, advancing solar cell materials, modelling solar radiation, and using predictive methods to estimate production. The interconnection of these themes confirms the field's maturity and the essential role of solar energy in the transition to a sustainable energy system.

Overall, the results highlight both technological progress and the diversity of solar energy solutions, from industrial applications and advanced materials to integration into smart grids and efficient resource prediction. This complexity confirms the central role of solar energy in the current context of European and global energy policies.

The analysis of solar energy highlighted the technological diversity and complexity of the processes by which solar radiation is converted into sound energy, emphasizing the role of this resource in the energy transition. To complete the overview of renewable sources, it is also necessary to address biomass, a resource with distinct characteristics that combines biological, technological, and energy components in ways distinct from those of solar energy.

Next, the section on biomass analyses how this resource contributes to the sustainable energy mix and current climate goals and the bibliometrics are presented in the following **Figure 3**.

Figure 3 presents the network of keywords related to the field of biomass, derived from a selection of 6,274 articles in the Scopus database filtered for the analyzed period. From the total number of extracted terms, VOSviewer selected 1,000 keywords with the highest frequency and relevance, distributed across five thematic clusters, highlighting the diversity and complexity of the bioenergy field.

The yellow cluster, located in the center, is dominated by the term "biomass" and covers general topics related to its role in sustainable development, its impact on climate change, and its integration into the renewable energy mix. Terms such as "renewable energy", "sustainable development", "climate change", "carbon cycle", and "bioenergy" show the direct connection between biomass used for energy and the goals of reducing emissions and energy transition.

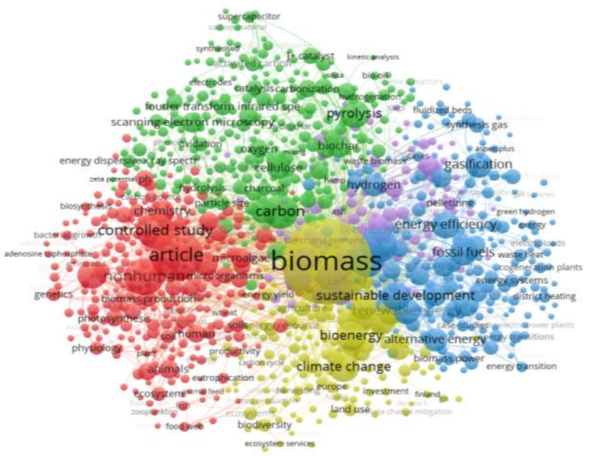


Figure 3. Network visualization map of co-occurrence of keywords (biomass) (Source: created by authors with VOSviewer).

The red cluster, located on the left, reflects the biological and microbiological dimension of biomass. The presence of terms such as "microorganisms", "biosynthesis", "genetics", "photosynthesis", "bacterial growth" and "controlled study" indicates research focused on biological processes that generate biomass resources, including studies of microbial cultures, cellular processes, and bioproduction. This cluster covers the fundamental area of biomass as a biological resource.

The green cluster at the top focuses on chemical transformations and biomass processing. Terms such as "pyrolysis", "hydrogen", "activated carbon", "biochar", "catalysis", "synthesis gas" and "fluidized beds" indicate an interest in thermochemical processes and materials resulting from various types of conversion. The cluster indicates a strong technological focus on the production of advanced fuels and functional materials from biomass.

The blue cluster, positioned on the right, captures the integration of biomass into energy and technological systems. Terms such as "energy efficiency", "cogeneration plants", "biomass power", "renewable energy systems", "fossil fuels" and "district heating" suggest applied research on the conversion of biomass into electrical and thermal energy, its role in the energy transition, and performance comparisons with fossil fuels.

The purple cluster, located on the right side of the map, brings together topics related to integrating biomass into modern energy systems and optimizing energy performance. It includes terms such as "energy efficiency", "biomass power", "cogeneration plants", "district heating", "renewable energy systems" and "electric loads", indicating a clear focus on the applied uses of biomass in electricity and heat production. Research in this cluster focuses on how biomass can improve energy efficiency, replace fossil fuels, and modernize existing infrastructure, particularly in cogeneration and district heating systems. These directions highlight the purple cluster's role as a practical and feasible solution for transitioning to a cleaner, more sustainable energy system.

Overall, the visualization highlights a highly diverse field in which biomass is studied simultaneously as a biological resource, a chemical material, a renewable fuel, and a strategic element in modern energy systems. The structure of the clusters shows that biomass represents a bridge between fundamental research in life sciences, energy engineering, climate studies, and sustainable development policies. The complexity of the topics confirms the importance of biomass in the energy transition and in the development of alternative solutions with low environmental impact.

Figure 4 shows a complex network of keywords associated with hydropower, based on a selection of 1,011 scientific articles from the Scopus database. Of the 9,057 terms extracted, 693 met the minimum-occurrence threshold and were automatically grouped into eight distinct clusters, highlighting both the field's diversity and the interdependencies between research topics.

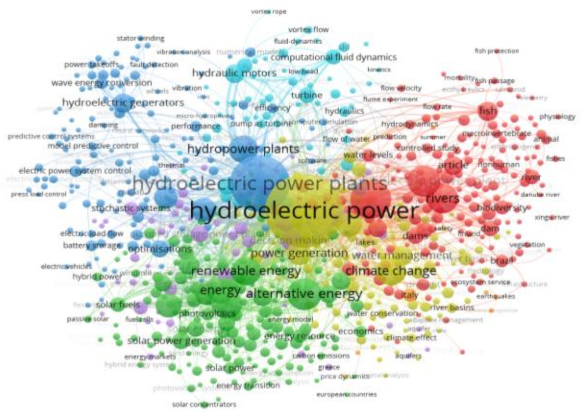


Figure 4. Network visualization map of co-occurrence of keywords (hydroelectric power) (Source: created by authors with VOSviewer).

The blue cluster, located in the center-left, is technical and includes topics such as "electric power system control", "stochastic systems", "load flow", "battery storage", "hybrid power" and "wave energy conversion". This cluster highlights the integration of hydropower into modern electricity grids, the optimization of energy flows and the development of hybrid systems.

The green cluster at the bottom highlights the relationship between hydropower and other renewable sources, as well as the energy transition. Terms such as "renewable energy", "solar power generation", "energy transition", "photovoltaics" and "hybrid energy systems" indicate that hydropower is analyzed in combination with other renewable technologies to ensure energy stability and flexibility.

The red cluster on the right includes ecological, hydrological, and water resource management topics. Keywords such as "rivers", "dam", "fish", "biodiversity", "ecosystem services", "river basin" and "water management" highlight concerns about the impact of hydropower plants on aquatic ecosystems, biodiversity, and hydrological regimes.

The yellow cluster, positioned centrally, focuses on sustainability, climate change, and socio-economic aspects. Terms such as "climate change", "water conservation", "ecosystem services", "economic analysis" and "decision making" show that hydropower is also evaluated from the perspective of climate change adaptation and socio-economic impacts.

The turquoise cluster at the top is highly technical, dedicated to fluid dynamics and turbine performance. Terms such as "hydraulic turbines", "hydrodynamics", "vortex rope", "fluid dynamics", "turbine performance" and "numerical models" indicate advanced research on turbine optimization, flow dynamics, and hydraulic energy conversion efficiency.

The purple cluster, also located at the top but more centrally, is focused on efficiency and control. Terms such as "efficiency", "pump as turbine", "predictive control", "low head turbines", and "simulation" indicate a concern for the technological optimization of hydroelectric systems.

The orange cluster, located on the periphery, includes topics related to hydrological risks, the environment, and extreme events—earthquakes, floods, hydrology, and disaster management—highlighting that hydropower is also analyzed in terms of vulnerability to natural phenomena.

The light red cluster includes applied research and case studies, often related to specific regions, such as "Brazil", "Italy", "Greece" and "Danube River", reflecting the geographies where hydropower plays a significant role.

The visualization shows that hydropower is an interdisciplinary field, where hydraulic engineering, ecology, water resource modelling, energy integration, and environmental policies intersect. The eight clusters highlight both the technical aspects—turbines, flows, control—and the ecological, climatic, and socio-economic dimensions, confirming the essential role of hydropower in the sustainable energy mix.

The bibliometric analysis of the four primary sources of renewable energy — biomass, solar energy, wind energy, and hydropower — highlights a highly complex, diverse, and interconnected scientific landscape that reflects global and European priorities in the transition to a sustainable energy system. Although each technology has its own thematic characteristics, the results show that research in renewable energy is characterized by complementarity, interdisciplinarity, and a strategic focus on integrated solutions.

In the case of biomass, the visualization revealed a thematic structure that combines the biological dimension, advanced chemical processes, environmental impact, and energy integration. Biomass is a pivotal link between biological resources and energy technologies, attracting interest for both its material potential (biochar, hydrogen, catalysts) and its role in reducing emissions, improving waste management, and supporting rural development. Research is intensely focused on optimizing thermochemical processes, using microorganisms, and assessing ecosystem sustainability.

Regarding solar energy, the conclusions highlight two directions: the development of advanced materials to increase photovoltaic conversion efficiency (perovskites, thin films, nanomaterials), and the integration of solar systems into modern energy infrastructures (microgrids, storage, intelligent forecasting). Solar energy is a highly dynamic, innovative field, characterized by rapid technological advancement and an increasingly strong intersection between materials engineering, artificial intelligence, and energy policy.

The analysis of wind energy shows a mature field that is extremely well represented in the scientific literature, particularly due to the development of onshore and offshore turbines. Research focuses on aerodynamic optimization, increasing system reliability, integration into smart grids, and the assessment of climatic and atmospheric resources. Wind power is an essential component of the energy transition, and the visualizations confirm a strong focus on digitalization, control algorithms, prediction and hybrid solutions combining wind power with solar or storage.

In the case of hydropower, the results highlight a balance between the technical side—fluid dynamics, hydraulic systems, and turbine optimization—and the ecological side, including biodiversity, aquatic ecosystem protection, and watershed management. Hydropower is approached both as a mature and stable technology in the energy mix and as an element vulnerable to climate change and water resource dynamics. The research reflects the need to adapt hydropower infrastructure to new hydrological conditions and integrate it into hybrid systems.

Taken together, the four visualizations show that renewable energies do not evolve in isolation, but in synergy, forming a technological ecosystem in which biomass contributes to the circular economy, solar to material innovation and storage, wind to the expansion of large production capacities, and hydropower to grid stability and flexibility. Interdisciplinarity manifests itself through close links among energy efficiency, climate policy, digitalization and sustainable development, demonstrating that the energy transition is simultaneously supported by technological advancement, environmental sustainability and systemic coordination.

In conclusion, the bibliometric analysis confirms the scientific community's growing interest in renewable solutions and the significant contribution of each technology to a safer, cleaner, and more sustainable energy future. The four energy sources, although different in nature and mechanisms, converge through common goals of reducing emissions, increasing energy independence, and promoting innovation, outlining a clear direction for global energy development.

The previously conducted bibliometric analysis provided a qualitative perspective on the research directions for each of the four renewable energy sources, highlighting the dominant themes, relationships among concepts in the literature, and the degree of maturity of each field.

Table 5. Number of publications on various RES types per country for the period 2022-2025 (EU and Balkans).

Nr.crt.	Country	PUBS_Total RES	PUBS_biomass	PUBS_hydroelectricity	PUBS_wind	PUBS_Solar energy
1	Germany	6489	1018	144	1966	3361
2	Spain	5332	914	161	1381	2876
3	Italy	5119	946	160	1351	2662
4	France	3975	628	81	1218	2048
5	Poland	2878	757	87	737	1297
6	Sweden	2199	418	97	568	1116
7	Netherlands	2118	374	61	760	923
8	Denmark	1735	325	20	725	665
9	Portugal	1489	344	68	388	689
10	Finland	1331	233	43	407	648
11	Belgium	1297	214	17	409	657
12	Greece	1238	198	40	388	612
13	Austria	1012	218	70	286	438
14	Czechia	975	256	23	200	496
15	Romania	816	139	31	214	432
16	Ireland	735	121	20	310	284
17	Hungary	634	101	10	153	370
18	Croatia	327	89	17	85	136
19	Slovakia	307	71	11	55	170
20	Lithuania	296	77	10	59	150
21	Cyprus	277	34	10	75	158
22	Estonia	245	55	5	65	120
23	Latvia	232	60	6	50	116
24	Slovenia	201	50	18	38	95
25	Bulgaria	178	40	3	38	97
26	Serbia	149	34	7	42	66
27	Luxembourg	99	8	2	22	67
28	Bosnia and Herzegovina	57	13	3	17	24
29	Malta	46	3	1	21	21
30	North Macedonia	41	5	4	13	19
31	Montenegro	23	2	3	5	13
32	Albania	16	3	3	4	6
33	Moldova	13	7	0	1	5

Note: PUBS_Total RES is the arithmetic sum of PUBS_biomass + PUBS_hydroelectricity + PUBS_wind + PUBS_Solar energy and is not a separate Scopus query. Multi-technology articles (i.e. articles that satisfy more than one of the four sub-queries) are counted in each technology where they qualify and therefore enter PUBS_Total RES more than once; PUBS_Total RES is consequently an upper bound on a country's unique RES research output. Country counts come from the four Stage-3 Scopus queries reported in Table 3, applied with DOCTYPE = "ar" (peer-reviewed articles only) and LANGUAGE = "English", run on 23 November 2025.

4.2. *Descriptive analysis on RES publication and RES penetration in the energy mix*

To complement this approach and to understand how scientific interest is distributed geographically, a quantitative analysis of publication volumes at the level of European countries is necessary. **Table 5** provides this comparative perspective, showing how the themes identified in the bibliometric analysis are reflected in each country's research activity and highlighting regional differences in academic investment in renewable energy.

Thus, the correlation between bibliometric maps and the distribution of publications by country provides a complete picture of how conceptual, technical, and thematic developments are reflected in scientific output at the European level, outlining a coherent picture of research dynamics in renewable energy.

A comparative analysis of the total number of publications was conducted to rank countries by scientific output in renewable energy. **Figure 5** presents the top 10 countries by total publications in the field of renewable energy sources (RES) in ascending order. Germany ranks first, followed by Spain and Italy. Additionally, there is a notable concentration of scientific output from Western European countries.

Analysis of **Figure 6** reveals that scientific research trends in both the EU and the Balkans are similar, with solar energy and wind power comprising approximately 78% of total publications. Biomass ranks third in research interest, followed by hydropower.

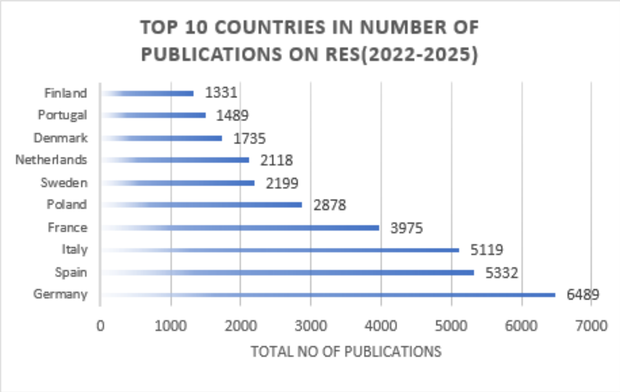


Figure 5. Top 10 Countries by Total Number of RES Publications (2022–2025).

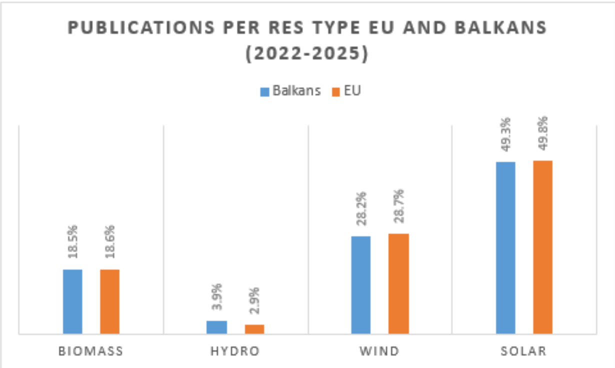


Figure 6. Publications by RES Type (%) for the Period 2022–2025 (EU and Balkans).

The analysis of scientific publications trends on the four major types of renewable energy—biomass, hydropower, wind power, and solar power—reveals significant differences across European countries in research intensity and national energy priorities. Large Western European countries such as Germany, France, Italy, and Spain stand out as centers of excellence in renewable energy research. Germany has the highest number of publications in all four areas, reaching a remarkable peak in solar and wind energy research, confirming both its scientific capacity and its strategic focus on energy transition. France and Italy show a balanced profile, with substantial contributions to biomass, wind, and solar. At the same time, Spain combines a strong interest in solar energy with intense activity in wind energy, reflecting its favorable natural resources.

A second group of countries shows high activity, though lower than that of the European leaders. Denmark stands out for its strong focus on wind energy, an area in which it is globally recognized, but it also makes solid contributions to solar and biomass energy. Finland and Sweden show consistent results in solar and biomass energy, confirming their focus on bioenergy and sustainable technologies. Poland stands out for its intense activity in biomass, complemented by significant research on solar and wind energy, reflecting recent changes in Polish energy policy. The Netherlands and Portugal also show high levels of publications, particularly in solar and wind, in line with their investments and natural resources.

Countries such as Greece, Romania, the Czech Republic, Austria, Belgium, and Ireland are characterized by moderate levels of activity. Greece excels in solar and wind energy research, benefiting from favorable climatic conditions, and Romania shows a balanced distribution among solar, wind, and biomass. At the same time, its hydropower contribution is lower than its natural potential would suggest. The Czech Republic and Austria have significant results in biomass and solar, while Belgium stands out for its high activity in solar and wind energy, despite limited natural resources.

Countries with low activity in renewable energy research include the Western Balkans and wider Eastern Europe, such as Serbia, Bosnia and Herzegovina, Albania, North Macedonia, Moldova, and Montenegro. These countries have a low number of publications, often less than 50 for most fields, indicating both low scientific visibility in international databases and the need for additional investment in research, infrastructure, and the integration of renewable technologies. Of course, the populations of those countries are small, which also affects the number of publications. Although some of these countries have considerable natural resources, particularly in hydropower, these are insufficiently reflected in the scientific literature.

Overall, the analysis shows a geographical concentration of research in Western and Northern Europe, where energy policies, investments, and academic infrastructure strongly support the development of renewable energies. Central and Eastern European countries show growing potential, but it is still underutilized, and the Balkan region remains the least represented. The distribution of publications highlights both national priorities and each country's institutional capacity, contributing to a broad understanding of how scientific research reflects the progress of the energy transition at the European level.

The results indicate significant differences between countries regarding research capacity and interest in renewable energy. Additionally, the high publication volume in leading countries likely reflects sustained investment in research and development alongside the prioritization of energy transition within national policies.

To provide a more detailed understanding of thematic distribution, **Figures 7 to 10** present the distribution of publications dedicated to renewable energy sources (RES) in the analyzed countries of the EU and the Balkan region. These maps illustrate territorial differences in research intensity within this renewable energy subfield.

According to **Figure 7**, Germany clearly stands out as the leader in biomass research, with the highest number of publications, followed at a distance by Italy and Spain, reflecting the high research capacity of these developed economies. At the opposite end of the spectrum, countries such as Montenegro, Albania, and Malta have the lowest values, highlighting significant differences between European countries in terms of the intensity of biomass research.

Next, the analysis is extended to research in the field of hydroelectric energy, in order to highlight the geographical distribution of publications at European level. The following **Figure 8** illustrates the differences between countries in terms of the intensity of scientific interest in this type of renewable energy.

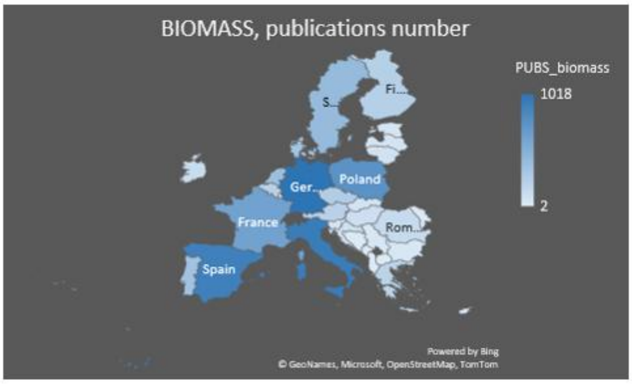


Figure 7. Highlighting countries with a higher share of publications in the field of biomass.

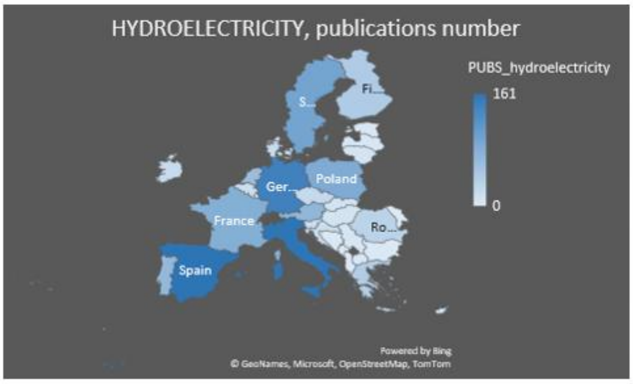


Figure 8. Highlighting countries with a higher share of publications in the field of hydroelectricity.

It can be observed that research in the field of hydropower is mainly concentrated in countries such as Spain, Italy, and Germany, which have the highest number of publications. In contrast, countries such as Malta, Luxembourg, and Albania have a very low number of research projects, highlighting significant differences between Balkan countries in terms of available natural resources and tradition in hydropower exploitation.

Next, the distribution of research in the field of wind energy, a key sector in the transition to renewable energy sources, is analyzed. **Figure 9** highlights the differences between Balkan countries in terms of the number of scientific publications dedicated to wind energy.

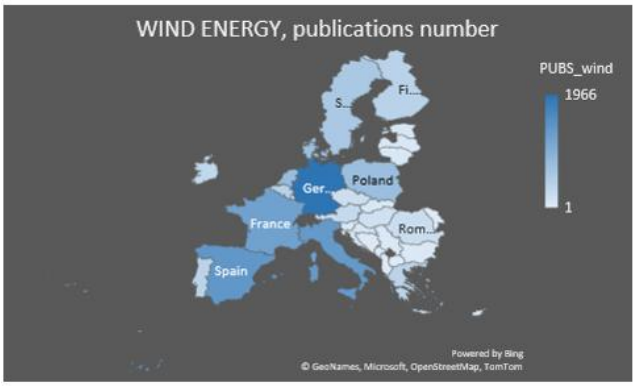


Figure 9. Highlighting countries with a higher share of publications in the field of wind energy.

The map highlight that Germany ranks first in wind energy research, followed by Spain and Italy, confirming the dominant position of these countries in the development of wind energy technologies. At the opposite end of the spectrum, countries such as Croatia, Slovakia, and Lithuania have significantly fewer publications, indicating a lower level of research activity in this field.

Finally, we analyzed the distribution of solar energy research at the European level to highlight the countries with the highest number of publications in this sector. The following **Figure 10** illustrates the territorial differences in the development of solar energy research.

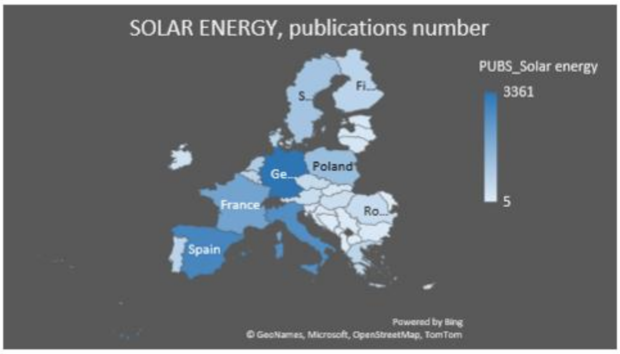


Figure 10. Highlighting countries with a higher share of publications in the field of solar energy.

Germany stands out as the main center for solar energy research, followed by Spain and Italy, countries with intense scientific activity in this sector. In contrast, Central and Eastern European countries such as Slovakia, Lithuania, and Croatia have significantly lower values, highlighting regional disparities in the development of solar energy research.

Turning our attention to RES usage (**Figure 11**, based on Eurostat data for 2023), the Balkan countries, especially those with a low share of RES, have a high potential to transition to a more sustainable energy system through electricity. Among the Balkan countries, following the analysis, we observed that Albania has the highest share of RES in total energy sources, approximately 46% in 2023 (Eurostat, 2025b). According to Tuerk *et al.* (2013), Albania has made significant progress in the electricity sector, considering its available potential. Albania has long-term solar and wind energy resources sufficient to cover the national consumption needs (Lalic *et al.*, 2011). Furthermore, the RES share of the total energy mix is high in Bosnia and Herzegovina, Montenegro, and Croatia. All those Balkan countries heavily depend on hydroelectricity, since water resources are abundant in the area and the geographic setting favors hydropower. At the opposite end of the spectrum in terms of RES usage in the Balkan countries are North Macedonia, with around 20% of total energy from RES in 2023, and Bulgaria, with around 23% in 2023 (Eurostat, 2025b). According to Stankova and Toneva (2021), Bulgaria faces a deficit in RES use due to legislative barriers related to double taxation, authorization procedures, and the need for grid connectivity.

The other Balkan countries fall between the two examples mentioned above. Regarding publications in RES from Balkan countries, most research has been conducted in Greece and Romania. However, the countries still have the capacity for further development of RES, as they are at around 25% RES penetration in the energy mix.

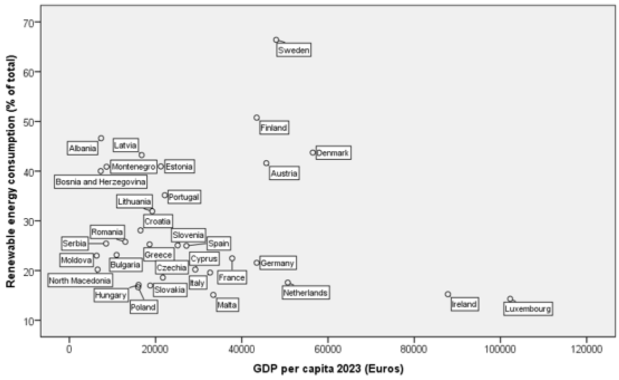


Figure 11. GDP per capita and RES% % for the sample countries (2023).

We looked at the relationship between two variables for 2023: the share of renewable energy in gross final energy use (% RES) and GDP per capita (GDP_CAP) across 33 EU and Balkan countries in our sample (see the methodology section for definitions; 2023 is the most recent year with data for both Eurostat indicators). We calculated the Pearson correlation coefficient between % RES and GDP_CAP for all countries and found $r = 0.29$ ($n = 33$), which shows a weak positive linear association that is not statistically significant at the 5% level ($p \approx 0.10$). When we limited the analysis to the EU-27, the correlation was $r = 0.31$, which is also not significant. The Balkan-only group ($n = 11$, including five countries that overlap) is too small for a reliable correlation estimate. Because of this, we treat the link between RES penetration and GDP per capita as a possible association, not as proof of a causal relationship. The following points should be seen as descriptive patterns that suggest ideas for further research, not as evidence of cause and effect. For example, Nordic countries tend to have both high RES penetration and high GDP per capita; Finland and Sweden are good examples. This pattern fits with two possible explanations: having a lot of renewable resources might help countries become wealthier, and wealthier countries may be better able to invest in renewable energy. Our cross-sectional data cannot tell us which explanation is correct, so we do not claim that RES leads to GDP growth.

On the other hand, some Balkan countries like Moldova and North Macedonia have both a low share of renewable energy and low GDP per capita. We describe this as an association, not a cause-and-effect relationship. Previous studies suggest that relying on conventional energy sources can make countries more vulnerable to fossil-fuel price changes and less energy efficient, which might limit economic growth. However, our current data cannot confirm if this is happening in our sample. To find out, we would need time-series analysis with proper controls. For now, we present this pattern as a possible idea for future research, not as proof that low RES penetration leads to slow economic development.

In the middle zone, on average, countries like Spain, Italy, France and Germany fall within a range of RES utilization of 20% to 30% and have high GDP, indicating the need to focus their efforts on minimizing their economies' dependence on fossil fuels. Luxembourg and Ireland, while having the highest GDP per capita, still need to advance quickly to RES technologies since current RES penetration into the energy mix is very low 14% and 17% respectively, exhibiting high dependence on fossil fuels.

Finally, as depicted in **Figure 11**, several countries, such as Germany, the Netherlands, Ireland, and Luxembourg, have lower RES penetration in their total energy consumption than many other EU countries. This can be attributed to the geography and building conditions, which make it difficult to install some renewable technologies on a large scale. For example, Luxembourg and the Netherlands have less potential for hydropower and less available land than Nordic countries, where hydro and biomass resources promote renewable energy use (European Commission, 2023). These countries have also traditionally relied on fossil fuels, especially natural gas. The Netherlands built extensive gas infrastructure after discovering domestic gas reserves, and gas heating is still common in Germany and Ireland, which slows the switch to renewable heating technologies (IEA, 2024). Another factor is the high energy demand linked to their economic and industrial setups. Germany, for example, has one of Europe's largest energy-intensive industries, which increases total energy use and lowers the share of renewables in the mix (IEA, 2025). Also, limited use of renewable and district heating in Ireland and Luxembourg has slowed growth in the heating and cooling sector, which accounts for a large share of energy use (Eurostat, 2023). A recent study indicates that differences in national energy systems, industrial needs, and technology use lead to uneven progress in renewable energy across EU countries (Bąk *et al.*, 2025). So, even with strong growth in renewable energy, fossil fuels still account for a large share of energy use in those countries.

Comparing **Tables 5** (publications by country) and **Figure 11** (RES penetration and GDP per capita, 2023) shows four main country profiles. Profile A includes countries with both high research output and high RES penetration, such as Sweden, Finland, Denmark, Portugal, and Latvia, though Latvia has fewer publications but high RES shares. Profile B covers countries with high research but only low to moderate RES penetration, like Germany, the Netherlands, Belgium, Ireland, and Luxembourg. Profile C features countries with low research but high RES penetration, including Albania, Bosnia and Herzegovina, Montenegro, and North Macedonia, though North Macedonia's RES share is moderate at about 20% in 2023. Profile D includes countries with both low research and low RES penetration: Moldova, Bulgaria, Hungary, Cyprus, and Malta. The distinction between EU and Balkan countries does not fit neatly into these profiles. For example, Albania, a non-EU Balkan country, is in Profile C, while Bulgaria, an EU Balkan country, is in Profile D. This shows that EU membership alone does not determine RES outcomes.

Two main findings emerge. First, three Profile B countries—Germany, the Netherlands, and Ireland—have very high research output but RES shares below the EU average. This suggests that their main barriers to RES penetration are not related to knowledge, but to factors like dense built environments, reliance on gas infrastructure, and a mix of energy-intensive industries. This view matches recent IEA country reviews (IEA, 2024; IEA, 2025) and Bąk *et al.* (2025). Second, the Profile C group, especially Albania, Bosnia and Herzegovina, and Montenegro, shows that high RES penetration can result mainly from favorable hydrological conditions, even without a strong domestic research base. This raises questions about whether these RES levels can be maintained or adapted as climate change affects hydrology. Some technologies and countries are clearly under-researched compared to their RES potential or deployment. For example, hydropower research in the Western Balkans makes up less than 4% of the region's RES publications, even though hydro is the main RES source there. Similarly, biomass research in Southern EU countries like Greece, Cyprus, and Portugal is limited, despite their strong agricultural-residue resource base. These mismatches highlight the value of analyzing the EU and Balkans together.

Based on the four profiles above, policy directions for the EU and Balkan region should be tailored to each group instead of using a single approach. For Profile A countries (high research, high RES), the focus should be on strengthening their lead through better cross-border connections, regional market integration, and sharing expertise with neighbors. For Profile B (high research, low-to-moderate RES), the main challenge is on the deployment side, not the knowledge side. Policies should focus on modernizing gas-heating systems, electrifying buildings, and reducing the carbon intensity of energy-intensive industries through electrification or hydrogen, rather than increasing R&D funding. For Profile C (low research, high RES), priorities include making existing hydropower more climate-resilient, expanding into wind and solar (which the region's climate supports), and building up domestic research capacity for long-term independence. For Profile D (low research, low RES), the focus should be on regulatory improvements aligned with EU accession—especially for Bulgaria, where Stankova and Toneva (2021) note specific legal barriers like double taxation, authorization procedures, and grid-connection rules—and on using EU funding for both deployment and research. These recommendations are based on the actual profiles, not generic advice. In addition to these targeted measures, some broader strategies apply to both regions: accelerating cross-border cooperation and grid interconnection. Improved electricity interconnectors, regional market integration, and shared balancing mechanisms can significantly enhance system resilience and support the efficient deployment of variable renewable energy sources. New advances in materials can help develop low-power technologies that support sustainable energy and smart infrastructure goals in the EU and Balkan regions (Aturi *et al.* 2026). Second, establishing long-term and predictable policy signals is essential. A stable regulatory environment—backed by multi-decade targets, clear market frameworks, and consistent support schemes—is vital for reducing investment risks and attracting sustained private capital. More investment in energy storage and digital infrastructure should also be prioritized, especially in advanced storage technologies, demand-response solutions, and overall grid digitalization, which are crucial for managing high shares of renewables. Promoting decentralized energy systems and prosumer-oriented models, such as rooftop PV, community energy cooperatives, and microgrids, empowers citizens and ensures that communities share in the economic gains from the energy transition. In addition, expanding green financing mechanisms—such as green bonds, concessional lending, and tax incentives—is an option to accelerate private-sector participation, particularly among small and medium-sized enterprises. Developing regional centers of excellence dedicated to renewable technologies would also further strengthen innovation capacity and technical expertise.

5. Conclusions

Since the adoption of the Renewable Energy Directive, 2009/28/EC, the share of renewable energy sources in the EU's total energy consumption has risen steadily and measurably from 12.5% in 2010 to 21.8% in 2021. This trend has been further strengthened by the adoption of the Repower EU plan, which puts security of energy supply and economic resilience at the forefront of EU strategic priorities. In this respect, Sweden leads the way with the largest share of renewable energy in its consumption mix, at 62.6%, followed closely by Finland, at 43.1%, and Latvia, at 42.1%. Such progress testifies not only to the long-term coherence of policies but also to the key role of national strategies in mobilizing investment, driving innovation, and gaining public acceptance.

The same goes for the Western Balkan region, though it is also more driven by its hydropower potential. Albania has reached around 46% RES penetration, while Bosnia and Herzegovina and Croatia maintain a share close to 40%. Hydropower and solar PV development are in the leading position in scientific research and investment trends within the region, while EU countries show increasing interest in biomass technologies, reflecting broader diversification strategies across the continent.

According to the analysis, a gradual transition to adopting RES is advisable for countries in the Balkans in order to gain economic, social, and environmental benefits from their use. In fact, due to the particular characteristics of the Balkan region, it has relatively high solar, wind, geothermal, and biomass potential, above all from crops and forests.

The descriptive co-occurrence of higher RES shares with higher GDP per capita levels is observable in our sample (Pearson r = 0.29 for the full 33-country sample), but, given the cross-sectional design, we frame it as an association consistent with the hypothesis that RES deployment and economic development are mutually reinforcing rather than as evidence that RES adoption causes more pronounced economic development.

In addition, this more continuous transition or development to RES could decrease vulnerability towards changes in the global energy market because of the reduced effect of increasing or fluctuating prices of fossil fuels on the national economy. From a social perspective, the renewable energy sector can contribute positively to job creation and the stimulation of innovation processes within communities; all this creates a new labor market and supports the creation of new industries.

As for environmental factors, the utilization of RES will contribute considerably to the reduction of greenhouse gas emissions and environmental impact, while at the same time having a positive effect on the improvement of the image and competitiveness of countries in international markets. Adopting these energy sources also affects the trade balance, reducing dependence on fuel imports, keeping capital within the countries, and alleviating pressure on financial resources.

The research included an exhaustive effort to collect and analyze relevant literature, emphasizing publications published between 1 January 2022 and 23 November 2025. The most important bibliometric findings that the current research trend focuses on, concerning the various types of RES, both for EU countries and the Balkans, are:

- *Solar PV*: Energy Efficiency, Storage Technologies, and Latest Technological Advances
- *Biomass:* Different Technologies, Sustainable Development, and Renewable Energy
- *Hydroelectricity:* Hydropower plants, Optimization technologies, Water consumption
- *Wind-turbine:* Wind turbine technology, Economic aspects, Power system advances

From the point of view of the analysis carried out on the fields of relevant research interest on the subject of renewable energy sources and the other four visualization maps made for biomass energy sources, PV, hydroelectricity and wind energy, we observe similarities:

- The focus is on research into the variability of natural resources used to generate electricity. This research addresses detailed perspectives on adapting technologies to local conditions. It facilitates decision-making on the optimal strategies to use, depending on geographical location and the availability of natural resources.
- A critical aspect emphasized in the conducted research concerns the social and economic effects and the sustainable development of communities through contributions to employment and reductions in greenhouse gas emissions.
- Another aspect addressed in the research was technical support for energy storage and the key elements that comprise the equipment used in this process. Technical details, such as battery types or storage system components, were examined to highlight advances and innovations in all examined types of RES.
- Research also focused on the costs of generating electricity from renewable sources, including operating and maintenance costs. However, the most important aspect is how these strategies contribute to reducing energy costs and achieving energy independence.

These elements reflect the complexity of renewable energy research and provide a comprehensive picture of the key directions and interconnections in sustainable electricity generation.

5.1. *Limitations and future work*

Several limitations of the present design should be made explicit. First, the analysis is descriptive and cross-sectional: causal relationships between research output, RES penetration and GDP per capita cannot be established with the present methodology, and all associations reported in Section 4.2 should be read as patterns suggesting hypotheses for further empirical testing rather than as causal inferences. Second, the four Scopus sub-queries (wind, solar, biomass, hydroelectric) are not deduplicated, so multi-technology studies are counted in each technology in which they qualify; PUBS_Total RES is therefore an upper bound rather than a unique-document count, and the inflation has been quantified at 10–15% for high-output EU countries and below 5% for smaller Balkan economies (see Section 3.3). Third, Scopus may underrepresent regional Balkan journals that publish primarily in local languages and are not Scopus-indexed; the publication counts reported for Balkan countries should therefore be read as lower bounds. Fourth, the publication-as-research-activity proxy is unweighted: future work could weight publications by citations, by author affiliation share, or by journal impact. Fifth, the 2023 Eurostat reference year is the latest year for which RES share and GDP per capita data are simultaneously available; subsequent annual updates may shift the country profiles identified in Section 4.2.

Future research could look more closely at the link between scientific research activity and the growth of renewable energy. In this study, we ran preliminary correlation tests between research trends and renewable energy source (RES) penetration percentages, but we didn't find a statistically significant relationship. This might be due to limitations in the methods rather than a real lack of connection. Future studies might use time-lagged models to see if research output comes before changes in RES penetration by a few years, like checking publications from three years before the observed RES deployment. This approach could better show the delayed effects that scientific research and innovation have on energy transitions. Also, using other measures of research intensity—such as publications per capita (total publications divided by population)—or other normalized metrics could give a clearer comparison between countries. Adding more explanatory variables and using more advanced econometric methods could help explain if and how research activity supports renewable energy adoption.

In the coming years, the implementation of the European Green Deal, the Repower EU plan, and the UN Sustainable Development Goals will continue to intensify the EU's and the Balkans' renewable energy trajectory. These frameworks are expected to stimulate unprecedented investment in renewable technologies, foster research and development at residential, industrial, and national levels, and reshape the broader energy landscape. A coordinated policy approach—combining regulatory stability, infrastructure modernization, innovation support, and community engagement—will be essential for ensuring that the transition to renewable energy delivers sustained economic growth, environmental protection, and social prosperity across Europe.

Author contributor statement (Credit Roles)

Stamatios Ntanos: Conceptualization, Methodology, formal analysis, writing-original draft; **Madalina Ioana Moncea**: Methodology, formal analysis, writing-original draft; **Andreea Claudia Serban:** Supervision, resources, project administration; **Ioannis Salmon:** Supervision, resources, project administration; **Sofia Ioannidou:** writing—review and editing, validation.

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Competing interest

The authors have no competing interest (financial or non-financial) to declare that are relevant to the content of this article. The views and interpretations expressed here are those of the authors and do not necessarily represent the organisation they work with.

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