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RESEARCH

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Urban expansion of *Energiewende* in Germany: a systematic bibliometric analysis and literature study

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Abstract

Background: Despite Germany's world leadership of *Energiewende*, there have been mounting challenges, such as the slowdown of German renewable energy growth since 2017, when the Merkel administration dramatically changed the German renewable energy promotion policy from feed-in tariffs to competitive auctions. These challenges pose important research questions about whether and how an emerging urban expansion of *Energiewende* can serve as a vital solution to counteract the challenges to the energy transition. Answering these research questions provides a unique opportunity to explore the academic and historic foundations of the energy transition and its urban expansion, the emerging events that exemplify urban expansion, and the viable solutions this growing trend of urban expansion might be able to provide to the challenges to the German energy transition.

Methods: This paper conducted visual and manual bibliometric analyses, examined the results of case studies, and reviewed secondary literature and data on urban expansion of German *Energiewende*.

Results: By analyzing the bibliometric and investigative results, this paper identified political, socioeconomic, and technological challenges to *Energiewende* and a new trend of solar energy expansion in German cities aimed at meeting Germany's carbon neutrality targets by 2045. The new trend of the urban expansion of the German energy transition manifests itself in the focused research efforts on identifying the vast untapped potential on new building rooftop areas in most populous German cities and/or detached and two-family houses in Germany and the recent booming of building-related solar PV and heating mandates in German cities and states, the expanding solar heating and cooling systems, and the government policy support at various levels in this urban expansion through aggressively strengthening climate and renewable energy targets.

Conclusions: In search for answers to the recent challenges of *Energiewende* in Germany, this paper conducted both visual and manual bibliometric analyses and applied desk research and reviews of secondary literature and data. This paper found an emerging trend of the urban expansion of *Energiewende*, including the awareness of the vast potential and gap of urban solarization and the enhanced urban municipal policies, actors, actions, and accomplishments of exploiting this potential. These findings were based on academic knowledge on the German energy transition and contribute to expanding this academic knowledge. To help more effectively exploit the vast potential in solarizing all German cities, especially the largest ones, this study recommends that further research more closely track the progress of this trend and apply more quantitative tools and approaches in future tracking.

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Keywords: German energy transition, Solarizing cities, Solar district heating, Tenant power, Decarbonization

Background

Energiewende (or the German energy transition in English) played a pioneering and leading role in initiating the world's energy transition, sustainable development, and climate protection. The main drivers of the *Energiewende* were long-term climate protection and renewable energy (RE) targets and promotional policies for grid-based renewable power expansion. The centerpiece of the German renewable energy supportive policy tool was the feed-in tariffs (FITs) for RE generation [1].

The FITs are a generous promotional scheme in Germany that guaranteed above-market incentives for renewable power fed into the power grid for 20 years at technology-differentiated and degressive rates for both residential and commercial applications. This promotion tool allowed Germany to rapidly increase its RE installation and generation, especially from 2006 to 2012 [2]. Record-high levels of solar photovoltaic (PV) projects were installed by residential, small business, and commercial investors because the investment returns with RE FITs were significantly higher than the power generation costs [3]. The FIT-based RE policy energized not only RE deployment, but also the growth of more than 120,000 "prosumers"—homeowners and small businesses as renewable power producers and consumers [4].

Energiewende, especially the rapid development of solar PV, achieved remarkable positive economic and environmental impacts [5]. It allowed Germany to stand out as the world's top wind power generator until 2008 [6] and the world's top solar power generator until 20,013 [7]. In the last 30 years from 1990 to 2020, it was able to grow its economy by 45% without increasing its gross power consumption, but with its primary energy consumption reduced by 22% and its greenhouse gas emissions decreased by 41% [8]. With its largest shares (58% in 2019 and 59% in 2020) of residential and business solar photovoltaic (PV) power generation capacities, Germany was one of the countries with the most distributed solar in Europe and one of the five such countries in the world [9]. Because the costs in Germany were optimized, it has, like China, some of the lowest distributed PV investment costs in the world [10]. Therefore, Germany is still widely considered a worldwide pioneer and leader in sustainability and RE penetration [11].

However, there have been mounting challenges for the German RE growth since 2017, when the Merkel administration dramatically changed the German RE promotion policy from FITs to competitive auctions. Although renewable energy continued to grow, the 5-year average annual growth rates of the German RE accelerated from 6.6% and 8.2% in the 1990s to 12.1%, 10.9% and 12.4% during 2000–2015 but decelerated to 6% during 2015–2020 (see Fig. 1).

The slowdown of RE deployment growth poses an important question of whether and how Germany can use the urban expansion of *Energiewende* as a vital solution to tackle the challenges of *Energiewende*.

The term "urban expansion" commonly used in the academic and professional literature means urbanization, urban crawl, and expansion of urban areas and population [13–15]. The term "urban expansion" used in this paper is different from that common definition.

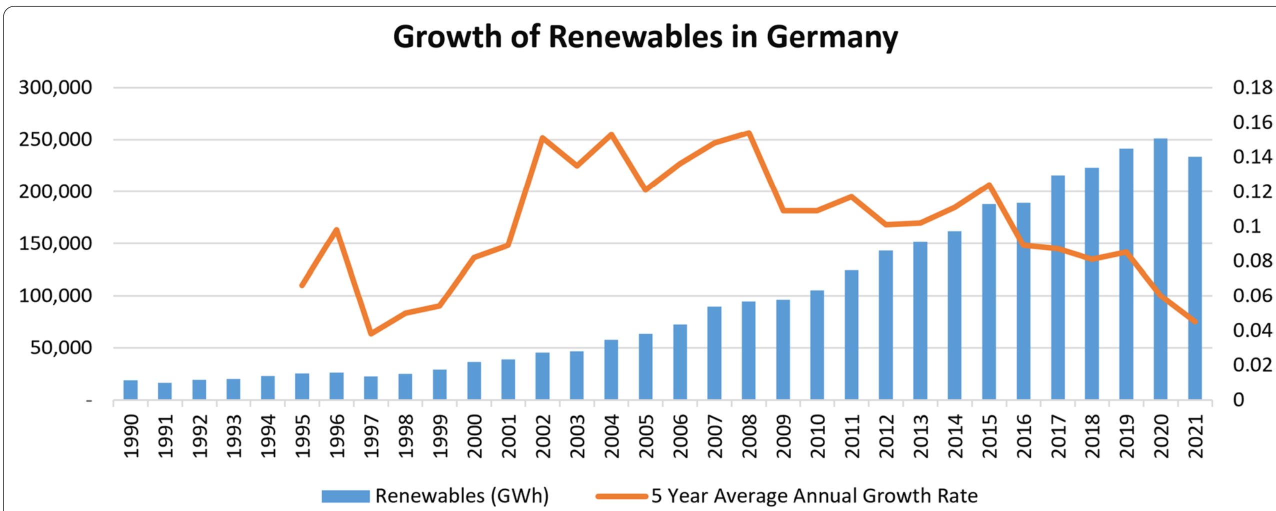

Fig. 1 Growing renewables with declining growth rates [12]

It is narrowly defined as the expansion of *Energiewende* from areas outside of cities into urban areas. In fact, some researchers also touched on the essence of this narrow definition when they discussed the necessary urban responses to the challenges cities are facing, such as urban citizens' responsibility for, governance of, and action on climate change and decarbonization, as well as the expansion of renewables and energy efficiency in cities [16].

Answering this research question provides a unique opportunity to explore the academic and historic foundations of the energy transition [17] and its urban expansion (see Table 2), the events that exemplify the emerging urban expansion, and the viable solutions that this growing trend of urban expansion might provide to the challenges to the German energy transition. In addition, the results of this inquiry will help the reader better understand how the stakeholders of the energy transition—residents, businesses, governments, researchers, and educators—tackle the challenges to the German energy transition and how they bridge the gap between the committed climate neutrality targets and the real policy support and action on climate protection and renewable energy penetration. This investigation will also contribute to the interdisciplinary knowledge and understanding of the renewed leadership of *Energiewende* for scholars, professionals, educators in the German Studies and other fields.

To answer the research question, this study reviewed research papers, documents, data, and reports to examine the status and trend of *Energiewende*. The RE FITs introduced by the German Electricity Feed-In Law 1991, which allowed RE investors to receive above-market remuneration, were the main driver of the German energy transition. Although there is an abundance of research on this topic, there is a lack of research on the barriers and challenges and potential solutions to address the problems of the German energy transition. To identify solutions that can effectively address the challenges, it is important to have an overview of the energy transition and an accurate understanding of the knowledge gap on the challenges and solutions of the transition. It is also vital to examine the legal and political measures and strategies that have been put into effect, action, or discussion against their long-term decarbonization and climate protection objectives. More importantly, we need to examine what role the most recent German RE policy innovations will to play in promoting the sustainable decarbonization of German urban areas. To focus on the solutions provided by the urban expansion of the energy transition in Germany, this paper has moved the section on the exploration of the challenges to the transition to the Appendix.

The rest of the paper is structured as follows: " Methods" describes the two-stage research process of the study and the methods used in these two stages, which include three bibliometric analyses and a focused investigation of the studies and research data on the challenges and solutions of *Energiewende*, including how research materials are selected and assessed. " Results" presents the findings of the two-stage investigation, of which the first stage encompasses both visual bibliometric results and manual bibliometric ones, and the second stage shows results structured in findings on both challenges [see Appendix] and solutions, the latter of which is focused on urban expansion as a major potential solution to the challenges. " Discussion and Conclusions" presents the implications of the urban expansion for *Energiewende* and the academic knowledge, as well as the limitations of the study.

Methods

This study was designed to consist of two major stages: (a) bibliometric analyses and (b) thematic analysis. The first stage consisted of three bibliometric analyses of research papers combined. It was intended to provide a valid and accurate account for both the research on energy transition in Germany and the knowledge gap on the challenges and solutions of the recent *Energiewende* and the recent urban expansion of this transition. This stage prepared for the second stage of a more detailed and focused investigation on the latter issue, which was focused on analyzing the studies presented in the last manual bibliometric analysis. To ensure the reliability of this study, it used both the latest bibliometric tools for large-scale data analysis of the *Energiewende* research, the findings from expert case studies, and other reputable data sources on the urban expansion of energy transition. An overview of the structural design and procedure of this study is shown in Table 1.

The first stage of exploration includes three bibliometric data collection and data analyses: (a) broad visual bibliometric analysis, (b) narrow visual bibliometric analysis, and (c) manual bibliometric analysis. The two visual bibliometric analyses were conducted by first collecting the large amount of bibliographic data of all relevant research papers from research databases and then using bibliometric data processing software to automatically generate statistical and mapping visual presentations. The results of the visual bibliometric analyses are presented in charts and figures. In contrast, the manual bibliometric analysis was conducted by analyzing the bibliographic data of a small number of focused studies using classification and categorization methods instead of using data analyzing software applications. The results of the manual bibliometric analysis are presented in a categorized table.

Table 1 Structural design of the study

Urban Expansion of Energiewende in Germany Relating to its climate neutrality target					
Search and Analysis Strategy					
Step	1	2	3	4	Discussion & conclusion
Goal	Background research	Current issues research			
Type	Bibliometric Analyses & Results (Stage 1)			Dedicated study & fndings (Stage 2)	
Tool	Visual bibliometric analys 1	Visual bibliometric analys 2	Manual bibliometric analysis	Desk research & literature review	
Math	Quantitave & qualitative review & results			Qualitative review & results	
Data	Datebases on Energiewende Scopus and ScienceDirect			Datebases on Urban Expansion Scopus, ScienceDirect & Internet research data	
Issues	History: Success & Role Model	Challenges and solutions in general		Urban expansion as a solution	
Period	1982-2022	Recent studies since 2013			
Focus	Growth of studies	Energiewende in general	German Energiewende as a focus		
Purpose		Urban expansion as knowledge gap		German urban expansion as a focus	
Number	1125 studies	444 studies	40 case studies	40 case studies & 100+ pertinent local data sources	
Forensis	The growth of studies	High-frequency keywords, o-occurrences & clusters	German national and urban energiewende Issues		
Results	Annual & Cumulative numbers (**Figure 1**)	Co-occurrence & cluster network map (**Figure 2, Figure 3**)	Findings and knowledge gap (**Table 2**)	Findings and limitations (**Table 3**, **Figure 4**, **Figure 5**)	
Criteria Recognized terms in academic literature and internet data					

The first visual bibliometric analysis used the research data generated using the search string of "Energiewende" OR "energy transition" OR "energy transformation" in Scopus and ScienceDirect. The initial search generated 1225 results published in the period from 1982 to 2022. The bibliometric analysis of these search results was intended to generate a dynamic picture of the growth in the research on *Energiewende* in its entire research period. The primary aim of the initial bibliometric exploration was to generate an overall picture of the growth of the research on energy transition as both background information and research gaps for the present study.

The second visual bibliometric analysis used the filtered data of published articles in the more recent shorter rapidly growing period of 2013–2022. This narrow bibliometric exploration aimed to show the thematic network of the research on the transition in the recent period, in which the transition displayed substantial achievements but also faced significant challenges. The purpose of this step of investigation was to see if the existing research had addressed the challenges of *Energiewende,* such as its slowdown, and if urban expansion had been recognized as a solution to the challenges.

The third manual bibliometric analysis further filtered the research data into 55 studies on the recent *Energiewende* performance in Germany and, more specifically, in German cities, such as the increased role of municipal governments, the municipalization of city utilities, the urban solarization rates of rooftop PV installations and solar thermal heating installations, as they relate to this paper's main topic of urban expansion of *Energiewende* as a solution to its challenges in the current period.

Following the first-stage exploration with three bibliometric analyses, the data search for the second stage of investigation (i.e., detailed and focused study) included, in addition to studies presented in the last manual bibliometric analysis, both additional available scientific publications and reports, as well as raw data from the German

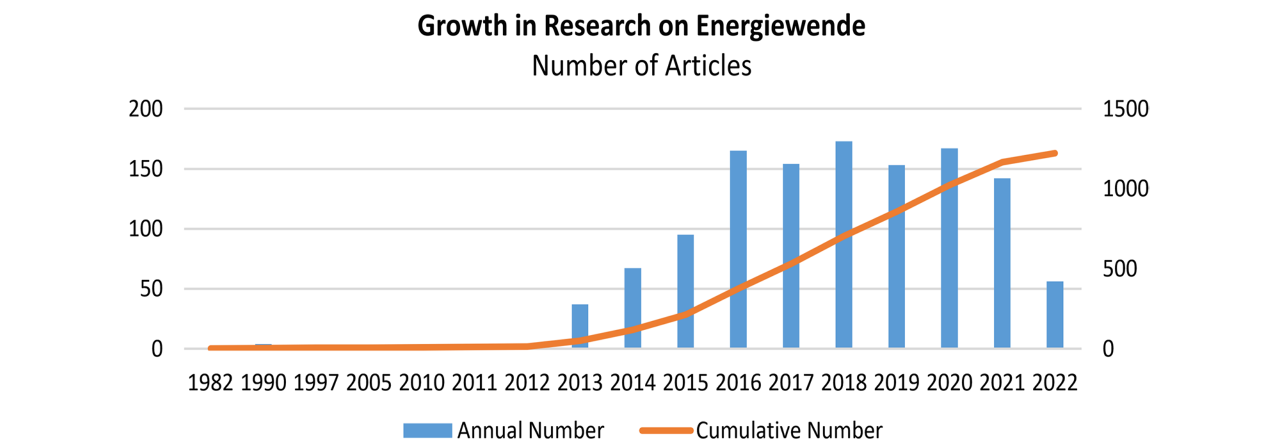

Fig. 2 Annual and cumulative growth of research on Energiewende (cumulative: 1225)

national and federal statistical offices, government data, as well as related studies, analyses, statistical data from other sources, such as government documents, reports, press releases, and news articles by intergovernmental and nongovernmental international organizations—such as the International Energy Agency, International renewable energy Agency, and REN21—and German federal and municipal governmental agencies and nongovernmental organizations—such as the German Parliament, German Federal Ministry of Economy and Climate Protection, Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE). For the latter to be considered in the study, the data needed to fulfill the following two criteria: (a) relevance to the objectives of the *Energiewende* in urban areas (i.e., primarily expansion of renewable energy and climate neutrality) and (b) availability of a time series to cover the relevant period of change (i.e., between 2016 and 2021). Following the search, the available data were screened for relevance, adequacy, and completeness. The material selection was focused on the political, socioeconomic, and technological changes and developments taking place in the urban areas aimed at helping the reader gain academic knowledge of the viable solutions that are taking place now and will take play in the future.

Results

This section presents the results of the two-stage data collection and analysis of the research on *Energiewende*, which includes (1) two visual analyses, (2) a manual bibliometric analysis, and (3) a critical review.

Visual bibliometric analyses

The two visual bibliometric analyses generated three datasets, which are presented in the three bibliometric figures. Figure 2 shows the results of the first visual bibliometric analysis. They provide the reader with the temporal information on the dynamic research development since 1982, showing that the research on this topic was dormant in the first 20 years, but it took off in 2013, has presented a rising trend since then, and reached cumulatively 1225 as of March 27, 2022.

The other two figures show the publishing venues and the topics of the 444 selected journal papers. Figure 3 shows that journals on energy, environmental sciences, social sciences, and engineering make up approx. 70% of the publishing venues. Figure 4 illustrates a map of the thematic systems of the research topics surrounding *Energiewende* with "Germany" as the geographic locus and "RE" and "energy policy" as subthemes of the narrative, further interwoven with other related details of the storyline of energy transition. Although the three visual bibliographic analyses show a comprehensive picture of the research on *Energiewende* in the entire research period and in the shorter period since 2013, none of them shows the wanted information on the workable solutions for the challenges to the energy transition in Germany or the urban expansion to this transition.

Manual bibliometric analysis

The third analysis, a manual bibliometric analysis, generates a classification of 54 studies that are focused on issues related to German Energiewende either at the national level or the municipal level. These studies were collected using the search string ("energiewende" OR "energy transition") AND ("german").

The results of the manual bibliometric analysis are shown in Table 2. Among these studies, 37 address various issues related to energy transition in German cities.

The resulting data show the following features:

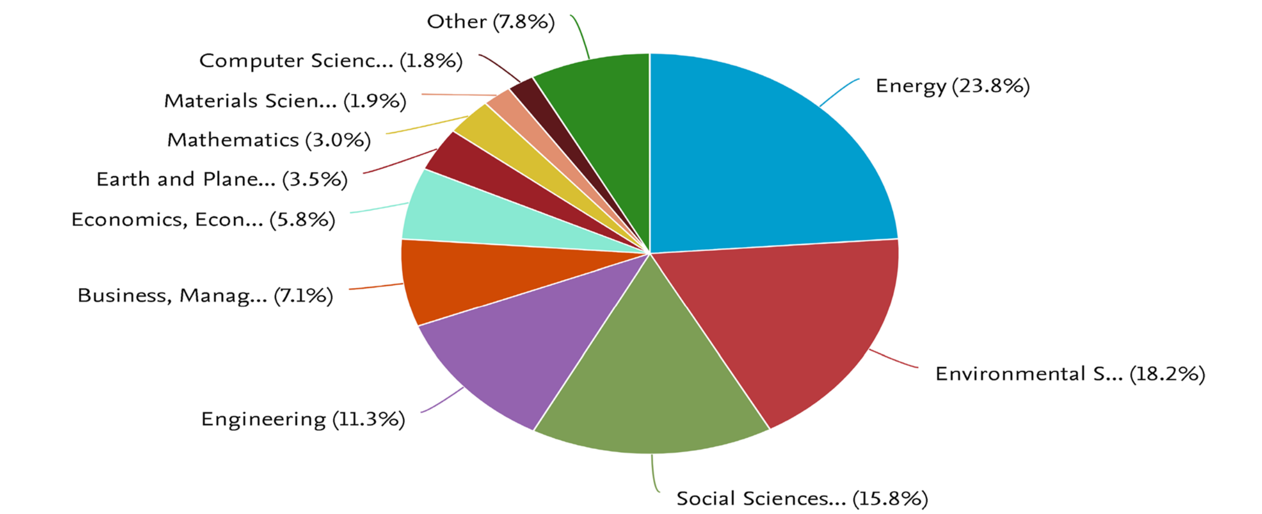

Fig. 3 Journal by subject areas

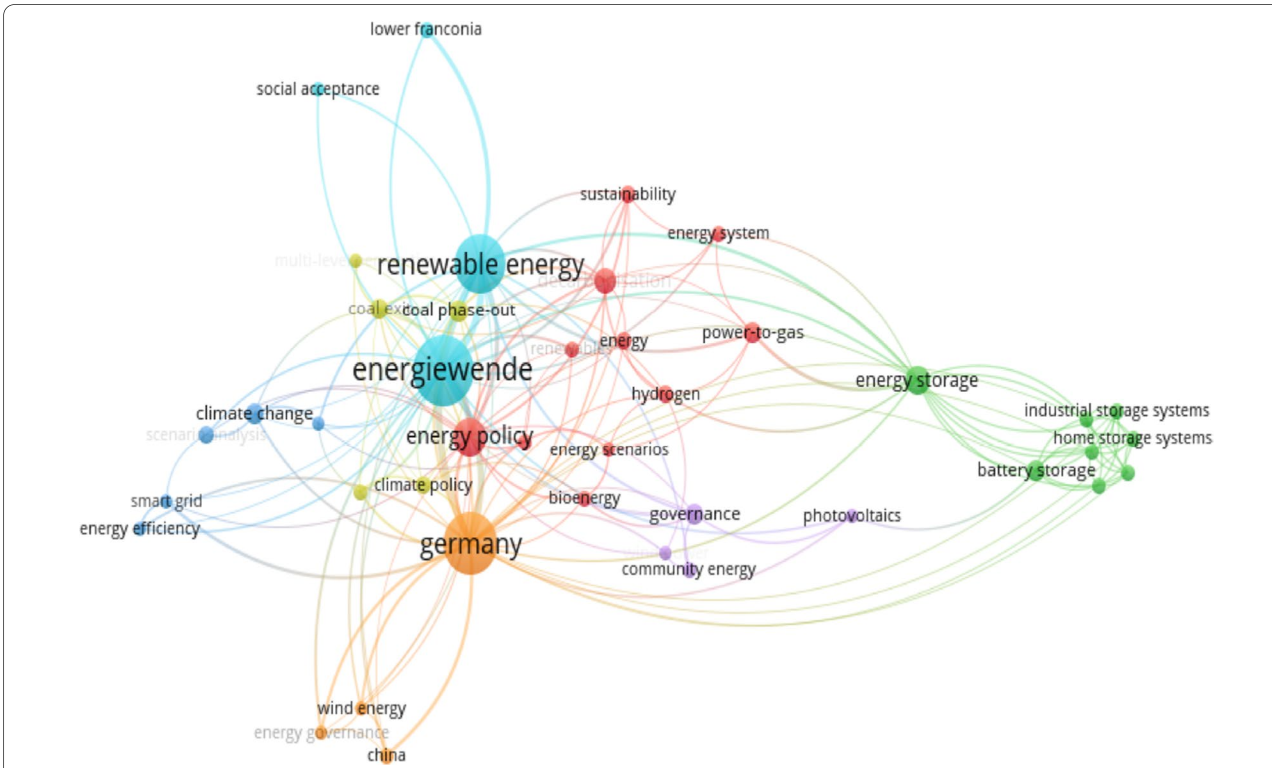

Fig. 4 Topics of the studies of selected 444 studies since 2013

a. Approximately 31% of the studies deal with issues relating to the national-level energy transition in Germany, and 69% of the studies are case studies on city-level renewable energy initiatives lowering carbon emissions in Germany.

b. While the national-level studies explore more general and conceptual issues—energy transition pathways and strategies (such as solar power agency and initiative design [18, 19], climate protection strategy [20]), policy and technical innovations (such as virtual

Table 2 Studies on German *Energiewende* [43]

Authors	Field	Issues	Country/city	Urban expansion specific?	Date of publication
Bulkeley, Betsill [32]	Urban politics of climate change	Urban governance of climate change	Partly Germany	Yes	2013
Hall et al. [33]	Utility ownership	Remunicipalization of power sector	Partly Germany	No	2013
Burger et al.	Energy market	Disruption of utility, challenges	Germany	No	2014
Galvin, Gubernat	Rebound effect studies	Effect of energy efficiency on increased energy consumption	Germany	No	2016
Truffer et al.	Technology assessment	Electric mobility	Germany	No	2017
Loßner et al.	Economic assessment	Virtual power plants in the German energy market	Germany	No	2017
Centgraf	Civic engagement	Human scale development approach supporting civic engagement—German energy cooperatives	Germany	No	2018
Leiren, Reimer	Renewable energy policy	policy shift from feed-in tariffs to auction	Germany	No	2018
Weiss et al.	Energy market	Disruption of utility business models in the "prosumager-world, digitalization, decentralization, and decarbonization	Germany	No	2019
Busch-Geertsema et al.	Climate strategy analysis	German transport	Germany	No	2019
Arning, Ziefle	Public actor survey	Anti-decarbonization efforts and the pro-diesel protest movement	Germany	No	2020
Bosch, Schmidt	Social study of energy transition	Inequalities and injustices of the German *Energiewende*	Germany	No	2020
Fabianek et al.	Green power	Electric vehicles	Germany	No	2020
Leonzio	Technology assessment	Power-to-gas plant	Germany	No	2020
Pinker et al.	Actions and politics	Energy initiatives and the politics of regulation	Partly Germany	No	2020
Sturm [34]	Politics, policies, paths study	Challenges and drawbacks of energy transition	Germany	No	2020
Günther et al.	Tariff, capacity investment	Prosumage	Germany	No	2021
Morlet, Keirstead [35]	Business, economics	Lowest cost technology pathways to achieve emission reduction targets	Berlin	Yes	2013
Bulkeley et al.	Climate justice	Climate justice focused on urban climate change actions	German cities	Yes	2014
Fuchs, Hinderer	Renewable energy governance	Local renewable energy governance	Berlin	Yes	2014
Mainzer et al.	Technical potential assessment	Technical potential for residential-roof-mounted photovoltaic systems in Germany	All 11,593 German municipalities	Yes	2014
Blanchet	Urban struggle over energy transition	Grassroots initiatives affect local energy policymaking	Berlin	Yes	2015
Mattes et al. [36]	Business	Energy transitions in small-scale regions	Emden and Bottrop	Yes	2015
Moss et al.	Energy politics	Role of environmental groups in remunicipalization of grids	Berlin	Yes	2015

Table 2 (continued)

Authors	Field	Issues	Country/city	Urban expansion specific?	Date of publication
Urbaneck	RE cogeneration pathway study	Solar district heating	East Germany	Yes	2015
Viétor et al.	Barrier study	Decentralized combined heat and power	Ruhr Valley	Yes	2015
Becker et al.	Actor study	Influence of social movements as actors in urban energy politics	Hamburg and Berlin	Yes	2016
Beermann, Tews	Actor study	Reinvention of the local RN initiatives	Local renewable energy initiatives	Yes	2017
Saighani, Sommer	Regional transport market	Renewables for regional transportation	Northern Hesse	Yes	2017
Münzberg et al. [37]	Vulnerability assessment	Responses of German disaster management system to power outage	Mannheim	Yes	2017
Brummer	Expertise, social capital, and democracy	Organizational governance and decision-making	Renewable Energy Cooperatives	Yes	2018
Busch et al.	Local climate governance	Transnational municipal climate networks (TMCNs) impact local climate governance	Seven German cities	Yes	2018
Dunkelberg et al.	Low-carbon heat supply	Low-temperature district heating system	Berlin	Yes	2018
Fastenrath, Braun [38]	Sustainability transition pathways	Energy-efficient buildings	Freiburg	Yes	2018
Frank et al. [39]	Policy mix	General innovation policy criteria	727 middle and large German municipalities	Yes	2018
Hellweg [40]	Case study	Building energy efficiency	Wilhelmsburg	Yes	2018
Hirschl	Climate strategy analysis	Conflict between carbon neutrality needs and actual politics	Berlin	Yes	2018
Köhrsen	Innovative approach to energy transition	Urban energy transitions as social fields	Emden	Yes	2018
Mahzouni	Sustainability transition pathways	Urban brownfield redevelopment and energy transition pathways	Three city districts in Freiburg: Rieselfeld, Vauban, and Gutleutmatten	Yes	2018
März [41]	Spatial multi-criteria decision analysis	Fuel poverty vulnerability of urban neighborhoods	Oberhausen	Yes	2018
McKenna et al. [42]	Local preference for governance	Feasible energy concepts in small communities	A community in the southwest of Germany	Yes	2018
Weiß	Implementation approach study	Building heating	Municipalities	Yes	2018
Jenniches, Worrell	Energy economics	Positive economic and environmental impact of solar PV	Aachen Region	Yes	2019
Brown et al.	Actor study	Prosumer		Yes	2020
Cheung and Oßenbrügge	Transition pathway	Urban energy transitions	Hamburg	Yes	2020
Moss and Francesch-Huidobro	Urban energy transitions	Urban energy autarky	Berlin and Hong Kong	Yes	2020
Pohlmann and Cole	Utilities policy	Community energy movements	Berlin and Hamburg	Yes	2020
Tschopp	Technological pathway study	Large-scale solar thermal systems	Denmark, China, Germany, Austria	Yes	2020
Broska	Sustainable community action	Social capital, social needs, and environmental concern in sustainable community action	Communities	Yes	2021

Table 2 (continued)

Authors	Field	Issues	Country/city	Urban expansion specific?	Date of publication
Byrne	Urban transport assessment	Resident mobility behavior	Hamburg	Yes	2021
Otto et al.	Municipal climate policy	Adaptation readiness	104 German cities	Yes	2021
Wagner et al.	Ownership of utilities	Municipal utilities in Germany	Approximately 900 Stadtwerke	Yes	2021
Dorst et al.	Barriers study	Urban nature-based solutions	urban Germany	Yes	2022
Quitzow	Decentralized grid, prosumage	Smart grids, smart households, smart neighborhoods	Berlin	Yes	2022

power plants [21], power to gas plant [22]), actors (such as civic engagement [23], anti-decarbonization movement [24], energy market analysis [25]), and impacts (such as energy poverty [26], rebound effect [27]), the city-level studies investigate more locational issues such as urban energy transition pathways [28], urban municipal governance [29], resident mobility behavior [30], the discrepancies between the municipal carbon neutrality ambitions of the investigated cities and their diverse actions either driven or constrained by their climate protection politics [31].

While the visual and manual bibliometric analyses combined show both a general picture of *Energiewende* research and a more detailed landscape of this research at the national and city levels, they also reveal a significant knowledge gap on the challenges and solutions of the German energy transition and the urban expansion of *Energiewende*. More specifically, the bibliometric analyses show that there is no resolute, in-depth study that focuses on the new challenges to *Energiewende* and explores the new trend of its urban expansion. However, the manual bibliometric analysis of the municipal and urban level studies does reveal interesting findings of both weaknesses and strengths related to the urban expansion of renewable energy deployment.

Critical review

The results of the above three bibliometric analyses reveal not only general background information on *Energiewende* but also a notable knowledge gap on the challenges to the energy transition and the potential solutions to these challenges. This revelation indicates a logical need for a dedicated study on the recent challenges and solutions to the German energy transition. Such a study is needed to identify the existence and trend of the urban expansion of renewable energy, especially the use of solar PV and heating or the "solarization" in the German cities, and the role this expansion might play to tackle the challenges to the transition.

In the following, this paper will review, analyze, and synergize the findings from the studies presented in the manual bibliometric analysis of the selected studies, especially those focused on urban municipal energy transition. At the same time, it will explore additional relevant academic studies and research materials from reputable renewable energy R&D and official sources to trace the trend of energy transition in German cities. By presenting and examining the data and research findings on urban expansion, this study aims to bridge the knowledge gap of challenges to the energy transition and investigate whether the urban expansion of *Energiewende* can play a vital role in counteracting the difficulties in and barriers to the energy transition.

Urban expansion of Energiewende as a solution

The detailed analysis of the results from the manual bibliometric exploration of journal papers, as well as other academic studies and research materials, reveals that bringing RE into cities has been a new trend, focus, and strategy of *Energiewende*; the widening and deepening of the energy transition counteracts the challenges presented and analyzed above, and German city and municipal governments, municipal utilities, and urban residents and businesses have increasingly become a new driving force in the transition. Many research papers and case studies based on expert interviews, documents and data analysis also reveal that this new trend does not come from nowhere but benefits from *Energiewende*'s historical achievements of socioeconomic, political, and environmental movements [44, 45].

Urban socioeconomic, political, and environmental movements

The grassroots movement of climate protection in Germany allowed municipal governments to play a more key role in *Energiewende* by creating favorable climate commitments to RE transition and climate protection strategies. The policy data show that 62 German city governments have 100% RE consumption targets, and 17 of them have already reached their targets [46].

Like 61 other German cities, Frankfurt has a master plan of climate change mitigation to reduce its energy demand by 50% from 2010 level by energy savings and energy efficiency by 2050 and then cover the remaining 50% energy demand entirely by RE sources, namely, 25% from the city and 25% from the region [47]. Recently, Frankfurt, Darmstadt and Gießen set the target of climate neutrality by 2035 [48]. The city of Mülheim was among the 411 cities worldwide that issued climate emergency declarations in 2020 alone. A total of 1200 residents in Münster helped the city draft its climate master plan targeting a 95% reduction in greenhouse gas emissions by 2050 [49]. The urban expansion of *Energiewende* also has the backing of the municipal fiscal authority and capacity. In contrast to their counterparts in other European countries, municipal governments in Germany are entitled to a share of the income tax and VAT according to the constitutional tax equalization principle [50]. They have the authority and capacity to control their own revenues and to provide grants, loans, and subsidies to support the decarbonization of urban systems.

Greater municipal fiscal autonomy and capacity in the governance structures allow local governments, more commonly in Germany than in other European countries, to participate in the energy transition and set municipal RE targets [51]. Using this authority and capacity, German city governments used their own funds to finance infrastructure projects, with federal and state government allocations and other earmarked funds [52]. Only approximately 20% of funds for local infrastructure in Germany came from borrowed money, mostly bank loans [53]. For example, the cities of Freiburg, Berlin, Braunschweig, Jena, Stuttgart, and Wallenhorst provided subsidies to fund new energy storage systems [54]. German city and municipal governments have become a new driving force in Germany's energy transition [42, 55].

More importantly, the new trend of urban *Energiewende* is associated with remunicipalizing or working with local utilities. Many German city governments, such as that in Munich, own their own utilities called *Stadtwerke* in German. These local government-owned utilities expanded in Germany from approximately 152 established between 2005 and 2016 to approximately 900 today. *Stadtwerke* were considered a successful model, as they have greater control over their energy sources and can provide renewables to their residential customers directly [56].

Although the *Stadtwerke* might be financially not as influential as their larger national or private counterparts, they might be capable of more effectively conducting their customers' demands, such as RE consumption. With the increased role of civic engagement and environmental groups in climate protection governance [57–60], a total of 305 (approximately 80%) of the 369 energy-related (re-)municipalization cases took place in German cities [33, 61]. The residents in Wolfhagen initiated the remunicipalization of the local power utilities in 2012, and the city owned (at 75%, seven seats on the company board) the power company jointly with a resident cooperative (at 25% along with two seats on the company board) by 2020 [62].

Residents in Heidelberg and Munich are working with their municipally owned utilities to achieve RE targets [63, 64]. For example, Munich's SWM is a coowner of the DanTysk offshore wind farm, which is helping the city achieve its target of being fully powered by renewable sources by 2025 [65]. Its innovative *M-Sonnenbausteine* project effectively attracted "climate aware" residents to participate in investments in installing rooftop solar PV equipment on available rooftops of the city, which not only contributes to the expansion of the solar generation capacity in the city but also helps residents become solar producers and consumers, or "prosumers", who can increase both their wealth and their solar power consumption even if they do not have their own rooftops to do so [66].

It is important to see the connection of this new trend with a major portion of the actors of the early *Energiewende*, i.e., rural households and small businesses as producers and consumers of RE, especially solar power [67]. In urban expansion, urban residents, mostly tenants and landlords, started to join the ranks of solar prosumers or "prosumagers" [68], i.e., grid-connected producer and consumer of renewable energy with energy storage, and the members of environmental and climate protection groups are no longer only sociopolitical actors but have also become environmental, economic, and technological actors of *Energiewende* [69] and are increasingly making it an urban community energy movement [70]. Different from community energy projects in the United States, where the power utilities or third-party providers sell "shares" to local consumers, the German community energy initiatives are driven by the feed-in tariff (FIT) incentivized, homeowner and community solar power projects [71]. In the first 20-year German *Energiewende* period, 120,000 RE prosumers [72] emerged and grew by benefiting from the RE FIT, and RE owned by citizens (homeowners and farmers) made up more than 40% (see Fig. 5) [73].

With an estimated 1750 community energy development projects in 2020, Germany has been a leading country in community energy development [74].

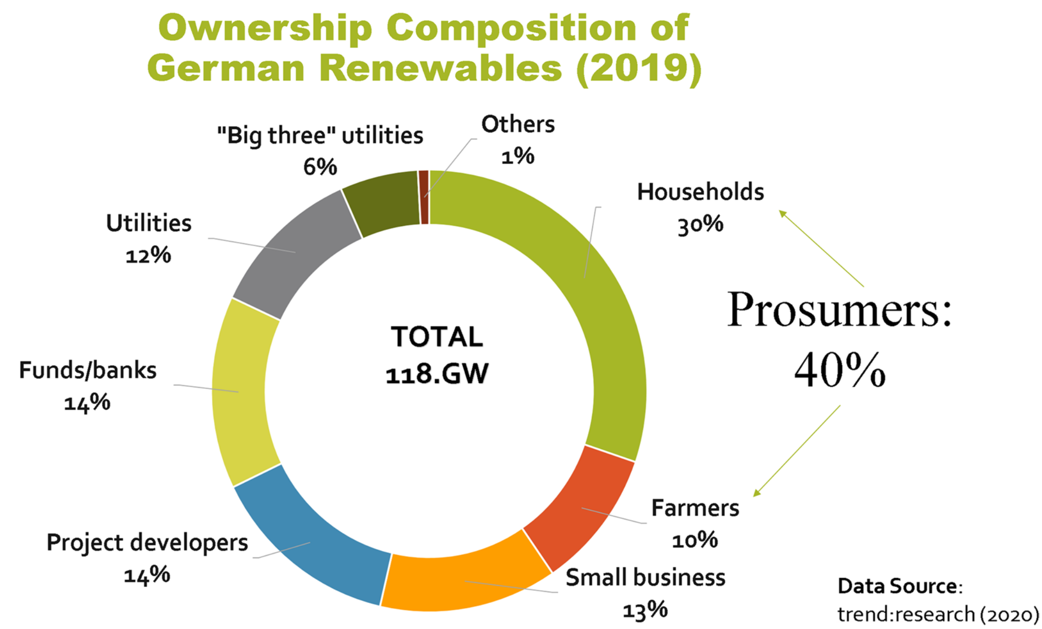

Fig. 5 German renewable ownership 2019

Solarization: PV power generation

The results of the second-stage study also showed that Germany has focused on utilizing its favorite RE—solar PV power—to expand RE deployment into cities. Solar PV power has benefited most in the past 20 years of FIT promotion. Based on the already significantly reduced solar PV costs, German cities started to explore how to advance building-related solar power installation and how to involve most city residents, i.e., the tenants to further reduce PV power generation costs and how to use RE and digitization to decarbonize heating and cooling systems, transportation systems and ports.

To more aggressively facilitate urban *Energiewende*, the largest cities, such as Berlin [75, 76] and Hamburg [77], mandated rooftop solar PV equipment for all new buildings by 2023. A number of German cities have had solar mandates for years, such as Vellmar since 2004, Tübingen since 2018, and Amberg, Constancy, Pfaffenhofen, Waiblingen and Wiesbaden since 2019. [78] Alheim [79], Amberg [80], and Heidelberg [81] planned or passed mandates requiring solar PV in their future city developments, such as rooftop solar power equipment on residential and nonresidential buildings, private and commercial new buildings, roof renovations, and open parking spaces (solar carports/solar filling stations or eco-power filling stations) [82].

In addition, as Germany plans to have a nation-wide solar mandate, many German states passed building integrated solar mandates in 2021. Table 3 shows a summary of the solar mandates passed on new buildings and/or existing buildings for major roof renovations.

Significantly increasing rooftop solar power installation is one of the key indicators of the urban expansion of *Energiewende*. A study by Fraunhofer ISE on the solar potential in Berlin found that using the city's available rooftop space can power up to 25% of city-wide power needs. Accordingly, the city created its master plan to achieve this target by 2045 [86]. Another study conducted by Fraunhofer ISE jointly with Leibniz Institute for Ecological Spatial Development calculated the building-integrated PV potential on rooftops and façades in Dresden and Germany. These data show that fully utilizing this new PV potential, with the further necessary improvement in the architectural integrability and design for PV power generation, is more than sufficient to meet the power consumption demand in the city and in the country [87]. These studies indicate that the urban expansion of building-integrated PV (BIPV) solutions can reduce land use and increase the social acceptance of significantly more actors, including policy-makers, planners, residents, and businesses. In addition, cities can better harness their respective solar potential by creating and introducing supportive policies that create the right enabling environments for investment [88]. For example, Berlin created several RE supporting systems, including a partnership between public and private actors' "Berlin Partner" in the city (1994), an online solar energy map "Solaratlas Berlin" (2013), and a "Solarcity Master Plan"

Table 3 *Solar Mandates in the German States*. Data Sources: Sutter 2020 [83], Wörrle 2022 [84], Solaridee 2022 [85]

State	Law passed	On new buildings	On existing buildings for major roof renovations	Notes
Baden-Wurttemberg	Fall 2021	01/01/2022	01/05/2022	Mainly on business buildings
Bavaria	–	Discussed	Discussed	Mainly on business buildings
Berlin	03/02/2021	01/01/2023	01/01/2023	
Brandenburg	–	–	–	
Bremen	6/10/202	Planned	–	
Hamburg	**0**	01/01/2023		
Hessen	01/08/2021	–	Planned	
Mecklenburg-Vorpommern	–	–	01/01/2025	
Lower Saxony	–	01/01/2022		
North Rhine- Westphalia	03/01/2021	01/01/2022	–	Mainly on business buildings, parking lots Mainly on business buildings, Pm On parking lots business buildings, parking lots
Rhineland-Pfalz	Jul-21	2023	–	
Saarland	9/22/2021	–	–	
Saxony	–	Planned	Planned	
Saxony-Anhalt	–	–	–	
Schleswig–Holstein	06/01/2021	01/01/2022	01/01/2022	
Thiiringen	–	–	–	

(2020) to encourage homeowners to investigate installing solar PV and solar heating systems [89, 90]. The degrees of the cities' solar PV power generation can be observed in the 2019 data collected by the green power supplier Lichtblick, which measures the "solar factor" of a city, that is, the ratio of a city's rooftop areas used for solar power generation and the total rooftop areas of its new buildings (Fig. 6) [91].

Among Germany's 14 most populated cities, Cologne and Leipzig managed to harness half of their available rooftop potential (47.2% and 46.5%, respectively) by the end of 2019, and Essen even achieved the highest solar factor of 63%. However, the largest German cities are still much less successful. Berlin's solar factor was 14.9%, Frankfurt's was 11.8% and Hamburg's was only 10.3% by the end of 2019 [92]. In total, 77% of the potential new building areas in these cities were untapped for solar installation. Another study found that 89% of the solar potential on detached German single- and two-family houses is still unused [93, 94]. However, another technical assessment study found the residential rooftop solar capacity potential in all 11,593 German municipalities to be 148 TWh/a and the installable capacity to be 208 GW_p [95]. According to Fraunhofer energy production data, Germany's renewable energy production was 225 TWh/a in 2021, accounting for 45.6% of the total energy production of 492 TWh/a with a gap to the 100% renewable energy target of 267 TWh/a [96]. The combined analysis of the technical assessment data and Fraunhofer energy production data indicates that utilizing the rooftop solar power potential technically assessed alone would make up 148 TWh/a out of the pending addition of 267 TWh/a, thus more than half the remaining balance to reach the carbon neutral energy generation target.

These studies highlight that solar power expansion in German cities has enormous potential, either through building-integrated, rooftop PV or solar thermal systems. However, they also reveal the hurdles of the urban expansion of *Energiewende*, especially in the largest cities.

Along with the government RE policy switching from government-set FIT to auction-determined FIT, there was also a new policy focus on promoting the growth in city RE prosumers through increased resident participation in community projects, such as tenant solar power programs, and/or municipal or local government-led power projects, such as government-owned utilities [97]. However, landlords of apartment buildings often do not have enough incentives to compensate for the cost of billing, retailing, and metering power to install solar PV units on these houses and let their tenants use it [98]. The German RE Act 2021 raised the level of the tenant power surcharge to exempt landlords from paying commercial taxes to increase the incentive for installing solar PV systems on apartment buildings [99].

The finding of Berlin's solar power penetration was also confirmed by the finding from another survey on the tenants who participated in the city's tenant power program that the current tenant power rooftops made up only less

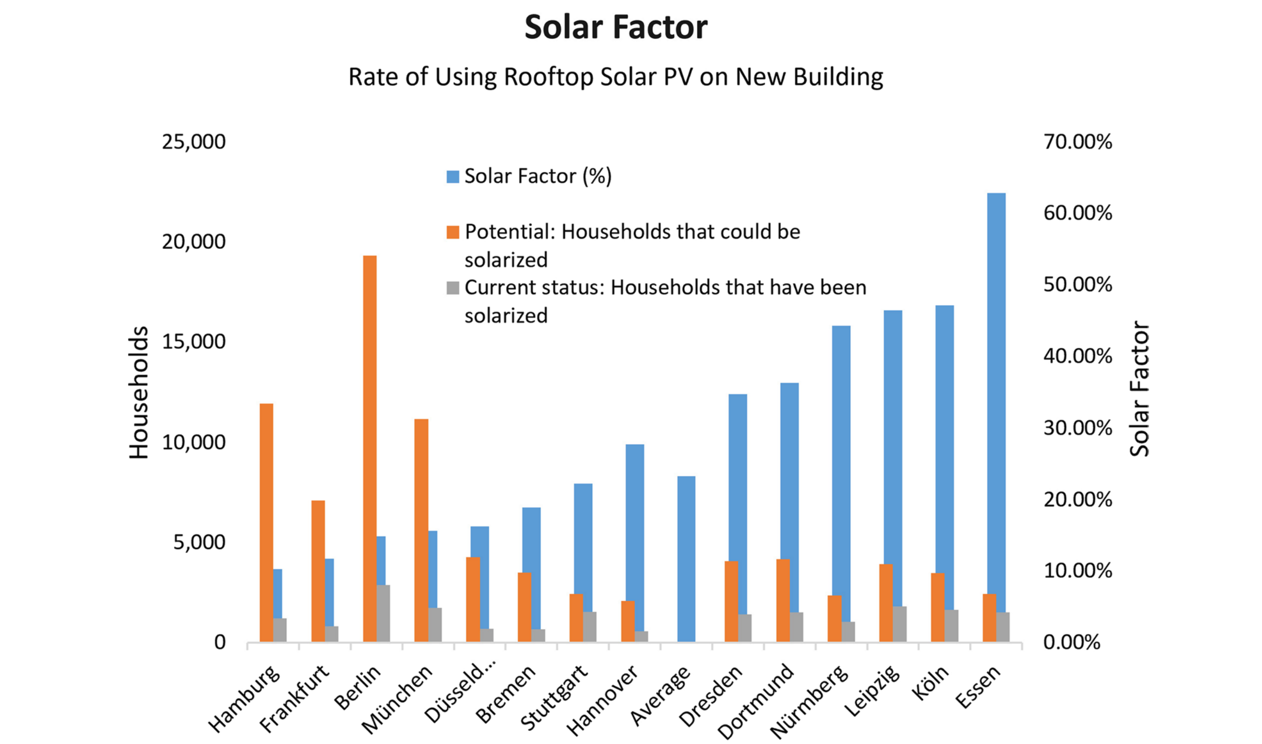

Fig. 6 Solar PV factor on new buildings in Major German cities (Data source: SolarCheck 2021 by Lichtblick)

than 1% of all tenant power potential in Berlin, and the enormous solar potential has rarely been exploited [100].

The main hurdles for large cities to embrace solar PV are the insufficient profitability for operators and the lack of incentives for tenants to become involved under the current laws that promote only large solar installations. Compared with smaller cities, larger cities have a higher ratio of tenants to homeowners, such as 76:24 in Berlin and 72:28 in Hamburg as of 2019 [101]. Surveys showed that the necessary profitability exists for an apartment building with approximately 20 tenants and large rooftop PV systems. However, two-thirds of the apartment buildings in Berlin have fewer than 17 tenants [102]. Well-placed cities, such as Leipzig, Bremen, Dortmund, and Essen, also depended more on large rooftop PV systems—more than half of all new rooftop PV systems in smaller cities were large ones with an output of at least 100 kilowatts, and smaller systems on multifamily houses and business buildings were exceptions [92].

Research found a number of other hurdles for lower success rates of solarization in large cities, including political constraints; limited collaborative governance; lack of required knowledge, data and awareness; low private sector engagement; utility ownership issues (i.e., if the utilities are owned by private companies or municipalities such as *Stadtwerke*), or "biophysical" issues such as roofs on buildings too old for solar installations [103]. These studies indicate that more widespread solar mandates will have a catalyzing impact on the new urban energy transition, but much more supportive mechanisms are also necessary and instrumental, such as promotional government policy, tax credit, and business, banking, market, and technological innovations.

Solarization: solar heating and cooling

Another key indicator in the urban expansion of *Energiewende* is in the effort of decarbonizing urban heating and cooling and increasing the share of renewable heat and waste heat by developing and expanding new low-carbon heating and cooling technologies [104, 105]. This move is important because urban heating and cooling in Germany still largely depend on fossil fuels, and the share of renewable energy in heating and cooling was only 16.5%, despite the share of renewable energy in total power generation of 41.1% in 2021 [106]. To promote the energy transition in urban heating and cooling, Berlin supports the owners of residential buildings in replacing oil heating systems with grants for wood pellet boilers, solar thermal systems, and heat pumps from a total budget of up to EUR 6 million (USD 7.4 million) for 2020 and 2021 [107, 108]. Hamburg has implemented a ban on oil-based heating since late 2021 [109]. Frankfurt

International Airport has also signed PPAs for offshore wind power and solar PV plants to meet their power needs and climate commitment [110].

Data showed that solar district heating systems played a significant role in the German urban energy transition. In densely populated German urban areas, solar district heating (SDH) systems provide thermal energy to residential, commercial, public, and industrial buildings. Six new SDH plants (9.9 MWth) were added in 2019 [111]. By the end of 2020, 41 such plants were operating in Germany, with an installed capacity of 70 MWth, or ca. 100,000 m^2 [112] and a market potential of 20 GWth [113]. Germany's largest SDH plant with 1088 solar heat collectors (approximately 15.000 m^2, 10.4 MWth) has been in operation in Ludwigsburg since May 2020 [114]. The significant expansion in SDH in Germany in recent years has helped the country challenge Denmark, the world's leader in SDH despite its less favorable solar radiation source compared with those of many other countries, including Germany [115]. The combination of a number of factors made this positive change possible, including SDH as a mature, scalable, tested technology capable of decarbonizing district heating for decades; German's need for effective pathways for avoiding the climate crisis; the imminent carbon pricing in Germany in 2021; the government subsidy programs that help upset initial high investment costs; and the long-term low operating costs for SDH systems [116]. Decentralized combined heat and power was considered a cost-effective renewable energy pathway. However, research has found that its uptake and integration are slow because of several blocking factors [117].

District cooling systems were not as extensive as district heating in Germany, and they have also been operational networks for years in some German cities, such as Berlin, Hamburg, and Munich [118, 119]. Munich's geothermal plant would fuel district cooling using the systems absorption chiller—a closed-loop cycle that uses waste heat instead of power to provide cooling or refrigeration—as well [120]. In addition to SDH systems, a variety of other forms of RE technologies are used in the energy transition of urban heating and cooling, such as rooftop solar thermal systems and modern biomass stoves and boilers (fueled by, for example, wood pellets and forestry or agricultural residues, such as bagasse and straw). In addition, renewable power is instrumental to heat or cool with electrically driven appliances such as heat pumps. In urban areas, stand-alone solar PV systems appear increasingly on rooftops, façades and outside of buildings. Stand-alone solar thermal systems with storage-integrated heat pumps are also common for multifamily buildings, such as those new projects in Heilbronn and Regensburg completed in 2020 [121, 122]. The data of the German Solar Industry Association showed that the number of solar heating systems installed in Germany reached approximately 2.4 million by the end of 2019, mostly on buildings, including more than 2000 solar houses [123]. This means that solar energy covered at least half of the heat required for space heating and hot water.

However, the total installed heat network capacity in the industrial and service sectors was still insignificant; only two solar farms existed in this category: a 1330-m^2 system built for the Festo company in 2007 and 477 m^2 for a hospital commissioned in 2012 [124]. The installations of heat network capacity in the industrial and service sector are expected to increase significantly in the next few years, and the total district solar heating is expected to triple between 2019 and 2025 [125] and cover 15% of the total German district heating or a total collector area of 30 million m2 by 2050, which is more than 100 times the capacity in 2020 [126].

Because heating and cooling needs represent more than half of the power demand in Germany, solarization of the urban building heating and cooling systems is a major task for the country to reach its ambitious climate neutrality target. Several studies recommend accomplishing this mission based on the energy efficiency refurbishment of existing private and public buildings and the transformation of district heating systems. For the former test, concerns about historical preservation and social issues need to be addressed. The latter allows for the cost-efficient integration of renewable energy and waste heat sources but needs to modify operating conditions and, in some cases, network structures [127]. Since both retrofitting existing building heating and cooling systems and expanding large-scale SDH with heat storage are found to be mature, economical, and transferrable technologies in German and international studies [128], the solarization of district heating might significantly help German cities meet their carbon neutrality targets.

Green transportation

Green electrification of transportation emerges as another key indicator of the urban expansion of *Energiewende*. Different from most other cities with e-mobility targets that do not link them directly to renewable power, Hamburg is among the few cities that have adopted separate targets for e-mobility and renewable power. It has pledged to procure only zero-emission buses since 2020 [129]. The Marburg-Biedenkopf district provided financial support to the installation of electric vehicle charging stations and to set the requirement that the power supplied to the stations must be renewable. Many cities in Germany have announced bans on circulating diesel vehicles in their jurisdictions [130]. Since

2020, diesel cars up to the Euro 5 emission standard have been banned on certain roads in Stuttgart and Berlin [131].

Since 2019, new electric buses have circulated in Hamburg, and it will go 100% electric for its bus fleet and order 530 new electric buses by 2025 [132]. The world's first hydrogen filling station for passenger trains in Bremervörde, Lower Saxony. Began construction in late 2020, with the hydrogen to be produced on-site using renewable power [133]. The world's first hydrogen-powered passenger trains, produced by France's Alstom, are evaluated on regional/interurban systems, and will start to operate in Lower Saxony in March 2022 [134, 135]. According to the expert interviewees' advice, all these decarbonizing initiatives, renewable energy regulations, and financial support guidelines for urban development and transportation can be seen as initiative-taking and pioneering [136–138].

In cities with ports and airports, decarbonization also started to take place. The first shore-based wind power supply plant at the Port of Kiel has been in operation since 2019, supplying ferries with renewable power. It adopted carbon neutrality targets and strategies that affect not only port activities, but also the diverse industries often hosted by the port, including shipping, cruise tourism, heavy transport, and power generation [139]. Frankfurt Airport also planned to meet most of its electricity consumption by using renewable sources by 2030, to decrease its annual CO_2 emissions from 170,000 to 80,000 t and to become carbon-free and eliminate all emissions by 2050 [140].

Policy and legislation support

The urban *Energiewende* is also supported by the Grid Expansion Acceleration Act [141], which the German *Bundestag* (federal parliament) passed with the majority support of the CDU-CSU and SPD coalition in 2019. It is a law to accelerate the construction of power grid connections by streamlining and simplifying approval procedures. Despite faster and less complex procedures, the law also provides for early citizen participation in grid infrastructure projects [142]. Germany is planning to commission two long-distance HVDC transmission grids, direct current underground cables with a length of 1160 km, in 2025. Renewable power transmission will help avoid future worsening grid congestion in transmitting northern wind power to southern load centers. The costs for the grid expansion are estimated to be 52 billion euros, up from 35 billion euros in the estimates 2 years ago [143].

Most importantly, Germany has substantially upgraded its carbon neutrality target. According to a Supreme Court ruling that the current federal government's climate action targets are insufficient and need tougher updating for climate protection, the German government announced a 65% emissions reduction by 2030 and climate neutrality by 2045.

Discussion

Energiewende is an iconic example of Germany's leadership in global action against climate change. However, with the slowdown of German RE development in recent years, the German leadership has been questioned. To investigate the causes for the deceleration of *Energiewende* and the solutions to the related challenges, this study conducted a three-step bibliometric analysis and a focused critical review of research papers, data, documents, and reports published after Germany's shift from FIT-based promotion to auction-based market competition. The findings on the emergence, performance, hurdles, and perspectives of the urban expansion of energy transition in this study were based on the existing research on *Energiewende* and climate protection, i.e., more than 70 papers on *Energiewende* in Germany published in reputable socioeconomic and energy-related academic journals as well as German municipal and federal governments and international organizations. All sources and references have been validated for accessibility and reliability. These findings of emerging urban expansion contribute to the existing academic knowledge in German *Energiewende* and climate protection.

By grounding this study on 54 journal papers relating to various aspects of *Energiewende* in general and its urban expansion as solutions to its challenges in particular, this paper contributes to the academic body of literature on governance of, and action on, energy transition and climate change mitigation, especially on its governance and action in cities.

Based on previous research, this study considered three major factors through which the expansion of renewable energy in urban areas has become both necessary and important for addressing the recent challenges of the energy transition: (a) the recent slowdown of renewable energy growth, (b) the urgent need to meet the rising demand for renewable energy and energy efficiency following multiple exits of nuclear and carbon energy, and (c) the urgent need to meet the nation's accelerated climate protection goal.

By analyzing the results from a manual bibliometric analysis and a focused investigation of 54 related journal articles and more than 100 other research materials, including government publications and statistical data related to *Energiewende*, this paper identified the German RE policy switch under Merkel from FIT to auction as the main factor causing major challenges to *Energiewende*, such as market and economic risks, policy uncertainty, red tape, regulation loopholes, and the related slowdown of renewable energy growth in Germany. More importantly, this study also found an emerging yet rising trend of solar mandates for new buildings, old buildings that need renovation, or public facilities in neighborhoods, which require installation of solar PV power and solar heating on building rooftops or in open areas in the German cities. This new trend will play a significant role in solar penetration in German cities, which aim to meet Germany's carbon neutrality target by 2045 [144].

This urban expansion of *Energiewende* manifests in many aspects, including the objectives, structures, pathways, actors, awareness raising, designs, and technological innovations. The detailed research efforts focus on identifying the vast untapped potential on new building rooftops and/or façade areas, in public areas, and even in urban brownfields [145], as well as detached single- and two-family houses in Germany. The recent solar mandates in German cities and states, as well as the federal policy and legislation, support this urban expansion trend by strengthening climate and RE targets.

The urban expansion of *Energiewende* might play a vital role in climate change mitigation and energy transition because urban areas account for 77.5% of the German population [146], and urban residents' readiness for climate change adaptation was found to correlate with the size of the cities they live in [147]. It might also play an exemplary leading role in the global energy transition, as urban areas account for 80% of the global economy, 60–80% of global energy consumption, 75% of carbon emissions, and more than 75% of the world's natural resource consumption, although they only occupy 2% of the Earth's land surface [148]. Synergizing the findings from these studies along with additional relevant material from sources makes the existence, development, and importance of this new trend clear and relevant.

The moves in the urban expansion of *Energiewende* discussed in this paper might have multiple important impacts on the German energy transition, including further significantly reducing rooftop solar installation costs and more quickly expanding Germany's renewable energy penetration and its urban CO_2 emissions. The findings that the large German cities lag in the energy transition and that they have issued solar mandates on new buildings to catch up with the more successfully solarized cities are especially important. Exploiting the vast untapped solar potential of new building areas and/or detached and two-family houses in all cities in Germany, especially most populous ones, are expected to have multiple benefits, including further significantly reducing rooftop and façade solar installation costs, more quickly expanding Germany's renewable energy penetration, and increasing its urban CO_2 emissions.

At the same time, it is important to understand that the sustainability of this new trend needs macroeconomic policy support and the political, financial, socioeconomic, and technological efforts of all actors or stakeholders in German cities—governments, residents, businesses, scientists, engineers, scholars, and educators. Therefore, it is important to observe that German federal support—such as climate protection commitment, targets, mandates, and governance at the federal level—has been strengthened in recent years. Germany has issued a new carbon pricing policy. A major component of the German Climate Action Program 2030 adopted in November 2019 is to set up a new national emissions trading system to cover the transportation and building sectors. The carbon pricing system was launched in 2021 with a fixed per ton CO_2 price system. The initial fixed price will be €25 per ton CO_2 and will rise to € 55 per ton by 2025 [149].

Conclusions

Through a three-stage analysis, this paper identified a knowledge gap on the recent challenges to *Energiewende*, found a new trend of the German energy transition, and answered the research question about whether and how this new trend will play a key role in addressing the issues this energy transition is facing.

The first-stage visual bibliometric analyses of 1225 academic studies published in the period from 1982 to 2022 presented not only an overview of the academic literature on energy transition but also revealed an obvious knowledge gap on the recent challenges that *Energiewende* has been facing since the Merkel administration's renewable energy policy switch from FIT to auction in 2017.

To bridge this knowledge gap on challenges to the German energy transition and search for solutions to those challenges, the second, manual bibliometric analysis of 54 studies found an academic body of literature on the urban governance of energy transition and climate change mitigation. This finding prompted this study to raise its main research question of whether and how the emerging urban expansion of *Energiew[ende* will play a vital role in Germany's future renewable energy transition.

The third critical thematic analysis was focused on answering this main research question. In addition to analyzing and synergizing the findings from the studies presented in the manual bibliometric analysis, especially those focused on urban energy transition, it also explored many other academic and governmental research materials to trace the trend of energy transition in German cities. By examining the data and research findings in academic and governmental studies on urban expansion, this paper bridged the knowledge gap of challenges to the energy transition and found that German municipal governments have started to take major innovative and determined steps to expand *Energiewende* in their cities. These steps include, among others, setting 100% municipal renewable energy consumption targets, expanding solar heating and cooling, decarbonizing urban transportation, and most recently, implementing solar mandates. The solar mandate, which requires all new buildings, old buildings that need renovation, or public facilities in neighborhoods to include solar PV power or solar heating installations on building rooftops and/or façade areas or public areas in the German cities, can be seen as a major step of German cities to help the German energy transition reach the nation's carbon neutrality and renewable energy goals.

In summary, while the visual bibliometric analyses of a large body of academic literature on *Energiewende* found a knowledge gap regarding the recent challenges and solution of the energy transition, the manual visual bibliometric analysis of a smaller number of hand-picked studies and the more focused critical analysis of the findings of these studies and other academic and governmental research generated findings that confirm that the urban expansion of the German energy transition will play a vital role in advancing the transition through the solarization of urban power consumption and satisfying urban heating and cooling needs.

In Discussion, the author further explored the vital role the expansion of *Energiewende* is expected to play in counteracting the difficulties in and barriers to the energy transition, the multiple potential impacts this urban expansion trend will have for the German energy transition and carbon neutrality future, and the financial, socioeconomic, environmental, and technological efforts this urban expansion needs to depend on for its successful implementation.

It is important to point out that despite the two large-scale bibliometric analyses and the statistical data used in this paper, the main portion of this paper, including the third manual bibliometric analysis, is an initial exploration based on qualitative analysis using techno-economic and interdisciplinary approaches. This combination of the quantitative and qualitative approaches in this study was determined by the need to quantitatively identify the knowledge gap on the challenges and solutions of *Energiewende* in a large body of literature on the energy transition and to determine the foundation, causes, and forms of its urban expansion as one of the solutions to its challenges using more qualitative than quantitative academic and governmental research data.

The author hopes that the focus and findings of this paper, especially those on the urban expansion of *Energiewende* as a major solution to its challenges, contribute to establishing a new focus or area for future energy transition research and employing more quantitative approaches, such as correlational, causal-comparative/quasi-experimental, and experimental studies, to more research data sources on energy transition-related issues, such as policy, governance, and action. In particular, the data on the impact of urban solarization—solar PV power and heating and cooling installations on building-integrated rooftop and façade areas and public facilities in cities—on the country's renewable energy and climate neutrality goals and the relationship between urban expansion and the urban policy, governance, and action need to be more accurately, qualitatively, and quantitatively tracked, collected, and studied.

Appendix

Challenges to *Energiewende*

Challenges

This section will analyze the results of the in-depth investigation of academic studies and other research materials and reveal the causes of the slowdown of *Energiewende* and the challenges it faces. The results showed that the slowdown and some other challenges facing the transition, such as increased competition and increased market and planning risks, were directly related to the policy switch from RE FIT incentives to RE competitive auction. At the same time, technological and economic issues, such as insufficient storage and grid technology capacities to stabilize and transmit increasingly dominant intermittent renewable power [34, 37], significantly increased power bills for residents and small businesses also cause socioeconomic challenges such as energy poverty [41] to the transition. [36, 150]

The most important political challenge to *Energiewende* is the policy switch from FITs to auctions. The rapid growth in distributed PV installation and generation has questioned the effectiveness of administratively setting incentive schemes and their costs to governments, businesses, and consumers [35]. As a result, Germany significantly reduced tariff levels, which in turn led to the slowdown of renewable deployment, and the subsequent policy change from FITs to auctions slowed the expansion of RE in Germany [9].

Studies have shown that this policy switch increased market, price, and planning risks for RE technology investments and installations [151, 152]. The number of new community energy projects in Germany peaked in

2011, with 167 initiatives added that year [153]. Since then, changes in national legislation – in particular, a shift from renewables FITs to a renewables auction system – have created increased price and planning risks for RE investments [154] and community energy groups. In 2017, many community wind power projects won in auctions without a permit, which caused them to become failed projects that nevertheless have continued to be built with generous realization terms. As a result, only 14 new projects were added in 2019 [155].

It also posed many regulatory, technical, and methodological challenges [156], such as early loopholes in wind power auctions. Administrative red tapes, such as permission restrictions and delays for onshore wind power, also caused more barriers to the implementation of the German energy transition. The reduced availability of regional development zones, tougher permission requirements and mounting lawsuits by environmental organizations and local wind power opponents caused the permissions to become much restrictive and lengthier, which used to take approximately ten months but now up to two years [157, 158]

Policy uncertainty for solar PV deployment has become one of the main new challenges for solar PV development in Germany since 2020. A draft of the RE Act (the EEG 2021) released in September 2020 proposes that rooftop systems greater than 500 kW compete in competitive auctions capped at 200-400 MW per year starting in 2021, which is substantially lower than the 1 GW deployed in 2019 under self-consumption. There was no auction schedule for utility-scale solar PV systems, nor was it clear if remuneration would be extended for distributed PV expansion beyond the 52 GW cumulative installed capacity cap set by the German government, which the German solar industry viewed as a larger threat than the COVID pandemic [159]. This will cause a contraction in distributed PV and declining PV additions in 2022 [160]. It should be pointed that limiting solar expansion by the Merkel Administration was unappropriated for *Energiewende* because although wind power is the largest RE in Germany and has the largest share in the German power generation (23% in 2021) [161], there is little space for its expansion in cities.

In addition, increased local resistance to onshore wind power projects further complicated the process of energy transition in Germany. Although the onshore wind power projects were supported by the overwhelming majority of local residents (more than 80%), a growing movement of local opponents filed lawsuits on a large number of wind power projects in 10 German states, which included 325 approved or already commissioned projects with a total capacity of 1 GW by the second quarter 2019, representing an increasing trend of shares of all wind power projects in the six years (from 8.6%, 1.5% and 7.5% in 2014, 2015 and 2016 to 37.4%, 32%, and 13% in 2017, 2018 and 2019, respectively) 20% of approved projects. The wind power opponents who filed lawsuits were environment and nature protection organizations (61%), private people (36%), citizen initiatives (14%) and local communities (12%) [162].

On the other hand, the achievements of the energy transition in Germany came about with major new economic and technological challenges. Rising land procurement costs for RE are a good example. Because the land area has become increasingly scarce, the land prices in Germany have risen sharply. Agricultural land prices increased by 174% in Germany in 2018 from 2001, [163] and rising land procurement costs for renewable power installations became one of the increasing obstacles for RE growth. Germany has called for innovative ways to generate renewable power in cities [164]. The tenant power initiative was designed to encourage landlords to install solar panels and offer their tenants cheap, locally produced power. However, this policy was considered by some as a failure in generating the expected financial and political appeal [165]

The rapid energy transition also raises the demand for green power and requires a greater supply of green power to meet this demand. The demand for green power is expected to increase significantly for two reasons. First, sector integration with e-mobility, green hydrogen and heat pumps will increase the use of RE [166, 167]. Second, the energy vacuums caused by a number of energy-related changes also need to be filled. These changes include the closure of the last hard coal mine in 2018, [168] the deadline of the nuclear phase-out by the end of 2022, [169] the ban on combustion engines by 2035, and the planned exit from coal-fired power generation by 2038, [170] as well as climate protection and economic and political urges. All these factors force the conventional power capacities off the grid, [171] but these changes also raise questions about Germany's ability to implement its energy transition and meet its ambitious climate protection objective of carbon neutrality set by its revised RE law 2021.

The most obvious economic and technical challenge is the shortage of storage capacities for intermittent RE. By design, the existing German *Energiewende* mainly relied on grid integration of various RE technologies. However, because of the intermittency of the solar and wind energy sources and increasing share and relevancy of RE in the total energy mix, Germany needs significantly more large-scale energy storage capacities to ensure the stability, efficiency and affordability of the RE supply. The current insufficient RE storage capacities constitute a major challenge to the increasingly dominant intermittent renewable power deployment in Germany and caused the ironic contradiction between the decreasing RE costs and increasing higher power bills for consumers and small businesses. The energy storage capacity building is still at the initial stage, with the exception of pumped-storage facilities, which are geographically limited. Accumulators are available but still too expensive, and their capacity is too limited. There is an urgent need for research into completely new types of energy storage devices with potentially novel materials, physical, chemical characteristics." [34]

Decommissioning or depowering older turbines built in the early stage of the energy transition in Germany also poses a new challenge. Germany's annual wind capacity growth continued to decline in 2020 because of the decline in offshore wind projects created during the policy switch from FITs to competitive auctions. At the same time, the decommissioning of early projects that have reached the end of their 20-year FIT incentives also cast a major uncertainty on Germany's wind capacity development. In the first half of 2020, 84 MW was taken offline, an amount that could rise further in the second half of the year [172].

Another obvious economic and technical challenge for the *Energiewende* is the inadequate power grid capacity. In Germany, wind power generation is concentrated in the north,but the load centers are located in the south. The high volume of long-distance transmission causes congestion in power grids. To circumvent congestions, the power to be transmitted to the south needs to take detours on the grids of neighboring countries, such as Poland, the Czech Republic, the Netherlands, and Belgium [173]. The current temporary solution of this bottleneck issue also affected the grids of its neighboring countries [174]. The current power transmission capacity will become even more inadequate to transmit wind power from northern Germany to southern Germany to fill the power demand because of the reduced conventional power generation after the nuclear phase-out (8386 MW until 2022) and coal exit. Additional transmission capacity will be needed between where the renewable power is generated and stored and where power load centers are located but conventional power plants are closed.

Abbreviations

BIPV: Building-integrated photovoltaics; CDU: Christian Democratic Union of Germany; CO_2: Carbon dioxide; CSU: Christian Social Union in in Bavaria; EU: European Union; FIT: Feed-in tariff; GW: Gigawatt; GWth: Gigawatt-thermal; HTW: Hochschule für Technik und Wirtschaft Berlin; HVDC: High-voltage, direct current; MW: Megawatt; RE: Renewable energy; REN21: Renewable Energy Network for the twenty-first century; SDH: Solar district heating; SPD: Social Democratic Party of Germany; SWM: Stadtwerke München; TWh/a: Terawatt-hour per year; VAT: Value-added tax.

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Author contributions

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