Emerging Energy Research Driving Sustainable Development Goals in Developing Countries with an Indonesian Perspective

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Abstract: This study analyzes Indonesia's energy research landscape via bibliometric analysis of 19,588 Scopus publications. Findings reveal a dominant shift towards renewables (72.2% of publications), led by bioenergy, and high institutional specialization. Thematic mapping identifies robust themes like biomass but underexplored areas such as ocean energy. The study underscores the need for strategic collaborations and policy support to bridge research gaps, foster innovation, and guide Indonesia toward energy self-sufficiency, providing a data-driven foundation for future research and policy development.

Keywords: bibliometric analysis; energy studies; fossil fuels; renewable energy; research collaboration; thematic research map.

1. Introduction

Research in developed countries prioritises high-tech innovations and often serves as the foundation for long-term energy policy development, positively contributing to the achievement of energy transitions[1)]. Developed nations have demonstrated the effectiveness of energy transitions and other environmental technological innovations in reducing their emissions[2,3)]. Consequently, developing countries often adopt energy policies and technological advancements modelled by developed nations. However, this collective global effort to reduce emissions faces challenges, particularly due to the United States' decision under the Trump administration to withdraw from the Paris Agreement. This move could not only encourage developing countries to follow suit by opting for cheaper fossil fuels but also reduce international support for those countries to pursue innovation in energy transitions[4)].

Developing countries have learned extensively from developed nations regarding clean energy technologies and policies since the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992. Among these, China stands out as the developing country with the largest capacity and production of renewable energy. Moreover, it has successfully become the world's leading exporter of clean energy technology[5)]. Another notable example is Vietnam, which has made significant progress through the adoption of feed-in tariff policies inspired by developed nations[6)]. However, many developing countries have yet to achieve success in advancing renewable energy, including Indonesia.

Under the new leadership of President Prabowo Subianto, energy policies in Indonesia are being directed toward energy self-sufficiency to addressing global geopolitical challenges. Energy self-sufficiency refers to a country's ability to meet its energy needs without relying on imports. However, Indonesia has not yet achieved this status, as domestic energy production is still insufficient to meet national consumption. For instance, in 2023, total domestic liquefied petroleum gas (LPG) demand reached 8.7 million tons, while production was only 1.9 million tons, indicating a significant deficit and heavy reliance on imports[7)]. This also highlights Indonesia's continued

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dependence on fossil fuels. Additionally, Indonesia has set a net zero emission target for 2060 which will increase the risk to energy security[8]. Thus, Indonesia faces the dual challenge of achieving energy self-sufficiency while ensuring a sustainable energy transition. For this, Indonesia can learn from developed countries to enhance clean energy transition[9,10]. Increasing renewable energy production will make Indonesia more resilient to fossil fuel price increases[11]. In this light, a highly skilled workforce is fundamental to technological self-reliance[12], as it enables the adaptation, enhancement, and innovation of energy technologies tailored to Indonesia's unique needs and resources. Without strong capabilities in research, engineering, and technical expertise, the country will continue to depend on foreign expertise, which may hinder its ability to develop competitive and sustainable energy solutions.

Despite this global context and Indonesia's specific challenges, a systematic, quantitative overview of the nation's entire energy research ecosystem is lacking. Existing bibliometric studies on Indonesia, as shown in Table 1, are fragmented, focusing on specific energy types like solar or bioenergy. This fragmentation obscures the broader research landscape, hindering the identification of cross-sectoral synergies, institutional strengths, and critical gaps. Without a holistic map, policymakers and researchers cannot efficiently allocate resources or foster the collaborations necessary to accelerate the energy transition.

To address this gap, this study conducts a comprehensive bibliometric analysis of energy supply research in Indonesia with the following objectives: (1) To quantify the volume, growth trajectory, and distribution of publications across all major energy sources (fossil fuels, nuclear, and renewables).(2) To identify the most prolific and impactful authors, institutions, and international collaborations shaping Indonesia's energy research. (3) To map the thematic evolution and current research fronts within each energy sector using trend topic and thematic map analyses. (4) To derive actionable insights and policy recommendations for enhancing research collaboration and aligning Indonesia's energy research agenda with its goals of self-sufficiency and sustainable development.

2. Literature Review

Bibliometric analysis serves as a valuable tool to map research developments within the energy sector. For instance, in the domain of solar energy, Lyu et al. (2024)[13] conducted a global review of solar-related studies, while Abdul Jabar et al. (2023)[14] focused specifically on solar photovoltaic–thermal hybrid systems. Regarding energy utilization, Afrane et al. (2022)[15] mapped global research trends on clean cooking technologies. Other bibliometric studies on clean energy have addressed topics such as energy resilience[16], emissions from the power generation sector[17], renewable energy in South Africa[18], bioenergy[19], energy subsidies[20], green finance and the impact of carbon trading on renewable energy[21,22], sustainable energy supply chains[23], the integration of renewable energy and circular economy principles[24], systems thinking and artificial intelligence (AI) applications[25,26], barriers to renewable energy adoption in ASEAN[27], micro-electro-mechanical systems (MEMS) for energy harvesting[28], and organic Rankine cycle (ORC) technology[29].

Bibliometric studies in the oil and gas sector have been expanding. Research on oil fuels, for example, encompasses the application of artificial intelligence for crude oil projection[30], investigations into hydrocarbon pollution[31], analyses of oil and gas production[32], examinations of the economic impacts of oil crises[33], and studies addressing heavy oil[34]. In parallel, bibliometric investigations in gas research have concentrated on the conversion of natural gas hydrates into energy[35], evaluations of natural gas combined cycle power plants[36,37], assessments of shale gas[38], and other related topics[39,40].

Global research on coal and nuclear energy has similarly been examined using bibliometric review methodologies. Studies on coal have reviewed literature concerning trace elements in coal and ash[41], coal combustion[42,43], coal seam hydraulic fracturing[44], coal gasification[45], circulating fluidized bed technology[46], coal modelling[47], and coal-fired flue gas[48], among other topics[49,50]. For nuclear energy, bibliometric studies have addressed issues such as nuclear disasters[51], nuclear desalination[52], small modular reactor[53], human factors on nuclear power plant operations[54], and emerging trends and innovations in nuclear research[55–58].

The overall body of bibliometric literature covering various energy types remains relatively limited. For instance, Harichandan et al. (2022)[59] employed the query "energy transition" alongside related terms, retrieving 2,169 articles for bibliometric analysis. Their study examined research trends, leading authors, highly cited articles, prominent journals, and principal publishing countries, ultimately identifying key knowledge gaps and proposing recommendations for future inquiry toward an achievable energy transition. Similarly, Chen et al. (2016)[60] used the query "energy and fuels" to analyze 19,089 articles produced by Chinese authors, focusing on leading journals, top institutions, international collaborations, major keywords, and central research topics.

In light of these studies, our work aims to enrich the current literature by reviewing the evolution of fossil and renewable energy supply research in Indonesia. To the best of our knowledge, no bibliometric study has yet provided a comprehensive review of energy supply research and its future directions in the Indonesian context. Table 1 lists

Table 1: Energy supply related bibliometric studies by Indonesia institutions

Topic	Studies
Solar	61,62,69–73)
Bioenergy	63,74–79)
Hybrid RE	80–82)
RE policies	21,22,24,27,65)
Supply chain	23)
Analytical tools	25,26,83)
Nuclear	52,64)
ORC	29)

bibliometric studies conducted by Indonesian institutions. While many of these adopt a global perspective, some focus on Indonesia as a case study. Nevertheless, bibliometric analyses in Indonesia have thus far been limited to specific energy types. For an example, Madsuha et al. (2021)[61] reviewed three decades of solar energy research in Indonesia. Damayanti and Dinaseviani (2024)[62] examined the adoption of solar PV systems by Indonesian households, while Setyanansyach et al. (2023)[63] focused on biogas power plants. Shafii et al. (2024)[64] reviewed global studies on nuclear energy policy from 2002 to 2022 and discussed their implications for Indonesia, which currently does not have nuclear power plants yet. As an exception, Akbar et al. (2020)[65] conducted a bibliometric study addressing five types of renewable energy in Indonesia. A non-bibliometric literature reviews on Indonesia context are also limited to one type of energy resources, such as rooftop solar power[66,67], and wave energy converter[68].

The extant bibliometric literature provides valuable insights into global energy research trends and isolated snapshots of specific technologies in Indonesia. However, a critical synthesis reveals a significant lacuna: the absence of an integrated analysis that places Indonesia's diverse energy research efforts within a single, comparable framework. Global studies often lack the granularity to inform national policy, while Indonesia-focused studies are too narrow to reveal the relative priorities and interdependencies between different energy sectors. This study bridges this divide by applying a unified bibliometric methodology to the entire spectrum of Indonesia's energy supply research, enabling a comparative assessment of maturity, focus, and collaboration patterns across all key energy domains.

3. Methods

3.1. Literature Search

The methodology involves sequential steps: The first step is the literature search in the Scopus database using keywords in Table A.1 from December 13 to 28, 2024. The files downloaded from Scopus are in BibTeX and CSV formats. The BibTeX file is used for analysis in the Bibliometrix application, which is an open-source tool designed for conducting comprehensive science mapping analyses of scholarly literature[84]. It is developed in R and offers flexibility and seamless integration with various statistical and graphical packages[85].

3.2. Data Collection and Cleaning

The literature search was conducted in the Scopus database from December 13 to 28, 2024. Scopus was selected for its comprehensive coverage of high-quality, peer-reviewed literature in the scientific and technical fields. The search query consisted of keywords related to twelve energy topics (Table A.1) combined with "Indonesia" or Indonesian affiliations. The initial search yielded 21,364 documents.

To ensure a non-redundant dataset, duplicate articles were removed. This was performed by first organizing the articles by the pre-defined topic order (as listed in Table 2: Wind, Solar, Geothermal, etc.). Records were then sequentially checked, and duplicates were identified and removed based on matching titles, authors, and publication years, prioritizing the first occurrence according to the topic order. This process resulted in a final corpus of 19,588 unique publications for analysis.

The chosen keywords were broad and technology-specific (e.g., "solar energy," "bioenergy," "oil fuel") to capture the maximum relevant literature for each sector. While this approach ensures breadth, it may exclude publications that use non-standard terminology. The analysis covers all publications in the database up to the search date, capturing the historical evolution of research from the earliest relevant publication to the present.

3.3. Bibliometrix analysis

The next step is the analysis in Bibliometrix to extract data on the most relevant authors, most relevant affiliations, most globally cited documents, most frequent words, trend topics, thematic maps, and countries' collaboration world maps. For the thematic map analysis in Bibliometrix, we used a minimum cluster frequency of 5 and a number of labels set to 3 for each quadrant to ensure clarity and interpretability. The map is based on a co-word network analysis, where centrality indicates the degree of interaction with other themes, and density indicates the internal development of the theme

3.4. Trend topics analysis and top author

The involves analyzing trend topics and consecutively specialty of top authors is discussed in the next step.

3.5. Recommendation discussion

The final step involves discussing recommendations related to the research agenda to support energy self-sufficiency based on thematic map analysis. The thematic map is a diagram with four quadrants: emerging or declining themes, basic themes, niche themes, and motor themes. The discussion of recommendations also

addresses countries that should be partners in research and innovation in the energy sector.

4. Results and Discussions

Table 2 shows the number of articles obtained from each keyword. The total number of articles across all topics is 21,364, with the highest number being on bioenergy (29%). Duplicate articles were then removed by organizing articles by topic order as shown in Table 1, resulting in 19,588 articles. Around 56% of these articles are conference papers, and 40% are journal articles. Research institutions in Indonesia have been involved in the preparation of 14 energy-related books.

Figure 1 shows the annual publication growth per technology. The oldest article in the Scopus database is about the development of a double stage soda sweetening process to sweeten the 6-8 copper number gasoline at the Palembang Refinery[86].

The number of publications was only 11 articles during 1970 to 1979, then increased to 72 articles during 1980 – 1989, and 200 articles during 1990 – 1999. The number of publications exceeded 100 articles per year since 2009, reaching more than 1,000 articles in 2017. The establishment of the Indonesia Endowment Fund for Education Agency (LPDP) in 2011 and various international publication requirements at universities and research institutions contributed to the increase in Scopus-indexed publications. However, the publication trend declined in 2021 to 2022 during the COVID-19 pandemic, which prevented students from attending physical classes, especially abroad, and redirected government and private budgets to address the pandemic. As a result, research and publications focused on the pandemic, leading to a decrease in publications in other fields[87]. After the pandemic, the number of publications increased again,

Table 2: The number of articles analyzed

Topic	Original	No duplicate
Wind	1,106	1,106
Solar	3,221	3,012
Geothermal	1,475	1,419
Hydro	584	507
Ocean	204	183
Bioenergy	6,164	5,978
WtE	506	334
Other RE	1,767	1,609
Coal	2,271	1,846
Oil	2,829	2,762
Gas	899	519
Nuclear	338	313
Total	21,364	19,588

reaching over 2,500 articles. The number of publications for the 2025 edition has already reached 78 articles, mostly related to bioenergy (35%) and solar energy (23%).

4.1. Fossil Energy & Nuclear

Publications related to fossil energy significantly dominated from 1950 to 2010, with a total of 613 articles, compared to 273 articles on renewable energy.

4.1.1. Oil Fuel

Figure 2 illustrates a shift in research topics from oil well production and drilling (in 1990 – 1999) to petroleum reservoirs, offshore oil well, infill drilling, heat exchanger, and enhanced recovery. For an example, Suhadi et al. (2023)[88] investigate the degradation of structural integrity in refinery heat exchangers by examining how deposit-induced corrosion affects their tube walls.

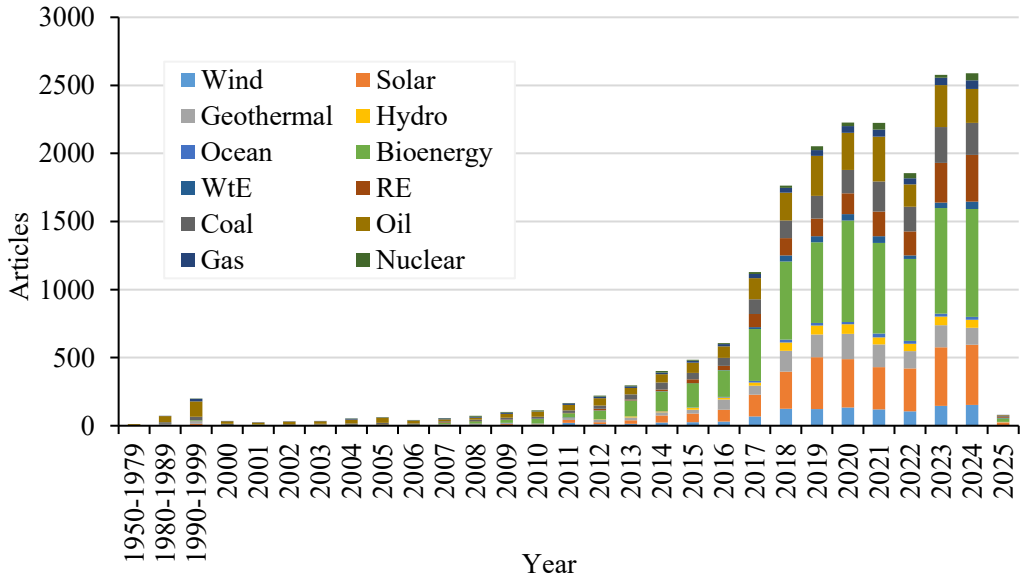

Fig. 1: Annual publication growth per technology

Hartono et al. (2024)[89] analyzed the impact of CO2 flooding on oil production and concluded that higher injection temperatures improve oil recovery, asphaltene, and resin fractions. One of the most frequently discussed topics is offshore oil well production, including exploration efforts in the offshore Southern Ardjuna Northwest Java basin[90] and performance evaluation of electric submersible pumps in an offshore Natuna field[91]. The top author is Rini Setiati, from the University of Trisakti, who contributed 41 articles since 2018. Rini's research encompassed various enhanced oil recovery techniques (e.g., terrafloc polymer, eco-enzyme, artificial neural networks), surfactants, and sandstone formation. The institution with the highest number of oil fuel publications is Bandung Institute of Technology (ITB) (431 articles), with two primary authors being Asep Kurnia Permadi and Taufan Marhaendrajana. Some of their publications analyzed oil well performance[92], and the impact of CO2 injection/flooding[89,93]. The University of Indonesia (UI) ranks second with 257 articles, with the primary author being Abdul Haris, whose publications include reservoir and facies modeling[94,95]. Two other authors with significant contributions are from the University of Trisakti (USAKTI), one of whose publication topics is related to surfactants[96–98].

4.1.2. Natural Gas

The topics of natural gas publications have experienced a trend shift from petroleum geology to infill drilling (2011 – 2017), to the use of machine learning (2023 – 2024) as shown in Figure 3. Examples are the application of machine learning to predict natural gas transmission pipeline failures[99]. Another important issue is to design efficient gas transportation mode, such as Budiyanto et al. (2024)[100] who optimizes the principal hull dimensions of small-scale LNG carriers by applying spiral design theory to balance volume, mass, and linear dimensions. The top author is Semin from Sepuluh Nopember Institute of Technology (ITS) with 29 articles since 2008. Semin's publications were mainly related to dual-fuel diesel engine, marine fuels, and lateral swirl combustion system[101–103]. The University of Indonesia (UI) and ITS lead in natural gas-related publications, with 178 and 149 articles respectively. Two top authors from UI are Widodo W. Purwanto and Nasruddin, whose research topics include the optimization of gas production[104] and the conversion of CO2 from natural gas into chemicals and fuels[105] as well as activated carbon[106]

4.1.3. Coal

One of the publication topics that remains relevant from the 1990s is peat, as shown in Figure 4. Generally, the trend of publication topics has evolved from upstream issues, such as sedimentation[107] and upgraded coal[108], to coal combustion in coal-fired power plants, including co-firing with biomass and fouling issues[109,110]. Other frequently researched topics include the utilization of coal fly ash[111] and coal deposits[112]. Yudha et al. (2024)[113] developed a synthesis pathway for crystalline silicon (c-Si) from coal fly ash via carboxylic acid-assisted gel formation, producing high-purity Si suitable for lithium-ion battery anodes.

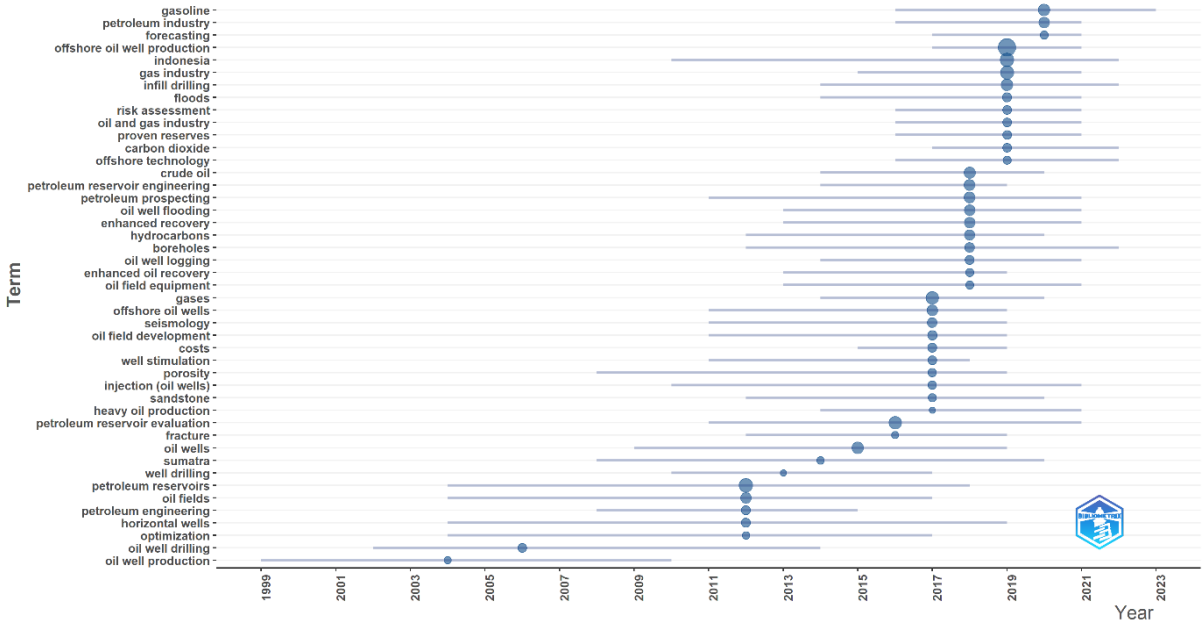

Fig. 2: Trends in publication topics related to oil fuel

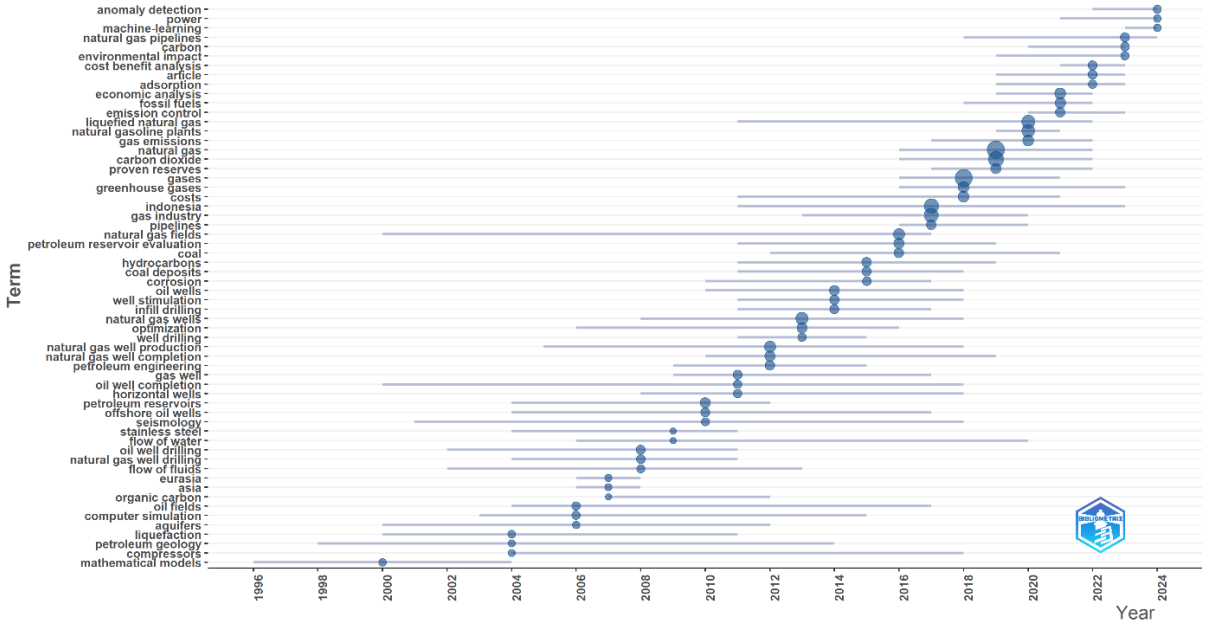

Fig. 3: Trends in publication topics related to natural gas

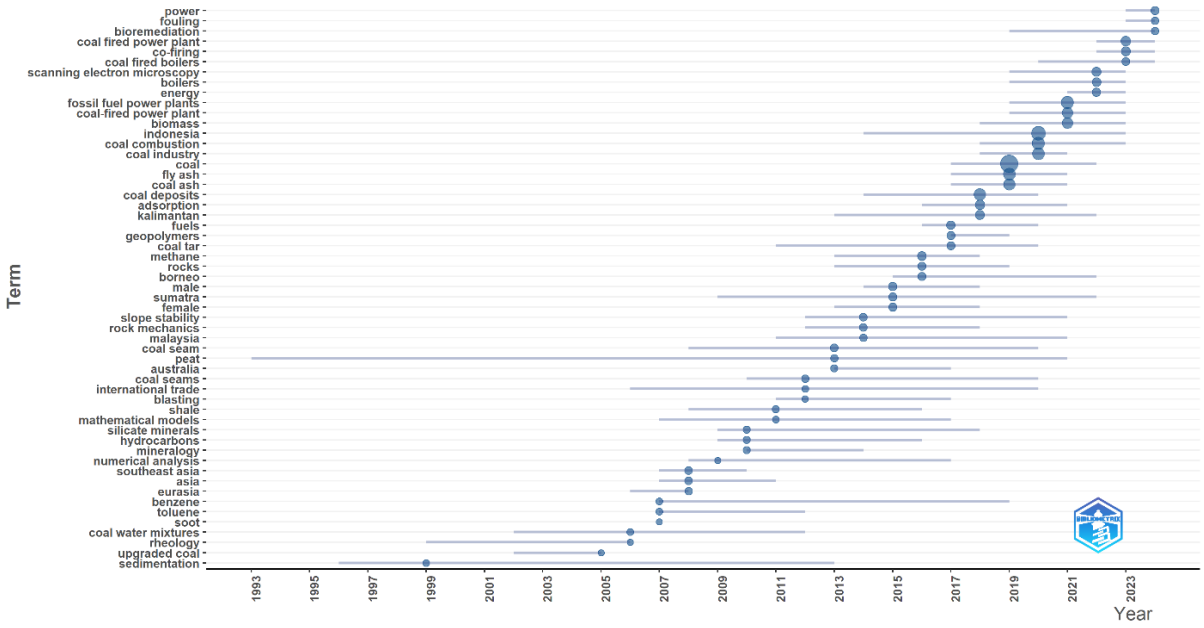

Fig. 4: Trends in publication topics related to coal

Additional investigations addressed the socio-economic and ecological multiplier effects of coal mining Sutriadi et al. (2024)[114], as well as the structural strength and durability of flat carriage coal transporters[115]. Figure 4 also shows topics related to certain countries (such as Australia and Malaysia), indicating increased involvement of Indonesian researchers in analyzing coal issues in other countries[116,117].

Coal research is led by the University of Gadjah Mada (UGM) and ITB, contributing 283 and 275 articles respectively. two top authors from UGM focus on topics such as fly ash[118,119] and CO2 injection into coal reservoirs[120]. Another top author is Hariana from the National Research and Innovation Agency (BRIN) (43 articles since 2021). His publications focus on coal co-combustion and its issues, such as slagging, fouling, and other ash-related problems.

4.1.4. Nuclear

Figure 5 shows the trend of nuclear research. In the late 2010s, trending publication topics included heavy water and plutonium. Between 2017 and 2024, the most widely published topics focused on nuclear power plants and fuels, particularly gas-cooled reactors.

Juarsa et al. (2024) examined transient natural circulation flow, a critical mechanism during failures of active cooling systems in nuclear power plants. Meanwhile, Santosa et al. (2023) utilized the LEAP model to conduct a scenario

analysis evaluating the potential role of nuclear power in advancing Indonesia's net-zero emissions vision.

Nuclear-related publications are predominantly led by BRIN, with 247 articles. Their research topics encompass the assessment and enhancement of nuclear power plant safety. Additionally, Zaki Su'ud from ITB ranks first, contributing 18 articles since 2008. His research focuses on the design and optimization of small and long-life nuclear reactors, fuel recycling, fuel cycles, reactor safety and performance, thermal hydraulics and neutronics analysis, and integration with renewable energy systems.

4.2. Renewable Energy

The total number of articles analyzing renewable energy has reached 14,148, which is approximately 72.2% of the articles reviewed. Publication topics related to renewable energy have undergone significant transformations, as shown in Figures 6 to 13. This evolution reflects shifts in research priorities and advancements in technology and policies.

4.2.1. Solar Energy

The first solar energy publication in Indonesia was an analysis of solar radiation in Jakarta[121]. As shown in Figure 6, early solar energy publications focused on heat exchangers for absorption cooling systems[122] and solar tunnel dryers[123]. The trend of publication topics then evolved to supporting components of solar energy systems, such as power converters[124] and inverter[125]. Research trends in the past five years have centered on solar concentrators[126] and improving the efficiency and performance of solar energy systems[127].

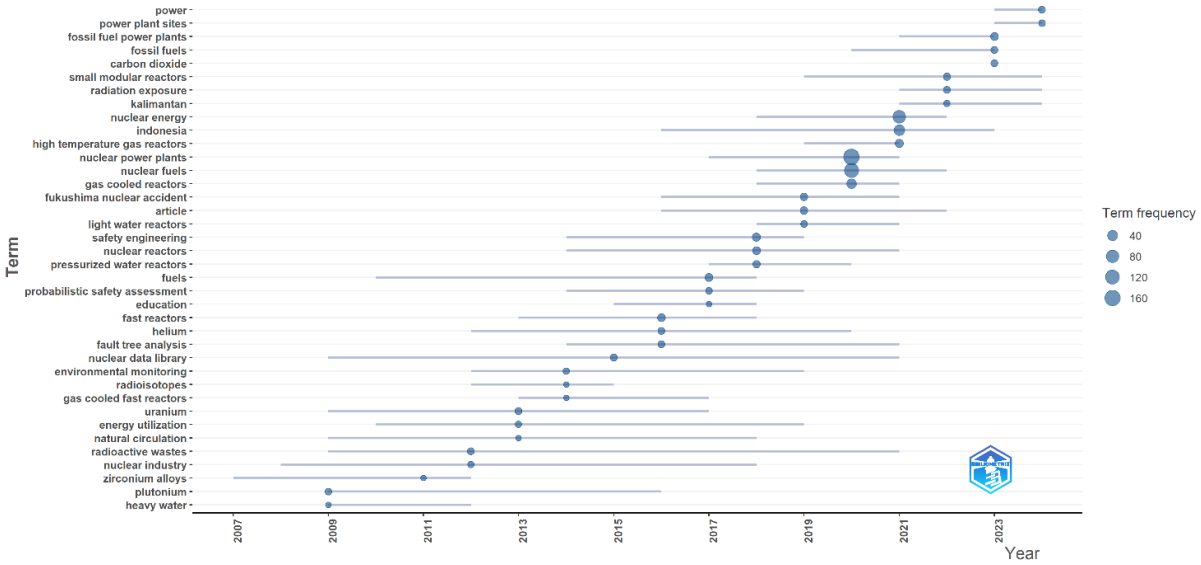

Fig. 5: Trends in publication topics related to nuclear

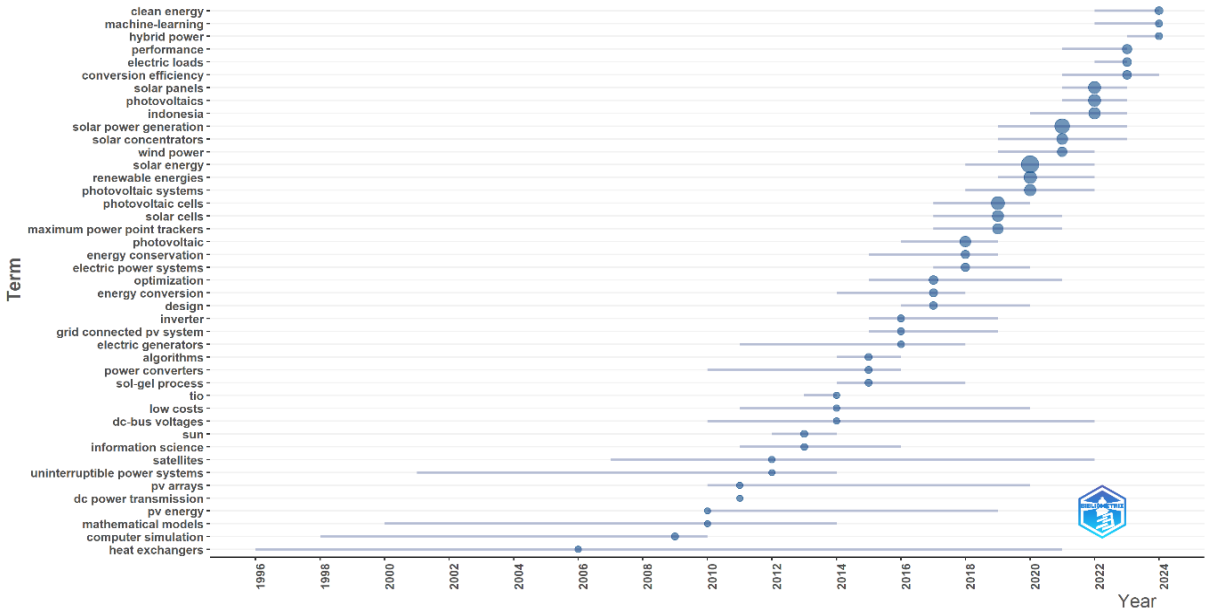

Fig. 6: Trends in publication topics related to solar energy

Publications on the use of machine learning for solar energy applications have increased since 2022[128]. Other publication topics include hybrid floating photovoltaic systems[129], PV rooftop systems[130], incentive policies[131], optimal sizing and placement of battery energy storage systems (BESS) in photovoltaic-rich networks[132], and the feasibility of PV rooftop systems to reduce electricity subsidies[133].

Publications related to solar energy are dominated by ITS (349 articles) and UI (312 articles). Meanwhile, the top authors in this field are Ahmad Fudholi (62 articles) from BRIN and Zainal Arifin (60 articles) from the University of Sebelas Maret (UNS). Publications by Ahmad Fudholi were mainly related to photovoltaic thermal[134] and cooling systems[135]. Similarly, publications by Zainal Arifin were mainly related to photovoltaic thermal[136], cooling systems[137], and also hybrid solar-wind energy systems[138].

4.2.2. Geothermal

The trend in geothermal publication topics in Figure 7 initially focuses on subduction[139] and evolving to reservoir analysis[140,141], geothermal field modeling[142–144], geothermal silica[145], and the Organic Rankine cycle[146]. Other publication topics include lithium recovery from geothermal brine[147], geothermal potential map using remote sensing[148], geothermal polygeneration[149], projection uncertainty[150], and socio-economics-environmental issues on geothermal developments[151–153].

Three institutions dominate geothermal-related publications: ITB (398 articles), UI (241 articles), and UGM (241 articles). The top contributing author is Yunus Daud from UI with 52 articles mainly focusing on geochemistry[154], and geological and structural characterization[155]. Leading authors from ITB are Heru Berian Pratama and Suryantini who focus on numerical reservoir simulation and optimization[156], geological and structural characterization[157], geochemistry and hydrothermal processes[158], and resource assessment[159].

4.2.3. Hydropower

Figure 8 shows the topic trends on hydropower publications. Topics that have remained relevant from 20 decades ago include small-scale hydropower[160] and turbine technology development[161,162]. The topic of publications later evolved to large hydroelectric sustainability[163] power plants, environmental impacts, water availability, climate change, and disaster risk assessment[164,165]. Other topics include the development and mapping of hydro energy potential[166].

The National Research and Innovation Agency (BRIN) comprising the Indonesian Institute of Sciences (LIPI), the Agency for the Assessment and Application of Technology (BPPT), and the Indonesian Space Agency (LAPAN) leads in hydropower-related publications, with a total of 79 articles. Among BRIN's contributors.

Pudji Irasari and Anjar Susatyo have each authored nine publications, covering topics such as feasibility studies[167,168], water vortex turbines[161], permanent magnet generators[169], watershed management[170,171], and satellite-based site selection for hydropower development[172]. The most prolific individual author is Syamsul Hadi from Universitas Sebelas Maret (UNS), with 12 articles focusing on various water turbine technologies, including horizontal axis turbines[173], Savonius turbines[174], and Vortex turbines[175].

4.2.4. Bioenergy

Publication topics in bioenergy in Figure 9, initially focused on jatropha in the early 2010s[176], reaching a peak with topics such as biodiesel, biogas, ethanol, biomass, and palm oil from 2017 – 2022. The most impactful article (2,504 citations) discusses three methods to reduce oxygen content in carbohydrates in biomass: removal of small oxidized carbon molecules, hydrogenolysis, and

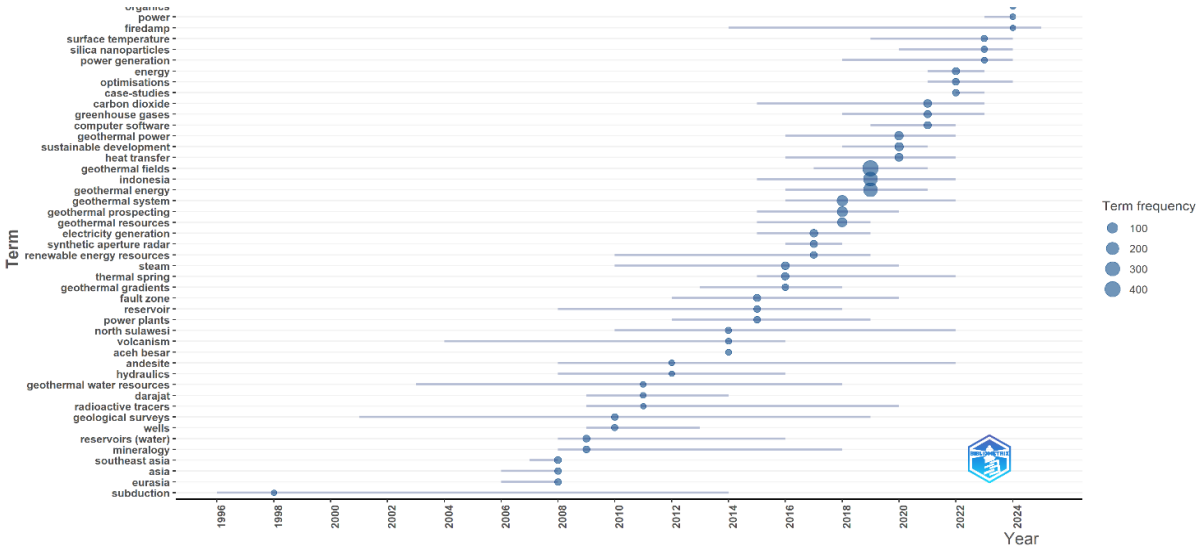

Fig. 7: Trends in publication topics related to geothermal

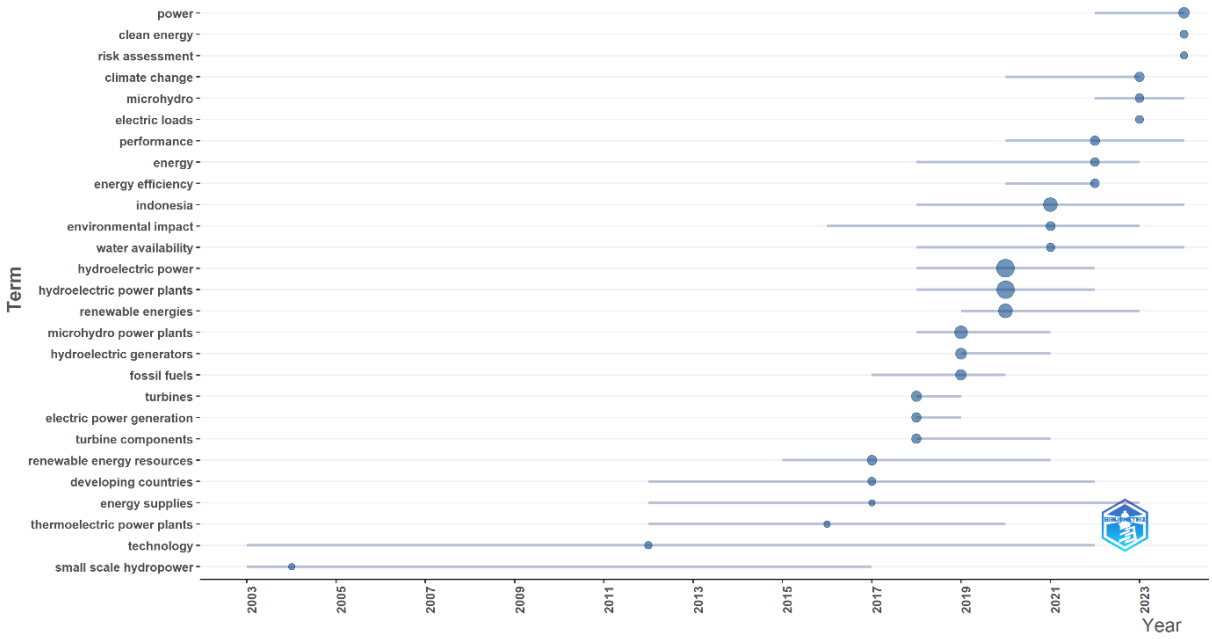

Fig. 8: Trends in publication topics related to hydropower

dehydration[177]. Other bioenergy publication topics include performance analysis of diesel power plants using a 30% biodiesel and 70% high-speed diesel blend[178] and crude palm oil[179] as well as the importance of biofuels for energy supply security[180]. Emerging topics include carbon sequestration based on microalgae[181] and tree[182], biofuel production [183], and biogas system[183].

Universitas Gadjah Mada (UGM) leads bioenergy-related research in Indonesia, contributing 814 publications. Among its most prolific researchers is Arief Budiman, with 73 publications on biodiesel production from a variety of feedstocks, including algae[184], biogas[185], bio-avtur fuel[186], and biomass[187]. The University of Diponegoro (UNDIP) ranks second with 674 publications, led by two prominent authors: Hadiyanto (81 publications) and Widayat (67 publications). Hadiyanto has contributed extensively to research on biodiesel production[188], and catalytic processes[189]. Additional notable topics include the use of microalgae as biodiesel feedstock[190], waste-to-energy conversion[191], life cycle and energy assessments[192], and the application of machine learning to optimize engine performance for bioenergy use[193]. Notably, the most prolific author is Arridina Susan Silitonga from Medan State Polytechnic, with 82 publications focusing on biodiesel and bioethanol production from diverse feedstocks—such as rice bran oil[194] and Reutealis Trisperma oil[195] —as well as on engine performance when utilizing biofuels[196].

4.2.5. Waste to Energy

Figure 10 illustrates a shift in waste-to-energy research trends, from life cycle analysis (LCA) toward refuse-derived fuel (RDF) applications. For instance, Sari et al. (2024)[197] employed LCA to compare the environmental impacts of unmanaged landfills with five waste-to-energy technologies. Meanwhile, Farahdiba et al. (2024)[198] conducted material flow analysis (MFA) to illustrate food waste steam to energy recovery facilities. Research on RDF spans various topics, including feedstock trials[199], supply chain assessments[200], and policy lessons from countries with successful RDF implementations[201]. The most frequently discussed topic is incineration with studies addressing incinerator design[202], performance evaluations[203], emissions characteristics[204], and the integration of Internet of Things (IoT) technologies[205]. Among institutions, the University of Diponegoro (UNDIP) leads with 78 publications, although none of the top contributing authors are affiliated with UNDIP. BRIN, including its predecessors LIPI and BPPT, ranks second with 58 publications. The most prolific author in this field is Muhammad Aziz from the University of Tokyo, who frequently collaborates with two leading BRIN researchers. Their work predominantly focuses on the co-firing of solid waste with coal[206–208], positioning them as key contributors to both waste-to-energy and coal-related research. Other notable authors hail from the University of Pertamina and Universitas Sebelas Maret (UNS), often collaborating on RDF-related studies[197].

4.2.6. Wind Energy

Figure 11 highlights evolving trends in wind energy research. Between 2011 and 2015, key topics included superconducting magnets[209], propeller systems[210], and smart power grid[211]. From 2018 to 2021, the focus shifted toward wind turbines[212]. Since 2020, emerging areas of interest have included wind turbines[213,214], windmills[215], and hybrid systems[138]. Additional growing topics include wind energy potential mapping[216,217], power plant

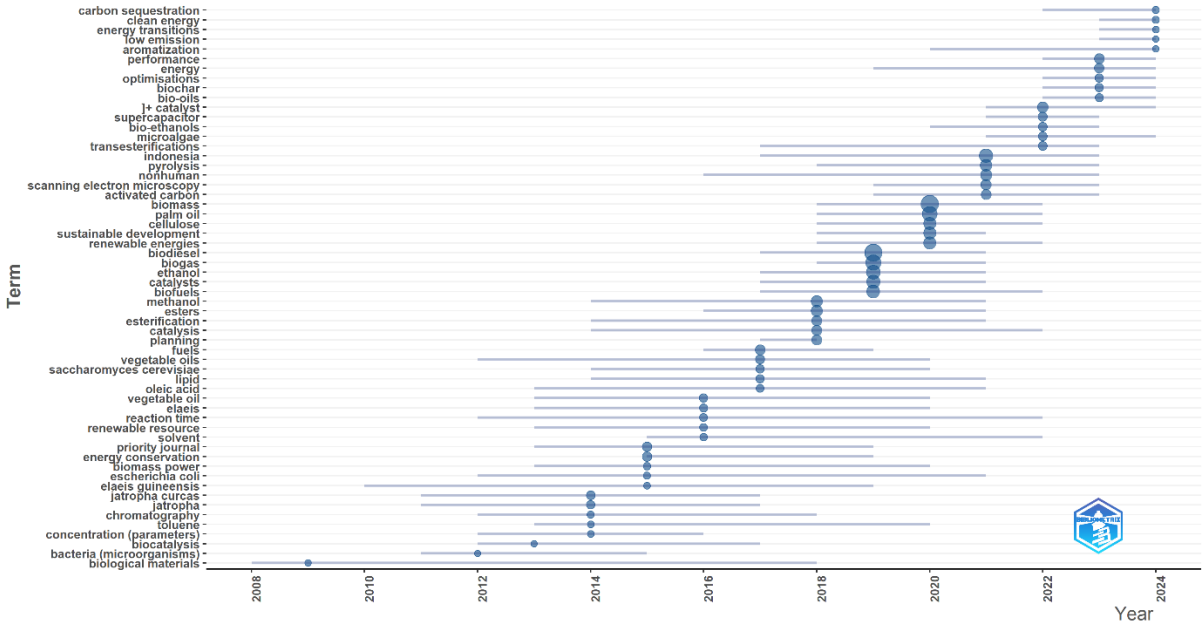

Fig. 9: Trends in publication topics related to bioenergy

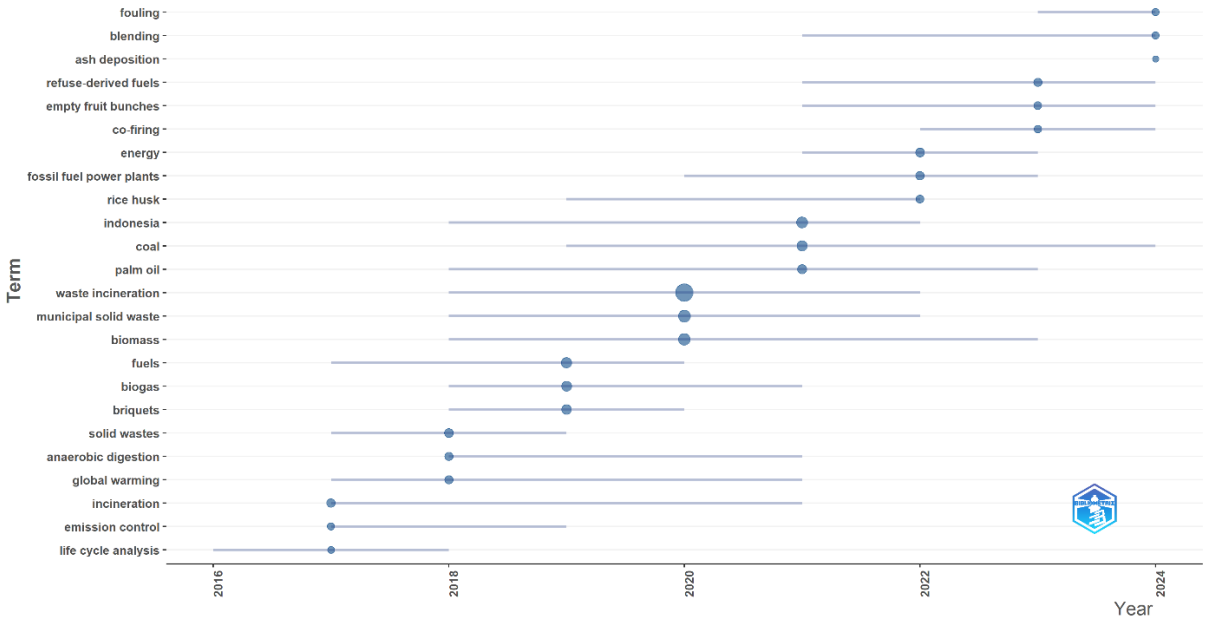

Fig. 10: Trends in publication topics related to waste-to-energy (WTE)

expansion[218], and the application of wind energy for hydrogen production[219].

The Institut Teknologi Sepuluh Nopember (ITS) leads in wind energy publications, contributing 178 articles and featuring three authors among the top contributors. Mochamad Ashari and Soedibyo have explored control systems to stabilize electricity production from variable renewable energy[220] and developed multi-input DC-DC converters[221,222]. Ratna Ika Putri has also focused on control systems for optimizing hybrid renewable energy, including the design of multi-input SEPIC converters[223].

The most prolific author is Dominicus D.D.P. Tjahjana from Universitas Sebelas Maret (UNS), whose research emphasizes both electrical and mechanical components, such as turbines[212,224], flat winglet deflector[138], and generator[138,225]. Another prominent contributor is Langlang Gumilar from Malang State University (UM), whose work focuses on wind turbine inertia and pitch angle control[226,227].

4.2.7. Ocean Energy

Figure 12 illustrates that ocean-energy research over the past decade has coalesced around three primary themes: wave energy (2017 – 2020), marine current energy (2017 – 2024) and tidal power (2019 – 2024). Wave-energy studies have spanned technology design[228,229]; numerical

modelling and experimental studies[230,231]; resource-potential assessments[232,233]; stability and control systems[234,235]; integration and policy frameworks[236,237], oceanography characterization[238]; and education and dissemination[239]. Marine-current research has focused on blade design[240], mooring systems[241,242], prototype testing[243,244], as well as self-starting and pitch mechanisms[245]. Tidal-power publications similarly center on turbine design and augmentation, material innovations, blade configurations and performance optimization[246–248]. Leading institutions in this field include Institut Teknologi Sepuluh Nopember (ITS), which accounts for 70 publications. Its three most prolific authors Mukhtasor (19 publications), Dendy Satrio (18), and I. Ketut Aria Pria Utama (12) together with Erwandi (11) from BRIN, have driven advances in vertical-axis tidal current turbines[249,250], cross-flow Savonius turbine[251], straight-bladed hydrokinetic turbine[252], and ocean thermal energy conversion[252]. Another key contributor is Nining Sari Ningsih of Institut Teknologi Bandung (ITB), whose work maps wave-energy potential at diverse coastal sites[253].

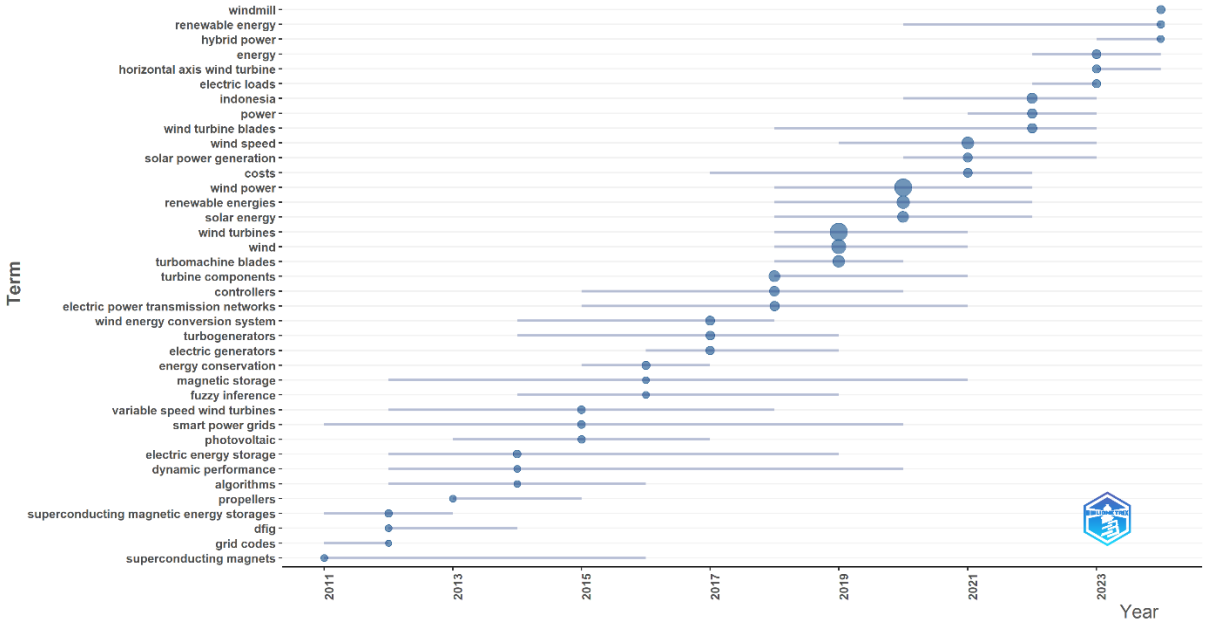

Fig. 11: Trends in publication topics related to wind energy

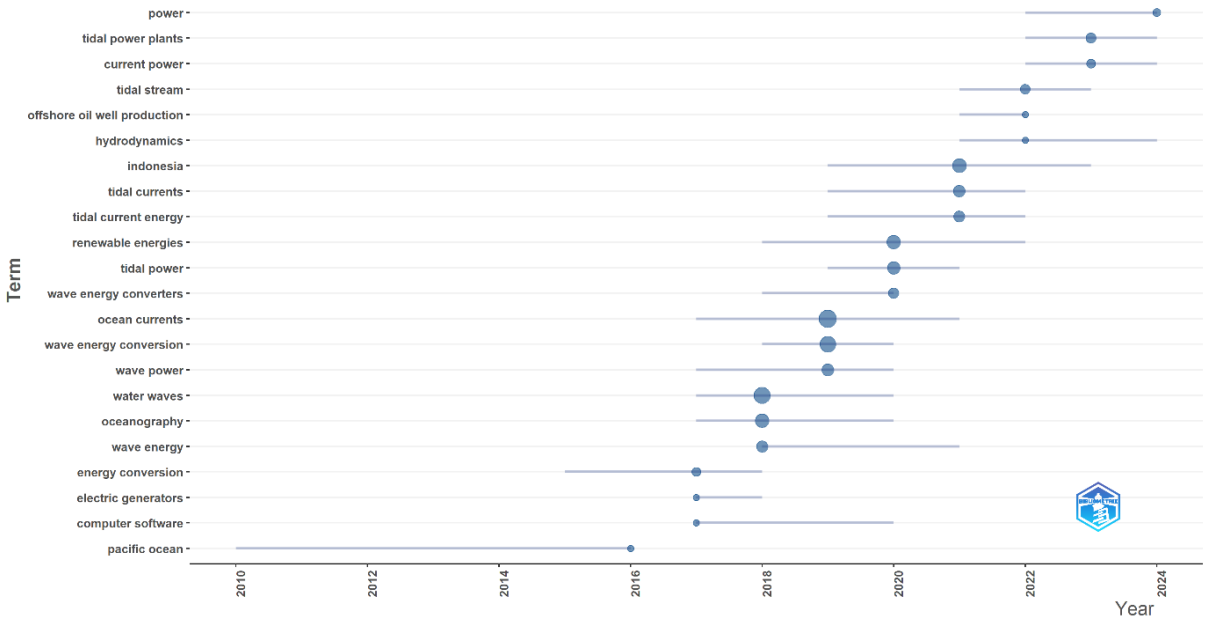

Fig. 12: Trends in publication topics related to ocean energy

4.2.8. Other Renewable Energy

Publications related to renewable energy, in general, do not contain keywords for Sections 4.2.1 through 4.2.7. However, publications in these sections may include those categorized under Other Renewable Energy. Figure 13 shows that the most prominent trend—particularly from 2017 to 2020—is the assessment of renewable energy resources. Notable examples include studies on wave energy potential in the Natuna Islands (Idris and Gammaranti, 2018) the energy potential of Calophyllum inophyllum[254]. Additional topics span energy policy modeling[83], plastic-to-liquid fuel conversion[255], energy storage materials[256,257], and sustainable development[258]. Since 2019, there has also been growing attention to the role of renewable energy in decarbonizing the energy sector[259,260].

Leadership in this publication category is held by Universitas Gadjah Mada (UGM) with 172 articles, followed by Universitas Indonesia (UI) with 162. UGM's leading contributors include Sarjiya (34 articles since 2012), Lesnanto Multa Putranto (21 since 2018), and Sasongko Pramono Hadi (15 since 2012), with research covering renewable energy integration in power systems[261,262], expansion planning[263], system reliability[264,265], as well as environmental and policy implications[266]. Miguel Angel Esquivias of Universitas Airlangga (UNAIR) ranks third with 16 publications since 2022, focusing on energy and environmental economics[267,268]. Another notable contributor is Arif Nur Afandi from Universitas Negeri Malang (UM), whose work centers on power quality evaluation for renewable plants[213] and power system modelling[269].

4.3. Most Impactful Paper

Table 3 highlights the most impactful publications across various energy sources. In the oil sector, Peters et al. (1999)[270] conducted geochemical analyses of 27 crude oil samples from eastern Indonesia, distinguishing Tertiary- and Triassic–Jurassic-sourced oils based on latitude and depositional environments. Their findings indicate that Tertiary oils—primarily from Irian Jaya and Sulawesi—originate from suboxic marlstones and account for 16% of the region's recoverable reserves.

In natural gas research, Khalil et al. (2017)[271] discussed the design, applications, and challenges of using advanced nanomaterials in the oil and gas industry. As a result, Khalil et al. (2017) identified key deployment barriers such as particle aggregation, instability in harsh conditions, and limited knowledge of nanoparticle transport mechanisms.

In the coal domain, Wibowo et al. (2007)[272] used a coal-based activated carbon F-400 to analyze the influence of surface chemistry and solution pH on the adsorption of benzene and toluene. They demonstrated that thermal treatment enhances carbon basicity and dispersive interactions, yielding the highest adsorption performance, especially under varied pH conditions.

In nuclear publications, Purba et al. (2014)[273] explored the development of a fuzzy reliability algorithm to estimate failure probabilities in nuclear power plants where quantitative historical data is unavailable. By converting expert linguistic evaluations into fuzzy numbers, the proposed algorithm enables qualitative estimation of basic event failure probabilities, demonstrating strong agreement with actual failure data.

Gonzalez-Pedro et al. (2014)[274] presented a detailed investigation into the underlying mechanisms governing $CH_3NH_3PbX_3$ perovskite solar cells, revealing that both

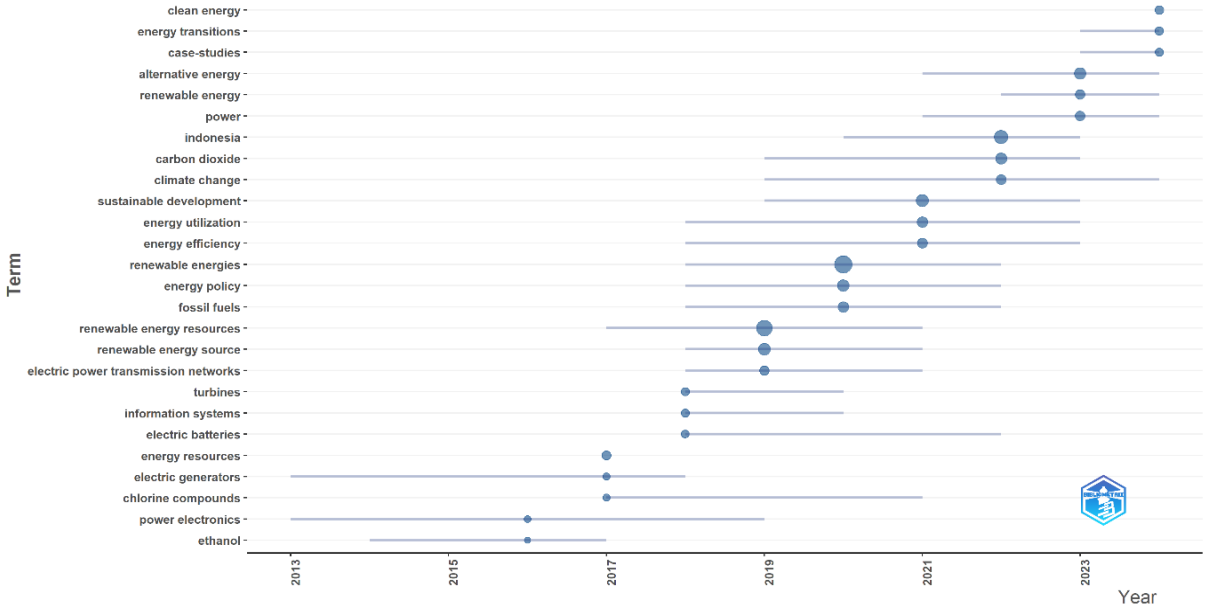

Fig 13: Trends in publication topics related to other renewable energy

compact thin films and nanostructured configurations share a common photovoltaic operation dominated by the perovskite absorber. Moreover, the research results are useful to establish a comprehensive model of the optimal working process of perovskite solar cells.

In geothermal publications, Herdianita et al. (2000)[275] discussed temporal changes in the mineralogy and texture of 29 silica sinter samples ranging from modern to Miocene age. Over time, silica sinter undergoes crystallization from opal-A to opal-C, and finally to microcrystalline quartz, displaying an aging profile that can serve as a guide for understanding the paleohydrology of geothermal systems.

Hasan et al. (2012)[276] assessed Indonesia's energy landscape, highlighting a continued dependence on fossil fuels despite the nation's vast renewable energy potential, including hydro power. Thus, Hasan et al. (2012) emphasized the urgent need for more proactive, collaborative action across government, institutions, and the public to ensure long-term energy security and environmental resilience.

Van Putten et al. (2013)[177] discussed hydroxymethylfurfural (HMF) as a pivotal bio-based platform chemical derived from hexose dehydration, with significant potential for conversion into fuels and value-added chemicals. They emphasized persistent challenges in scaling up to economically viable industrial processes particularly those based on glucose or lignocellulosic feedstocks due to HMF's instability and the complexity of separation and recycling systems.

In waste-to-energy publications, Nizami et al. (2017)[277] explored the transformative role of waste biorefineries in advancing circular economies within developing countries, where unmanaged waste can become a valuable feedstock for energy and material recovery.

In wind energy publications, Tjiu et al. (2015)[278] comprehensively evaluated Darrieus vertical axis wind turbine configurations, tracing their evolution from early curved-blade designs with guy-wires to modern cantilevered structures. Tjiu et al. (2015) highlighted how contemporary variants—such as Helical and Tilted H-rotors—offer improved reliability and lower energy costs.

In ocean energy publications, Sprintall et al. (2010)[279] provides definitive observational evidence of the South Java Current (SJC) and its deeper undercurrent (SJUC) flowing eastward through the Savu Sea into the Ombai Strait. Drawing on three years of moored velocity data, it distinguished the mechanisms driving surface and subsurface currents, including Kelvin waves, Ekman dynamics, monsoonal shifts, and regional topographic influences.

In other renewable energy publications, Erdiwansyah et al. (2021)[280] evaluated the complex integration of variable renewable energy (VRE) sources—like wind, solar, and hydro—into modern power systems, emphasizing both the technical challenges and potential technological solutions. By proposing a structured matrix of solutions tailored to specific integration barriers, the study offers a roadmap for improving system reliability, economic viability, and policy transparency in the global transition to sustainable energy.

Table 3: A summary of most impactful papers

Sectors	Articles (citations)	Topics
Oil fuel	Peters et al. (1999) (235)	Geochemistry of crude oils[270]
Natural gas	Khalil et al. (2017) (235)	Advanced nanomaterials[271]
Coal	Wibowo et al. (2007) (301)	Coal-based activated carbon[272]
Nuclear	Purba et al. (2014) (94)	Failure probabilities[273]
Solar energy	Gonzalez-Pedro et al. (2014) (802)	Perovskite solar cells[274]
Geothermal	Herdianita et al. (2000) (232)	Silica sinter[275]
Hydropower	Hasan et al. (2012) (221)	Energy supply[276]
Bioenergy	Van Putten et al. (2013) (2,504)	Hydroxymethylfurfural (HMF)[177]
Waste to Energy	Nizami et al. (2017) (433)	Waste biorefineries[277]
Wind Energy	Tjiu et al. (2015) (227)	Darrieus vertical axis wind turbine[278]
Ocean Energy	Sprintall et al. (2010) (61)	Current system[279]
Other Renewable Energy	Erdiwansyah et al. (2021) (330)	The integration of renewable energy[280]

5. Discussions

The trends in energy supply publication topics continue to evolve. Table 4 divides these topics into four quadrants based on the number of themes (referred to as density or development degree) on the y-axis and the correlation of these themes with other topics (referred to as centrality or relevance degree) on the x-axis. The four quadrants provide a strategic framework for identifying areas of strength and opportunity within the field. By fostering connections between niche and motor themes, revitalizing emerging or declining topics, and innovating within basic themes, the renewable energy sector can enhance its overall impact and contribute to a more self-sufficiency energy future.

5.1. Motor Themes

Themes in this quadrant exhibit high density and interconnectivity, indicating that they have developed rapidly and are closely linked to various other studies. These themes play a key role in the energy transition and innovation

One example in this category is biomass and biogas, which

Table 4: Thematic publication map

Development degree (density)	Niche themes	Motor themes
	Oil fuel: diesel engines and fuels	Oil fuel: gases, gasoline
	Natural gas: -	Natural gas: carbon dioxide, natural gasoline plants
	Coal: deposits, mines, mining, fly ash, coal ash, soils	Coal: -
	Solar energy: dry-sensitized solar cells, titanium dioxide, semiconductor	Solar energy: energy policy, power transmission networks
	Geothermal: -	Geothermal: fields, systems
	Hydropower: electronic load controller, load management, sustainable development	Hydropower: -
	Bioenergy: activated carbon, carbonization, supercapacitor	Bioenergy: biomass, biogas, biofuels
	Waste to energy: incineration process, circular economy, plastic bottles	Waste to energy: municipial solid waste, sustainable development
	Wind energy: asynchronous generators, turbogenerator, electric fault currents, controllers, dc-dc converters, permanent magnets	Wind energy: solar energy
	Ocean energy: energy conversion, electric generators	Ocean energy: Indian ocean, current and flow velocity
	Other renewables: alternative energy, carbon dioxide	Other renewables: resources, source, power
	Nuclear: small modular reactors, nano particles, scanning electron microscopy, x-ray diffraction	Nuclear: fast reactors, reactors, fuels, nuclear power plants, cesium
	Emerging or declining themes	**Basic themes**
	Oil fuel: crude oils, oil well flooding, enhanced recovery, offshore well production, gas industry, cost	Oil fuel: petroleum reservoirs and their evaluations, oil wells
	Natural gas: gases, gas industry	Natural gas: -
	Coal: -	Coal: power plants, carbon dioxide, combustion, coal industry
	Solar energy: PV systems, maximum power point trackers, inverters, efficiency, performance,	Solar energy: power generation, PV cells
	Geothermal: power plants	Geothermal: -
	Hydropower: -	Hydropower: fossil fuels, solar energy, energy policy, power plants
	Bioenergy: ethanol, bioethanol, fermentation, biodiesel, catalyst	Bioenergy: palm oil, diesel engines
	Waste to energy: briquets, combustion, fly ash	Waste to energy: waste incineration, biomass, calorific value
	Wind energy: turbomachine blade, turbine components, computational fluid dynamics	Wind energy: sources/ resources, power transmission networks, turbines
	Ocean energy: simulation	Ocean energy: ocean currents, tidal power, waves, wave energy conversion
	Other renewables: calorific values, hydroelectric power plants, turbomachine blades	Other renewables: sustainable development
	Nuclear: zirconium alloys, linear calibration, zircaloy, safety engineering, fault tree analysis, probabilistic safety assessment	Nuclear: power plant sites, risk assessment, nuclear energy
	Relevance degree (Centrality)	

are central topics in bioenergy research. Studies in this field cover various aspects, from raw material optimization and improving energy conversion efficiency to integration with energy storage technologies and distribution systems. Biomass and biogas serve as crucial solutions for diversifying renewable energy sources and reducing dependence on fossil fuels[281)]. Additionally, the development of renewable energy-based power grid systems is also a critical driving theme, considering the need for more flexible and reliable systems to support the integration of renewable energy into the national grid.

The dominance of biomass and biogas as motor themes directly aligns with Indonesia's national biofuel policy (B30/B35) and its vast agricultural resources. This reflects a successful alignment of research with policy and economic opportunity, contributing directly to SDG 7 (Affordable and Clean Energy) and SDG 9 (Industry, Innovation, and Infrastructure). However, the focus on combustion and conversion efficiency suggests research must now also intensify on sustainability aspects (SDG 12:

Responsible Consumption and Production) to ensure long-term viability

As a driving theme, research in this field tends to be the primary driver for technological and energy policy advancements, thereby accelerating the transformation of Indonesia's energy system toward greater sustainability and self-sufficiency. This quadrant does not include publications on coal and hydropower, indicating that while these energy sources are still widely used, they are not currently at the forefront of innovation in energy research.

5.2. Niche Themes

This quadrant includes themes with high density but low connectivity to other research areas. This indicates that while these topics have been extensively studied, they remain specific and have not been widely integrated into broader energy research.

Some themes in this category include carbon-based supercapacitors in bioenergy (e.g., Diantoro et al., 2024a[282]) and the use of titanium dioxide microparticles to prevent dust accumulation on solar panels (e.g., Syafiq et al., 2024[283]). These topics have undergone in-depth research but have not yet been significantly integrated with other themes in the energy sector.

Although still specific, these themes have the potential to expand if linked to more applied research. For example, the development of biomass-based supercapacitors could be connected to energy storage technologies[284], while innovations in solar panel cleaning could contribute to improving solar power plant efficiency[283]. Therefore, research in these fields could further develop if supported by cross-disciplinary collaboration.

However, this quadrant does not include publications on natural gas and geothermal energy, indicating that while these energy sources hold significant potential in Indonesia's energy mix, related research is more interconnected with other themes and does not fall into a highly specific niche category. This suggests that natural gas and geothermal energy have already established broader research networks and are not confined to a particular specialized scope.

5.3. Emerging or Declining Themes

Themes in this quadrant have low density and connectivity, indicating that they are either in the early stages of development or are being phased out. This could be due to various factors, such as changes in energy policies, technological limitations, or a lack of investment supporting further research.

One example in this category is offshore oil well production, which, although still a subject of research, has been declining as energy policies shift toward energy transition and reducing dependence on fossil fuels. In many countries, including Indonesia, the government and industry sectors are beginning to focus more on renewable energy and energy efficiency as part of efforts to achieve decarbonization and net-zero emissions targets[285]. This shift has made research on offshore oil exploration and production less relevant compared to previous decades.

Additionally, some studies on nuclear energy utilization are still in the early exploratory stages in Indonesia. Although nuclear energy holds significant potential as a long-term clean energy source, regulatory challenges, safety concerns, and investment constraints remain major obstacles to its development[286,287]. As a result, research in this field remains sporadic and has not yet become a primary focus in national energy policy. If stronger policy support and investment in safe and efficient nuclear technology emerge, this theme could become more significant in the future.

Interestingly, this quadrant does not include research on coal and hydropower. This suggests that these energy sources are no longer classified as emerging or declining themes but have instead secured a more established position in energy research. Coal, despite remaining a dominant energy source in Indonesia, is increasingly discussed in the context of efficiency, co-firing with biomass, and decarbonization strategies, meaning it does not fall under the category of emerging or declining themes. This indicates that research on coal has already built a strong foundation and is more integrated with other topics, such as energy transition and carbon emission reduction.

Meanwhile, hydropower is also absent from this category, which could indicate that hydropower technology and research are already mature and have broader connections with other renewable energy studies. However, it may also suggest that hydropower research in Indonesia is stagnating, with little new innovation to place it in the emerging themes category. Given the increasing demand for clean energy, Indonesia still holds vast potential for hydropower development, particularly in small-scale and micro-hydro power plants, which are more suitable for remote areas. If research and investment in hydropower technology are enhanced, this theme could regain prominence in national energy research.

5.4. Basic Themes

The Basic Themes quadrant includes topics with high connectivity but still low density, indicating that these topics have broad relevance in energy research but remain underexplored in-depth. Themes in this category serve as foundational elements for energy technology development but have not yet become a primary focus in national energy research.

One key example in this category is ocean currents, tidal energy, and wave energy conversion. Although marine energy holds significant potential as a renewable energy source in Indonesia[288,289], research in this field remains relatively limited. Ocean energy conversion technologies, such as tidal turbines and wave energy systems, are still in

the early stages of development and have yet to be integrated into the national power grid. The main challenges in this research include high technology development costs, limited supporting infrastructure, and a lack of investment in research and innovation. The classification of ocean energy as a 'basic theme' is high relevance but low development highlights a critical strategic gap. Indonesia, as the world's largest archipelago, possesses immense ocean energy potential, yet research remains nascent. Prioritizing investment and international collaboration in this area is not just a research imperative but a national strategic one to enhance energy security (SDG 7) and build climate resilience (SDG 13).

Additionally, themes in this quadrant require greater attention to ensure that research in these areas progresses and contributes to the national energy system. With further support from the government, industry, and academic collaborations, research in this field could serve as a foundation for future energy innovations. Developing policies that support marine energy exploration, including incentives for industries and research partnerships with international institutions, could accelerate the adoption of these technologies in Indonesia.

Interestingly, this quadrant does not include natural gas and geothermal topics. There are several possible reasons for their absence from this category. Natural gas already has a well-established research ecosystem and has been integrated into various energy studies. Research on natural gas is typically not considered a "basic theme" but is more often linked to energy transition, emissions reduction, and integration with renewable energy. Additionally, natural gas research tends to focus on technical aspects such as exploration and production optimization, efficient utilization, and liquefied natural gas (LNG) processing technologies. As a result, natural gas is more likely to be found in research categories that are already well-developed or undergoing transformation, rather than as a basic theme still in its early exploration stages.

Meanwhile, geothermal energy is also absent from the Basic Themes category because Indonesia already has extensive research and experience in geothermal exploration and utilization. As one of the world's largest geothermal energy producers[290,291], research in this field has advanced further and is well-integrated into national energy policies. Current geothermal research focuses more on resource optimization, drilling technology, improving energy conversion efficiency, and co-generation potential (using waste heat for purposes beyond electricity generation). Therefore, geothermal research has already established a strong foundation and is no longer categorized as a basic theme requiring extensive new exploration.

5.5. Collaboration

Collaboration with institutions in other countries helps in determining research topics. Table A.3 in the Appendix shows that the frequency of collaboration with foreign institutions has reached 1,735 times. Foreign partners mainly come from Malaysia (23%), Japan (15%), and China, USA, and Australia, each about 7%. Publications with partners from Malaysia generally relate to natural gas, wind energy, solar energy, hydro power, bioenergy, waste-to-energy, and other renewable energy. Partners from Japan are usually involved in coal, nuclear, and geothermal publications, while partners from the USA often collaborate on oil and ocean energy publications. These partnerships are not limited to universities but also include industries. For an example, Texaco Energy Technology has several publications with its subsidiary in Indonesia[292]. Domestic companies have also been significantly involved in research and publications, such as the use of bleaching earth to improve the performance of biodiesel-cooking oil plants[293].

To enhance energy research collaboration with international partners, a more proactive strategy is needed to expand academic and industrial networks, increase funding schemes, and simplify regulations for cross-border research. Moreover, research in Indonesia should be aligned with globally relevant issues that attract foreign collaborators, such as energy transition, energy storage technologies, and industrial decarbonization, to encourage greater international participation in research partnerships.

5.6. Implications for Policy and Research

The bibliometric trends offer clear, data-driven guidance for Indonesian policymakers and research institutions. Firstly, the success in bioenergy research should be leveraged, with policies encouraging cross-institutional collaboration to address sustainability challenges. Secondly, the significant potential in solar and geothermal is not fully matched by research density, suggesting a need for targeted funding and public-private partnerships to overcome technical and economic barriers to deployment. Thirdly, the 'basic themes' of ocean, wind, and advanced nuclear technologies represent strategic frontiers. Establishing national research consortia with international partners from Japan, the USA, and Australia (as shown in our collaboration analysis) could accelerate development in these high-potential but underexplored areas. Finally, achieving energy self-sufficiency requires integrating these research strands into a coherent national energy innovation strategy that explicitly links research outputs to the targets of the Sustainable Development Goals.

6. Conclusions

Our study provides the first comprehensive bibliometric map of Indonesia's energy supply research, revealing a dynamic and specialized landscape rapidly shifting towards renewable energy. The analysis demonstrates that no single institution holds a monopoly on expertise;

instead, a distributed network of universities and research agencies drives progress in specific domains. This presents both a challenge and an opportunity for coordinated national action.

Based on our findings, we propose three actionable recommendations:

Foster Strategic Collaboration: The government should establish a national energy research and innovation council to facilitate partnerships between leading institutions (e.g., ITB in geothermal, UGM in bioenergy, ITS in ocean energy) and the private sector, focusing on translating research into deployable technologies.

Prioritize Underfunded Frontiers: National research grants should be strategically allocated to develop 'basic themes' with high strategic relevance, particularly ocean current and wave energy, where Indonesia's natural endowment is unmatched but research is sparse.

Enhance International Linkages: Building on existing ties with Malaysia and Japan, Indonesia should proactively seek research partnerships with countries leading in specific technologies (e.g., Denmark for wind, Germany for solar storage) to fast-track technological learning and innovation.

By adopting a more integrated and strategic approach to energy R&D, informed by this bibliometric landscape, Indonesia can better leverage its intellectual capital to achieve energy self-sufficiency and secure a sustainable, resilient energy future. Future research should incorporate non-Scopus publications, project data, and analysis of energy storage and conservation to provide an even more complete picture.

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