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TOPICAL REVIEW

# Review on 100% Renewable Energy System Analyses–A Bibliometric Perspective

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**ABSTRACT** Concerns related to climate change and global warming caused by anthropogenic activities and fossil energy use in particular have been increasing lately. Air pollution and volatile conventional fuel prices emphasize the need to transition global energy systems towards very high shares of renewables. 100% renewable energy systems have been analyzed by many researchers starting from 1975. This bibliometric analysis reviews more than 600 scientific articles in which 100% renewable energy systems were surveyed. This study uses tools of bibliometric analysis based on publication databases and data mining together with review elements to understand the status and trend of 100% renewable energy systems research. The focus of results is on quantitative parameters relating to number and publication types, collaborative links among authors, institutions, and countries. Collaborative networks illustrate the significant concentration of published papers within organizations and co-authorships globally. The results reveal that the dominant organizations and thus number of published papers are from Europe and the USA; however, almost all the established research organizations in the field of energy system analysis are not active in the field of 100% renewable energy systems analyses. The journals *Energy* and *Applied Energy* have the most articles, and accordingly the most citations. EnergyPLAN and LUT Energy System Transition Model have been the most active tools used to analyze 100% renewable energy systems according to numbers of articles and received citations. The topic of modeling approach indicates the term 'Energy System' has the highest frequency due to its emergence in the articles. This research provides a holistic overview on the more than four decades of research, and it reveals dynamics within the field with a compound annual growth rate of articles of 26% in the 2010s, the trend of increasing the number publications, and author growth that comprises almost 1400 published authors.

**INDEX TERMS** 100% renewable energy, energy transition, bibliometric analysis, data processing machine, social networks, collaborative maps, topic model.

## ABBREVIATIONS

| | |
|---|---|
| CAGR | Compound Annual Growth Rate. |
| CDR | $CO_2$direct removal. |
| $CO_{2eq}$ | $CO_2$-equivalent, the emissions of $CO_2$ plus other greenhouse gases. |
| DACCS | Direct air carbon capture and storage. |
| DIW | Deutsches Institut für Wirtschaftsforschung. |
| ESMs | Energy system models. |
| IAMs | Integrated Assessment Models. |
| IPCC | Intergovernmental Panel on Climate Change. |
| GHG | Greenhouse gas. |
| LDA | Latent Dirichlet Allocation. |
| LUT-ESTM | LUT Energy System Transition Model. |
| MINES | MINES Paris, officially École Nationale Supérieure des Mines de Paris. |
| PIK | Potsdam Institute for Climate Impact Research. |

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|---|---|
| RE | Renewable energy. |
| RLI | Reiner Lemoine Institut. |
| SAARC | South Asian Association for Regional Cooperation. |
| SDGs | Sustainable Development Goals. |
| SNA | Social Network Analysis. |
| USA | United States of America. |
| UN | United Nation. |
| VTT | Valtion Teknillinen Tutkimuskeskus. |
| WoS | Web of Science. |

## I. INTRODUCTION

The energy system is the largest contributor to global greenhouse gas (GHG) emissions, composing of energy extraction, conversion, storage, transmission, and distribution activities [1]. Anthropogenic GHG emissions have climbed from 53 to 58 $GtCO_{2eq}$/yr (carbon dioxide equivalent emissions per year) between 2010 and 2019 and strongly impact global climate change [1]. $CO_2$ emissions have risen from an average of 33.0 $GtCO_2$/yr in the 2000s to an average of 38.9 $GtCO_2$/yr in the 2010s, with a projected 39.3 $GtCO_2$/yr in 2021 by fossil and land-use change emissions [2]. It is proven that global warming caused by humans has led to increased events of heavy precipitation and droughts, soil erosion, and change in vegetation cover [3]; thus, an uncontrolled incremental trend of climate change might lead to a global societal collapse in the 21$^{st}$ century. Air pollution triggered by burning fossil fuels is a major health burden and induces high societal costs [4], [5], and biomass for cooking causes massive negative impacts in developing countries, especially for women and children. Such issues are avoidable by shifting to renewable and sustainable energy and feedstock sources for the energy-industry system [6]. Furthermore, United Nations Sustainable Development Goals (SDGs) highlight the expansion of renewable energy (RE) in the energy system and the enhancement of energy efficiency [7]. There are several possibilities to both reduce the GHG emissions from the energy-industry system and meet the growing global energy demand. Some options are energy efficiency, phasing out fossil fuels, and thus the promotion of RE [8], [9], finally leading to an entirely RE system [10].

100% RE systems have been analyzed by a growing number of researchers to find solutions for a sustainable energy system [11] and to understand a feasible approach to mitigate climate change impacts, air pollution, energy poverty, and develop the most cost-effective energy systems [10], [12], [13].

Analyses of 100% RE systems started by Sørensen [14]. In the following year, energy policy analyst Lovins introduced the term 'soft energy path' to showcase an alternative future where RE sources replace the centralized 'hard' energy system [15]. The first global 100% RE systems analysis article for the world was published by Sørensen [16], more than 10 years before the second one had been published by Jacobson and Delucchi [17], [18], which remains the most cited article on 100% RE systems research.

Czisch published his dissertation showing that a 100% RE supply could match demand in every hour of the year in Europe, North Africa, and Western Eurasia [19]. This had been a methodological breakthrough, as both historic weather data and an hourly resolution for all regions of a year had been used for an interconnected multi-node design. Lund published a paper in which optimal combinations of renewables were indicated [20]. Before 2006, only 13 articles on 100% RE systems were published, thereof 7 from Sørensen. Since 2006, at least 5 articles were published every year by energy experts worldwide on the transition from a fossil-nuclear energy system to a 100% renewables-based system. In his dissertation, Sterner [21] introduced the Power-to-Gas concept to energy system modeling with two major new concepts in the field of 100% RE systems analysis: seasonal storage based on an electricity-to-molecules concept and sector coupling utilizing renewable electricity.

The Power-to-Gas concept has since been further developed into a Power-to-X framework [22]. The concept of electricity-based sector coupling is equivalent to the smart energy systems concept introduced by Mathiesen and Lund [23]. Bogdanov and Breyer et al. [24], [25] advanced the field of 100% RE systems analysis by introducing a cost-optimized transition pathway for the world structured in 145 regions, whereas practically all global models use 20-30 regions. This scenario identified the first cost-neutral 1.5 °C compliant pathway without negative $CO_2$ emissions and assuming substantial increase in energy services demand. This pathway revealed the impact of low-cost photovoltaics-battery-electrolyzer systems as the core of modern energy systems, leading to very high levels of energy system efficiency, overall electrification, and solar photovoltaics (PV) energy system supply shares on the global average of about 70% [24]. In 2021, the threshold of more than 600 scientific articles on 100% RE systems was surpassed and was used as a basis for a bibliometric analysis in this research.

Bibliometric analysis is the use of a quantitative approach to analyze articles and scientific publications. Bibliometric analysis is one of the interdisciplinary research methods that has been expanded to scientific fields to virtually all scientific fields [26]. The wider field of energy has been covered by several bibliometric analyses, such as for the specific fields of energy security [27], energy justice [28], energy performance contracting [29], energy efficiency [30], bioeconomy [31], [32], resource use and GHG emissions [33], sustainability of RE sources [34], hybrid PV-wind-storage systems [35], sustainable siting and design optimization of hybrid RE systems, [36], multi-energy systems [37], energy storage for decarbonization [38], electric vehicles [39], [40], [41], direct air capture [42], negative emissions [43], transition and transformation [44], [45], and municipal energy system planning [46]. One recent bibliometric analysis has been published for the wider field of energy system analysis [47]. This wider

field is narrowed to the specific field of 100% RE systems articles in this research.

Bibliometrics are used for statistical analyses to show the significance of specific topics within a research field as well as networks of researchers and organizations. They are also used to identify the impact of specific research articles, individual researchers, research teams or organizations. Bibliometrics are increasingly used to measure research output among institutions on a national or international level. They identify research strengths and advise decisions about future research interests.

In this article, a bibliometric analysis is presented for all 100% RE systems articles identified until mid-2021. Since the 100% RE systems literature is very scattered and has not been comprehensively gathered via bibliometric analysis, this research serves to provide a central literature database for 100% RE systems research, which will be especially useful for researchers who want to enter this growing field and investigate specific aspects of the available literature. The purpose of this article is to provide insights into the 100% RE systems research field, which includes insights on the full identified spectrum of articles, their analyzed regions, the growth of the research field, where the research has been published, and the research groups active in this field. The most influential articles are identified, and the most used models are presented. To have a more holistic view on the research field, in addition to the bibliometric analysis, a literature review is conducted to provide further insights on facets of the field. The central research questions addressed in this paper are:

- What temporal dynamics can be found in the research field for articles and citations?
- Which teams and countries contribute and how dynamic is their contribution?
- What collaboration networks for teams and countries can be observed?
- What regional heterogeneity in researched countries can be found?
- What are the most influential articles in total and at their time of publication?

The aim of this research is to answer the research questions with the full body of literature identified in the field of 100% RE systems analyses from a comprehensive perspective. The article is organized as follows: section 2 describes methods and data, section 3 provides the literature review, section 4 presents results and discussion, and section 5 draws final conclusions.

## II. METHODS AND DATA

As bibliometric analysis is the use of a quantitative approach to analyze articles and scientific publications, the beginning step is to identify and collect all available literature for 100% RE systems published in scientific journals. Next, bibliometric features are extracted to analyze the literature quantitatively. Finally, bibliometrics tools and models are applied to investigate the structure of the research field in detail.

### A. ARTICLE SELECTION

The search for 100% RE systems articles was done as follows:

(a) To carry out structured research regarding the field of energy systems, the search was restricted to using the keywords *renewable energy system*, *fully sustainable system analysis*, *100% renewable energy*, *energy system transition*, and *clean energy system* in the online platforms Scopus, Science Direct, and Google Scholar.
(b) Already identified 100% RE systems literature [12], [13] were collected and added to the database.
(c) Individual tracing (1): back and forth tracing of identified articles to identify further 100% RE system articles.
(d) Individual tracing (2): contacting research peers for complementary articles, both from their research group and beyond.

The criteria applied for 100% RE systems articles are classified as follows:

(a) An energy system article should have at least one system analysis with a minimum of 95% RE share for at least one energy sector. This shall ensure all features of 100% RE systems.
(b) The year of the publication is not a limit for an article.
(c) The identified 100% RE systems articles are sorted into three main categories:
    - One: analysis for at least one specific geographic entity is carried out. The minimum size is a village and the maximum size the world.
    - Two: generic analysis without any geographic context.
    - Three: articles with a substantial literature review on any aspect on 100% RE systems.

In the present research, the bibliometric analysis is performed based on the three given categories with further emphasis on category one due to the number of identified publications and focus of the paper. All identified 100% RE systems articles were linked to scientific literature datasets for a comprehensive analysis. The collected articles are introduced to the Scopus database. Scopus is the largest database of abstracts and citation information of scientific literature and data sources; thus, the most comprehensive analysis was enabled using this database. Scopus provides diverse data on each publication with analysis and comparison [48]. Web of Science (WoS) was also considered; however, Scopus contributes a higher accuracy and more comprehensive article and journal coverage of scientific publications for all major disciplines. Thus, WoS was sorted out, and Scopus was used as the data source [49].

### B. BIBLIOMETRIC CHARACTERISTICS

Scientometrics is the science of measuring and analyzing science. Scientometrics is done by bibliometrics, which

comprises statistical methods to measure the characteristics and patterns of publications [50]. The central bibliometric metrics and parameters to measure the level of influence are summarized below:

(a) number of citations that an article receives per year and through the years.
(b) average normalized citations that is calculated by dividing the total number of citations by the average number of citations published per year in each field [51].
(c) h-index, as the measure of influence, is a dimensionless number that represents cumulative quantity and quality or impact of an author's academic publications and depends on a set of the author's most frequently cited articles. The researcher's h-index highlights the point in which the citation number crosses the publication order, according to Hirsch [52], [53], [54]. The h-index can also be applied to journals. One may also present a normalized version of the h-index, i.e., h-index of 100% RE articles as a ratio to the entire h-index of a researcher, which may indicate the role of the research field for the researcher.
(d) g-index is defined as a value that the top g articles are cited by an average of $g^2$ times or more, according to Egghe [55].
(e) m-index is an alternative form of h-index and is defined as an individual's h-index divided by the number of years since the individual's first publication [53]. Hirsch [52] characterizes the m-index values for $m \approx 1$ for a 'successful scientist', $m \approx 2$ for an 'outstanding scientist' and $m \approx 3$ for a 'truly unique individual', while he assumes an average of 20 productive years for this rating.

### C. TOOLS AND PROGRAMS

The bibliometric analyses are carried out by applying the Bibliometrix functions of the R programming environment to scan the body of the literature [56]. R is a language for statistical analysis and graphics, which has large numerical and visualization procedures with a highly scalable functionality. Bibliometrix in R is an open-source tool that allows the user to import bibliography information once the data is retrieved from the Scopus or WoS database with BibTex and Plaintext [56].

VOSviewer is a software tool that creates maps and networks of bibliometric data. To build a network, bibliographic files are extracted from Scopus, WoS, or other databases. VOSviewer can create a map through three ways: First, map creation via an adjacency matrix of a network in which pairs of items in the network are connected to each other. Second, a map is created through bibliometric data, which is gathered from the database. Third, map creation based on a text corpus in which the data is stored in a text file. This text is then extracted from the corpus file and a term map is produced. The second approach was used in this research to create maps of topographic networks and clusters consisting of (1) scientific publications and journals, (2) research and researcher organization, and (3) keywords or terms used in the articles. Items to be provided by such networks can be co-authorship, co-occurrence, citation, bibliographic coupling, or co-citation links [57].

Topic modeling has been broadly used by scientists to analyze the incremental amount of text documents. This is a machine learning approach for forming a set of documents based on their semantic themes. There are several techniques for the topic modeling used by data experimenters. Latent Dirichlet Allocation (LDA), which is extensively used for the topic modeling method, is used in this research. Every topic is modeled by a probability distribution over words with the number of predefined topics. Topic models predominantly reduce the extension of a set of words in documents into compact and purposeful topics. LDA analyzes the relationships between topics and keywords using a Python library for coding and visualization by the tool Gephi [58].

UCINET is a tool used to perform the social network analysis (SNA) of authors' organizations [59]. Typically, UCINET is used to analyze one-mode and two-mode matrix data to find a spot for nodes, groups, and items. The two-mode matrix is used in this research to analyze the SNA of organizations. An outline on the methods and results is provided in Figure 1, where the methods consist of different statistical techniques and tools to achieve the respective results.

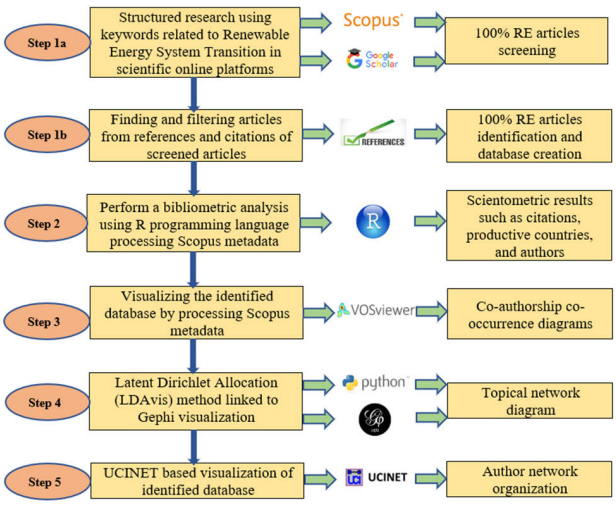


**FIGURE 1. Flow of the methodological scheme of the applied bibliometric analysis representing databases, tools, and output data with diagrams. Scopus and Google Scholar are input databases, R and Python are programming languages, and VOSviewer, Gephi, and UCINET are software tools.**

## III. LITERATURE REVIEW

According to the definition of category one, a 100% RE systems article should consider at least one geographic entity. Based on that central criterion, 550 related category one articles have been identified. The geographic entities can

be global, continent, country, state, county, city, village, and island. In addition, 37 articles were classified for category two with no geographic consideration, and thus a more generic 100% RE systems analysis. Finally, 37 articles were classified as category three, which covers substantial literature reviews typically without a concrete geographic analysis. Additionally, the combination of category one and three can be found, which applies to 4 articles. In total, 620 articles have been identified in the field of 100% RE systems analyses. All category one, two, and three articles are listed in the Supplementary Material. The number of articles were fixed at mid-2021 for this research. Table 1 provides a structured overview on the 550 identified articles for category one, based on their geographic context.

The articles are structured according to their world regions, the level of investigation from world region to country or sub-country (e.g. state or region; city, village or off-grid; islands). Islands are researched globally with 65 publications identified until mid-2021, with almost 100 articles by mid-2022 [60]; however, most of the island states in the Caribbean and the Pacific are still not researched as shown in Table 1. The roughly 100 articles on 100% RE systems on islands are reviewed in more detail [60], along with further review articles with an island focus [61], [62], [63], [64], [65]. Other geographic entities have not yet been reviewed in detail, except some overviews on selected global 100% RE systems analyses in general [10], [12], [66], [67], and sector-specific analyses for the transport sector [68], heat sector [69], and storage [70]. The most studied cities in the world are New York City [71], [72], [73], [74], [75], [76] and Aalborg in Denmark [77], [78], [79], [80] with six and four studies, respectively, but no further city with more than two detailed studies could be identified. Only a very few articles focus on city level, such as cities on global level [71], in the US [72], in China [81], and in Morocco [82]. The megacities of the world [83], [84] are practically not yet investigated for their individual 100% RE supply options, with Delhi, the largest megacity by mid-century, analyzed recently [85]. Remote and off-grid 100% renewable and decentralized autonomous energy systems are reviewed [61], [86], [87], [88]. The country distribution is discussed more in section 4.3 and visualized in Figure 8. All 550 category one articles are listed in the Supplementary Material.

As can be seen from Table 1, the largest portion of the research is done for Europe, the Americas, and Australia, which reflects a substantial research gap for other regions, especially for the Global South and Eurasia. The Global South is defined according to [617]. Figure 2 shows the countries in the world where 100% RE systems analyses have been conducted at the country-level (refer to Table 1). The USA is the country for which the most category one studies have been performed, with 45 studies in total. Europe leads with 181 studies in total, thereof Denmark with 39 studies, followed by Germany and the United Kingdom, with 35 and 14, respectively, and Finland and Sweden with 13 studies each. Australia, the world's 6th largest country, has been analyzed with 30 studies.

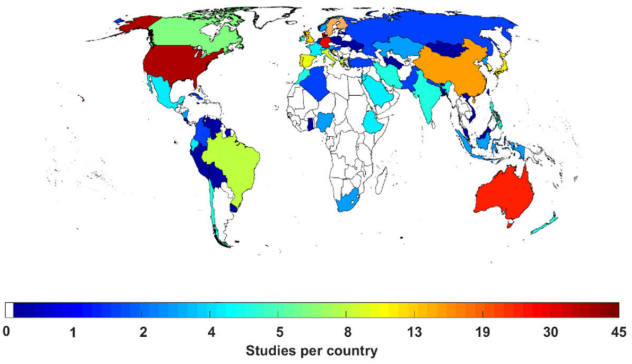


**FIGURE 2. Global distribution of 100% RE systems studies for countries und sub-country regions around the world. The white areas show no single study published for the respective country. Details for all countries are listed in the Supplementary Material.**

Even though Africa has an excellent RE potential, only 15 country-level research studies are known for Africa, thereof 6 studies for La Réunion, which is geographically Africa, but politically an overseas territory of France. This strongly showcases the massive gap of energy system transition insights for the Global South, which requires more concentrated research efforts [10]. The Middle East countries comprise 4% of the research, while this region contributes very high shares in the fossil energy system. China and India, the two most populous countries, and Russia, the largest country by area in the world, have been investigated by 17, 5, and 2 studies on 100% RE systems analyses, respectively. These low numbers for these countries indicate substantially higher research demand for investigating the opportunities of the energy system transition ahead.

A 100% RE systems analysis requires a modeling tool, which either simulates or optimizes an energy system cost for a concrete geographic entity. An energy system model (ESM) can cover a single or a multi-sector energy system, the latter of which can enable sector coupling from hourly to annual resolution. Many studies focus only on the power sector, whereas an incremental share of research in the past five years has focused on the entire energy system, including heat and transport sectors [12]. Sector coupling can reduce the overall system cost in a region, and simultaneously reduce the energy demand through the efficiency gains across sectors [285], [500], [618]. Additional segments including the industry sector and negative $CO_2$ emission options have not yet been covered well in the research of 100% RE systems [10].

ESMs that have been used at least five times to analyze 100% RE systems are EnergyPLAN [619], [620], the LUT Energy System Transition Model (LUT-ESTM) [24], [25], [500], TIMES [101], HOMER [621], [622], REMix [264], [493], [623], AU model [267], PyPSA [277], [285], [624], LOADMATCH [95], [111], NEMO [578], ISA model [588], $H_2$RES [490], GENeSYS-MOD [96], [625], and MESAP/PlaNet [99], [116].

**TABLE 1. Articles analyzed in this research with a geographic focus. The global articles are structured to their features on energy, energy-related for jobs, material availability, specific technology focus, and water. The world regions are structured into Global, Africa, Americas, Europe, Eurasia, Middle East, Sub-Saharan Africa, South Asian Association for Regional Cooperation (SAARC), East Asia, Northeast Asia and Southeast Asia and Pacific. Island countries are listed in the category Country. For a better overview, articles for a region on a sub-country level are sorted in columns for state or region, city, village or off-grid, and island.**

| World Region | Region | Country | Sub-Country (state, region) | Sub-Country (city, village, off-grid) | Sub-Country (island) |
|---|---|---|---|---|---|
| Global | energy [17], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [25], [16], [103], [104], [105], [106], [107], [108], [109], [110], [66], [111], [112], [113], [71], [114], [115], [24], [116]; energy-related for: jobs [117]; material availability [118], [119], [120], [121]; technology specific focus [122], [68], [123], [124], [125]; water [126], [127], [128] | | | | |
| Africa | Africa [106], [129]; North Africa [130]; Sub-Saharan Africa [131], [132]; West Africa [133] | Algeria [134], [135]; Cape Verde [136], [137]; Ethiopia [94], [138], [139], [140]; Ghana [141]; La Reunion [142], [143], [144], [145], [146], [147]; Mauritius [148], [149], [150]; Morocco [151], [134], [152], [153], [154]; Nigeria [155], [156], [135]; South Africa [157], [158], [135]; Tunisia [154] | | | |
| Americas | Americas [159], [160]; North America [161], [162]; South America [163] | Bolivia [164]; Bonaire [165]; Brazil [166], [167], [94], [168], [169], [170], [171], [172], [173]; Chile [174], [175], [176], [177], [178]; Colombia [179], [180]; Costa Rica [181]; Ecuador [181], [182]; Mexico [183], [181], [184]; Jamaica [185]; Montserrat [186]; Nicaragua [187]; Suriname [188]; Uruguay [189]; USA [190], [191], [192], [193], [194], [195], [196], [197], [198], [199], [106], [200], [201], [15], [202], [203], [204], [205], [206], [207], [208], [209], [210], [211], [212]; Venezuela [213] | Canada [214], [215], [216], [217], [218]; USA [219], [73], [220], [221], [222], [94], [223], [224], [225], [226], [227], [228], [74], [75], [229], [230], [231], [76], [232], [233], [218] | Canada [234], [235]; Ecuador [236]; North America [72]; Peru [237]; USA [238], [239] | Cuba: Isla de la Juventud [240], [241]; Ecuador: Galapagos [242]; Mexico: Cozumel Island [243]; Nicaragua: Ometepe [244], [245]; USA: Hawaii [88]; Puerto Rico [88] |
| Europe | Baltic Sea Region [246]; Europe-MENA/NA [247], [248], [249], [250], [251], [252]; Nordic [253], [254], [255], [256], [257]; Southeast Europe [258], [259]; Europe [260], [261], [262], [263], [264], [265], [266], [267], [268], [269], [270], [271], [272], [273], [274], [275], [276], [277], [278], [279], [280], [281], [282], [283], [284], [285], [103], [286], [287], [288], [289], [290], [291], [292], [293], [294], [199], [295], [106], [296], [297], [298], [299], [300], [301], [302], [303], [204], [304], [305], [306], [307], [308], [309], [310], [208], [311], [312], | Austria [321], [322], [323]; Belgium [324]; Croatia [325], [326]; Denmark [327], [23], [328], [329], [330], [331], [332], [333], [334], [335], [336], [337], [338], [339], [14], [340], [341], [342], [20], [343], [344], [345], [346], [347], [348], [349], [350]; Italy [336]; UK [94], [351], [352], [353], [354], [355], [356], [357], [358], [359]; Finland [360], [361], [362], [363], [364], [365]; France [366], [367], [368]; Germany [369], [266], [370], [371], [372], [373], [374], [375], [376], [377], [199], [378], [379], [380], [381], [382], [383], [384], [385], [386], [387], [388], [389], [390], [391], [392], [393]; Sweden [355], [394], [395], [396], [397], [309], [398], [399], [400], [401], [402]; Hungary [403], [397]; Ireland [404], [405], [406], [397], [407]; Italy [408], [409], [410] Latvia [411]; Macedonia [412]; Norway [413], [414], [415]; Poland [94], [358]; Spain [416], [355], [397], [358], [417]; Portugal [418], [419], [420], [416], [421], [422]; Netherlands [423]; Switzerland [424], [425], [426], [427]; Turkey [428], [94]; Ukraine [429] | Germany [430], [431], [432], [433], [434], [435]; UK [436], [437] | Belgium [438]; Croatia [439], [440], [441]; Denmark [77], [80], [78], [79], [442] , [443], [444], [445]; Finland [446], [447], [448]; Germany [449], [450]; Italy [451], [452], [453]; Netherlands [454]; Slovenia [455]; Sweden [456] | Croatia: Vis [457], Island of Hvar [458], Island of Mliet [459], [460], Croatian islands [461], Korcula [462], Denmark: Aero [457], Samsø [463], [464]; Faroe Islands [465], [466]; UK: Orkney [464]; Finland: Åland [467], [468], [469], [470]; France: Yeu [471]; Greece: Aegean Islands [472], Agathonisi [473], Agios Efstratios [474], Astypalaia [475], Crete [476], Island of Dia [477], Greek Islands [478], [479], Karpathos Island, [480], Sifnos [481]; Italy: Favignana Island [482], [483]; Sardinia [484]; Portugal: Azores [485], [486], [487]; Flores Island [488], Madeira [489], Porto Santo [490], [491], [492]; Spain: Canary Islands [493], [494], [495], [496], [497]; UK: Isle of Eigg [498] |

**TABLE 1.** *(Continued.)* **Articles analyzed in this research with a geographic focus. The global articles are structured to their features on energy, energy-related for jobs, material availability, specific technology focus, and water. The world regions are structured into Global, Africa, Americas, Europe, Eurasia, Middle East, Sub-Saharan Africa, South Asian Association for Regional Cooperation (SAARC), East Asia, Northeast Asia and Southeast Asia and Pacific. Island countries are listed in the category Country. For a better overview, articles for a region on a sub-country level are sorted in columns for state or region, city, village or off-grid, and island.**

| | | | | | |
|---|---|---|---|---|---|
| | [313], [314], [315], [316], [317], [318], [319], [320] | | | | |
| Eurasia | | Kazakhstan [499], [500]; Turkmenistan [501] | | Kazakhstan [502], Russia [503] | Russia: Popova [504] |
| Middle East | MENA [505] | Iran [506], [507], [508], [509], [510]; Israel [511], [512], [513]; Jordan [514], [515], [516], [154]; Saudi Arabia [517], [518], [94], [519] | | | |
| SAARC | SAARC [520] | Bangladesh [521]; India [522], [523], [524], [525]; Bhutan [526]; Maldives [527], [528]; Nepal [526], [529]; Pakistan [530], [531] | | | India: Andaman Islands [532] |
| East Asia | East Asia [533], [534], [535] | | | | |
| Northeast Asia | Northeast Asia [536] [537], [538] | China [539], [540], [541], [542], [295], [543], [544], [545]; Japan [546], [547], [548], [549], [550], [551], [552], 452, [553], [554]; Korea [215]; Mongolia [555] | | China [81], [556], [557], [558]; Japan [559], [560] | China: Town Island [561], [562], [563], [564], [565]; Japan: Awaji Island [566]; Korea: Jeju Island [567]; Ulleungdo Island [568]; Taiwan: Wang-An Island [569] |
| Southeast Asia and Pacific | ASEAN [570]; Southeast Asia [571], [572] | Australia [573], [574], [575], [576], [577], [578], [579], [580], [581], [582], [583], [584], [585], [586], [587], [588], [589], [590], [591], [592], [593], [594], [595], [596], [597], [208], [598], [599]; Brunei [600]; Malaysia [600]; Singapore [600]; Cook Islands [601]; Indonesia [94], [602]; New Zealand [603], [604], [605], [606], [607]; Philippines [608]; Vietnam [609] | Australia [610], [611]; Indonesia [612] | Philippines [613], [614] | Philippines: Gilutongan Island [615], Philippine islands [616] |

EnergyPLAN is one of the most widely used ESM tools to evaluate energy systems with high shares of RE, applying simulation assumptions. The main target of EnergyPLAN is to design a local to national-scale energy system with technical and economic parameters. EnergyPLAN is not used to project a future energy system based on a transition pathway, but rather to enable a comparison of diverse alternative development strategies for an energy system [619]. LUT-ESTM is a linear optimization ESM operated under certain constraints for a full set of energy supply, conversion, storage, and transmission technologies to find the most cost-optimal transition solution including the legacy system. It can be applied to entire energy-industry systems on local, national, continental, or global level. LUT-ESTM performs multi-node system designs on an hourly resolution for each time step, which increases the reliability of the results compared with annual energy balancing [24], [500]. Similar to LUT-ESTM, TIMES uses linear programming to find the minimized total integrated energy system cost for comprehensive energy-industry transition investigations. Within the model, there are several interconnected regions regarding energy commodity and GHG emissions trade [101]. HOMER is an ESM tool for designing hybrid RE systems often applied to off-grid cases to find optimal sizes of the used components by carrying out techno-economic analyses. Essential input data for simulations using HOMER are meteorological data, load profile, equipment characteristics, search space, and economic and technical data, among others [621]. REMix is a deterministic model, which keeps the running times as low as possible. Similar to LUT-ESTM and TIMES, the objective of REMix is to minimize the total system costs under certain restrictions. The inputs are fixed parameters for costs, hourly data of energy demand, generation profiles, and resource potentials. REMix is designed to provide the least-cost energy supply structure in the long term for the area under investigation. PyPSA is a comprehensive ESM for simulating and optimizing modern energy systems over multiple time periods. PyPSA consists of a model for conventional generators, renewable generation, storage, sector coupling, and alternating and direct current grids. It is designed in a

**TABLE 2. Energy system models used for 100% RE systems analyses. All models used at least five times for 100% RE systems analyses are listed and ranked to the number of published articles applying the model. Some key features of the leading ESMs are indicated. Citations for the 550 category one articles are allocated to the models used as of mid-2022.**

| Model | articles | citations | | model used for 100% RE | | inter-connected multi-node | full hourly | multi-sector | detailed industry | relevant CDR | optimi-sation | simu-lation | transi-tion | over-night | off-grid integration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | total | 2021 | earliest | latest | | | | | | | | | | |
| EnergyPLAN | 74 | 7797 | 1293 | 2006 | 2021 | yes | yes | yes | no | no | no | yes | no | yes | no |
| LUT-ESTM | 63 | 2833 | 939 | 2015 | 2021 | yes | yes | yes | yes | no | yes | yes | yes | yes | no |
| HOMER | 22 | 1298 | 310 | 2007 | 2021 | no | yes | no | no | no | yes | yes | no | yes | no |
| TIMES | 19 | 745 | 134 | 2011 | 2021 | no | no | yes | yes | no | yes | yes | yes | yes | no |
| AU model | 16 | 1313 | 134 | 2010 | 2018 | yes | yes | no | no | no | yes | yes | no | yes | no |
| PyPSA | 16 | 704 | 274 | 2017 | 2021 | yes | yes | yes | no | no | yes | no | no | yes | no |
| LOADMATCH | 10 | 1188 | 302 | 2015 | 2021 | no | yes | yes | no | no | no | yes | yes | yes | no |
| REMix | 10 | 604 | 147 | 2016 | 2021 | yes | yes | yes | no | no | yes | yes | no | yes | no |
| GENeSYS-MOD | 10 | 226 | 90 | 2017 | 2021 | yes | no | yes | no | no | yes | no | yes | no | no |
| ISA model | 9 | 183 | 62 | 2016 | 2021 | no | yes | yes | no | no | yes | no | no | yes | no |
| NEMO | 7 | 647 | 84 | 2012 | 2017 | yes | yes | no | no | no | yes | no | no | yes | no |
| $H_2$RES | 6 | 715 | 84 | 2004 | 2011 | no | yes | yes | no | no | no | yes | no | yes | no |
| MESAP/PlaNet | 6 | 270 | 51 | 2009 | 2021 | no | no | yes | no | no | no | yes | yes | yes | no |
| others | 282 | 11709 | 2362 | | | | | | | | | | | | |
| total | 550 | 30232 | 6226 | | | | | | | | | | | | |

way to be expandible, to scale with sizable networks, and to have long time series. PyPSA has the capability to perform various network clustering algorithms to reduce the number of buses in a network while maintaining significant transmission lines [624].

The ESM NEMO comprises three core elements: a framework that supervises the simulation, a sizable integrated database of historical meteorology and electricity sector data, and a library of simulated power generators. NEMO assumes ideal generator and transmission network availability with excellent meteorological predicting. The simulation can be described as a bottom-up tool, which is used to model national energy systems [578], while it is applied in publications exclusively on investigations for Australia. GENeSYS-MOD targets national, continental, and global energy issues, and for this aim, it divides the investigated geographic entity in regions. Each region acts as a node connecting with other regions for the exchange of fuels and electricity, but not heat. Regions can trade fuels with one another. For the analysis, all hours throughout a year are summed up into a few time slices, which represent seasonal and daily variations of demand and supply [96], [625]. LOADMATCH is coupled with GATOR-GCMOM and used to match the power demand with variable supply. GATOR-GCMOM provides a five-year time series of renewable resources, with output each 30 s, for usage in LOADMATCH [95].

All mentioned ESMs are summarized in Table 2 according to their key model features, number of articles applying the model, and received citations until mid-2022 for the basis of the 550 category one articles. The used modelling tools are identified in the Supplementary Material for the 550 articles.

The two leading models applied for 100% RE systems analyses are EnergyPLAN and LUT-ESTM. EnergyPLAN and LUT-ESTM model have been used for 74 and 63 articles, receiving 7797 and 2833 citations and thereof 1293 and 939 in the year 2021, respectively. The core difference between the two models is the target functionality of each. While EnergyPLAN simulates an energy system, LUT-ESTM is used for energy system optimization. EnergyPLAN was introduced in 2006 by Aalborg University [20] and is the ESM that has been used for the longest period for 100% RE systems research, whereas the LUT model is relatively young, as it was introduced [536]. The only discontinued models are $H_2$RES and the AU model, while the AU model has been embedded in PyPSA. Virtually all ESMs can cover multi-sector modelling, and only the LUT-ESTM and PyPSA are capable of detailed industry modelling [500], [626].

A clear deficit of all ESMs for 100% RE systems analysis is that none of them have the capability to describe the most relevant $CO_2$ direct removal (CDR) options [10], [627], while the LUT-ESTM has recently embarked to introduce the direct air carbon capture and storage (DACCS) [134] applied in full energy system integration for Egypt [628]. All ESMs are capable of so-called overnight [629] solutions excluding GENeSYS-MOD. The LUT-ESTM and PyPSA are the only ESMs consisting of the pivotal characteristics for thorough

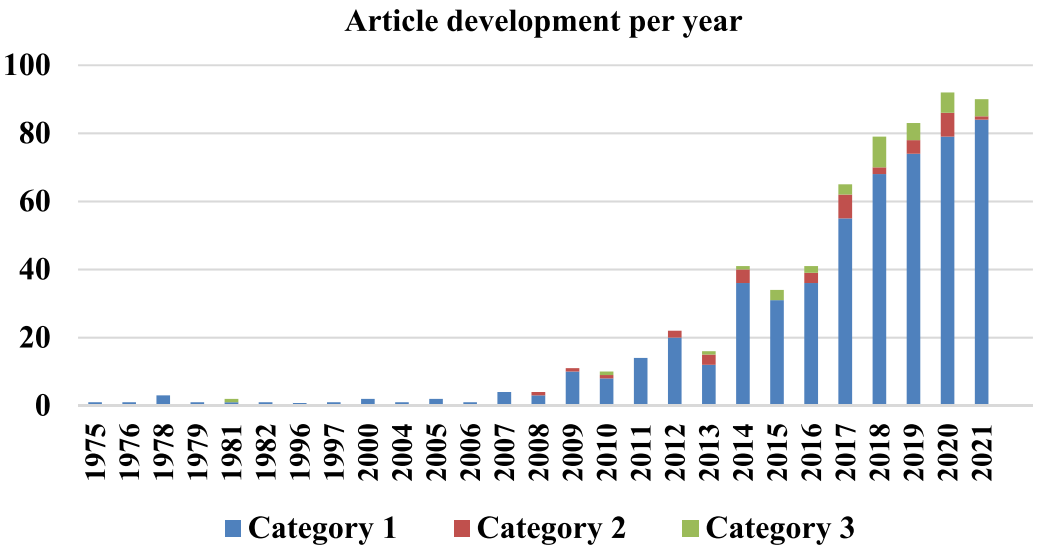


**FIGURE 3.** Number of articles on 100% RE systems for categories one, two, and three according to year of publication. Category one considers at least one geographic entity for which the 100% RE research was carried out. Category two is a generic analysis, not mentioning a concrete region. Category three is dedicated to review articles with or without a concrete geographic analysis Category one starts in 1975 with at least one article per year since 2004. Category two starts in 1996 with almost regular articles since 2008. Category three starts in 1981 with regular articles since 2013. All articles per category are listed in the Supplementary Material.

energy system analyses: multi-node, multi-sector, full hourly resolution, optimization, and transition model, with detailed industry representation. Some core facets of ESMs include full hourly resolution, an overnight and transition approaches, sector coupling, and simulation and optimization approaches.

In the recorded 550 journal articles on a 100% RE system, 72% are in full hourly resolution. Roughly 75% of all articles utilize an overnight approach analyzing 100% RE systems. Almost half of all 100% RE systems analyses research the power sector without other energy sector integration. Conversely, 29% of all articles target power, heat, and transport sectors, approximately 10% of all articles cover power and heat, and about 5% investigate power and desalination sectors. Around three-fifths of all 100% RE systems analyses have an optimization target, and the rest are of the simulation type.

Not a single ESM has the functionality for off-grid integration, which would be of highest importance for energy transition studies in sub-Saharan Africa [10]. Further, no ESM is able to provide an alternative for Integrated Assessment Models (IAMs) for complex energy system analyses under long-term climate change constraints, which has been identified as a relevant target, as IAMs largely ignore 100% RE systems research [10], though there has been some recent progress [630].

Several review articles feature the models used for 100% RE systems analyses in general [629], [631], [632], [633], [634], [635], [636], while some analyze the progress achieved for a single model [619], [620], [625], or single geographic applications [64], or limit their focus only on the group of open-source models [637], [638]. Three reviews analyze models in concrete test cases for model intercomparison [629], [636], [639].

## IV. RESULTS AND DISCUSSION

### A. THE EVOLUTION OF ARTICLES AND CITATIONS

The evolution of journal articles published per year for categories one, two, and three through the years until 2021 is shown in Figure 3. In category one, the growth in the number of articles published over the last decade has been quite dynamic, increasing from 8 articles in 2010 to 80 in 2020, documenting a compound annual growth rate (CAGR) of 26%. Thus, a large portion of all the publications is concentrated in the last five years, with around 66% of the 550 articles. This trend also indicates the steeply rising interests in this research field. The first article was published for category two in 2008. There is moderate growth in the number of publications for this category, with more articles in 2017 and 2020, reaching a total of 37. In the year 1981, the first article with substantial review elements was published in the field of 100% RE systems. In total, 37 review articles have been published within this category; however, several facets of the field are not yet reviewed intensively.

In category three, one-third of the total articles were published until 2017, and two-thirds since 2018. Most articles in the field have been published since 2017. However, until 2013, the year before the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) [640], 98 articles have been identified, which was not sufficient to even mention this research field in that report. It required the 279 articles until 2017 for the existence of a 100% RE system opportunity for mitigating climate change and diminishing low-cost fossil fuels to be mentioned in the special report on global warming of 1.5 °C [3], more than 40 years after the first 100% RE system study [14], and more than 20 years after the first global 100% RE systems analysis [16]. In the recent sixth assessment report of the IPCC, 100% RE systems

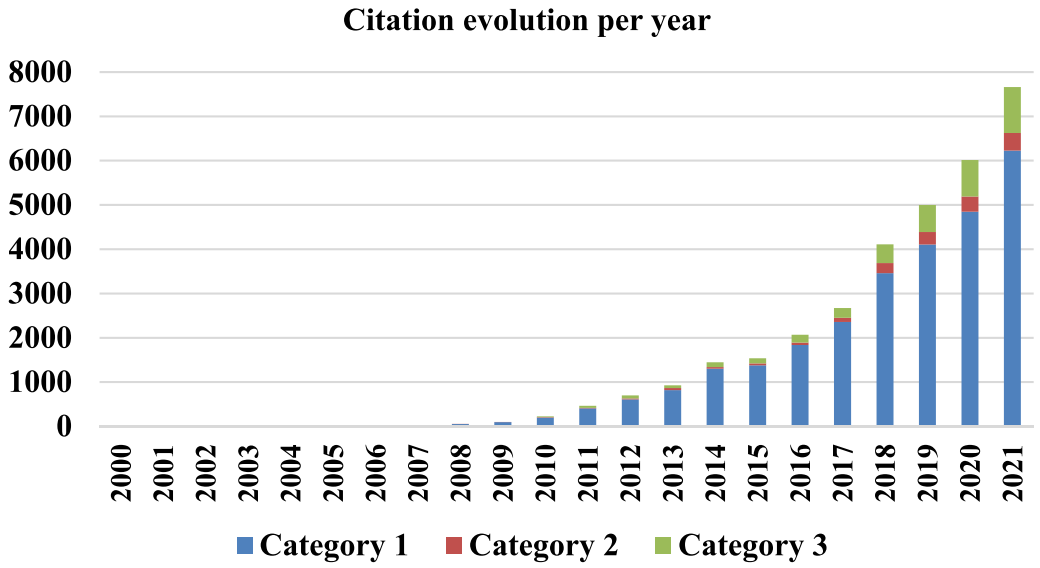


**FIGURE 4.** Evolution of annual citations of 100% RE systems articles for the three categories from 2000 to 2021. Citations are recorded as of May 2022 in the Scopus database. All citations per article, year and category are listed in the Supplementary Material.

are mentioned as a technical feasible solution [1], but are not yet recognized as a major opportunity for solving the climate emergency related energy crisis [10], and only very recently did the first global IAM scenario fulfill the criteria for 100% RE systems research [630]. The lack of policy support for 100% RE systems from the local to country and global level may be related to ignorance on this research field in major IPCC reports.

The trend in the number of citations within the last two decades for categories one, two, and three is displayed in Figure 4. The entire research field received 35,952 citations until May 2022 for articles published until mid-2021. In the year 2010, the annual citations rose to 197 for category one articles. The annual citations experienced a substantial increase to 1376 in 2015 and 4847 in the year 2020, representing a CAGR of 38% from 2010 to 2020. The number of citations in category two grew moderately throughout the years with 10 citations in the year 2010 and 43 in 2015, reaching 340 for the year 2020. Category three received 19 citations in the year 2010, growing to 415 in 2015 and 809 for the year 2020, representing a CAGR of 46%. In total, there are 88 articles with at least 100 citations in the field, and 7 articles with at least 100 annual citations in 2021 [12], [23], [92], [224], [330], [618], [631].

The ten most cited articles of 100% RE systems research are presented in Table 3. The most cited article is a review from Connolly et al. [631] on ESMs with a special focus on 100% RE systems published in 2010 and has received 1093 citations so far. Jacobson and Delucchi [17] published an article in *Energy Policy* on the options for a global 100% RE system, which received the highest number of 912 citations for an original article within this discipline, following a previous comparable article in *Scientific American* in 2009 [18].

Lund [330] published an article entitled 'Renewable energy strategies for sustainable development', which received 900 citations by mid-2022. Three further articles of Lund [327], [333], [346] are among the most cited articles with 784, 617, and 449 citations so far. Nine in ten of the most cited articles were published before 2016. The article of Kroposki et al. [224] is the only publication after 2015 that reached the group of the ten most cited articles with 525 citations so far. Detailed citation data for all articles can be found in the Supplementary Material.

### B. NORMALIZED CITATION SCORE

Citation counts for articles typically have a long-tailed distribution, i.e., many articles may receive only a few citations in a field of study whereas some other articles receive a far higher number of citations within the same period. In addition, articles published years ago had more opportunity to receive a high total number of citations. Hence, it is less likely to effectively interpret an article's impact by the absolute number of citations. Applying a normalization allows for a better understanding of the relative impact of an article of its time. There is normalization by research field, article age, document type, citing sources, and citation place. Of these normalization criteria, the age of an article is an appropriate normalization in general [641], especially considering that all articles belong to the same research field.

The year of publication is used for the normalization, and is applied in three steps: First, each article is allocated to a group set of articles from the same year. Second, the number of citations in each group set is averaged. Third, the normalized

**TABLE 3.** List of top ten articles ranked by the highest citations number and their journals in the 100% RE systems research field. Abbreviation: original article (O), review article (R).

| First author | Ref | Year | Total Citations | Journal | Article Type | Title |
|---|---|---|---|---|---|---|
| David Connolly | [631] | 2010 | 1093 | Applied Energy | R | A review of computer tools for analysing the integration of renewable energy into various energy systems |
| Mark Jacobson | [17] | 2011 | 912 | Energy Policy | O | Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials |
| Henrik Lund | [330] | 2007 | 900 | Energy | O | Renewable energy strategies for sustainable development |
| Henrik Lund | [327] | 2009 | 784 | Energy | O | Energy system analysis of 100% renewable energy systems-The case of Denmark in years 2030 and 2050 |
| Brian Vad Mathiesen | [23] | 2015 | 664 | Applied Energy | O | Smart Energy Systems for coherent 100% renewable energy and transport solutions |
| Henrik Lund | [346] | 2010 | 617 | Energy | O | The role of district heating in future renewable energy systems |
| Benjamin Kroposki | [224] | 2017 | 525 | IEEE Power & Energy Magazine | O | Achieving a 100% Renewable Grid: Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy |
| Mark Delucchi | [100] | 2011 | 513 | Energy Policy | O | Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies |
| Brian Vad Mathiesen | [328] | 2011 | 474 | Applied Energy | O | 100% Renewable energy systems, climate mitigation and economic growth |
| Henrik Lund | [333] | 2012 | 449 | Energy | O | From electricity smart grids to smart energy systems - A market operation based approach and understanding |

citation score is identified as the total number of citations for a paper divided by the group set average citation [43]. A three-year average of citations has been applied for a better averaged normalization, considering the previous, same, and following year for each article. The list of top 21 articles by their normalization score is shown in Table 4. They are all at least four times more cited than the average of articles of the same age group, with 14 articles cited more than five times than the average of their age group.

However, no article has been cited more than ten times than the average of its age group. Mathiesen et al. [23] with the title *'Smart Energy System for coherent 100% renewable energy and transport solutions'* received the highest normalized score with 8.63 published in *Applied Energy* in 2015, while this article ranked 4$^{th}$ by absolute citations.

Notably, 14 in 21 articles are from the period 2017 to 2021, which indicates several high impact articles published in recent years. Only one of these articles, though, is part of the top ten most cited articles according to Table 3.

The leading teams with at least two high impact articles in Table 4 are Lund/Mathiesen, Breyer, Jacobson, and Brown with 8, 6, 2, and 2 articles, respectively. The leading journals with high impact articles are *Energy* (6 in 21 articles), *Renewable and Sustainable Energy Reviews* (5), and *Applied Energy* (4). All other journals do not contribute more than one article. A normalized score provides a different aspect of an article's impact, which reveals rather early, after just a few years of publication, the articles that will have a strong impact for the years to come. A high normalized score for recent articles can therefore be interpreted as an early indicator for high absolute citations in following years. All top ten most cited articles are also indicated as impactful by their normalized citation score. Information for all 620 articles in the research field indicating their normalized citation score can be found in the Supplementary Material.

Dominković et al. [47] define impactful recent articles by the average annual citations with a threshold of 50 citations per year for articles since 2015, and identify 9 articles, thereof 8 within 50 to 75 average citations per year, and one above an average of 100 citations per year. Applying these criteria to the field of 100% RE systems analyses leads to 14 articles, thereof 8 articles with an average of 50 to 75 citations per year [13], [24], [25], [262], [285], [374], [500], [642], 5 articles with an average of 75 to 100 Citations [12], [23], [92], [280], [618], and one article above the average of 100 citations per year [224].

The teams contributing to these articles more than a single one are Lund/Mathiesen (6), Breyer/Bogdanov (5), Brown (2), thereof two articles with a collaboration of two [12] or even all three [13] of these leading teams. Every single article following these criteria belongs to the 14 most impactful articles in the field of 100% RE systems analyses, which indicates that the normalized citation score is well suited to identify the most relevant articles, also of recent years. Interestingly, not a single one of these 14 articles was detected by Dominković et al. [47], despite applying identical criteria.

### C. CITATION AND ARTICLE DISTRIBUTION BY COUNTRY AND JOURNAL

The total global number of annual citations received for the 550 category one articles was 6226 in 2021, with values of 4847 and 4106 for the years 2020 and 2019, respectively, indicating a growth of 28% and 18% year-on-year, compared to the CAGR of 37% from 2010 to 2021. The distribution of

**TABLE 4. The top 21 articles ranked by the maximum normalized citation score within the field of 100% RE systems analyses. Normalization is done by the average citation of all articles of the previous, same, and following year. Abbreviation: original article (O), review article (R).**

| First author | Ref | Teams | Total Citations | Score | Year | Journal | Article Type | Title |
|---|---|---|---|---|---|---|---|---|
| Brian Vad Mathiesen | [23] | Lund/Mathiesen | 664 | 8.63 | 2015 | Applied Energy | O | Smart Energy Systems for coherent 100% renewable energy and transport solutions |
| Benjamin Kroposki | [224] | NREL | 525 | 8.54 | 2017 | IEEE Power & Energy Mag | O | Achieving a 100% Renewable Grid: Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy |
| Kenneth Hansen | [12] | Lund/Mathiesen; Breyer | 254 | 7.47 | 2019 | Energy | R | Status and perspectives on 100% renewable energy systems |
| Dmitrii Bogdanov | [24] | Breyer | 60 | 7.07 | 2021 | Energy | O | Low-cost renewable electricity as the key driver of the global energy transition towards sustainability |
| Henrik Lund | [618] | Lund/Mathiesen | 433 | 7.05 | 2017 | Energy | R | Smart energy and smart energy systems |
| William Zappa | [280] | | 234 | 6.88 | 2019 | Applied Energy | O | Is a 100% renewable European power system feasible by 2050? |
| Mark Jacobson | [92] | Jacobson | 418 | 6.80 | 2017 | Joule | O | 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World |
| Dmitrii Bogdanov | [500] | Breyer | 51 | 6.01 | 2021 | Applied Energy | O | Full energy sector transition towards 100% renewable energy supply: Integrating power, heat, transport and industry sectors including desalination |
| Herib Blanco | [642] | | 294 | 5.86 | 2018 | Renew and Sustain Energy Reviews | R | A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage |
| Daniele Groppi | [62] | Duic | 47 | 5.54 | 2021 | Renew and Sustain Energy Reviews | R | A review on energy storage and demand side management solutions in smart energy islands |
| Michael Child | [284] | Breyer | 191 | 5.61 | 2019 | Renewable Energy | O | Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe |
| Mark Jacobson | [17] | Jacobson | 912 | 5.61 | 2011 | Energy Policy | O | Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials |
| Dmitrii Bogdanov | [25] | Breyer | 177 | 5.20 | 2019 | Nature Communications | O | Radical transformation pathway towards sustainable electricity via evolutionary steps |
| David Connolly | [262] | Lund/Mathiesen | 376 | 5.04 | 2016 | Renew and Sustain Energy Reviews | O | Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union |
| Henrik Lund | [327] | Lund/Mathiesen | 784 | 4.90 | 2009 | Energy | O | Energy system analysis of 100% renewable energy systems-The case of Denmark in years 2030 and 2050 |
| Tao Ma | [561] | Ma | 390 | 4.86 | 2014 | Applied Energy | O | A feasibility study of a stand-alone hybrid solar-wind-battery system for a remote island |
| Henrik Lund | [330] | Lund/Mathiesen | 900 | 4.59 | 2007 | Energy | O | Renewable energy strategies for sustainable development |
| Kenneth Hansen | [374] | Lund/Mathiesen | 153 | 4.50 | 2019 | Renew and Sustain Energy Reviews | O | Full energy system transition towards 100% renewable energy in Germany in 2050 |
| Tom Brown | [285] | Brown; Greiner | 225 | 4.49 | 2018 | Energy | O | Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system |
| Tom Brown | [13] | Brown; Breyer; Lund/Mathiesen | 219 | 4.37 | 2018 | Renew and Sustain Energy Reviews | R | Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems' |
| Cory Budischak | [219] | | 358 | 4.37 | 2013 | J Power Sources | O | Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time |

citations per country of the first author affiliation is shown in Figure 5.

The total citations for the 550 articles until 2021 are 27,766. Denmark received the highest number of citations with 7117, followed by the United States, Germany, and Finland with 3761, 3416, and 2112 citations, respectively, representing 25.6%, 13.5%, 12.3%, and 7.6% of all total citations for these 550 articles, respectively. In total, European countries received the highest number of citations, which accounts for 71%.

The 550 category one articles identified have been published in 91 different journals, thereof 54 journals published only one article in the field of 100% RE systems analyses. The leading 20 journals in the field according to published articles

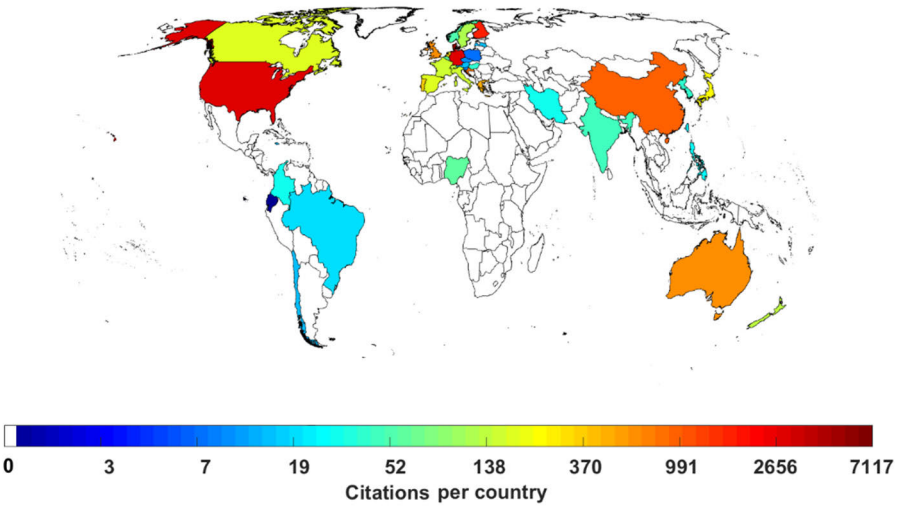


**FIGURE 5.** Global distribution of citations for category one articles according to the country of first author affiliation. The white countries indicate no category one article with first author affiliation. All citations for category one per country are listed in the Supplementary Material.

are presented in Figure 6. At least 5 articles are required to belong to the top 20 journals in the field. The journal *Energy* has the highest number of published articles with 91, followed by *Applied Energy*, *Renewable Energy*, *Energies*, *Renewable and Sustainable Energy Reviews* with 67, 57, 51, and 42 articles, respectively. The top five journals shown in Figure 6 published 56% of all articles in the field. In addition, the bar diagram in Figure 6 (right) shows the growth trend for the annually published articles in the resolution per journal.

Citations received by journals is a metric that shows the relative relevance of a particular journal for the category one group of the total 550 articles.

The highest number of citations with 7843 was received by the journal *Energy*, followed by *Applied Energy*, *Renewable and Sustainable Energy Reviews*, *Renewable Energy*, and *Energy Policy* with 6376, 3650, 3461, and 3334, respectively.

The top five journals shown in Figure 7 received 89% of all citations in the field. Figure 7 shows the citations per journal and annual citations for the top 20 journals for the years 2000 to 2021.

Two further metrics indicate the relative impact and relevance of journals: the h-index of a journal in the field and the citations per article of a particular journal in the field. For well averaged results, a threshold of at least 5 articles per journal was chosen, which was fulfilled by 20 journals. These 20 journals are identified as relevant for the field of 100% RE systems analyses and ranked according to their highest h-index in Table 5. The journal *Energy* is the most productive journal in number of articles as well as in its impact, reaching an h-index of 44, while the *IEEE Power & Energy Magazine* has received the highest citations per article with a score of 134. *Applied Energy* and *Renewable and Sustainable Energy Reviews* are comparably ranked given their number of articles, citations per article, and resulting h-index. Though the journal *Energies* has published 51 articles in the field, its number of citations per articles is comparably low with only 19 resulting in an h-index ranking sixth of all relevant journals in the field; however, most of the articles have been published in recent years representing a different age structure than the aforementioned journals. The lowest number of citations per article in the list of the 19 leading journals in the field is found for the journal *Sustainability* with a score of 17. Notably, the journal *Energy Policy* benefits from early and highly impactful articles in the field until the first half of the 2010s but became almost irrelevant more recently as relevant articles in the field have not been published in this journal. Remarkably, the top leading journals in energy science are almost all missing in the list, except *Joule*, since 100% RE systems articles are hardly published in these journals. However, less ambitious energy transition research can be found in these journals, which may indicate a less progressive and more conservative positioning of the otherwise perceived top leading journals in energy science, as said except Joule, which seems to be faster in indicating top trends in energy science. This seems to also reflect the less progressive positioning of the IPCC as well as the organizational disjunction of overall energy system analysis and 100% RE systems analysis as discussed in section 4.4.

On a global scale, 42 countries contributed to articles on 100% RE systems, counted in the country of the first author affiliation. Figure 8 represents the distribution of all countries contributing research in the field, measured by the total number of articles, aggregated to the country of the first author affiliation. The top five countries (Germany, Finland, Denmark, USA, and Australia) covered about 58% of the total publications. Germany tops the list with 98 publications, followed by Finland and Denmark with 75 and 72, respectively, and the USA and Australia with 46 and 24, respectively. The

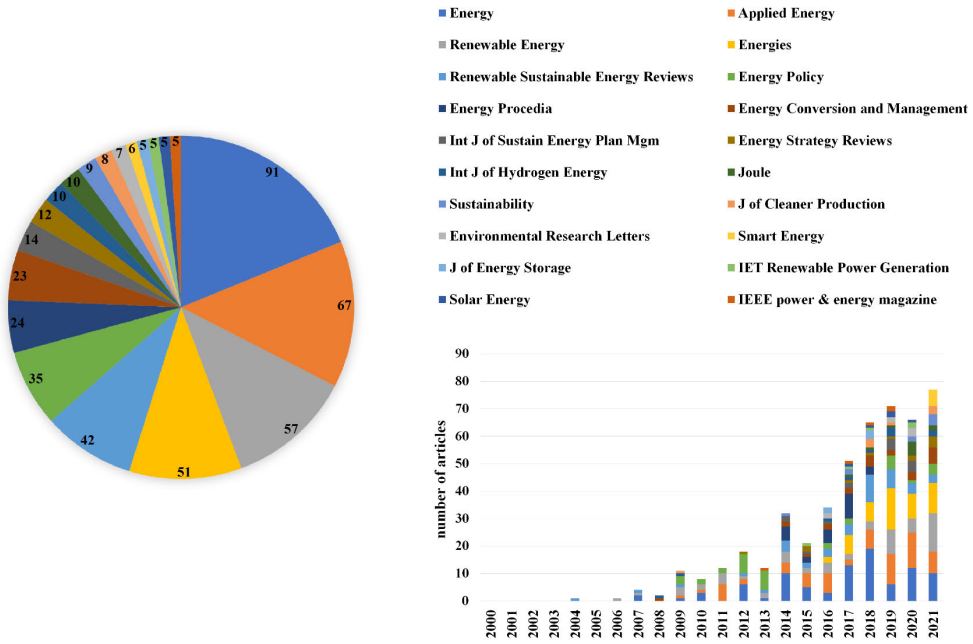


**FIGURE 6.** Top 20 journals by number of articles. The pie chart provides the total number of articles per journal published. The stacked bar diagram in the right shows the annual number of articles for the top 20 journals for the years 2000 to 2021. Details for all journals are listed in the Supplementary Material.

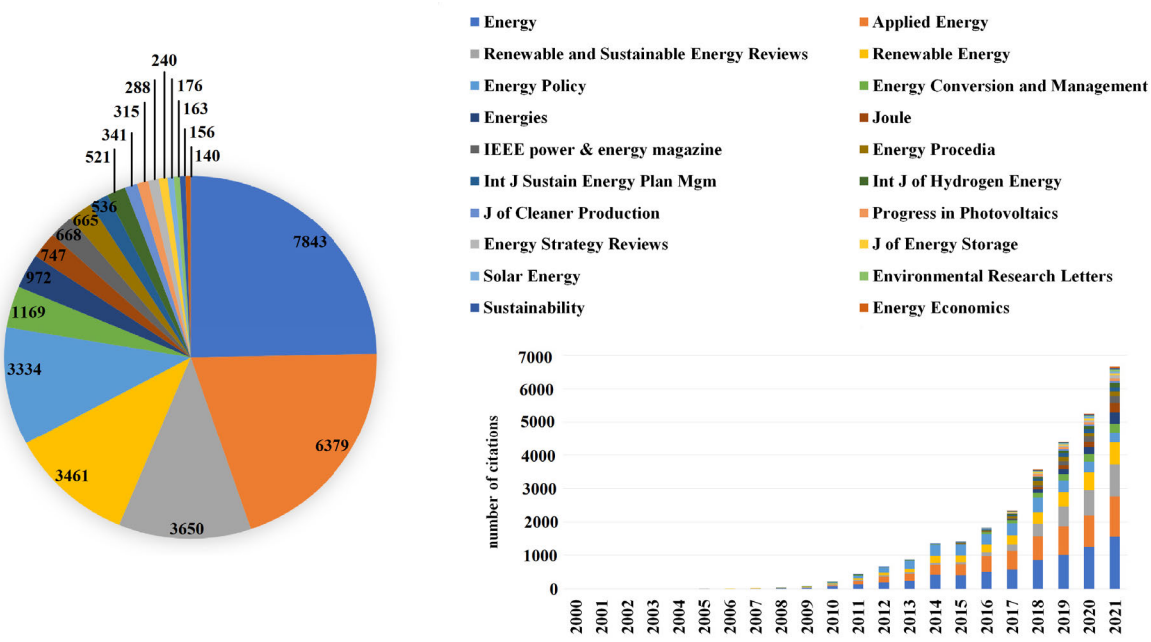


**FIGURE 7.** Top 20 journals by citations for category one in the field of 100% RE systems research. The pie chart provides the total number of received citations of the top 20 journals. The stacked bar diagram shows the annually received number of citations of the top 20 journals. Details for all journals are listed in the Supplementary Material.

vast share of 100% RE systems research has been carried out in Europe, North America, and Australia.

In Africa, only Nigeria contributed to the 100% RE systems research and not a single country in Eurasia has published a 100% RE article. Research activities in South America and South and Southeast Asia are similarly very low on 100% RE systems analyses. All publications per country are listed in the Supplementary Material.

Comparing the top ten countries in the field of 100% RE systems analyses with the overall field of energy system

**TABLE 5.** Lists of top journals in the field of 100% RE systems analyses. The ranked metrics are: total citations, total number of published articles, the number of citations per articles, and journal h-index, based on all 550 articles of category one. Details for all journals are listed in the Supplementary Material.

| Journal | Total Citations | Total Articles | Citations per Article | h-index |
|---|---|---|---|---|
| Energy | 7843 | 91 | 86 | 44 |
| Applied Energy | 6379 | 67 | 95 | 34 |
| Renewable and Sustainable Energy Reviews | 3650 | 42 | 87 | 33 |
| Renewable Energy | 3461 | 57 | 61 | 28 |
| Energy Policy | 3334 | 35 | 95 | 20 |
| Energies | 972 | 51 | 19 | 17 |
| Energy Conversion and Management | 1169 | 23 | 51 | 14 |
| Energy Procedia | 665 | 24 | 28 | 13 |
| Energy Strategy Reviews | 288 | 12 | 24 | 10 |
| Joule | 747 | 10 | 75 | 9 |
| Int J of Sustain Energy Planning Management | 536 | 14 | 38 | 9 |
| Int J of Hydrogen Energy | 521 | 10 | 52 | 8 |
| Environmental Research Letters | 163 | 7 | 23 | 6 |
| J of Energy Storage | 240 | 5 | 48 | 5 |
| J of Cleaner Production | 341 | 8 | 43 | 5 |
| IEEE Power & Energy Magazine | 668 | 5 | 134 | 5 |
| Solar Energy | 176 | 5 | 35 | 5 |
| Sustainability | 156 | 9 | 17 | 5 |
| Smart Energy | 85 | 6 | 14 | 5 |
| IET Renewable Power Generation | 92 | 5 | 18 | 3 |

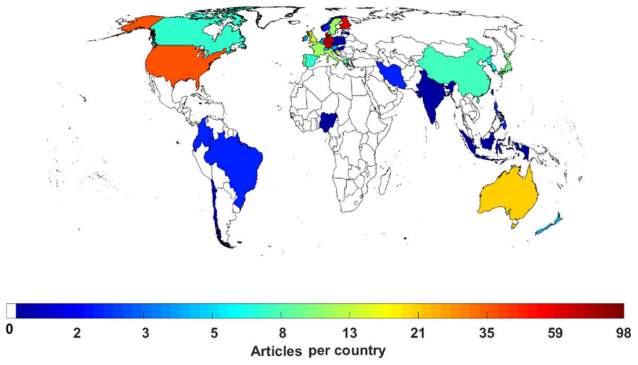


**FIGURE 8.** Distribution of articles per country of first author affiliation. The white countries indicated that no single 100% RE systems article has been published from this country, dark blue at a minimum indicates 1, and dark red at a maximum indicates 98 articles as contributed by Germany.

analysis [47] reveals that six countries belong to both groups (Germany, Denmark, USA, UK, Italy, and Sweden), and additional leading countries in the field of 100% RE systems analyses are Finland, Australia, Croatia, and France, substituting China, India, Canada, and Spain for the overall field of energy system analysis.

The specific research output of the leading countries based on article output reveals another perspective on the true leaders in the research field according to the relative impact of research. For deriving the specific output, the articles are set in ratio to the public energy research and development expenditures for the year 2020 according to the International Energy Agency [643], to the gross domestic product for the year 2020 according to the World Bank [644], and to the population for the year 2020 according to United Nations [645]. The specific research output in the field of 100% RE systems analyses is presented in Figure 9. Dedicated international research leaders according to specific output are Finland and Denmark, followed by Croatia. Portugal, Australia, and Germany, who seem to focus on 100% RE systems analyses as part of their public research and development expenditures, while all other countries would have more financial resources, but its use is extremely limited for 100% RE systems research.

### D. MOST PRODUCTIVE TEAMS

Several leading teams have been identified by highly cited and impactful articles. For a more detailed analysis of research teams in the field of 100% RE systems analyses, the metrics articles and citations per team are analyzed. A team is defined as having contributed at least five category one articles to reflect a repetitive character. Different articles per team are typically identified via the senior scientific

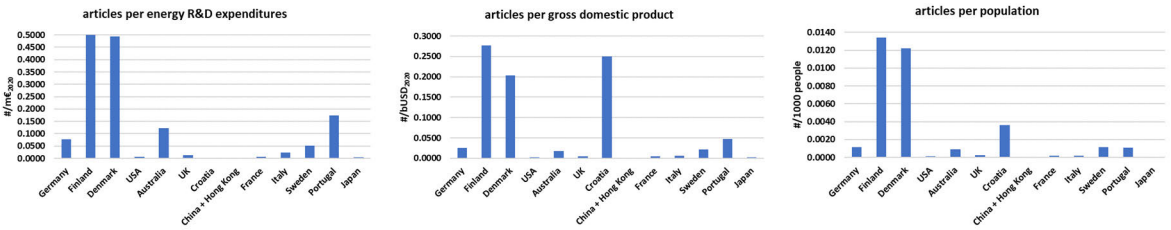


**FIGURE 9.** Specific research output in the field of 100% RE systems analyses according to public energy research and development expenditures (left), gross domestic product (center), and population (right). The countries displayed reach at least 10 articles in the field.

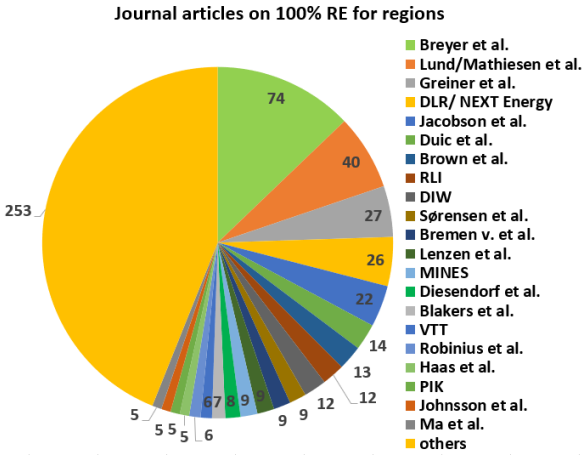


**FIGURE 10.** Research teams in the field of 100% RE systems analyses. The teams are ranked according to the contributed articles in category one. A minimum of five articles are required to be identified as a repeatedly active team in the field. All articles are linked to research teams in the Supplementary Material.

leader in the team. Applying this definition, 21 teams in the world were identified, which are located at universities, institutes, and research centers. In total, 318 in 550 articles can be allocated to these 21 teams, as depicted in Figure 10. Several articles are counted for more than one team due to respective collaboration of different teams. Some researchers have moved from one affiliation to another, such as Breyer, Brown, Haas, Ma, and the German Aerospace Centre (DLR), which merged with NEXT Energy in 2017. For individual researchers, their lifetime publications are counted, and for DLR and NEXT Energy, their lifetime publications have been grouped together. For the case of splitting a team with continuation of both parts in the field, the articles are counted for both teams; this has been applied to Breyer and the Reiner Lemoine Institut (RLI).

Breyer et al. (LUT University, Finland) top the list with 74 journal articles published from 2014 onwards. Lund/Mathiesen et al. (Aalborg University, Denmark), Greiner et al. (Aarhus University, Denmark), DLR/NEXT Energy (Stuttgart and Oldenburg, Germany), and Jacobson et al. (Stanford University, USA) follow with 40, 27, 26, and 22 articles, respectively. The number of annual citations for these teams are displayed in Figure 11 for the years 2006 to 2021. The total number of citations for the 620 articles on 100% RE systems analyses for all three categories is 36,075 citations from 1975 until May 2022. The five leading teams in total citations are Lund/Mathiesen et al., Breyer et al., Jacobson et al., Greiner et al., and DLR/NEXT Energy with 10,084, 3913, 3394, 1978, and 1320 total citations for the 620 articles assessed by May 2022. On an annual citation basis in 2021, the leading teams are Lund/Mathiesen et al., Breyer et al., Jacobson et al., Greiner et al., Brown et al. with 1610, 1264, 500, 389, and 322 citations. Among the five leading teams, the relative share of citations in 2021 is only growing for Breyer et al. and Brown et al. Among the other research teams with at least 100 citations in 2021, the relative share of citations is growing strongest for German Institute for Economic Research (DIW) and RLI. The high dynamics in published articles and relative citations may change the leading teams in the years to come. Citation statistics for the identified teams can be found in the Supplementary Material.

Another most interesting result is obtained if the leading teams in the field of 100% RE systems analyses are compared to the findings of Dominković et al. [47] for the leading organizations in the more general field of energy system analysis. Aalborg University (Lund/Mathiesen et al.) is identified as a globally leading research hub for both perspectives, and only Chalmers University (Johnsson et al.) is found among the top 20 organizations in both research results. Thus, 90% of all global leading organizations in general energy system analysis do not contribute to the research of 100% RE systems analyses at a relevant level, indicating that a strong position in general energy system analysis leads to a strong bias against highly RE systems analyses. This surprising but clear finding requires more research to understand the drivers as to why newcomer research organizations are in a much better position to establish 100% RE systems analyses research, and why those research organization with best preconditions in researching highly complex energy systems obviously fail to establish or even contribute to the very fast-growing research field of 100% RE systems analyses.

### *E. SOCIAL NETWORKING ANALYSIS*

Social networking of author organizations indicates the cooperation among authors based on their affiliations. A social networking analysis (SNA) was performed to understand the authors' teamwork contribution and measure different types of centralities in the networks, such as degree centrality and betweenness centrality. Degree centrality can be defined as

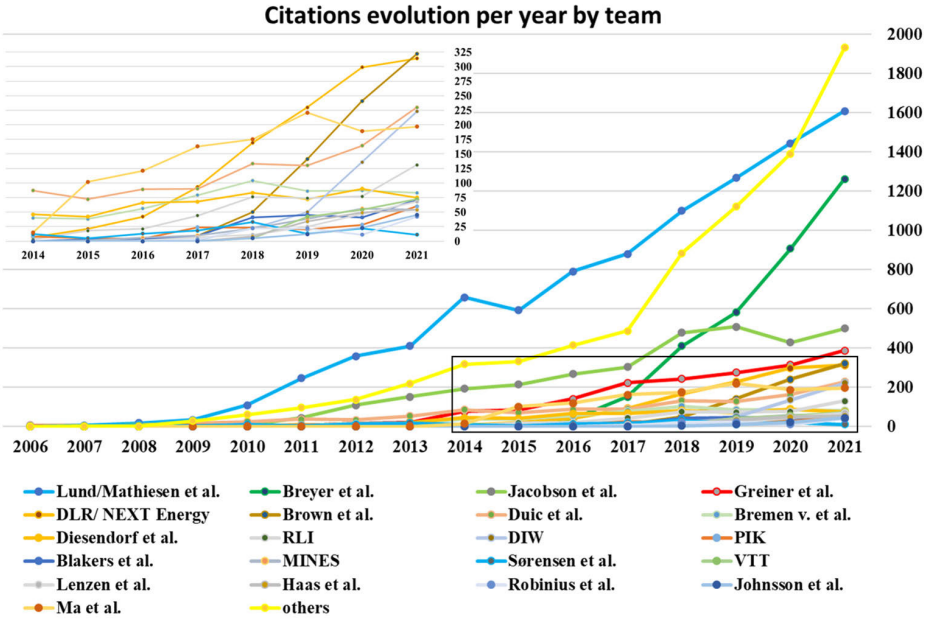


**FIGURE 11.** Annual citations for the identified teams in the field of 100% RE systems analyses for the years 2006 to 2022. A team is defined by at least five articles in the category one group to ensure repeated research in the field. The dense part of the diagram for the years 2014 to 2021 up to 325 citations per year is enlarged in the inlet.

the number of links incident around a node [646]. Betweenness centrality is defined as the degree to which a node acts as the shortest path among other nodes [647]. Both indexes are calculated by UCINET 6 designed by Borgatti et al. [59], and network diagrams were created with the help of NetDraw developed by Borgatti et al. [648]. Figure 12 (top) shows the social network diagram of the authors' organizations. The diagram is based on the degree centrality in the co-authorship network that depicts the connected organizations and some sub-networks of organizations in which the researchers are affiliated.

In Figure 12 (top), 336 nodes are used, consisting of universities, institutes, and research centers, out of which the most dominant organizations based on the number of articles are universities. The organizations with more than 13 nodes are the core organizations, which are colored green by the box indicators. These organizations have at least five published articles. Organizations with 9 to 13 nodes are considered the second-ranked organizations, which are colored light blue. The rest are dark blue with less than nine nodes, connecting around the core nodes. 97 out of 336 nodes have no central connection to the core organizations.

These nodes are distributed with their connections around the core organization. Figure 12 (bottom) focuses the diagram on the centrally connected organizations. Aalborg University has the highest number of links at 23, followed by LUT University and DLR at 22, indicating that the authors in these organizations have the most external cooperation with their counterparts in other organizations. The University of Rio de Janeiro, with only five articles, was able to reach 22 links.

Degree centrality and betweenness centrality for the seven core organizations with minimum criteria of five articles are provided in Table 6. It should be noted that these values are calculated by applying the tool UCINET 6. Aalborg University has the highest number of degree centrality, due to the high number of nodes, and DLR is ranked first regarding betweenness centrality.

The SNA diagram in Figure 12 (top) shows that the field of 100% RE systems analyses is ubiquitous. However, only a few organizations, such as Aalborg University, LUT University, Aarhus University, Stanford University, and DLR are among the most influential ones due to a high number of articles aligned to international cooperation. The key reason for low or lack of availability of other organizations is that their publications cover other facets of the energy system and do not necessarily establish 100% RE scenarios. However, existing barriers can be overcome due to renewal of science and changing policy priorities. This can be observed for the case of Sweden, where Johansson et al. at Chalmers University recently joined the group of established teams in the field of 100% RE systems analyses (see section 4.4), which was also a consequence of lacking interests in new nuclear power plants and fossil carbon capture and storage options, making entirely RE systems the logical solution. Similarly, such a trend can be already observed for the National Renewable Energy Laboratory in the USA with an increasing number of articles in the field [211], [212], [224], which is also a consequence of ongoing policy chances on the state level. Policy changes are also facilitated by ongoing pressure of stakeholders from civil society, such as the young

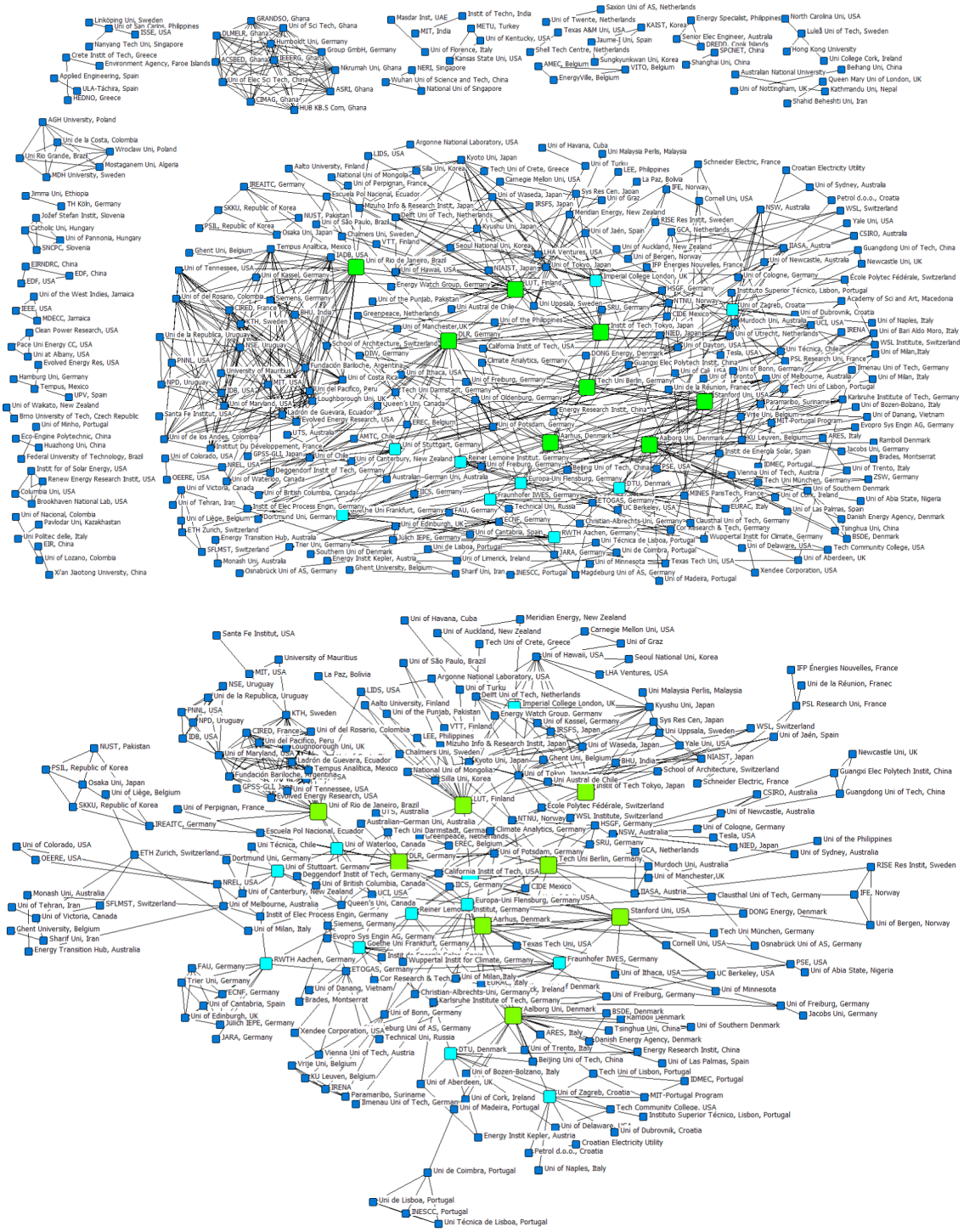

**FIGURE 12.** Social network diagram of the authors' organizations based on degree centrality in full (top) and focusing the central connections to the core organizations (bottom). The diagram consists of both coupled and decoupled organizations. Decoupled organizations enjoy less international cooperation with a minimum at two and a maximum at 12 nodes. Social network diagram of the authors' organization are based on degree centrality.

generation voiced in actions of Fridays for Future, pushing the results of the Paris Agreement [649] into political action. Science is supporting the concern of the young generation [650], [651], which in turn increases research activities on 100% RE systems analyses [652].

### F. MOST PRODUCTIVE AUTHORS BY THEIR PUBLICATIONS

Measures were used to evaluate the researchers' productivity through the number of published articles, received citations, h-index in the field, and for all publications of the researcher, g-index, and m-index. The h-index for an author is considered

**TABLE 6.** Total articles, degree, and betweenness centrality for the seven dominant organizations ranked based on their degree centrality. The quantities for both centralities have been determined by the tool UCINET 6.

| Organization | Total Articles | Degree Centrality | Betweenness Centrality |
|---|---|---|---|
| Aalborg University, Denmark | 40 | 23.0 | 11994.2 |
| LUT University, Finland | 74 | 22.0 | 10148.7 |
| DLR, Germany | 26 | 22.0 | 17457.0 |
| Tech Uni Berlin, Germany | 11 | 21.0 | 13126.1 |
| Aarhus University, Denmark | 27 | 16.0 | 5166.7 |
| University of Tokyo, Japan | 6 | 16.0 | 2004.1 |
| Stanford University, USA | 22 | 13.0 | 9172.2 |

the aggregated impact and relevance of scientific output [52]. The measure shows the number of h papers of an author that has been cited h times. For instance, if 15 articles of an author have at least 15 citations, then the author's h-index is 15. Hirsch [52] introduced the m-index as a quantity that shows the time since the first article of an author received citations per h-index. For example, if an author has an h-index of 15 after ten years of scientific activity, then the m-index is 1.5. An individual with an m-index of $m \approx 1$ is regarded a 'successful scientist', with $m \approx 2$ an 'outstanding scientist', and with $m \approx 3$ a 'truly unique individual' according to Hirsch [52], assumed for a productive period of about 20 years.

The g-index was introduced by Egghe [55] and reflects the largest number of top g most cited articles, which received together at least $g^2$ citations. For instance, considering ten publications where one is cited 31 times and the others only once each (40 citations in total), the resulting g-index and h-index would be six and one, respectively. Table 7 summarizes the most important unitless quantities for the authors within the field of 100% RE systems analyses based on the 620 category one articles. Breyer with 79 articles and 4063 citations has contributed the most in terms of articles within the field. Lund has received 9209 citations with 35 publications, which is the highest number of citations in the field. Mathiesen has received 7368 citations through 28 publications. It should be noted that the numbers for total citations, h-index, g-index, and m-index are assessed for the field of 100% RE systems analysis articles of an author, not the total research output across all scientific activities of a researcher. The h-index overall is used for this purpose to indicate the impact for all authors' articles. For example, Lenzen has the highest overall h-index of 76, followed by Jacobson at 70. Breyer has a m-index of 5.0, Brown of 3.7, Lund of 2.3, and Mathiesen, Greiner, Lenzen, and Oei all of 2.0, which indicates that the authors are highly productive in a much shorter period of scientific activity compared to scientific peers. Other researchers in the list with high m-index values typically belong to the teams of the senior researchers. The normalized h-index indicates the relevance of the 100% RE systems analyses field to the overall scientific impact of the researchers, with the highest team leader values for Breyer and Greiner with 0.71 and 0.74, respectively, i.e., this field represents their central research impact. Lund, Mathiesen, Brown, and Oei all have values around 0.5 indicating that this field is their strongest research impact, besides other relevant activities. The analysis also reveals a huge gender gap in the research community, as the top 25 list (Table 7) is dominated by male researchers with only three female contributors in the top 25 in the field: Caldera of LUT University, Finland, Becker of University of Kassel, Germany, and Maizi of MINES, France, all of whom are located in Europe. A high dynamic upwards trend is shown by Victoria of Aarhus University, Denmark, which may lead soon to her joining the group of top 25 researchers in the field. A more detailed list of top researchers in the field can be found in the Supplementary Material.

Comparing the top 25 researchers in the field of 100% RE systems analyses to the 49 leading and strongly networked researchers in the field of energy system analysis [47] leads to only 8 matches (Lund, Mathiesen, Østergaard, Breyer, Bogdanov, Duić, Krajačić, Robinius). This finding coincides with the similar one on research organizations, i.e., established researchers in energy system analysis avoid research on 100% RE systems analyses, which creates opportunities for independent researchers for scientific renewal.

### G. AUTHOR GROWTH TREND

Sørensen, in 1975, initiated the research field of 100% RE systems analyses with the first published article [14]. Several other authors, such as Lovins [15], Weingart [202], [203], Meibom [104], Nielsen [250], and Duić [490] contributed in the field until the year 2004, a year in which only eight individual researchers contributed to the field of 100% RE systems analyses. This number grew strongly to 84 authors by the year 2010. By 2015, 363 authors contributed to the field, which further increased to 1388 individuals in the year 2021. The low number of authors until 2010 shows that researchers did not recognize the significance of the field, and the idea of powering the entire energy system, or at least the power system, entirely based on renewables. The CAGR of individual researchers in the field of 100% RE systems analyses was 30% from the year 2010 to 2020. In total, the field has now attracted almost 1400 individual researchers as documented across the 550 articles investigated for category one as shown

**TABLE 7.** Top 25 authors in the field of 100% RE systems research ranked by number of total articles. Abbreviation: male (m), female (f). The quantities for h-index, g-index, and m-index are calculated by the Bibliometrix package. The quantity for the overall h-index is retrieved from the Scopus database. The normalized h-index indicates the share of 100% RE systems research among the overall research of researchers.

| Author | Gender | Total Articles | Total Citations | h-index | g-index | m-index | Affiliation | Overall h-index | normalized |
|---|---|---|---|---|---|---|---|---|---|
| Christian Breyer | m | 79 | 4063 | 35 | 62 | 5.0 | LUT University | 49 | 0.71 |
| Dmitrii Bogdanov | m | 46 | 2411 | 29 | 46 | 5.8 | LUT University | 32 | 0.91 |
| Henrik Lund | m | 35 | 9209 | 32 | 35 | 2.3 | Aalborg University | 63 | 0.51 |
| Brian Vad Mathiesen | m | 28 | 7368 | 24 | 28 | 2.0 | Aalborg University | 47 | 0.51 |
| Martin Greiner | m | 27 | 2012 | 20 | 27 | 2.0 | Aarhus University | 27 | 0.74 |
| Mark Jacobson | m | 25 | 3478 | 19 | 25 | 1.2 | Stanford University | 70 | 0.27 |
| Arman Aghahosseini | m | 24 | 1175 | 18 | 24 | 4.5 | LUT University | 21 | 0.86 |
| Michael Child | m | 22 | 1224 | 15 | 22 | 3.8 | LUT University | 18 | 0.83 |
| Neven Duić | m | 17 | 1433 | 16 | 17 | 1.0 | University of Zagreb | 48 | 0.33 |
| Ashish Gulagi | m | 17 | 985 | 13 | 17 | 3.3 | LUT University | 13 | 1.00 |
| Upeksha Caldera | f | 16 | 702 | 13 | 16 | 2.6 | LUT University | 15 | 0.87 |
| Poul Alberg Østergaard | m | 16 | 2189 | 16 | 16 | 1.8 | Aalborg University | 40 | 0.40 |
| Anderson Gorm Bruun | m | 16 | 2189 | 16 | 16 | 1.6 | Aarhus University | 30 | 0.53 |
| Tom Brown | m | 14 | 584 | 11 | 14 | 3.7 | Technical Uni of Berlin | 22 | 0.50 |
| David Connolly | m | 14 | 4224 | 14 | 14 | 2.0 | Aalborg University | 28 | 0.50 |
| Goran Krajačić | m | 14 | 1179 | 13 | 14 | 0.9 | University of Zagreb | 31 | 0.42 |
| Mark Delucchi | m | 13 | 2798 | 12 | 13 | 1.5 | University of California | 27 | 0.44 |
| Manfred Lenzen | m | 10 | 200 | 8 | 10 | 2.0 | University of Sydney | 76 | 0.11 |
| Solomon Oyewo Ayobami | m | 10 | 552 | 9 | 10 | 3.0 | LUT University | 9 | 1.00 |
| Bent Sørensen | m | 9 | 213 | 6 | 9 | 0.1 | Roskilde University | 18 | 0.33 |
| Stefan Schramm | m | 9 | 812 | 9 | 9 | 2.3 | Goethe Uni Frankfurt | 36 | 0.25 |
| Sarah Becker | f | 9 | 649 | 9 | 9 | 4.5 | University of Kassel | 10 | 0.90 |
| Alexander Kies | m | 9 | 430 | 8 | 9 | 2.0 | Goethe Uni Frankfurt | 11 | 0.73 |
| Pao-Yu Oei | m | 9 | 248 | 8 | 9 | 2.0 | University of Flensburg | 16 | 0.50 |
| Nadia Maizi | f | 9 | 240 | 8 | 9 | 1.3 | Mines Paris Tech | 19 | 0.42 |

in Figure 13 (top). More detailed author information can be found in the Supplementary Material.

As shown in Figure 13 (top), a steep growth in the number of individual authors occurred in the recent couple of years. Figure 13 (bottom left) shows the number of authors with at least 3 and 5 publications in the field, with almost 140 authors with at least 3 articles and more than 60 authors with at least 5 articles in the field. In the meantime, 20 authors managed to publish at least 10 articles, and 5 authors contribute at least 25 articles to the field of 100% RE systems analyses, who are Breyer, Bogdanov, Lund, Mathiesen, and Greiner, Figure 13 (bottom right).

### H. NETWORK MAP OF CO-AUTHORSHIP ANALYSIS

Scientific collaboration is defined as the interaction happening within a social context among scientists to fulfill a mutual goal. Co-authorship analysis in science enables the investigation of scientific collaboration patterns. In a co-authorship network, nodes are a proxy of authors, which are linked when they share the authorship of an article [653]. The size of the circle corresponds to the number of articles each author in the publication list has published, and the links between the circles represent co-authorship of articles. The network map for co-authorship with all the interconnected links of the authors is represented by Figure 14. Every color represents a different team, and the authors with the same color collaborate within one team. The map also shows if an author from one team had a common authorship with an author from another team. Breyer has the maximum co-authorships of 77 articles and a link strength of 238, followed by Bogdanov, Lund, Greiner, and Jacobson of 44, 34, 27, and 22 co-authorships with link strengths of 162, 97, 91, and 118, respectively. These values are extracted from the VOSviewer tool. Only connected authors to the teams are shown in Figure 14. However, in Figure 15 disconnected authors are also included, which increases the total number of displayed authors from 532 to 1000. It should be noted that for both networks, the minimum number of articles of an author is assumed to be one. Several teams are strongly linked to each other, such as Lund/Mathiesen et al. and Duic et al., or Greiner et al. and Brown et al. Several teams are weakly interconnected, such as Lund/Mathiesen et al., Jacobson et al., Breyer et al., and DLR/NEXT Energy. Several teams are very weakly connected or almost disconnected,

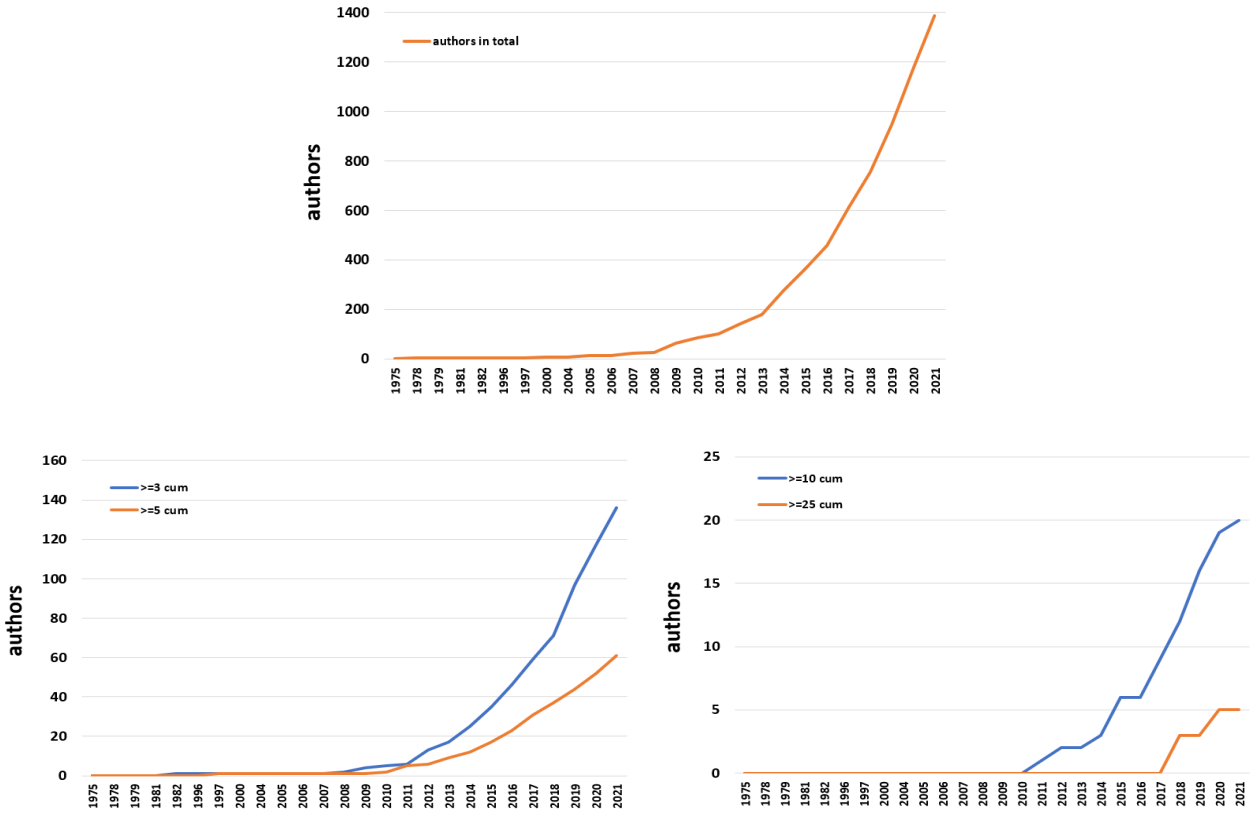


**FIGURE 13.** Cumulative author growth in the field of 100% RE systems analyses. The 550 category one articles have been used for this analysis (top). Cumulative author growth with at least 3 and 5 articles (bottom left) and 10 and 25 articles (bottom right) per author in the field of 100% RE systems analyses. The 550 category one articles have been used for this analysis.

such as DIW, RLI, PIK, Robinius et al., VTT, and Johansson et al.

Each cluster shows a different team, which is colored for all the team members with the same color. The leader of the team has a larger circle. For example, Jacobson, Breyer, Lund, Greiner, and the team members belonging to a group are not necessarily from one country and affiliation. One potential reason is that an author may collaborate with several teams from different affiliations and countries. According to the diagram, the number of team members in the team of Breyer and Greiner seems to be among the highest compared to other groups. There was no restriction on the number of team members to form a team, and the number of articles was assumed to be at least five.

Although the circle size shows the number of articles by an author, it fails to represent how many articles are published.

The authors of each team appear in proximity to their team members with further concentration, as displayed in Figure 14. It should be noted that the color used in this figure does not necessarily match the colors in Figure 15. This diagram clearly shows the authors who belong to their teams and authors who have not established a team due to having less than five articles as a threshold in this study. For example, Mathiesen, Lund, Østergaard, Skov, and Thellufsen belong to the Lund/Mathiesen et al. team. However, the tool failed in some points to form all defined teams, such as for the Diesendorf et al. and Blakers et al. teams.

### I. COLLABORATIVE NETWORK MAP AMONG COUNTRIES

A map of the co-authorship network representing the cooperation among the countries is visualized in Figure 16. The minimum number of documents for a country was set at one, which means a country with at least one article can be displayed in the map. The size of each circle, and the thickness of a link, show the countries' productivity. The bigger the circle and link thickness, the more articles and collaboration for the respective country. The collaborative network map indicates that a very high share of research for the 100% RE systems analysis field has been carried out in Europe and the USA. The top countries publishing a higher number of articles and collaborating with other countries are Germany, Denmark, and Finland.

Their publications comprise 158, 113, and 95 articles, and the link strengths are 125, 82, and 44, respectively. The USA and Sweden follow with 83 and 25 articles. These values are obtained from the VOSviewer tool. The countries with smaller nodes and fewer articles are distributed around the countries with more research activities. Like the social networking analysis in Figure 12 (bottom), the core countries are in the center with their links to countries with fewer

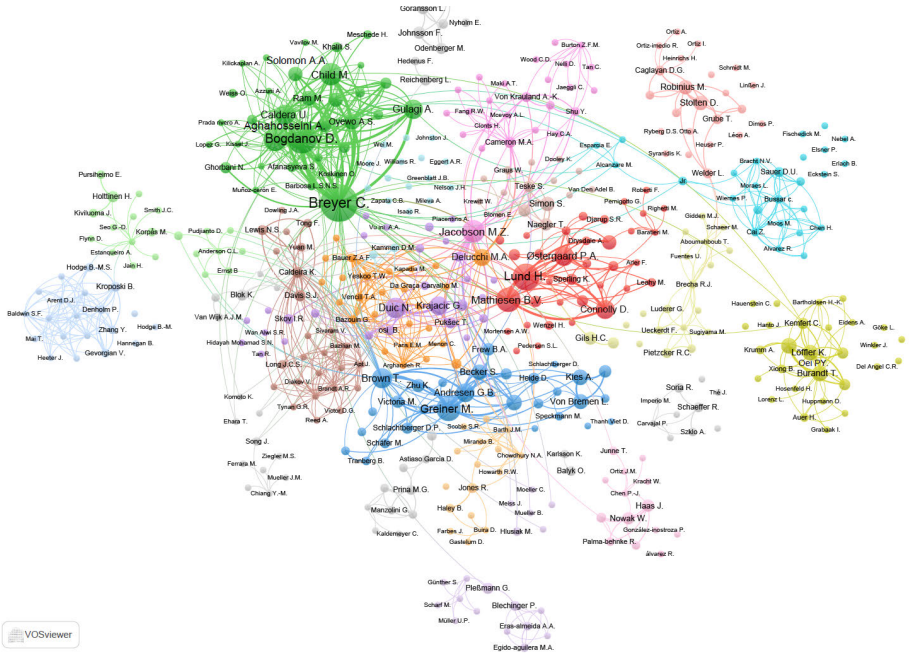


**FIGURE 14.** Network map of co-authorship analysis for all connected authors for the field of 100% RE systems analysis articles.

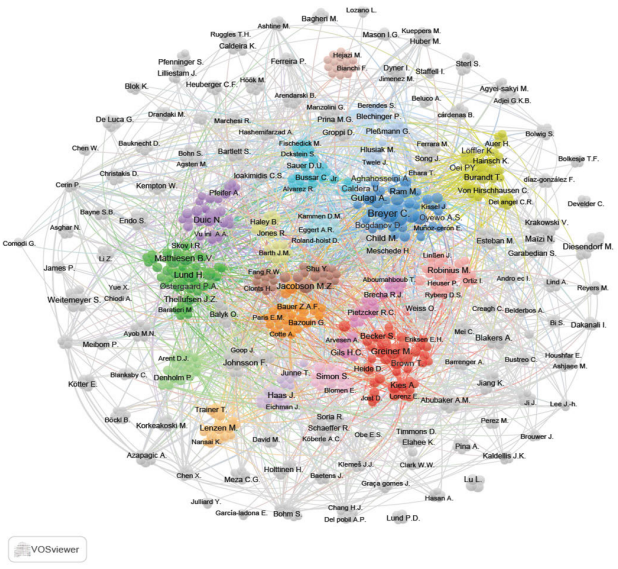


**FIGURE 15.** Network map of co-authorship analysis with all co-authorship.

publications. For example, Finland has common articles with India, Bolivia, and Cuba from the top of the diagram. At the same time, it also has published articles with Germany, Sweden, and Denmark, among others.

### J. NETWORK OF CO-OCCURRENCE KEYWORDS

Keywords are mainly used to show the pivotal focus of an article and are of practical use for readers to catch the main contexts of an article [654]. A network map of a keywords co-occurrence analysis for all 620 category one, two, and three articles is shown in Figure 17. All the keywords are extracted from the Scopus database and analyzed by using the tool VOSviewer. In the network map, nodes indicate the keywords and links represent the co-occurrence among nodes. The node size illustrates a keyword's significance. The larger the nodes, the more important the respective keywords are [655]. The large nodes show that the number of occurrences of an item is higher, and the larger an item, the more relevant it is. The core keywords of the 100% RE systems analysis articles are: '*renewable energy*', '*solar energy*', '*energy policy*', and '*wind energy*', as visualized in Figure 17. Obviously, the great majority of authors have established scenarios with solar and wind energy. At the same time, the *cost* keyword with further repetition in different forms documents the high importance of societally affordable energy transition solutions. Moreover, it reveals that the economic perspective has attracted more attention than social assessment, which is a central pillar of Sustainable Development. Important topics are indicated by keywords in light green colors pointing to studies on pollution (air pollution mortality, atmospheric pollution, pollution tax, etc.) and various sources of energy supply (photovoltaic, concentrated solar thermal power, bioenergy, battery storage system, etc.).

The yellow keyword group points to heat (heat pump, heat saving, geothermal heat, etc.). More insights can be identified by investigating the figure in detail.

### K. INTERACTIVE TOPIC MODELING

Topic models have lately appeared as a dominant set of techniques to uncover the fundamental semantic structure of sizable disorganized collections of documents [656]. The

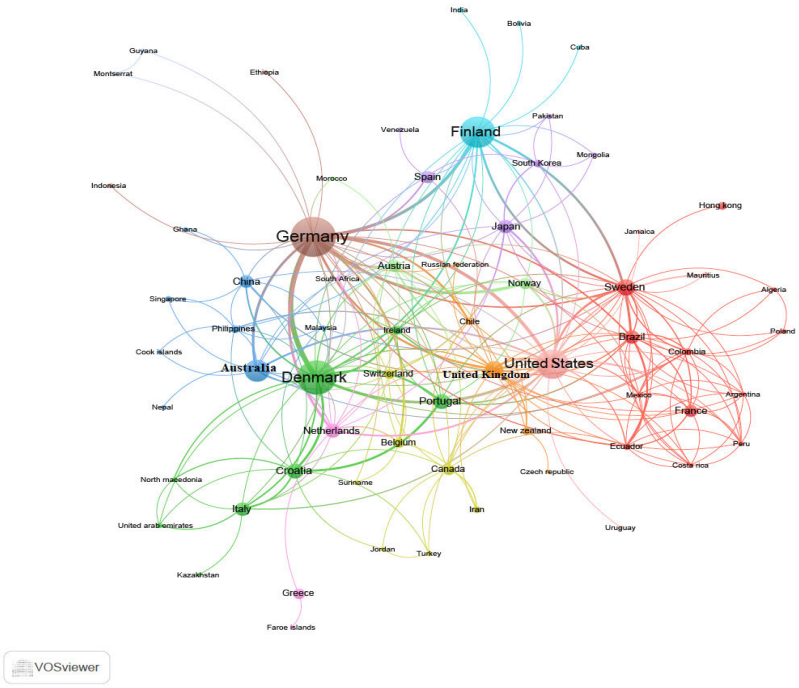


**FIGURE 16.** Collaborative network map among countries publishing articles in the field 100% RE systems analysis.

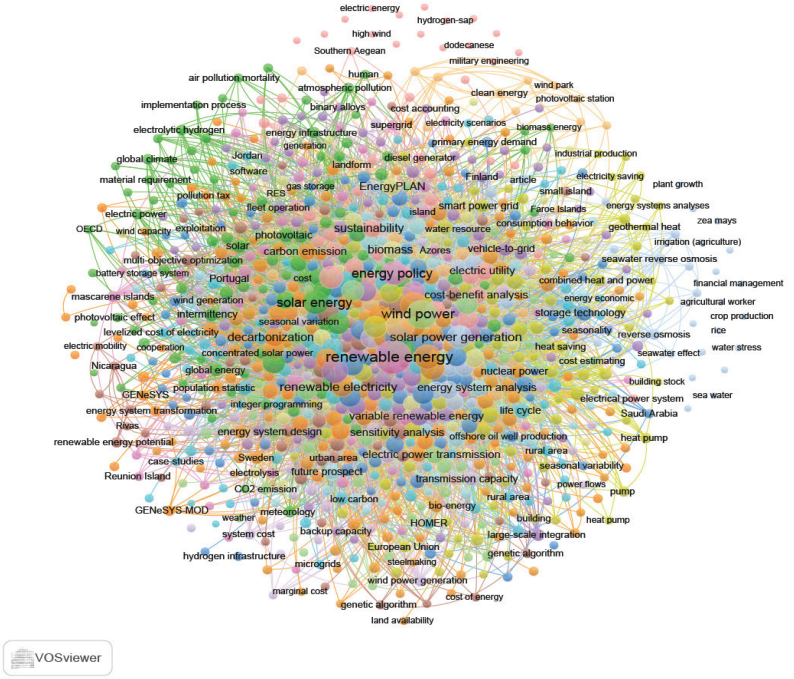


**FIGURE 17.** Co-occurrence keywords analysis by VOSviewer extraction from all identified 620 articles across all categories as extracted from the Scopus database for the field of 100% RE systems analysis.

approach used in this research for the topic modeling is LDAvis, which was used to find the theme that designates the body of the 100% RE systems analysis literature. LDA produces a list of topics of words that form a list with allocated probabilities and distributions. As the number of topics should be identified externally by users, experimentation was done with several different numbers of topics to observe the most meaningful word distributions. Altogether, nine topics were found to be the most relevant and purposeful, covering a proper scope of concepts. The nine illustrative

**TABLE 8.** List of evaluated topics and their eminent keywords. The four keywords for each topic are ranked by both the frequency and exclusivity of the term under that topic [657]. The marginal topic distribution indicates the share of each topic as part of the body of literature. The higher the marginal distribution of a topic, the more often that topic appears in the body of literature.

| No | Topic Name | Keywords Root | Marginal Distribution |
|---|---|---|---|
| (1) | Power System | Electricity, Solar PV, Wind, Power Plant, Storage | 26.77 |
| (2) | Energy System | Energy Modeling, Scenario Analysis, Decarbonization, EnergyPLAN | 25.23 |
| (3) | Heat & Water | Heat Sector, Desalination, Water Power, Water Stress | 10.50 |
| (4) | Island | Isolated, Remote Area, Geographic Entity, Off-Grid | 10.09 |
| (5) | Transport | Electric Vehicles, Hydrogen, Smart Charging, Road | 7.04 |
| (6) | Optimal Resource Mix | Economics, Optimization, Renewable Energy, Sector Coupling | 6.55 |
| (7) | International Grids | Grid Expansion, Interconnection, Power Transmission, Smart Grid | 5.88 |
| (8) | Transition | Climate Change, Energy Transformation, Energy Policy, Pathway | 4.79 |
| (9) | Heat Integration | District Heating, Heat Pump, Space Heating, Energy Efficiency | 3.14 |

names assigned are based on pivotal characteristics and four eminent keywords, as listed in Table 8. It should be noted that eminent keywords have the same root as their topics, either conceptually or lexically. Topics at the top of the table have a higher marginal topic distribution. For example, (1) '*Power System*' has the highest probability distribution of 26.77, meaning that this topic is the most likely to emerge in the 100% RE systems analysis literature. The topics distribution using the force-directed algorithm ForceAtlas2 in Gephi is visualized in Figure 18. The topic modeling figure represents which topics are closely related with one another based on their probability to emerge together in the same article [43]. The second most linked topic is (2) '*Energy System*', which is interesting, since the overarching theme of the entire research field should be (2) '*Energy System*'; however, the basis of the future 100% RE system, the (1) '*Power System*' shows an even higher probability distribution, suggesting that it may also be more researched. Moreover, (1) '*Power System*' and (6) '*Optimal Resource Mix*' are very related with each other since these topics are highly correlated. Hence, a cluster forms around (2) '*Energy System*', (4) '*Island*', and (3) '*Heat & Water*'. Interestingly, islands research appeared as a topic, presumably because 12% of the total articles investigated the 100% RE system transition on island, which is increasingly well reviewed [60], [61], [62], [63], [64], [65]. The other cluster is (8) '*Transition*' and (9) '*Heat Integration*.' The cluster for (5) '*Transport*' (7) and '*International Grid*' also has a strong correlation due to a high thickness of their links. With a further look at the topics that have few correlations, it is evident that (8) '*Transition*', and (7) '*International Grids*' are to some extent disconnected from the overall topics, i.e., the articles that are strongly associated with these topics do not have a high likelihood to be systematically related with other individual topics.

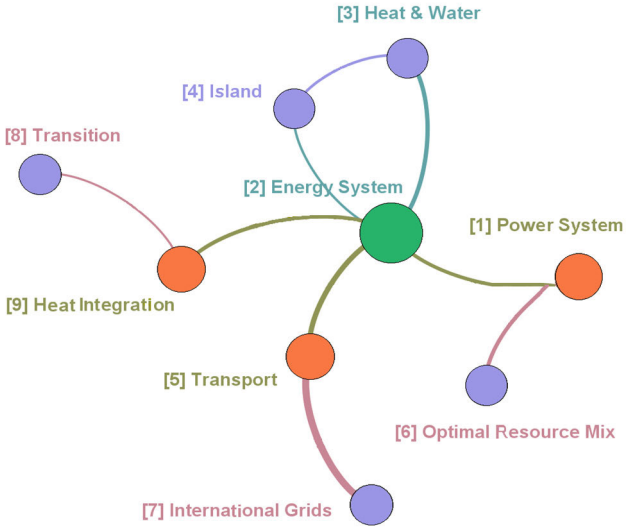


**FIGURE 18.** Nine significant correlated structural topics for 100% RE systems analysis.

### L. LIMITATIONS OF THE STUDY

The most relevant critique for both this study and for almost all bibliometric analyses is that the quantities analyzed are highly variable over time. For example, the citations received per article or journal are highly likely to be changed continuously. Hence, the document that tops the list by citation number at the time may not necessarily remain high sometime later. However, based on current results, one can estimate, for instance, what the top articles would be some time later. A substantial uncertainty of bibliometric research is the number of detected articles in a field, which is the case for the field of 100% RE systems analyses, a field that is substantially scattered and less interconnected, partially because of a lack of common keywords and used terms. To overcome this limitation in future research, all identified articles are cited, so that these articles are linked via this paper and fully accessible. In addition, various authors did not intend to research 100% RE systems but investigated such systems due to the set research assumptions. The identified 620 articles for this research increase steadily, so that any bibliometric research is limited and can only report the insights for the covered period and the body of identified articles, which is in this research mainly until mid-2021 for detected articles, where

the citations have been used for the status as of May 2022. Also, later identified articles may be published in earlier periods, which may distort the prepared results. Any impact assessment of published research is limited, since citations can be quantified, but how comprehensive the impact had been cannot. In addition, societal impact beyond scientific citations such as improved policies and adjusted legislation is hardly quantifiable.

## V. CONCLUSION

In this study, all identified 100% renewable energy systems articles were analyzed, which are characterized by an exponentially growing total number of articles, authors, and teams. Scopus and Google Scholar are used as sourcing databases to identify 620 scientific articles published until mid-2021 in the field of 100% renewable energy systems analyses. The research field was established in 1975, and since the mid-2000s, articles are published every year with a compound annual growth rate of 26% for the years 2010 to 2020. The most cited articles in the field analyzing a concrete geographic context received up to 900 citations so far. The total citations received in the field until mid-2022 reached 35,952 with a compound annual growth rate of 38% for the years 2010 to 2021. The two journals that are the most relevant for the field of 100% renewables energy systems analyses are *Energy* and *Applied Energy*, with a total number of published articles of 91 and 67, leading to a journal related h-index of 44 and 34 and citations per article of 86 and 95. The top five leading journals according to journal h-index combine 53% of articles and 82% of total citations.

The most productive teams according to published articles are from Denmark, Finland, Germany, and the USA, which also explains the relative strength of these countries in article output and their strong international networks, documented by social network analysis of organizations, co-authorship networks, and collaborative networks. The top five countries according to first authored articles combine 64% of articles and 73% of total citations, while the top five leading teams according to published articles combine 34% of articles, 57% of total citations, and 52% of all citations in the year 2021. Finland and Denmark are countries with the most research output in the field in ratio to public energy research and development expenditures by a significant margin. Besides the strongly networked teams, there are also weakly networked or even disconnected teams, which repeatedly publish in the field, but interact little with other teams. The research field is very weak in countries of the Global South and fossil fuel supplying countries in the Middle East and Eurasia, with virtually no teams doing research in Global South countries, which is partly compensated by established research teams carrying out research for these regions. The author base in the field is strongly growing by about 30% per year from 2010 to 2020, reaching almost 1400 authors in the field, thereof more than 60 authors with at least 5 articles in the field and five authors have published at least 25 articles in the field.

EnergyPLAN and LUT-ESTM are by far the most applied tools within the field of 100% renewable energy systems analyses. These two modelling frameworks are used for 25% of all articles in the field, whereas no other tool exceeds 4%. Additionally, these two received 35% of all total citations and 36% of the citations in the year 2021, while no other tool received more than 5% of citations either in total or for the year 2021. Interestingly, the core distinction of the two modelling frameworks is that EnergyPLAN is of simulation and overnight type, while the LUT-ESTM is of optimization and transition type.

The research field of 100% renewable energy systems analyses lacks diversity in several regards, with a massive observed gender gap documented in a lack of highly publishing female researchers. Additionally, there is a substantial gap in research from and for Global South countries.

This is partly balanced with researchers from the Global South being affiliated in the Global North and active in the field, but these affiliations vary substantially across teams. The diversity gap also comprises a lack of several major energy system models used for 100% renewable energy system analyses, in particular the lack of integrated assessment models.

This research field offers substantial opportunities for academic renewal since only 10% of the global top 20 research organizations in the more general field of energy system analysis play an important role in the field of 100% renewable energy systems analyses. Comparatively, the other 90% do not play any relevant role, including several of the global leading energy research organizations. This strong institutional bias against highly renewable energy systems research may be an interesting area for researching self-induced barriers in scientific renewal, and it opens the space for less prominent research organizations to head for international leadership in one of the of the fastest growing and most relevant fields for global sustainable development.

Trends in bibliometric analyses indicate a further stark increase in published articles in the field, and even faster growing citations at growth rates above 25% and close to 40%, respectively. An increasing trend can be observed with established energy system modelling teams joining the research field since non-renewable energy system solutions strongly loose societal attractiveness. For a successful global energy system transition reaching climate targets and sustainable development goals, substantially more research is required from and for countries of the Global South.

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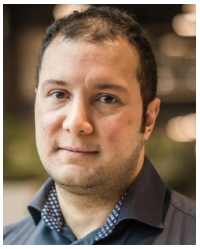

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