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The Quintuple Helix Model: Cooperation system for a sustainable electric power industry in Mexico

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Introduction: Achieving an energy transition in the power industry in Mexico is a complex task. Despite being one of the most promising countries in Latin America and the world for developing wind and solar photovoltaic energy, energy and climate change efforts are insufficient; therefore, changes are generated slowly and leisurely. This article attempts to make a proposal based on the Quintuple Helix Model as an analytical and decision-making framework to encourage the production and consumption of clean/renewable electric energy and reduce GHG emissions. It proposes the sum of strategic interactions to promote a cooperation system and knowledge transfer, know-how, and innovation through the active and committed collaboration of government, academia, industry, civil society, and the environment to achieve the sustainable development of the electricity industry in Mexico.

Methods: These hypotheses are the result of the development of a singular methodology based on Partial Least Squares (PLS), according to Structural Equation Modeling (SEM). The results point out that the five-helix approach is valid to solve the energy transition problem in the electricity industry in Mexico.

Discussion: Although it is not fully developed and consolidated, it can be replicated in scenarios with similar socioeconomic characteristics. Furthermore, the government is the most opportune intermediary driving agent for the development of the energy transition in the electricity industry, since it is the one that can lead and drive the energy transition process by modifying the electricity sector through structural change in the energy market.

KEYWORDS

energy transition, electric power industry, Quintuple Helix Model, renewable energies, sustainable development, climate change

1. Introduction

Global social and economic development dependent on carbon-fossil fuel consumption generates excessive greenhouse gas (GHG) emissions, causing climate change and global warming (Chapman et al., 2018; UNEP, 2021). It negatively impacts lives, ecosystems, livelihoods, health, the economy, services, and the infrastructure of society (IPCC, 2014). CO_2 emissions from electricity generation due to the burning of coal, oil, and gas make up a large share of overall GHG emissions driving the increase in global average temperature (Knaut et al., 2016). According to United in Science (2019), the scientific community estimates the global average temperature is 1.1°C above pre-industrial times (1,850–1,900) and 0.2°C higher than the period between 2011 and 2015 as a consequence of climate change and global warming. It is considered that the most important challenge facing humanity in the 21st century is to solve the problem of global warming through energy transition mechanisms (Miller et al., 2013).

The energy transition in the electric power industry requires a transformation of energy sources, technologies, production and consumption methods, actors, values, and governance (Huh et al., 2019). The electricity sector needs to change from a centralized to a decentralized system, where large companies are replaced by multiple small-scale generation and electricity networks (Defeuilley, 2019). Accordingly, the energy transition in the electric power sector is a change process that must simultaneously achieve multiple goals, such as decreasing GHG emissions from electric power generation; increasing the amount of electric power production from renewable sources; decreasing the price of electricity; achieving relatively simple, stable, and sustainable universal access to electricity; and providing a regular and permanent supply of electric power (Araújo, 2014; Singh et al., 2019; IRENA, 2020; World Economic Forum, 2021).

Mexico has the fourth largest share of fossil fuels in the energy matrix of the G20 countries, despite ranking third for the lowest electricity demand among them (Fulghum, 2021). It is one of the Latin American countries with the highest GHG emissions (Sánchez et al., 2018) as 75% of its electricity comes from fossil fuels (Fulghum, 2021). For Mexico, reducing GHG emissions and encouraging clean/renewable energy production and consumption is a priority. It is essential to reduce the vulnerability of its population, ecosystems, and infrastructure to climate change. Its geographic location in the tropics and between two oceans, as well as the poverty of its population make it highly sensitive to hydro-meteorological phenomena such as hurricanes, droughts, and landslides derived from the increase in temperature (INECC SEMARNAT, 2018). On the other hand, its geographical position and meteorological, topographical, and hydrological conditions make it one of the most promising countries in Latin America and the world for the development of wind and solar photovoltaic energy (SENER, 2016; IRENA, 2019b).

Likewise, Mexico is part of the international community that seeks to combat climate change, so it has signed international agreements such as the Sustainable Development Goals (Goal 13) and the Paris Agreement. In the latter, it ratified international commitments, therefore it is obliged to reduce 22% of GHG emissions by 2030 unconditionally and 36% conditionally. At the national level, given the relevance of the electricity sector in mitigating climate change and the fact that Mexico has a large number of renewable resources, in 2015 the Energy Transition Law (LTE) was published. It established as a goal a minimum participation of clean energy in the generation of electricity of 25% by 2018, 30% by 2021, and 35% by 2024 (Honorable Congreso de la Unión, 2015). It also generated a new regulatory framework to regulate the sustainable use of energy and allow all participants in the sector to coordinate long-term efforts to transition to the use of clean energy and reduce emissions at a lower cost.

Despite the existence of a favorable framework to incentivize the use of clean energy in Mexico, the current government (2018–2024) has proposed a constitutional counter-reform that reverses progress toward the implementation of climate change and energy transition policies. It curbs private investments in renewable electricity generation and the use of solar and wind plants to give dispatch priority to thermal power plants (Cámara de Diputados LXV Legislatura, 2021). This amendment to the Electricity Industry Law aims to return control of the electricity sector to the state-owned company, Federal Electricity Commission (CFE, for its acronym in Spanish) granting it at least 54% of the electricity market, prioritizing its power generation over private companies (Cámara de Diputados LXV Legislatura, 2021). This means that CFE electricity would be dispatched first despite being in most cases of fossil origin and more expensive than renewable energy generated by the private sector. A study published by the National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy indicates that if this constitutional amendment is approved, carbon emissions will increase between 26 and 65%, and electricity generation costs between 32 and 54%, in addition to an increase in power outages (blackouts) of between 8 and 35% (Bracho et al., 2022); hindering the possibility of electricity generation at more competitive prices and less pollution.

Unfortunately, no route has been defined in Mexico to achieve energy and climate change objectives, therefore efforts are insufficient and changes in the energy industry are being generated slowly and leisurely. In this sense, the importance of this work lies in establishing a framework that will contribute to the strategic planning of investments, infrastructure, human capital, programs, and forms of interaction between the public, private, academic, and social sectors, and the natural environment. The aim is to generate a more efficient energy transition process in the electric power industry in Mexico through helix modeling that establishes a strategy that considers the adoption of new forms of energy production and consumption, as well as the attraction of private capital and the transfer of technology and knowledge to meet Mexico's energy needs.

The article sets out to offer a comprehensive approach based on Quintuple Helix as an analytical framework and decision-making for the sustainable development of the electric power industry in Mexico (Carayannis and Campbell, 2010; Barth, 2011; Carayannis et al., 2012, 2017; Taratori et al., 2021). An exploratory model is developed from the relationship of several constructs drawn from the literature to verify the validity of such a model applicable to similar transition processes.

This article is organized as follows. Section 2 briefly discusses the theoretical background of N-Helix Models and the Quintuple Helix modeling as an analytical framework to achieve the energy transition in the electricity sector in Mexico and the application of the methodology based on Partial Least Squares (PLS) according to structural equation modeling (SEM). Section 3 presents the results of the analysis. Section 4 critically discusses the findings. Finally, conclusions and future research lines will be summarized and drawn in Section 5.

2. Materials and methodology

2.1. N-Helix models

Particularly, given the relevance of the electric power industry in the mitigation of climate change and the fact that Mexico has a large number of renewable resources, it is necessary to design energy transition strategies (GREENPEACE, 2020). These should not only encourage environmental care and compliance with international agreements but also promote development, social sustainability, and the wellbeing of its population. In this sense, a helix analysis is highly effective as it fosters economic and social development (Taratori et al., 2021). It integrates industry, academia, government, society, and/or the natural environment as a system to produce science, technology, and innovation through the collaborative work of all agents, where the N-Helix model is a nexus (Guillén, 2018).

The Triple Helix Model identifies three helixes or subsystems: the state (political system), academia (educational system), and industry (economic system), focusing on the knowledge transfer and the interaction between the helixes (Etzkowitz and Leydesdorff, 2000). This model recognizes the importance of academia for innovation, emphasizing the production of knowledge and innovation in the economy, making it compatible with the knowledge economy (Carayannis and Campbell, 2010). The disadvantage it presents is the isolation and marginalization of the social sector (Etzkowitz and Leydesdorff, 2000).

The Quadruple Helix Model emerged when the Triple Helix Model was expanded by adding to the academia-industry-government relations the fourth helix, "media-based and culture-based public" (Carayannis and Campbell, 2009). This helix disseminates knowledge in a nation-state as well as culture with its values, traditions, lifestyles, experience, and visions promoting knowledge for the knowledge society. Civil society is not limited to using and applying knowledge and demanding innovation in goods and services, it is an active part of the innovation system (Barbosa, 2019). Therefore, this model of innovation and social cooperation is an important tool to provide solutions to problems, needs, and society's proposals (Ramirez and Palos-Sanchez, 2018; Robina-Ramirez et al., 2019).

The Quintuple Helix is a five-helix model of innovation that integrates and contextualizes the Triple Helix and the Quadruple Helix by adding the helix of the "environment" (natural environments) (Carayannis and Campbell, 2010). It offers an analytical framework in which knowledge and innovation are linked to the environment, addressing the relationships among government, academia, industry, civil society, and the environment (Carayannis and Campbell, 2010; Carayannis et al., 2012). This model aims to include the "natural environment" as a new subsystem in knowledge and innovation models (Barth, 2011). Environmental or ecological challenges such as global warming and issues related to the survival of humanity, tare drivers of new knowledge and innovations and have the potential to make society, economy, and democracy thrive (Carayannis et al., 2022). "Nature" is established as a central component of knowledge production and innovation, emphasizing the necessary socio-ecological transition of society, economy, and democracy in the 21st century (Carayannis et al., 2012).

This model focuses on the sum of social interactions to promote and visualize a system of cooperation and transfer of knowledge, know-how, and innovation, thus it can be used as an interdisciplinary analytical framework for decision-making and transdisciplinary problem-solving related to sustainable development and social ecology (Carayannis and Campbell, 2010; Barth, 2011). It is a theoretical and practical model offered to society to understand the link between knowledge and innovation to promote living in balance with nature and achieve lasting development, since "the environment should be considered as an active partner of innovation, not as a resource to be exploited" (Carayannis, 2020). It has been used in some projects to boost green employment, growth, and sustainability in the construction industry (Fundación Laboral de la Construcción, 2021), the sustainable development of the energy platform of the Russian Arctic zone (Carayannis et al., 2017), and the creation of remote control and smart metering systems for a water supplying system and social awareness and education on the use of these services (Taratori et al., 2021).

2.2. The challenge of energy transition in the electric power industry in a Quintuple Helix Model

For Mexico, it is crucial to implement a strategy to achieve the energy transition in the electricity industry. This proposal is based on the Quintuple Helix Model to evolve from a state of greenhouse gas (GHG) emissions due to the generation of electricity through the use of fossil fuels to one where electricity generation is carried out through renewable energy sources.

The Quintuple Helix supports the formation of a win-win situation between ecology, knowledge, and innovation, creating synergies between economy, society, and democracy (Carayannis et al., 2012). It can be successfully achieved through the active and committed cooperation of the various stakeholders (subsystems): 1. Political System (Government), 2. Education System (Academia), 3. Economic System (Industry), 4. Media-Based and Culture-Based Public (Civil Society), and 5. Natural Environment. Each of these five helixes (subsystems) has a special and necessary asset at its disposal, with a social and academic (scientific) relevance for its use, as indicated below.

2.2.1. Political system (government)

The political system or government establishes, organizes, and administers the general conditions of the state (nation-state). It formulates the objective of where the state is heading concerning the present and the future through laws, policies, projects, and plans (Barth, 2011; Carayannis et al., 2012; Sánchez-Hernández et al., 2020).

Government support for the energy transition in the electric power industry in Mexico is necessary since it establishes the legal framework, national objectives, and pricing policies, and makes strategic decisions to support the development of renewable energies (Vargas et al., 2016). Consequently, the development of energy policies integrated into economic, industrial, labor, educational, social, and environmental policies in favor of electricity production/consumption from renewable sources is mandatory (Hoekstra et al., 2017; IRENA, 2020). In parallel, financial support is a key factor for the success of renewable energy integration. The government can create the framework and necessary conditions to encourage this type of support and investments from public or private sources for the early stages of technology development, capital, and/or operational costs (Abdmouleh et al., 2015; Liu and Chu, 2019).

Similarly, the government can incentivize renewable energy development by establishing strategic plans and mechanisms such as green subsidies for clean and renewable energy and imposing carbon or energy taxes on conventional energy sources, to modify the levels of fossil energy production and consumption (Abdmouleh et al., 2015; Zhao et al., 2017). This contributes to improving the efficiency of capital allocation in the electricity sector because the externalities (costs imposed on society due to air pollution and climate change) derived from the use of fossil fuels are not fully valued in the electric energy price (Pikk and Viiding, 2014; Taylor, 2020). Likewise, it is of utmost importance to avoid the loss of electricity, which, can be caused by storage, transformation, transportation, and distribution, as well as administrative errors, anomalies in metering, self-connected customers, and electricity theft (Vargas et al., 2016; CEPAL, 2022). In addition, to raise awareness and encourage the participation of the population in the transformation of a low-carbon electricity sector, the government can carry out non-formal education and outreach programs and campaigns on climate change, promote sustainable consumption and the use of renewable energies, at federal, state, and municipal levels (Yanfei and Zhao, 2008; Kuzemko et al., 2016; INECC SEMARNAT, 2018). In accordance with the previous text, H_1 is introduced:

H_1: G-Government -> ET-Energy Transition

2.2.2. Education system (academia)

The education system refers to academia, universities, research centers, higher education systems, and other institutions focused on academic activities and contains human capital, i.e., students, teachers, scientists/researchers, and intellectual capital, that is, knowledge (Barth, 2011; Carayannis et al., 2012). Knowledge is the basis for economic development and social progress; it is crucial for value creation (Wehn and Montalvo, 2018), and technology is the set of knowledge and techniques, which, applied in a logical and orderly manner, allow human beings to modify their environment to meet their needs (Tabares Quiroz and Correa Vélez, 2014). Because of the growing need to reduce GHG emissions from electric power generation, research, knowledge creation, and technology generation are fundamental for making the shift to a sustainable electricity system (FAES, 2018; Lantz et al., 2021; Sandin and Benner, 2022). Universities and research centers are indispensable, as they are the main source of knowledge and technology generation. In this sense, the knowledge and technology transfer between academia and industry is indispensable for innovation as it allows the adaptation of scientific research results to their application in the marketing, sale, and use of goods and services to meet economic and social demands (Miśkiewicz, 2018; de Wit-de Vries et al., 2019; Thomas and Paul, 2019). Within this context, knowledge and technology transfer is a key element for the development of a low-carbon electricity sector (Fernandez Sanchez et al., 2016; Miśkiewicz, 2018; IRENA, 2020).

For its part, the development of human capital is indispensable for the success of the energy transition. In coordination with the government, strategic planning and collaboration between educational institutions and renewable energy industries are necessary for the development of integrated cooperative education, training, and learning systems to reduce mismatches between the demand and supply of skills (Lucas et al., 2018; Maier et al., 2019; IRENA, 2020). Having conveyed the previous ideas, the following hypotheses are explained:

H_2: A-Academia -> G-Government
H_3: A-Academia -> ET-Energy Transition
H_4: A-Academia -> NE-Natural Environment
H_5: A-Academia -> CS-Civil Society
H_6: A-Academia -> I-Industry.

2.2.3. Economic system (industry)

This helix, also called industry, comprises firms, services, and industries, and therefore focuses on the economic or financial capital, that is, money, technology, services, products, etc. of a nation-state (Barth, 2011; Carayannis et al., 2012). The growing energy demand must be accompanied by increased investment in renewable energy to meet this demand, diversify the electricity supply, and thus reduce GHG emissions (Chapman et al., 2018). Energy infrastructure and distribution grid systems require large-scale investment because they are the basis for electrification, capacity expansion, energy flexibility, and demand management (Monitor Deloitte, 2021; BloombergNEF, 2022). Similarly, investments offer benefits to society such as sustainability, incentivizing competitiveness by contributing to the decrease in the price of electricity, increasing employment, and contributing to the development of the economy (Fragkos and Paroussos, 2018; IRENA, 2020). The deployment of renewable energies in the electric power industry generates direct, indirect, and induced jobs, which exceed the loss of jobs in conventional technologies. Jobs arise from activities related to electricity generation (renewable energies, energy efficiency, power grids, and energy flexibility) (Fragkos and Paroussos, 2018; IRENA, 2020).

In turn, innovation in the electric industry reduces costs and creates additional investment and business opportunities, in addition to making this sector a more efficient, competitive, and sustainable environment (DigitalES, 2019; IRENA, 2019c; United in Science, 2019). Innovation in areas such as grid digitalization, the Internet of Things (IoT), clean technologies, energy efficiency, electric energy storage, services, and business models, brings disruptive solutions that redefine and streamline the future of the low-carbon electricity industry (Kuzemko et al., 2016; Hoekstra et al., 2017; Olkkonen et al., 2017). In this sense, digitalization is a key factor for the transformation of the electricity sector, as it allows for managing large amounts of data, optimizing the electricity system, improving the performance and quality of service for consumers, and reducing costs and GHG emissions (IRENA, 2020; Torres and Eguia, 2020). It also facilitates the transformation to a system with decentralized renewable generation based on smart grids, increasing the number of connected devices, i.e., distributed generation (prosumers), smart meters, devices (IoT), etc. (Pacte industrial de la Regió Metropolitana de Barcelona, 2016; DigitalES, 2019). Therefore, the implementation of smart meters stands out, which allows the exchange of information regarding the state of the grid, reduces the time of supply interruption, and facilitates the active participation of the consumer in the electricity market by encouraging the use of renewable resources (Gil et al., 2017; DigitalES, 2019; Torres and Eguia, 2020). In connection with the previous text, the following hypotheses are introduced:

H_7: I-Industry -> ET-Energy Transition
H_8: I-Industry -> NE-Natural Environment
H_9: I-Industry -> CS-Civil Society.

2.2.4. Media-based and culture-based public (civil society)

The subsystem of the media-based and culture-based public, known as civil society, integrates and combines social capital and information capital. On the one hand, it contains social capital through the culture-based public, i.e., traditions, lifestyles, customs, and values (Barth, 2011; Carayannis et al., 2012). This capital is important and intangible (Makridisid et al., 2021) and includes the connections between individuals, social networks, and forms of reciprocity and trust that improve the efficiency of society by facilitating coordinated actions (Messner et al., 2004; Kawachi, 2006; Yip et al., 2007). Societies with higher levels of social capital function better and are more democratic, safer, wealthier, healthier, happier, and less corrupt (Makridisid et al., 2021). On the other hand, it has information capital, such as news, social communication, etc. using public based on media, for example, television, radio, newspapers, etc. (Barth, 2011; Carayannis et al., 2012).

The transition to a sustainable electricity sector can be achieved if citizens are empowered as active agents of change and if citizen-centered action steps are taken (Pel et al., 2021; Wahlund and Palm, 2022). Energy citizenship is related to meaningful public engagement and increased awareness of the need for a rapid, just, and inclusive energy transition focused on behavioral change and ways of active participation of individuals in energy systems (Vanegas Cantarero, 2020; Beauchampet and Walsh, 2021). Active participation of citizens refers to individual practices such as the adoption of renewable technologies, energy efficiency measures, use of household energy technologies, joining energy communities, supporting local initiatives, participating in energy decision-making, etc. Similarly, the active participation of prosumers (consumers + producers) in energy production contributes to the decentralization of the energy system, encourages energy efficiency, and reduces GHG emissions (Hoekstra et al., 2017; IRENA, 2019a; Yang et al., 2019). The digitalization of the electric system makes it easier for consumers to know how their consumption habits affect their electricity bills, giving them the ability to control and optimize their energy consumption (IRENA, 2020; Pel et al., 2021). After having brought up those statements, the next hypotheses are conveyed:

H_{10}: CS-Civil Society -> ET-Energy Transition
H_{11}: CS-Civil Society -> G-Government
H_{12}: CS-Civil Society -> NE-Natural Environment.

2.2.5. Natural environment

The natural environment provides natural capital, which is made available to the people (Barth, 2011). It also guides decisions and provides information about sustainable development (Carayannis et al., 2012). The natural environment is the space where the life of living beings develops; it is a system formed by natural and artificial elements that interrelate and are modified by human action (Shende et al., 2015). To encourage and raise awareness in society and governments about the importance of caring for the environment, the sustainable use of its natural resources, and the social good, several non-governmental organizations (NGOs) and associations have emerged (Robina-Ramirez et al., 2022). These organizations are committed to the defense of nature and the environment; therefore, they provide expert advice to the government (Kacar and Kartal, 2014; Roa and Alonso, 2015), i.e., secretariats, public institutions, city councils, politicians, etc. on various topics. In addition, they foster dialogue, agreements, and lobbying mechanisms to make the government comply with the commitments established in the constitution and/or international agreements and public policies to respond to the needs and demands of society (Bobadilla Díaz and Barreto Huamán, 2014; Servos and Servos, 2019).

NGOs and associations incentivize the transformation of the electric power industry and climate change mitigation. For example, distributed renewable energy sources projects provide local distributed employment integrating renewable energy needs with the interests of local communities contributing to ecology, sustainability of their economies, and encouraging self-consumption (Scholten and Bosman, 2016; Campos and Marín-González, 2020; IRENA, 2020). These challenges require citizen awareness and participation, which is why they carry out informative campaigns, conferences, debates, etc. through various mass media (Yanfei and Zhao, 2008; Kacar and Kartal, 2014; Roa and Alonso, 2015; Dai et al., 2017). Having conveyed the previous ideas, H_{13} and H_{14} are introduced:

H_{13}: NE-Natural Environment -> ET-Energy Transition
H_{14}: NE-Natural Environment -> G-Government.

2.3. Sample and population

According to Lepkowski (2008), the choice of the target sample was directed toward sectors directly related to the object of the sample. The respondents were recruited using purposive sampling (Roeters, 2014). For this purpose, several Mexican government agencies directly related to the electric power sector were selected, such as the Energy Regulatory Commission (CRE, for its acronym in Spanish), the National Commission for the Efficient Use of Energy (CONUEE, for its acronym in Spanish), the Ministry of Energy (SENER, for its acronym in Spanish), and the National Energy Control Center (CENACE, for its acronym in Spanish). In addition to incorporating these specific energy production bodies, we include the Federal Chamber of Deputies and the Senate as transmitter vehicles and connectors of the rest of the parts of the helix model, since in both chambers there are bodies representing the "Academia," "Industry," "Civil Society," and "Natural-Environment."

The distribution of employees in each of these bodies is as follows: CRE had 91 employees, CONEEE had 105 employees, SENER had 499 employees, CENACE had 639 employees, Federal Chamber of Deputies had 500 employees, and the Senate had 128 employees. In total there were 1,962 employees. In April, a letter explaining the objective of the investigation was sent to each of the presidents of the Commissions requesting their collaboration. The lack of response from some commissions led to a second, and sometimes a third letter, being sent. They were asked to send the final questionnaire by internal communication to all their employees, and a representation of 15 employees per Commission was asked to help carry out the pre-test of the study. The questionnaire was validated by 47 employees from all the commissions, accepting the indicators and making modifications to the wording of the questions in the final questionnaire. The questionnaires were sent out during the month of July. A total of 995 questionnaires were collected, representing 51% of the total sample. Table 1 shows the demographic variables such as gender, age, and education of the employees.

2.4. Selection of indicators

The Quintuple Helix Model as an analytical and decision-making framework was implemented through the involvement of the different stakeholders of each helix or subsystem in the

TABLE 1 Demographic characteristics of inhabitants ($n = 995$).

Attributes		Employees	Frequency
Gender	Female	597	60%
	Male	398	40%
	Total	995	100%
Age	18–25	102	10%
	26–35	195	20%
	36–45	265	27%
	46–55	301	30%
	56–65	111	11%
	Older than 66	21	2%
	Total	995	100%
Education	Without studies	11	1%
	Primary studies	109	11%
	Secondary studies	256	26%
	High school	298	30%
	University studies	321	32%
	Total	995	100%

electric power sector in Mexico, as follows: 1. Government: CRE, CENACE, CONUEE, SENER, Federal Chamber of Deputies and the Senate; 2. Academia: Researchers and academics from various universities, research centers, and educational institutions for technical professionals and high school technical professionals; 3. Industry: Staff from CFE and personnel from private electricity generation companies; 4. Civil Society: Consumers; and, 5. Natural Environment: Environmental NGOs and renewable energy associations. The conceptual model is formed by six constructs and twenty-four indicators, all of which were obtained from the literature and are summarized in Table 2.

2.5. PLS-SEM data methods

Partial least squares structural equation modeling (PLS-SEM) is a second-generation multivariate method that can be defined as a combination of simultaneous factor analysis and multiple regression analysis (Wong, 2013; Ravand and Baghaei, 2016). Its objective is to test the degree of fit of an observed data set to a hypothesized model represented through a plot of trajectories. This methodology has gained greater emphasis in recent years in various research areas because it overcomes the weaknesses of first-generation multivariate techniques, such as multiple regression, cluster analysis, or analysis of variance (Haenlein and Kaplan, 2004). It allows the simultaneous examination of a series of dependence relationships between independent and dependent variables (Gefen et al., 2000), between observed and latent variables, as well as between latent variables, and takes measurement error into account (Ravand and Baghaei, 2016). For the use of structural equation modeling (SEM), a strong theoretical foundation and justification of the studied phenomenon are required to achieve the specification of the dependence relationships and for the estimation of the proposed model (Mulaik, 2009). Therefore, SEM can be used to test theoretical assumptions with empirical data (Haenlein and Kaplan, 2004).

In SEM, two types or approaches can be found, the covariance-based (CB-SEM), recommended for testing, contrasting, or confirming theories, and the based-on variance or partial least squares method (PLS-SEM), which aims to maximize the explained variance of the dependent variables by adopting an ordinary least squares estimation method and is recommended when the objective is the prediction and development of new theories (Chin, 2010; Hair et al., 2011; Wong, 2013; Ravand and Baghaei, 2016). In addition, PLS-SEM is a more flexible modeling methodology since (1) it has no assumptions regarding the multivariate normality distribution of data because it is a non-parametric method; (2) it is robust to the presence of missing values; (3) it can use minimum sample sizes; (4) the number of items of each construct measured can be only one or more and in the relationships between latent constructs and their indicators (observable variables) reflective and formative measurement methods can be incorporated; (5) it assesses the reliability and validity of measurement models using various criteria; and (6) there is a high degree of statistical power (Dijkstra and Henseler, 2015; Ravand and Baghaei, 2016).

For the development of this model, the following decisions were made about the nature of the constructs and indicators involved in it: (1) the 5-helix model was modeled as a composite (Bollen, 2011; Bollen and Bauldry, 2011; Henseler, 2017) that can be estimated in Mode A or correlation weights (Henseler et al., 2014; Sarstedt et al., 2016), i.e., a composite whose indicators are expected to correlate with each other; (2) the presented model was measured across six reflexive common factor constructs (Henseler et al., 2016b), as they are behavioral constructs of the analyzed individuals (Henseler, 2017); and (3) given the nature of the indicators, they were constructed as reflexive common factor models, measurement models in which the variance of the indicators is assumed to be fully explained by the latent variable and random errors, these errors being uncorrelated with each other.

The evaluation of the measurement model and the structural model were developed using structural equation modeling (SEM), with a causal-predictive analysis approach (Shmueli et al., 2016; Hair et al., 2017, 2019). We used the multivariate PLS technique to process the information obtained from the questionnaires. Specifically, the study used the partial least squares (PLS) technique, through the Smart PLS V3 2.6 program. This version is especially recommended for composite models (Rigdon et al., 2017). This technique is ideal in social science analysis (Henseler, 2017) due to the precision of its predictions; this means that the model can be replicated in other settings (Carmines and Zeller, 1979).

2.6. Hypothesis and model

Based on the documentary compilation and the literature review which were carried out, a set of hypotheses were provisionally established as the basis of the research to respond in an alternative way and with a scientific basis to the problem of the energy transition in the electricity industry in Mexico. According to this series of assertions and the PLS-SEM methodology, a model was designed

TABLE 2 Model for energy transition in electric power industry.

Constructs		Indicators	References
Energy transition	ET_1	GHG emissions	Araújo, 2014; Singh et al., 2019; IRENA, 2020; World Economic Forum, 2021
	ET_2	Price	Pikk and Viiding, 2014; Taylor, 2020
	ET_3	Electrification rate	Monitor Deloitte, 2021; BloombergNEF, 2022
	ET_4	Share of electricity from renewables	FAES, 2018; Lucas et al., 2018; Miśkiewicz, 2018
	ET_5	Security of electricity supply	Araújo, 2014; Singh et al., 2019; IRENA, 2020
Government (political system)	G_1	Investment	Abdmouleh et al., 2015; Liu and Chu, 2019
	G_2	Cross-cutting and coherent policy making	Hoekstra et al., 2017; IRENA, 2020
	G_3	Taxes and subsidies	Abdmouleh et al., 2015; Zhao et al., 2017
	G_4	Information and best energy practices dissemination	Yanfei and Zhao, 2008; Kuzemko et al., 2016; INECC SEMARNAT, 2018
	G_5	Energy efficiency	Vargas et al., 2016; CEPAL, 2022
Academia (education system)	A_1	Research in cutting-edge energy technologies	FAES, 2018; Lantz et al., 2021; Sandin and Benner, 2022
	A_2	Knowledge and technology transfer	Miśkiewicz, 2018; de Wit-de Vries et al., 2019; Thomas and Paul, 2019; IRENA, 2020
	A_3	High-skilled human capital	Lucas et al., 2018; Maier et al., 2019; IRENA, 2020
Industry (economic system)	I_1	Investment in renewables	Chapman et al., 2018; Fragkos and Paroussos, 2018; IRENA, 2020; Monitor Deloitte, 2021; BloombergNEF, 2022
	I_2	Green jobs	Fragkos and Paroussos, 2018; IRENA, 2020
	I_3	Innovation	DigitalES, 2019; IRENA, 2019c; United in Science, 2019
	I_4	Digitalization	Gil et al., 2017; DigitalES, 2019; IRENA, 2020; Torres and Eguia, 2020
Civil society (media-based and culture-based public)	CS_1	Energy citizenship	Vanegas Cantarero, 2020; Beauchampet and Walsh, 2021; Pel et al., 2021; Wahlund and Palm, 2022
	CS_2	Prosumers	Hoekstra et al., 2017; IRENA, 2019a; Yang et al., 2019
	CS_3	Digitalization	IRENA, 2020; Pel et al., 2021
Natural environment	NE_1	Advising	Kacar and Kartal, 2014; Roa and Alonso, 2015
	NE_2	Influence	Yanfei and Zhao, 2008; Kacar and Kartal, 2014; Roa and Alonso, 2015; Dai et al., 2017
	NE_3	Projects	Scholten and Bosman, 2016; Campos and Marín-González, 2020; IRENA, 2020
	NE_4	Information and best energy practices dissemination	Yanfei and Zhao, 2008; Kacar and Kartal, 2014; Roa and Alonso, 2015; Dai et al., 2017

Source: Authors.

that proposes the sum of strategic interactions between government, academia, industry, civil society, and the natural environment to promote the sustainable development of the electricity sector in Mexico. The fourteen working hypotheses to be statistically validated are:

1) H_1. The government (G) shapes the energy transition (ET).
2) H_2. Academia (A) influences the government (G).
3) H_3. Academia (A) shapes the energy transition (ET).
4) H_4. Academia (A) affects the natural environment (NE).
5) H_5. Academia (A) influences civil society (CS).
6) H_6. Academia (A) affects the industry (I).
7) H_7. The industry (I) shapes the energy transition (ET).
8) H_8. Industry (I) influences the natural environment (NE).
9) H_9. Industry (I) affects civil society (CS).
10) H_{10}. Civil society (CS) shapes the energy transition (ET).
11) H_{11}. Civil society (CS) influences the government (G).
12) H_{12}. Civil society (CS) affects the natural environment (NE).
13) H_{13}. The natural environment (NE) shapes the energy transition (ET).
14) H_{14}. The natural environment (NE) influences the government (G).

Figure 1 shows the research model to convey the relationships among the constructs, indicators, and hypotheses.

3. Results

3.1. Measurement model results

In this section, we analyze the model's reliability and validity (Hair et al., 2017). The first one analyzes simple correlations of the measurements with their respective latent variables ($\geq$0.7 was accepted; see Table 3). For this reason, all indicators (GHG emissions, price, taxes and subsidies, high-skilled human capital, green jobs,

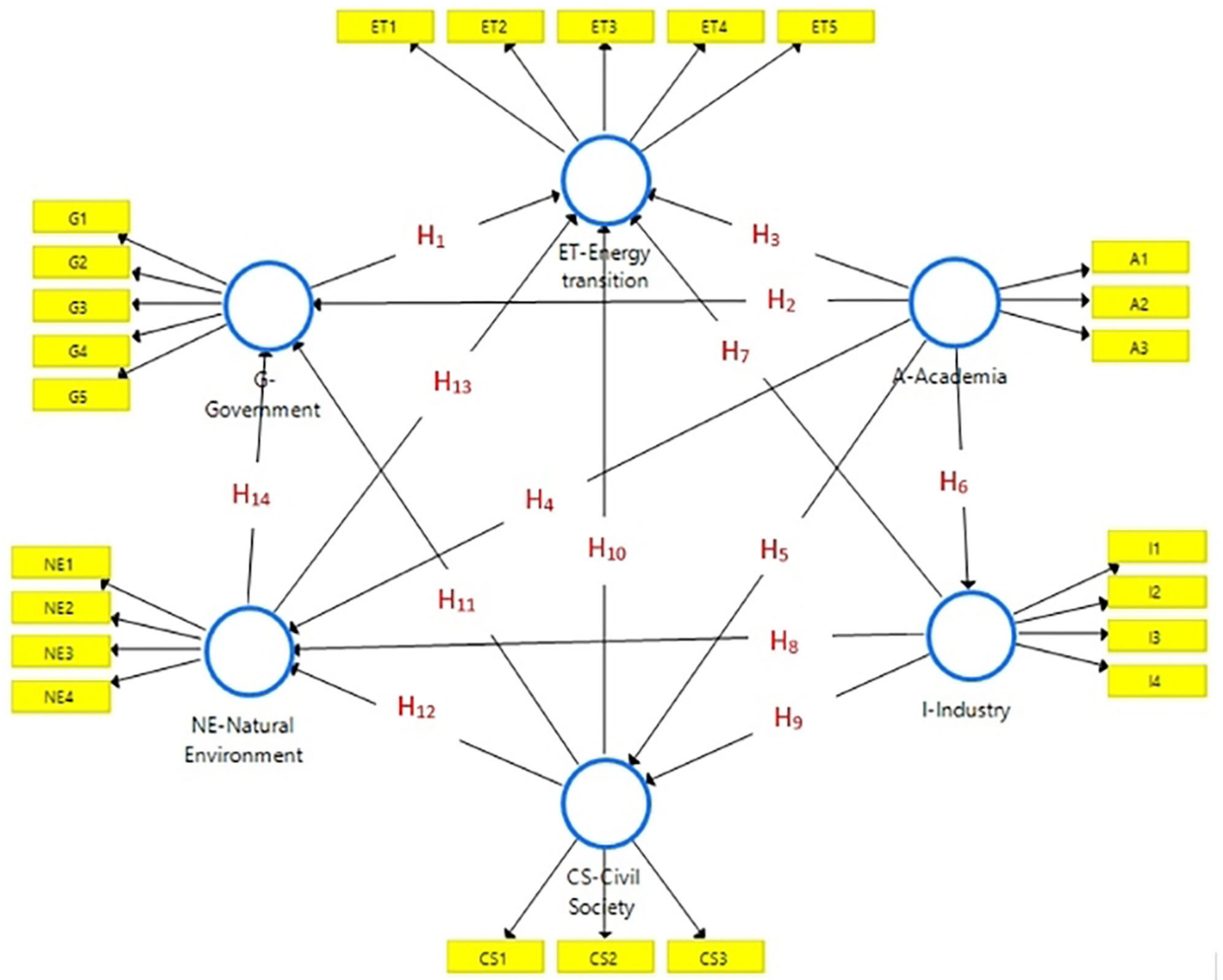

FIGURE 1
Research model.

energy citizenship, and advising, among others) associated with a particular construct or latent variable (energy transition, government, academia, industry, civil society, or natural environment) are highly correlated with each other.

Table 4 shows the main parameters. Cronbach's alpha coefficient was used as a reliability index of the latent variables. In addition, the composite reliability was calculated. To measure validity, the mean-variance extracted (AVE), known as "convergent validity" (accepted > 0.5), was evaluated (see Table 4). The discriminant validity was verified using the Fornell-Larcker criterion (Fornell and Bookstein, 1982). This was accepted as the square root of the AVE of each item exceeded the correlations with the other latent variables.

Furthermore, according to Henseler et al. (2015), the best technique to detect the lack of discriminant validity is known as the heterotrait-monotrait ratio (HTMT). Henseler et al. (2015) proposed testing the correlations between variables using the HTMT parameter. Since all values are <0.90, as observed in Table 5, this condition is accepted (Henseler, 2017). Table 5 reveals that the HTMT ratios for each pair of factors were <0.90 (Henseler, 2017).

3.2. Structural model results

PLS-SEM aims to maximize the amount of variance explained through the coefficient of determination (R^2). The structural evaluation of the model also analyzes the predictive relevance (Q^2), the size, and the significance of the standardized regression coefficients or path coefficients. The basic algorithm of the PLS follows a two-step approach. The first step is the iterative estimation of the scores of the latent variables, and the second step is the final estimation of the weights, loads, and path coefficients using the estimation of ordinary least squares p-value of >0.05 (Henseler et al., 2015) (Table 6). Figure 2 shows the results of the PLS algorithm.

According to Henseler et al. (2016a), the best-fit criterion for the global model is the residual root mean square normalization (SRMR) (Hu and Bentler, 1998, 1999). A model with an adequate fit is considered when the values are <0.08. Therefore, a value of 0 for SRMR would indicate a perfect fit and, in general, an SRMR value <0.05 indicates an acceptable fit (Byrne, 2008). A recent simulation study shows that a correctly specified model implies

TABLE 3 Indicators.

	A-Academia	CS-Civil society	ET-Energy transition	G-Government	I-Industry	NE-Natural environment
A1	0.873					
A2	0.902					
A3	0.839					
CS1		0.885				
CS2		0.868				
CS3		0.742				
ET1			0.769			
ET2			0.738			
ET3			0.777			
ET4			0.857			
ET5			0.848			
G1				0.799		
G2				0.844		
G3				0.788		
G4				0.809		
G5				0.811		
I1					0.813	
I2					0.842	
I3					0.766	
I4					0.742	
NE1						0.814
NE2						0.804
NE3						0.860
NE4						0.779

TABLE 4 Reliability and construct validity.

Parameters					Forner–Larker criterion						
	Alfa de Cronbach's	rho_A	CR	(AVE)		A	CS	ET	G	I	NE
A	0.841	0.844	0.904	0.760	A	0.871					
CS	0.782	0.822	0.872	0.696	CS	0.458	0.834				
ET	0.857	0.857	0.898	0.639	ET	0.696	0.444	0.799			
G	0.869	0.871	0.905	0.657	G	0.676	0.481	0.749	0.811		
I	0.802	0.814	0.870	0.627	I	0.569	0.495	0.700	0.678	0.792	
NE	0.831	0.833	0.887	0.664	NE	0.620	0.557	0.667	0.668	0.634	0.815

SRMR values >0.06 (Henseler et al., 2016a). SRMR is 0.065, so the model is appropriate for the empirical data used (Hair et al., 2017).

The R^2 values (see Table 7) obtained for the investigation led to the following conclusions: 0.67 = "Substantial", 0.33 = "Moderate", and 0.19 = "Weak" (Chin, 1998). The result obtained for the main dependent variable, Energy Transition (ET), in the intention to use the model (DCM) was $R^2 = 68.4\%$.

From these data, it is clear that the model has a predictive capacity (Chin, 1998). Following Stone-Geisser (Q^2) (Geisser, 1974; Stone, 1974), all endogenous constructions comply with $Q^2 > 0$, as can be seen in Table 7. Hair et al. (2017) also establish values of 0.02 as small, values of 0.15 as medium, and values of 0.35 as large in their predictive validity of the model. In our case, all the values exceed the maximum threshold, ET, G, and NE indicate a high predictive relevance, while I and CS have an intermediate predictive relevance.

4. Discussion

The cooperation model proposed for the strategic interaction between industry, academia, government, society, and environment is highly significant $R^2 = 0.684$ (Chin, 1998). This means that the model is valid for solving transdisciplinary problems related to sustainability and social ecology (Carayannis and Campbell, 2010; Barth, 2011). If the contribution of each of the elements in the variable "Energy Transition" is analyzed, it is observed in Table 8 as terms of the variance explained, the "Government" contributes to better explain the variable "Energy Transition" (Var = 0.234). Hence, our results suggest that the government may act as the driver of the energy transition, which is a common result in the literature as pointed out by Yanfei and Zhao (2008), Abdmouleh et al. (2015), Kuzemko et al. (2016), Vargas et al. (2016), Hoekstra et al. (2017), Zhao et al. (2017), INECC SEMARNAT (2018), Liu and Chu (2019), IRENA (2020), and CEPAL (2022). In other words, the government is the entity that can lead the energy transition process by modifying the electricity sector.

The "Industry" (Var = 0.188) and "Academia" (Var = 0.179) contribute to explaining the variable "Energy Transition" to a lesser degree. Our results indicate that the industry is a key factor for the development of the energy transition through innovation and digital solutions, adaptation to market trends, competitiveness, and generation of employment and social welfare, in accordance with Gil et al. (2017), Chapman et al. (2018), Fragkos and Paroussos (2018), DigitalES (2019), IRENA (2019c, 2020), Torres and Eguia (2020), Monitor Deloitte (2021), and BloombergNEF (2022). For its part, academia can provide and enhance education and information to foster a critical and participatory attitude toward climate change and the development of a sustainable electricity sector, as referred to by FAES (2018), Lucas et al. (2018), Miśkiewicz (2018), de Wit-de Vries et al. (2019), Maier et al. (2019), Thomas and Paul (2019), IRENA (2020), Lantz et al. (2021), and Sandin and Benner (2022).

Similarly, the other two variables with significant coefficient determinations are NE-Natural Environment $R^2 = 0.546$ and G-Government $R^2 = 0.563$. In the first case, the influence of "Industry" (Var = 0.211) and "Academia" (Var = 0.197) are determinants. According to Doh et al. (2012) and Abenoza et al. (2015), the industry has the capital and the influence of consumers. The knowledge, experience, and capabilities of industry and NGOs are different and complementary, together they can achieve more than they could alone. For its part, linking academia with NGOs in developing countries provides innovation in ideas, concepts, technologies, and projects, which, increases the impact, influence, and efficiency of NGOs and associations (MacLeod, 2009; Leege and Mcmillan, 2016). In the second case, the changes produced in the "Government" construct are explained thanks to the effect of "Academia" (Var = 0.276) and "Natural Environment" (Var = 0.243). According to authors Parker Gumucio (2014) and Vargas et al. (2016), academia provides expertise to the government for the development of policies, regulatory and investment frameworks, and the change toward a cleaner mode of production and consumption patterns. Likewise, NGOs and associations communicate and explain to the government the opinions, needs, and demands of society and ask for responses to them (Díaz and Bel, 2003; Roa and Alonso, 2015).

TABLE 5 Heterotrait-monotrait ratio.

Construct	DP1	DP2	DP3	EG1	EG2	EG3
A						
CS	0.542					
ET	0.818	0.537				
G	0.792	0.571	0.865			
I	0.686	0.611	0.833	0.809		
NE	0.740	0.670	0.790	0.784	0.766	

TABLE 6 Path coefficients.

Path coefficients		Confidence interval (%)			
	β	2.5%	97.5%	*t* (|O/STDEV|)	*P*-value
H_1: G -> ET	0.312	0.167	0.435	4.268	0.000***
H_2: A -> G	0.408	0.280	0.531	6.324	0.000***
H_3: A -> ET	0.257	0.128	0.376	4.071	0.000***
H_4: A -> NE	0.318	0.202	0.435	5.232	0.000***
H_5: A -> CS	0.260	0.127	0.394	3.610	0.000***
H_6: A -> I	0.570	0.461	0.671	10.069	0.000***
H_7: I -> ET	0.268	0.174	0.362	5.264	0.000***
H_8: I -> NE	0.332	0.222	0.445	5.754	0.000***
H_9: I -> CS	0.348	0.199	0.493	4.474	0.000***
H_{10}: CS -> ET	−0.042	−0.128	0.050	0.970	0.332
H_{11}: CS -> G	0.092	−0.021	0.182	1.809	0.071
H_{12}: CS -> NE	0.247	0.139	0.367	4.265	0.000***
H_{13}: NE-> ET	0.153	0.153	0.062	2.454	0.014**
H_{14}: NE -> G	0.364	0.359	0.059	6.189	0.000***

Statistical significance: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; n.s.: not significant (Hair et al., 2014).

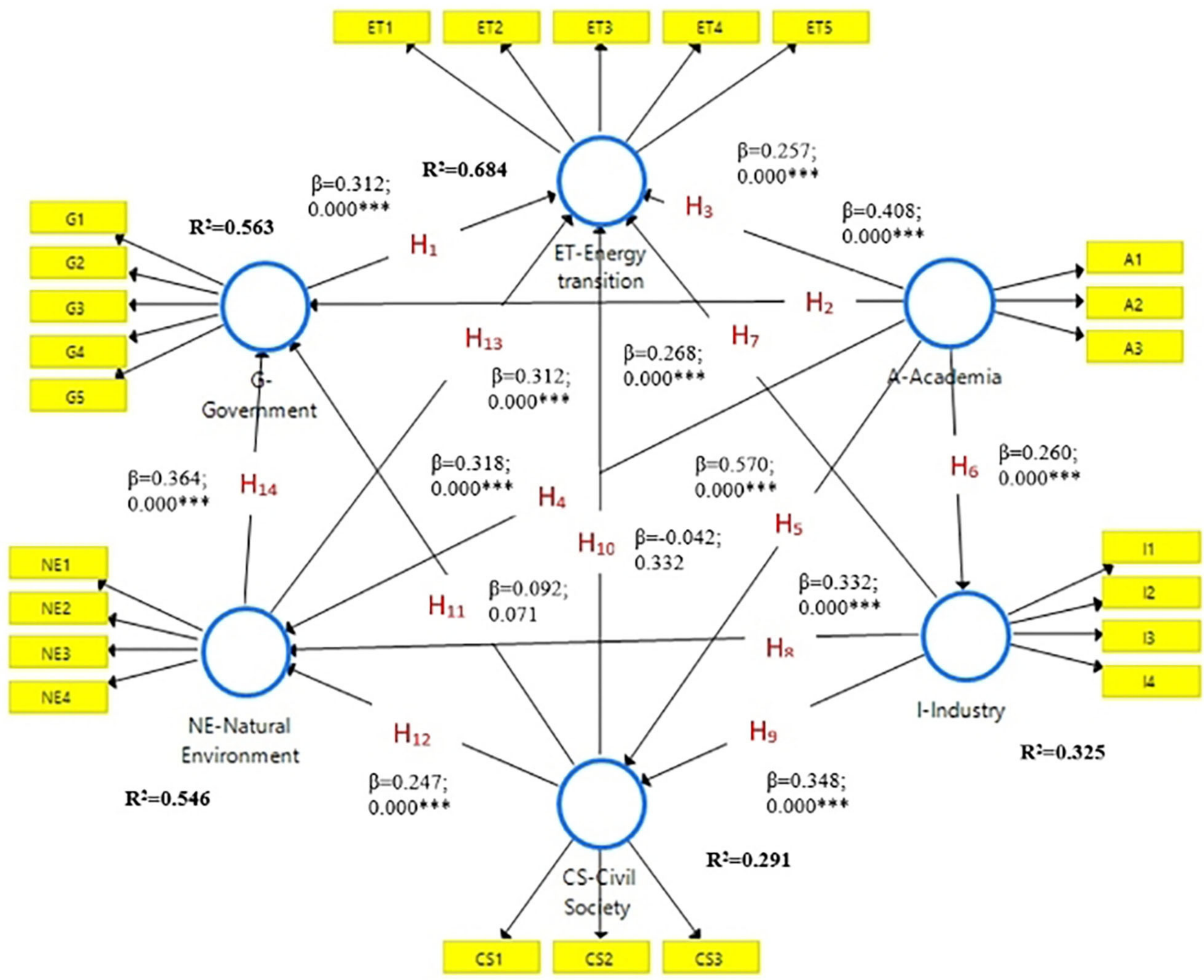

FIGURE 2
Results of the PLS algorithm. Statistical significance: $p < 0.05$; $p < 0.01$; $p < 0.001$; n.s.: not significant.

TABLE 7 Coefficient of determination (R^2) and Stone-Geisser test (Q^2).

Constructs	R^2	Q^2
CS-Civil society	0.291	0.192
ET-Energy transition	0.684	0.419
G-Government	0.563	0.357
I-Industry	0.325	0.195
NE-Natural environment	0.546	0.354

On the other hand, in terms of variance explained, "Civil Society" does not contribute to explaining the variable "Energy Transition" (V = −0.019), likewise, its influence on the variable "Government" is minimal (V = 0.044). These results can be explained by the fact that citizen participation in Mexico is very low in this type of issue due to several factors: the lack of information, the fact that most of these issues are solved by the citizens themselves due to low governmental performance, distrust in institutions, and because they do not feel represented, they consider it unnecessary to get more involved. Some others think that the solution to them is only the government's responsibility (Serrano Rodríguez, 2015; Del Tronco and Ramírez, 2021). However, "Civil Society" influences the variable "Natural Environment" (V = 0.138) since when citizens are members of associations, NGOs, etc. they tend to participate more in the solution of community problems (Del Tronco and Ramírez, 2021).

If the hypotheses are analyzed, twelve are significant and two are not. This indicates that the model, in general terms, has established relationships between constructs that are largely accepted by the large sample that participated in the study. Above all the hypotheses, the close relationship between the variables "Academia" and "Industry" (H_6: A I, β: 0.570, *t*: 10.069) stands out. This relationship is grounded in the fact that the transfer of knowledge and technology between academia and industry creates an intangible network of support, which drives innovation, growth, and prosperity of the economy (de Wit-de Vries et al., 2019; Thomas and Paul, 2019). A key element for the development of a low-carbon power sector (Miśkiewicz, 2018; IRENA, 2020).

TABLE 8 Analysis of variance by constructs.

	Adjusted R^2	Q^2	Direct effect	Correlation	Variance explained
ET	0.684	0.419			
G			0.312	0.749	0.234
NE			0.153	0.667	0.102
CS			−0.042	0.444	−0.019
I			0.268	0.702	0.188
A			0.257	0.696	0.179
					0.684
I	0.325	0.195			
A			0.57	0.57	**0.325**
CS	0.291	0.192			
A			0.26	0.458	0.119
I			0.348	0.496	0.173
					0.292
NE	0.546	0.354			
A			0.318	0.62	0.197
I			0.332	0.635	0.211
CS			0.247	0.557	0.138
					0.546
G	0.563	0.357			
A			0.408	0.676	0.276
CS			0.092	0.481	0.044
NE			0.364	0.668	0.243
					0.563

CS, Civil society; ET, Energy transition; G, Government, I, Industry; NE, Natural environment.

There is also a special significance to the relationship between "Academia" and "Government" (H_2: A G, β: 0.531, *t*: 6.324). It is logical to think that academia provides scientific support, empirical evidence, and expert knowledge to the government on technological, social, and economic issues so that it can establish the legal framework, national objectives, and strategic decision-making necessary to incentivize the transformation of the electricity sector (Vargas et al., 2016; Glied et al., 2018).

The statistical analysis rejects hypotheses H_{10} (CS ET, β: 0.050, *t*: 0.970) and H_{11} (CS G, β: 0.182, *t*: 1.809). The poor relationship between the variables of the two hypotheses is explained because the participation of Mexican citizens in matters related to community problems is infrequent due to distrust in institutions, lack of information, and because they consider that public problems should be solved by the government (Serrano Rodríguez, 2015; Del Tronco and Ramírez, 2021).

In general, the statistical analysis indicates that in Mexico it is feasible to adopt a five-helix approach, but it is not fully developed, much less consolidated. So, returning to particular relationships:

- It is clear that the government plays a fundamental role in Mexico's energy transition. From the results, one could interpret the Mexican government as the intermediary driver. This contrasts with other countries where academia has driven this process (the Netherlands, for example). This would imply that the government should strengthen the structural change of the energy market by promoting the activities of CENACE, CRE, and CNH (National Hydrocarbons Commission, for its acronym in Spanish), but the opposite is currently happening. Possibly, with these results, it could be suggested that CENACE should promote the updating of energy infrastructure, CRE should encourage competition to increase consumer welfare, and CNH should promote technology transfer with academia.
- The work reflects the lack of social participation. This is an expected result because public policies focused on the consumer only reward those who consume less. In other words, the CFE promotes lower consumption but is not a substitution for clean electricity. There is also no clear strategy for people to produce energy. These types of public policies only benefit small and medium-sized companies. It is important to emphasize that social mechanisms for participation in the energy transition practically do not exist; those that do exist only integrate certain types of companies. Then, in addition to the subsidy for low consumption, Mexico could implement subsidies for the connection of solar panels to the grid or withdraw the subsidy

received by the CFE to encourage the search for other suppliers (which exist but are not developed due to lack of demand).

- The network of technology transfer offices in Mexico is an initiative with an "appropriate origin",but it has never been consolidated. Perhaps, due to the relationship between government and academia, it would be convenient to change the agent that controls them. Its administration should be transferred to academia, and the development of academic programs focused on energy transition should be promoted.
- Another point that can be discussed is the lack of development in the energy market. In recent years, it has returned to a monopolistic situation, instead of promoting short, medium, and long-term markets.

5. Conclusion

Due to the wealth of renewable resources in Mexico, as well as the urgent need to achieve the transformation of the electricity sector and the mitigation of climate change, an exploratory model based on the Quintuple Helix Model was proposed as an analytical and decision-making framework to promote the production and consumption of clean/renewable electricity and reduce GHG emissions. It proposes a cooperation system and transfer of knowledge, know-how, and innovation through the active and committed collaboration of government, academia, industry, civil society, and the environment through the sum of strategic interactions to achieve the sustainable development of the electricity industry in Mexico, as well as to provide relevant information to decision-makers in the energy transition of the electricity industry and similar transition processes.

This study concludes that the five-helix approach is valid to solve transdisciplinary problems related to sustainability and social ecology, in this case, to evolve from a state of greenhouse gas (GHG) emissions due to electricity generation through the use of fossil fuels to one where electricity generation is carried out through renewable energy sources and can be replicated in scenarios with similar socioeconomic characteristics. In Mexico, it is possible to adopt such an analytical and decision-making framework, however, it is not fully developed and consolidated. In addition, it became clear that the government is the most appropriate intermediary driving agent for the development of the energy transition in the electricity industry, i.e., the government is the one that can lead and drive the energy transition process by modifying the electricity sector.

Likewise, industry and academia are key players in achieving the energy transition. The importance of industry lies in the fact that innovation, competitiveness, the generation of green jobs, and social welfare are fundamental to encouraging the sustainable development of the electricity industry. Likewise, the collaboration of academia is indispensable since it is the main source of knowledge and technology generation, which are indispensable for the training of highly qualified human capital; advising the government for the development of policies, regulatory and investment frameworks, and the change toward a cleaner mode of production and consumption patterns, as well as facilitating and enhancing information to promote collective actions and a critical and participatory attitude of society to achieve the energy transition in the electricity industry.

In the particular case of Mexico, the civil society, namely consumers, do not contribute to the energy transition in the electricity industry, but as part of NGOs or associations, they participate and have the influence to achieve the transformation of the electricity sector. Consequently, in Mexican society, it is important to encourage citizen participation in matters related to community problems. The government must emphasize the creation of public policies and mechanisms that motivate civic involvement in social problems and decision-making processes and facilitate access to information to transform the prevailing civic culture. On the other hand, it is convenient that academia encourages the sensitization and awareness of the population on the importance of the change to a sustainable electric industry and climate change mitigation through its technical training programs, university, and postgraduate programs, as well as in basic and high school education programs.

5.1. Future research lines

The results drawn from the study have allowed us to understand the importance of developing other lines of research. It is suggested that future researchers explore a temporal approach to citizen participation in the energy transition in the electric power industry, that is, how citizen participation accelerates or delays the change to a sustainable electricity sector. It is also recommended that future researchers investigate, in detail, the current patterns of social participation in communal issues to know the type of mechanisms necessary to implement a changE to a low-carbon electricity sector and/or similar transition processes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

VG-C conceived the ideas and designed the research with critical suggestions from RR-R. VG-C and RR-R collected, processed the data, and carried out the modeling. VG-C, RR-R, and D-EG-R analyzed the data and led the writing of the manuscript. D-EG-R and MS-O contributed critically to the drafts.

All authors reviewed the manuscript and gave final approval for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The need for better insights into voluntary renewable energy markets

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Introduction

Every year millions of retail electricity customers voluntarily buy more renewable energy than what is provided by their local grid. In the United States the voluntary renewable energy market accounts for around 38% of non-hydro renewable energy sales and about 6% of all retail electricity sales (O'Shaughnessy and Heeter, 2022). However, despite the market's size, little is known about the role of voluntary procurement in decarbonization policy. Here, we attribute this knowledge gap to analytical challenges of estimating the market's impacts and functional challenges of integrating voluntary actions into policy frameworks. We discuss the problems associated with this knowledge gap and suggest a research agenda. We focus on U.S. voluntary renewable energy markets, though much of our discussion can be extrapolated to voluntary markets in other countries with similar structures. We begin with some basic background on the U.S. voluntary market.

Background

Renewable energy buyers are often sorted into two broad groups. Compliance buyers comprise regulated entities (e.g., utilities) who procure renewables to comply with national or state mandates. Voluntary buyers are retail electricity customers who choose to buy more renewables than otherwise provided by the grid. Renewable energy markets exist to help both types of buyers substantiate renewable energy use claims. These markets address the fundamental problem of the physical impossibility of tracking the generation and use of electricity. The solution is to separately track renewable use through accounting mechanisms known in the United States as renewable energy certificates (RECs). RECs are involved in every legal claim to the use of renewable energy in the United States in both voluntary and compliance markets. A REC equates to an exclusive property right to the clean energy attributes of one megawatt-hour of renewable generation. That right is exercised when a buyer "retires" a REC, removing it from circulation and preventing double claims to the same output. In 2022, about 240 million RECs were retired in voluntary markets, compared to around 390 million RECs in compliance markets (Figure 1).

The voluntary market comprises a diversity of products, buyers, and market contexts. Distinct products package RECs and power in different ways that cater to different types of customers, ranging from residential households making relatively small purchases to non-residential buyers making large purchases. Some products entail contractual obligations allowing customers to make long-term commitments to specific projects, while other products allow customers to easily come and go. Products are offered by a variety of vendors, including project developers, utilities, retail electricity suppliers, and brokers specialized in

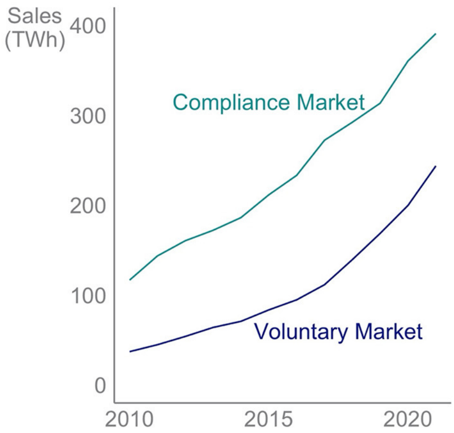

FIGURE 1
Voluntary and compliance market renewable energy sales, 2010–2021. Based on data from O'Shaughnessy and Heeter (2022) and Barbose (2021). For more detailed data for annual trends in sales for specific products, see O'Shaughnessy and Heeter (2022).

selling RECs. Many products use RECs that are "unbundled" from the underlying power, meaning that the RECs and electricity are sold separately. Note that prevailing market and legal frameworks ensure that REC buyers own the right to claim the use of renewable energy regardless of the treatment of the underlying power. Procurement also occurs in a diversity of market contexts. In some regions, low development costs and the lack of binding state mandates can result in relatively abundant supplies of low-cost RECs, while in other regions development constraints and binding mandates can drive significant REC scarcity. At any given moment REC prices vary by orders of magnitude across different markets. Hence, while we refer to the voluntary market as a singular entity for simplicity, it is crucial to bear in mind that the market is a mix of buyers, products, and market contexts.

The analytical challenge

As voluntary markets have grown, buyers, sellers, scholars, and other stakeholders have become increasingly interested in measuring the impact of voluntary procurement. While impact can have several meanings, for the purposes of our discussion impact refers to the degree to which voluntary procurement affects renewable energy supply. Identifying voluntary market impacts is a deceptively complex task, a problem we refer to as the analytical challenge. The simplest way to put the analytical challenge is that a marginal unit of REC demand cannot be directly mapped to an additional unit of deployed capacity. A useful analogy are concert tickets: an additional ticket purchase cannot be directly mapped to an additional concert. Still, in both cases, there is a theoretical if unobserved relationship between demand and supply. Conceptually, a marginal unit of REC demand makes RECs scarcer. REC scarcity is reflected in higher REC prices which signal to the market to deploy more renewable capacity.

Due to this analytical challenge, we lack a rigorous understanding of voluntary market impacts based on empirical data, statistical methods honed to address the specific statistical challenges of identifying voluntary market impacts, and analysis that appropriately accounts for market heterogeneity (we expand on these themes in Discussion). As a result, the default assumption in some analyses is that voluntary impacts are small or non-existent. The problem is that this default assumption could form the basis of assessments of the potential role of voluntary markets in decarbonization policy. The lack of understanding of these impacts could inefficiently constrain the contributions of the voluntary market to decarbonization efforts.

Some scholars may dispute our assessment that existing literature does not provide a rigorous understanding of voluntary market impacts. We note two reasons why the existing evidence on voluntary market impacts does not meet the standards of rigor we explore further in our Discussion.[1] First, existing literature does not address the specific methodological challenges of statistically identifying voluntary market impacts. The existing literature has, for example, not addressed the simultaneous causation of voluntary demand and renewable energy output, a theme we expand on further below. Second, theoretical assumptions about voluntary markets in specific contexts are often used to make generalized claims. For instance, one approach is to assume that voluntary demand does not affect REC prices and thus does not affect supply at all relevant levels of voluntary demand. Such assumptions may or may not be valid in specific circumstances with limited REC scarcity. However, broad analyses based on contextual assumptions homogenize the voluntary market to an unrealistic extent and do not necessarily extrapolate to valid conclusions for the broader market.

The functional challenge

The voluntary market is partly defined by its independence from policy. Because RECs are exclusive, all voluntary procurement is demonstrably exclusive of compliance procurement, a market characteristic known as regulatory surplus. Voluntary markets are perceived to pick up where regulations fall short. Booming corporate renewable energy demand in recent years, for instance, has been partly perceived as a reaction to a lack of federal action (Plumer, 2018). The notion that voluntary markets operate independently from policy poses a functional challenge: how to incorporate voluntary markets into decarbonization policy.

The functional challenge entails practical problems. The individual interests of voluntary buyers do not necessarily align with the needs of a decarbonizing grid (O'Shaughnessy et al., 2021). Certain buyers may, for instance, want to buy "local" renewables in a market already saturated with clean energy. Conversely, lack of cooperation between grid operators and voluntary buyers could result in missed opportunities. For instance, renewable energy developers need new transmission lines to finance their projects while regulators typically require developer commitments before approving transmission investments (Leisch and Cochran, 2016).

1 It is not our intention here to criticize specific studies, but the discussion and examples provided are all based on work published in the academic literature.

Voluntary buyers could potentially help solve this chicken-and-egg problem by committing to projects that will be supported by transmission expansions (Gardiner et al., 2018). Failing to engage voluntary markets could result in missed opportunities to solve such problems. Finally, in states with ambitious renewable targets, increasing competition between voluntary and compliance for dwindling REC supplies could inflate prices, potentially driving an inefficient allocation of decarbonization investments.

Discussion

The analytical and functional challenges broadly stem from gaps in knowledge. We therefore propose research directions to address both challenges. Beginning with the analytical challenge, we argue that what is needed is empirical, rigorous, and nuanced analysis of voluntary impacts. Let's explore each of these three characteristics.

First, we need empirical analysis based on market data. Given the nature of the analytical challenge, some theory and modeling are inevitable. Still, conclusions about voluntary market impacts should be based primarily on empirical claims. To that end, better data is required, meaning data on a diversity of market variables representing as much of the market as possible. Voluntary buyers and other stakeholders would do the market a service by increasing data transparency, such as open-sourcing more data on REC procurement terms. Better insights into REC procurement terms would inform how voluntary RECs drive deployment decisions in specific contexts. Further, access to a diversity of variables—beyond REC prices—would help inform how voluntary procurement may have qualitatively distinct impacts on deployment.

Second, we need rigorous analysis, meaning analysis designed with appropriate econometric identification strategies. Identification is a difficult but tractable challenge in this context. Part of this challenge is developing methods to map continuous demand to discrete and seemingly unrelated investments in new capacity. Another challenge is that voluntary demand is likely endogenous in models of renewable energy supply: voluntary demand may increase supply, but voluntary demand also responds to renewable energy supply. This simultaneity is partly based in the notion of voluntary demand as a reaction to renewable energy supply. The simultaneity is also partly mathematical, given that the potential voluntary market size is inversely proportional to state mandates. Accurate analysis of voluntary impacts will thus likely require some type of structural modeling.

Third, we need nuanced analysis, meaning analysis that estimates heterogenous impacts consistent with the diverse products and markets that comprise voluntary procurement. Voluntary market impacts likely vary substantially across different products and market contexts. Policymakers and buyers need to understand the factors that drive differences in impacts to make informed decisions to meet specific objectives. The need for nuanced analysis is increasing as the voluntary market innovates and develops new, more complex products. A prominent example is the emergence of so-called 24/7 procurement, where buyers aim to procure renewable energy that spatially and temporally matches their demand. Arguments can be made that 24/7 or similar approaches are more impactful than conventional procurement (Miller, 2020). Demonstrating such differentiated claims requires nuanced analysis that captures the market's diversity.

Moving on to the functional challenge, future research can build on common themes in a growing literature exploring the role of voluntary buyers in decarbonization. One prominent theme is the potential for increased customer choice and market access, such as by restructuring retail electricity markets or expanding open wholesale markets (Miller, 2020; Shawhan et al., 2022). Another theme is direct engagement between grid operators and voluntary buyers, such as engaging voluntary buyers in long-term procurement planning processes (Bonugli et al., 2021). Finally, regulators can help develop new standards and legal bases for innovative voluntary market strategies such as 24/7 products (Bird et al., 2021). Beyond these established themes remain unanswered questions related to the functional challenge. One challenge is defining a role for voluntary markets in "deep" decarbonization, generally meaning more than 80% carbon-free generation. Conventional voluntary market products are not equipped to address specific deep decarbonization challenges, such as the need for more system flexibility and a more diverse portfolio of clean generation and storage resources. Future research could further explore how voluntary markets could adapt, possibly with the assistance of policymakers and regulators, to the changing needs of decarbonizing grids.

The analytical and functional challenges are difficult but soluble problems. Addressing these challenges will help buyers make more informed decisions in their renewable energy procurement. Buyers would benefit from a clearer understanding of the heterogeneous impacts of different products and being able to make more precise claims about their procurement. Addressing these challenges would also inform policymakers about the potential contributions of voluntary markets to grid decarbonization and clean energy policies. Voluntary buyers have been trying to accelerate the clean energy transition for years. It is time to take them up on the offer.

Author contributions

EO'S: drafting and visualizations. JS: review and drafting. All authors contributed to the article and approved the submitted version.

Conflict of interest

Clean Kilowatts is the consulting alias of EO'S.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Review of application of high frequency smart meter data in energy economics and policy research

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The rapid popularization of advanced metering infrastructure (AMI) smart meters produces customer high-frequency energy consumption data. These data provide diverse options for energy economics and policy research. In this review, we examine studies applying high frequency smart meter data to explore the overall impact of household new technology adoption and COVID-19 on energy consumption patterns. We find that high frequency smart meter data boosts the accuracy of forecasting models with various data-driven algorithms. In addition, there is a lack of precise assessment and inclusive understanding of energy poverty in advanced economics. Smart meter data help expand and deepen the energy poverty research. Research on how vulnerable groups exhibit energy poverty can improve society's understanding of energy poverty and help implement related policy assistance programs.

KEYWORDS

smart meter, energy poverty, household technology adoption, high frequency data, energy economic, energy consumption patterns, review

1. Smart meter

Smart meters are used to accurately record the amount of electricity consumption at a very high frequency, dramatically changing the collection of electricity data and driving the household energy transition (Ribeiro Serrenh and Bertoldi, 2019). High frequency interval meter data, typically hourly and 15 min, provides important and rich information about household consumption patterns. Smart meter data can be used to cluster, classify, predict, and optimize electricity consumption patterns through a series of analytical methods and techniques (Yildiz et al., 2017). The popularity of smart meters has grown rapidly over the past decade, from <2.5 million smart meters deployed globally in 2007 to ~729.1 million in 2019, an increase of 294 times, with the United States and China accounting for the highest percentage, 85.4% (Sovacool et al., 2021). Smart meters provide utilities with detailed information and enable effective demand side management. Two-way AMI meters, which allow communication capability between electric utilities and customers, have been more prevalent after 2013 [U.S. Energy Information Administration (EIA), 2023]. By providing real-time or near real-time electricity data, it supports smart consumption applications based on customer preferences and demand.

The use of smart meters has increased the accuracy and breadth of research in the energy sector in three main dimensions. Firstly, high frequency electricity consumption data can inform hourly electricity usage in homes, the peak hours, and detailed outage information in the event of system disruption. It helps to understand in detail the patterns of electricity consumption as well as electric load. Secondly, high frequency data improves the accuracy of electricity power and energy demand forecasting, providing support for future energy supply management and energy transition. Thirdly, combining household smart meter data with household characteristics, and natural and socio-economic factors could further explore the relationship between energy consumption and socio-economic characteristics, promoting policies to address energy poverty, improve residents' electricity consumption habits, and advance overall social development.

2. Electricity consumption patterns and forecast

High-frequency electricity data helps understand the electricity consumption patterns in different consumer groups at various time periods, and the changes in behaviors after the adoption of new technologies and demand-side management measures. Further, high-frequency data increases the accuracy of energy consumption forecasts due to the larger variation provided by the data.

Applying high frequency electricity data during pandemic times, studies have analyzed and examined the overall impact of COVID-19 on energy consumption and transition in pre- and post-pandemic. The world has seen a shift in people's habits and daily activities due to the pandemic. Therefore, electricity consumption patterns in both residential and commercial buildings have changed. Ku et al. (2022) used individual hourly power consumption data within a machine learning framework to examine changes in electricity use patterns due to COVID-19 mandates in Arizona. Chinthavali et al. (2022) examined changes in energy use patterns on weekdays and weekends before and after the COVID-19 pandemic. Raman and Peng (2021) used residential electricity consumption data to reveal a strong positive correlation between pandemic progress and residential electricity consumption in Singapore. Li et al. (2021) analyzed data from apartments in New York to examine the impact of the number of COVID-19 cases and the outdoor temperature on residential electricity usage. Lou et al. (2021) found that the COVID-19 measures increased residential electricity consumption by 4–5% and exacerbated energy insecurity using individual smart meter data from Arizona and Illinois. Sánchez-López et al. (2022) explored the evolution of energy demands with hourly data among residential, commercial, and industrial demand during the first wave of COVID-19. Understanding how household hourly electricity demand changes after the pandemic, especially due to working from home, provides electricity system operators with valuable information in operation and management. Also, based on the changes in the spatial and temporal distributions of energy consumption, policymakers could make better decisions to increase the ratio of power supply from renewable energy sources.

The application of high frequency electricity data could help understand the electricity consumption patterns of specific consumer groups, especially families that have adopted new technologies [e.g., Photovoltaics (PV), batteries, and electric Vehicles (EV)]. Qiu et al. (2022a) applied a difference-in-differences approach to 1600 EV households' high frequency smart meter data and found that people increased EV charging in lower-priced off-peak hours. Another study (Oliva and MacGill, 2014) found that households who installed solar panels could consume more electricity than before. Similarly, Qiu et al. (2019) estimated an 18% solar rebound effect using hourly electricity consumption data and hourly solar panel data from 2013 to 2017 in Phoenix Arizona. Al Khafaf et al. (2022) compared the electricity consumption of consumers with PV and energy storage systems (ESS) against consumers without ESS using over 5,000 energy consumers' 30-min window smart meters recording. They found that on extremely hot days, installing batteries, to some extent, reduces peak power usage in the afternoon. Using household hourly electricity data in Arizona, Qiu et al. (2022b) found a high degree of heterogeneity in consumption patterns of PV consumers after adding battery storage. As to heat pump adoption, Liang et al. (2022a) provided empirical evidence from Arizona which suggested that heat pumps do not necessarily save energy. Besides, combining electric vehicle charging profiles with residential electricity data helps study the impact of EVs on electricity distribution networks (Hill et al., 2010; Neaimeh et al., 2015; Liang et al., 2022b). These patterns not only help residents explore the economic benefits of new technologies adoptions, but also answer whether and how those new technologies adoption has an impact on existing electric grid's capacity.

Forecast analysis relies on the data they're trained on, and high frequency smart meter data boosts the accuracy of the prediction model. High-resolution forecasting models with various data-driven algorithms need to be validated from high frequency data. Popularization of smart meters in recent years has created opportunities for improving household load forecasting. Accurate electricity load forecasting provides scientific theoretical support for the smart grid, like demand response, energy management, and infrastructure planning and investment. Sousa and Bernardo (2022) compared the accuracy of multivariate adaptive regression splines, random forests, and artificial neural networks to predict the load of the next day with 5,567 households' half-hourly readings. Shaukat et al. (2021) carried out short-term load forecasting by different models, such as artificial neural networks. Lin et al. (2022) combined smart meters, telephone surveys, demographic information, and physical attributes of 83 houses in Oshawa; and identified that the backpropagation neural network model is the best in predicting the annual electricity and gas consumption among eight data-driven algorithms. Fekri et al. (2021) proposed a load forecasting method that can continuously learn from new data and adapt to new patterns to test for load forecasting. Singh and Yassine (2018) proposed unsupervised data clustering and frequent pattern mining analysis on three datasets, then did forecasting with Bayesian network and achieved energy consumption forecast accuracies of 81.89%. The data resolution of the high-frequency smart meter reached 6 s and 1 min, respectively.

3. Further applications of smart meter data

Beyond tracking consumption patterns and forecasting, further applications of smart meter data include studying household energy consumption behavior from the socio-economic perspective and assessing the impact of energy management strategies. Studying consumers' demand choices helps optimize electricity operations and balance electricity supply and demand in a timely fashion.

Besides, smart meter data can be used to support utility companies to do revenue protection.

Many papers use smart meter data to study household energy consumption behavior from the socio-economic perspective (Kang and Reiner, 2022a). Kaur and Gabrijelčič (2022) divided the electricity consumption dataset of 5,038 consumers in Slovenia into clusters and conducted a cluster analysis to identify the primary consumption profiles. Wang et al. (2022) investigated the impact of relationships among household members, community, and identity on electricity use. Lu et al. (2022) studied electricity use and household characteristics in a dynamic pricing experiment in a collective housing area in a Japanese community. Al Khafaf et al. (2022) studied how residential battery installation leads to behavioral changes in energy consumption patterns. Tang et al. (2022) used machine learning to identify the influencing factors of residential energy consumption patterns from a socio-economic angle. Tran et al. (2021) studied the end-use of electricity in 12 households in a purely electric apartment in Japan and found a significant relationship between household characteristics and electricity end-use. Andersen et al. (2021) linked smart meter data from Denmark in 2017 with detailed household characteristics derived from an administrative register to analyze the relationship between hourly electricity consumption levels and these characteristics.

Research also assesses the impact of energy management strategies [e.g., Time-of-use (TOU) pricing] and economic incentives on the demand side using smart meter data. Qiu et al. (2018) evaluated a voluntary business TOU pricing plan in the Phoenix metropolitan area and found a significant reduction in energy demand during peak hours. Applying hourly electricity data, Liang et al. (2021) estimated the electricity savings and social benefits of energy-efficient AC replacements under different pricing plans. Liang et al. (2020) also found that TOU consumers are more likely to have solar panels and estimated that TOU correlates to the similar impact of incentives provided by tax credits or solar adoption rebates of $2,070 to10,472. Oliva and MacGill (2014) examined the financial implications of two net-metering feed-in-tariffs (net-FiT) policies for residential photovoltaics and the returns for households. In another study, Oliva et al. (2016) also investigated the financial advantages of PV in a home, using actual half-hourly PV generation and electricity data in Australia. Considering the cost of battery energy storage systems, researchers study the decision-making of energy storage with smart meter data (Ratnam et al., 2015; Li et al., 2019; Raillard-Cazanove and Barbour, 2022). For example, Li et al. (2019) concluded that energy storage with a battery cost of $0.2/kWh or more was not economically feasible based on smart meter data and real-time PV generation in the studied region. Kantor et al. (2015) studied hourly household data from Ontario, Canada, to analyse the potential for households to have storage systems by manipulating two financial policy triggers. A deeper analysis of smart meter data ensures making evidence-based policy decisions. For example, Liang et al. (2020) suggested that policymakers could combine TOU and solar panels when implementing educational programs or providing financial incentives to consumers. Smart meter data can be also used to support utility needs, such as load profiling, asset loading, and revenue protection (e.g., the detection of tampering, theft or leakage). Canizes et al. (2022) presented a new approach to enhance consumer demand response participation and flexibility of renewable energy as an ancillary service are proposed to alleviate congestion in the low voltage distribution network. Munoz et al. (2022) presented the design, construction, and validation of a smart meter as load control that will become part of a household energy management system. From smart meter data and computer science, energy theft can be detected and addressed with precision. Gerasopoulos et al. (2022) reviewed and classified the energy theft problem in European Union using smart meter data. By imitating normal consumption patterns and compromising neighborhood smart meters simultaneously, Cui et al. (2022) presented an advanced, covert energy theft strategy from machine learning. Then, they designed a feature extraction scheme that will capture the relationship between attacks and customers, and developed a detection model based on deep learning. Tanwar et al. (2022) proposed an energy theft detection strategy, GrAb, using DL-based long short-term memory (LSTM) model, which will categorize the energy losses into technical, energy theft, and normal consumption.

4. Energy poverty

Research in energy poverty has also evolved because of high frequency smart meter data. Before, energy poverty, the inability of a household to meet its energy needs, is characterized by univariate or multivariate approaches (Alkire and Foster, 2011; Deller et al., 2021; Sy and Mokaddem, 2022; Wang and Lin, 2022), including four index (Apergis et al., 2022). Rao et al. (2022) evaluated energy poverty from three aspects: energy availability, energy affordability, and energy cleanability. Energy availability mainly refers to the proportion of the population supplied with electricity. Energy affordability includes per capita GDP, per capita development index, etc. Energy cleanability includes energy intensity, clean fuel accessibility and technologies for cooking, fossil fuel energy consumption, etc. These indicators' data are mostly obtained by questionnaires, but the lack of household consumption data hinders in-depth research on energy poverty.

The use of high frequency data recorded by smart meter extends the methodology for describing energy poverty, helping promote more targeted and effective energy poverty policies. Fine-grained data on electrical consumption allows us to study the impact of economic and social activities on electricity consumption and energy poverty (Fezzi and Fanghella, 2020), and also can be translated into relevant parameters describing electricity consumption, such as electricity Gini, to study energy inequality. Matching the hourly smart meter data of each household with socio-economic data could reshape the understanding of energy poverty and the implementation of energy poverty assistance. Lou et al. (2021) used smart meter data from Arizona and Illinois to show the differential influence of COVID-19 on different demographic groups. Chen et al. (2022) used electricity Gini calculated by smart meter data to study the inequality of electricity consumption and the vulnerability of adaptation. Other studies utilize smart meter data to detect household disconnections to portray energy poverty and to study its relationship with natural factors and household characteristics (Kang and Reiner, 2022b).

For example, Longden et al. (2022) studied the length and number of disconnections in remote indigenous communities in Australia and analyzed its relation to temperature extremes. Barreca et al. (2022) used disconnection dates from the smart meter of 300,000 low-income households in California from 2012 to 2017 to study the relationship between temperature and the risk of disconnection. However, most of the current electricity disconnection calculated by smart meters focus on the duration and number of disconnections, without distinguishing the causes of disconnection in detail. Some of the disconnections that are not related to energy poverty, such as self-disconnection due to traveling, are still counted, which interferes with the accuracy of depicting energy poverty. Therefore, the algorithms using smart meter data to detect disconnection can be refined more in future studies, which will help study energy poverty more accurately.

5. Research gaps

We summarize several areas that need to be further improved in the existing literature. First, most research currently focuses on developed economies, possibly because smart meters are widespread in these regions. However, as smart meter adoption increases, it is also worthwhile to study higher-frequency electricity usage patterns in underdeveloped areas as the differing consumer behaviors, as well as institution and market conditions in developing countries, might imply different electricity usage patterns compared to those in the developed regions. Second, for research on household service disruptions using smart meter data, the existing literature did not clearly distinguish power outages (a disruption in the supply of electricity to a specific geographic area) and power disconnections (a disruption in the supply of electricity to a customer due to non-payment of bills). As higher frequency and longer duration smart meter data become available, there is an opportunity to use machine learning models in conjunction with demographic data to identify electricity disconnections. Third, there are few empirical studies that estimate the impact of new technology adoption such as battery storage and electric vehicle in-home charging, partially due to the lack of data on such technology adoption. More studies are needed to empirically evaluate the impact of these new technologies because the actual consumer behaviors after adopting these technologies may deviate from those predicted by engineering models. Lastly, few studies have focused on the dynamic tracking of electricity consumption behavior and the exploration of interannual regularities in electricity consumption behavior. This helps understand the patterns and reasons for changes in behaviors over time, which provide implications for better optimization of consumer electricity consumption behaviors.

6. Conclusion

High frequency smart meter data increases the breadth and depth of the analysis of household energy consumption patterns. Firstly, a rich amount of studies in recent years applied high frequency electricity data to explore the overall impact of COVID-19 on household energy consumption and transition in pre- and post-pandemic. They focused on examining the policy interruptions such as the "STAY AT HOME" order in different states. Other studies, with the help of high frequency electricity data, could explore the private and social benefits of household new technology adoption, such as EV, PV, and battery energy storage systems. With smart meter data, these new findings provide reliable information and empirical evidence for residents and communities to better plan for the adoption of new technologies. Also, these empirical studies and scenario analyses can help the government optimize interventions and design more targeted policies to improve the social benefits of adopting these technologies. Secondly, the data boosts the accuracy of various energy prediction models with data-driven algorithms and underpins household and utility companies' dynamic energy management. Better forecasting also supports the government in infrastructure planning and investment. Besides, integrating high-frequency smart meter data with information about household characteristics, as well as natural and socio-economic factors, can facilitate a deeper understanding of their interrelationships. By doing so, it may be possible to target households with potential energy poverty and inform the development of energy assistance policies and programs. This approach can serve as a foundation for more effective policymaking and program design. Current federal and state energy assistance programs, such as the Low Income Home Energy Assistance Program and the Weatherization Assistance Program, focused on low-income households instead of energy poverty households. Evolving energy poverty studies could provide targeted energy vulnerability household assessment methods, not only based on income.

Moving forward, there are a few important research areas worth further exploring with the assistance of smart meter data. First, the pandemic has changed the way people work, such as working from home and online education. In the post-pandemic era, what will the new normal bring to energy transition and energy consumption? Some evidence has shown that residential electricity demand increased more than before; the peak time for electricity demand shifted; people could increase EV charging after the pandemic (Jiang et al., 2021). High prices and volatility caused by political instability have placed an excessive burden on consumers. How is this reflected in residents' electricity consumption patterns and consumer behavior through smart meter data? These findings are important for utility companies for better grid operation and management. For example, utility companies could design a wider choice of contracts such as the option for long-term prices to avoid excessive risks. Second, smart meter data, especially household sub-meter data, can help innovate dynamic pricing contracts. Designing real-time demand response programs relies on smart meters and dynamic pricing plans. This is promising for residential customers to take advantage of price variability with increasing penetration of technologies such as electric vehicles, solar panels, and battery storage. Third, with the promotion of smart meters, policymakers can better answer questions such as how to accurately define energy poverty, identify households who are in energy poverty in a timely fashion, and implement targeted assistance. This could significantly enhance the protection of vulnerable groups. We also need to inclusively understand and evaluate the impact of current energy poverty programs, refine energy poverty determination and the analysis of influencing factors, and based on this, prompt policy action to better address energy poverty. And distinguishing the disconnection caused by energy poverty helps make policies to protect vulnerable consumers in arrears from being disconnected. The fourth is to apply smart meters to indicate broader social behaviors. Electricity smart meters can evaluate and track population migration and housing vacancy rates. Lastly, a promising research direction is to utilize smart meter data to study the threat of natural disasters and extreme weather to vulnerable communities and find ways to reduce negative effects. Determining the optimal timing for the restoration of services is an area that warrants further investigation. The electricity consumption patterns revealed by smart meter data (such as energy limiting behaviors) combined with factors such as the severity of weather conditions, poor quality housing, income status, and poor health conditions will imply different degrees of energy restoration urgency and the extent to which vulnerable households are affected. Therefore, further research is needed to identify best practices for restoring power in a timely and equitable manner using smart meter data, especially for vulnerable communities.

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Impacts on manufacturing workers as part of a whole-system energy transition

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Providing access to good employment opportunities has become a key area of focus to ensure a just energy transition and to ensure that there is sufficient support for the technology transitions necessary for deep decarbonization. However, a societal transition to a decarbonized energy system will impact workers beyond those involved in energy resource extraction and energy production. Workers involved in manufacturing, especially those working in manufacturing industries that are energy- and emissions-intensive may face additional changes as those industries undergo technological changes. While discussions of the quality of jobs have focused on things like compensation, employment terms, and representation, other job dimensions, like the intrinsic characteristics of the work, health and safety, and work–life balance, stand to be directly impacted by technology change and are largely excluded from consideration. As these new technologies are developed and new energy sources are introduced to support manufacturing, we should also consider sociotechnical solutions that balance worker quality of life among other considerations like the utilization of new capital resources. Incorporating considerations across a wider definition of job quality dimensions will help to ensure that there is a sufficient workforce available to meet the demands of a decarbonization transition.

KEYWORDS

labor impact, decarbonization, job quality, manufacturing, industrial policy

Introduction

Meeting decarbonization targets will not only require the production of new zero-carbon sources of energy but also requires that we develop technologies that can use this energy. While other high-emitting sectors in the US such as transportation and electric power generation have made progress in reducing emissions in recent years, industrial emissions have remained relatively consistent (Greenhouse Gas Inventory Data Explorer, 2023) and are poised to become the second largest source of emissions in the US. Eenergy-related industrial emissions are driven by emissions from manufacturing as well as emissions from mining, construction, and agriculture. The diversity of input energy sources and process operations are significant contributors to this delay in reducing industrial energy-related emissions (Cresko et al., 2022), but technical strategies are centering on a few strategies for achieving decarbonization: increasing energy efficiency, electrifying manufacturing processes, using low-carbon fuels, feedstocks or energy sources, and using carbon capture and storage for processes that cannot be decarbonized by other means.

These new technologies will also require a sufficient workforce to implement them at scale. As steps are taken to fund research, development, and deployment (RD&D) projects to begin the technology transition of the industrial sector, there are calls to incorporate community-based feedback into the development of a workforce to serve these new industries (Cresko et al., 2022), and projects soliciting RD&D support are tasked with providing information on how they will create and sustain "high-quality and good paying jobs," and support "inclusive and supportive workforce development" (The White House, 2021). Much of this language echoes early just transition concepts identified in labor movements in the 1970s. While fair wages are a clear and important factor in the overall quality of a job, using that as the primary metric for determining job quality minimizes the broader impacts that jobs have on people's lives; worker roles are some of the most important social and economic roles held by most adults, and they dictate how most adults spend much of their time (Hauser and Carr, 1995; Rogers et al., 1999). Access to higher-status jobs also results in a lower risk of death than lower status jobs, even when controlling for factors like income and education (Rogers et al., 1999). While many of the factors that may increase or decrease the status or quality of a job are organizational or human resource management decisions, job quality can also be influenced by the technologies being developed to decarbonize the production of goods, and therefore require sociotechnical solutions.

The remainder of this article is organized as follows: There is additional context about the development of the just transition as a concept from early labor movements. Then, data about how the industrial energy transition compares to the energy production transition is provided. Next, a brief overview is given of social science perspectives on job quality and the impacts of job quality on workers' quality of life. Finally, a discussion follows regarding how to begin to develop sociotechnical metrics for ensuring that the industrial decarbonization transition centers opportunities for good employment within their design.

Jobs as a component of just transitions

The beginnings of the concept of a just transition are often attributed to Tony Mazzocchi of the Oil, Chemical, and Atomic Workers Union (OCAW). He posited that the industries that OCAW members worked in were the cause of health and environmental problems, and he organized strikes at several refineries over health and safety concerns (Morena et al., 2018). By the 1990s, after several decades of corporate-sponsored studies asserting that environmental regulation would result in job losses, the concept of a labor-focused just transition solidified around the idea that labor unions can advocate for both worker and community benefits, along with providing workers with resources necessary to retrain for new jobs so that environmental protection did not result in mass unemployment (Henry et al., 2020; Wang and Lo, 2021).

Academic focus on just transitions began more recently. Many of the academic studies on the labor impacts of the energy transition tend to focus on the quantity of jobs that will shift away from fossil fuel energy production and toward renewable energy production (Wei et al., 2010; Garrett-Peltier, 2017; Ram et al., 2022). More recent studies also aim to determine the geospatial distribution of these labor impacts (Mayfield et al., 2021; Vanatta et al., 2022). Some studies have aimed to compare how the quality of these redistributed jobs may change as part of the energy transition (Popp et al., 2022), while others have examined how job quality, primarily in the form of wages, may impact the energy transition (Mayfield and Jenkins, 2021). Generally, these studies find the additional labor costs associated with wages and other benefits have minimal impacts on the cost of transitioning energy production. While some studies have focused on the manufacturing of the technologies used in low-carbon energy production, there has been little focus on how a decarbonization transition will impact other areas of manufacturing.

Comparing energy use transitions to energy production transitions

The scope of the manufacturing sector, both in energy-related emissions and employment, raises challenges when comparing the sector to energy production transitions. Figure 1A shows end-use energy-related CO_2 emissions in the US by segment of the manufacturing sector in 2021, along with total employment (Figure 1B) in each of those sectors. For comparison, energy-related CO_2 emissions and employment in the mining sector, which includes oil and gas extraction, coal mining, and other mining activities for metallic and non-metallic ores, is also shown. While employment within the mining sector is down from previous peak levels, the cumulative effects of a successful decarbonization transition of the industrial sector will ultimately impact more employees in the U.S. economy going forward.

While the number of employees impacted by industrial decarbonization may be larger, the impacts on jobs themselves will also be different. Unlike the energy transition, where many of the jobs lost were categorized as mining jobs while jobs gained were in sectors like construction or manufacturing, industrial decarbonization is unlikely to lead to cross-sector job switching. However, within the manufacturing sector, there are likely shifts away from some industries (e.g., refining) to other industries, especially to support the production of zero-carbon technologies. Even in industries that may not play a direct role in supplying the goods necessary to support the energy transition, the use of alternative sources of energy—for feedstocks or as process energy—may result in changes to manufacturing processes and associated jobs. It is important to note that these energy technology transitions are not the only challenge facing manufacturing. Automation is changing the skill sets necessary to perform job tasks, and overall, the sector saw a decrease in total employment during the COVID-19 pandemic. Trade reports indicate that manufacturers are already facing challenges to fill manufacturing positions, and workers cite concerns about both wages and work–life balance considerations as primary factors that may lead them to leave manufacturing (Wellener et al., 2021).

For manufacturing processes where the feedstock must change to decarbonize, while some feedstock replacements may be perfect drop-ins to existing processes, other manufacturing facilities may require additional retrofits or process changes to use zero-carbon

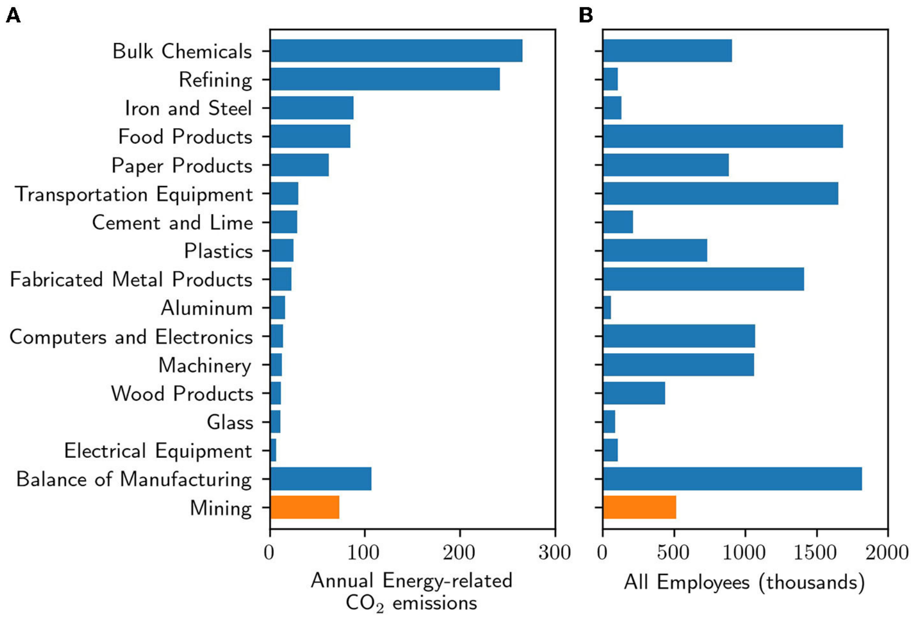

FIGURE 1
Energy-related CO_2 emissions **(A)** and employment **(B)** across the manufacturing sector in 2021. Data for the mining sector, which includes oil and gas extraction, is included (shown in orange) for comparison (U.S. EIA, 2022; U.S. BLS, 2023).

alternatives. These retrofits may include more automation, which has been shown to reduce the number of jobs, especially middle-skill manufacturing jobs, polarizing jobs as very low- or high-skilled (Autor et al., 2008; Acemoglu and Autor, 2011). However, if these process modifications include other technological changes, the introduction of new steps in the manufacturing process may counteract some of this polarization as combinations of low-skill and medium-skill processes are completed by workers (Combemale et al., 2021).

The transition to new energy sources may also impact manufacturing. Today, many manufacturing facilities, especially for energy-intensive industries such as chemicals, iron and steel, and cement, produce energy on-site from fossil resources. Often, these facilities have combined heat and power capabilities to provide both electricity and heat resources, and are therefore not dependent on the electricity grid for meeting their energy needs (Otis, 2015). While these facilities may experience energy outages as a result of a lack of access to energy resources, outage events for fossil fuel resources are infrequent, especially for industrial consumers with firm contracts (Freeman et al., 2020). Transitioning to using more electricity may result in additional scheduling challenges as a result of normal grid outages. Similarly, electricity prices are variable on an hourly time scale, while coal and natural gas contracts will last for months. This additional variability may also introduce new opportunities for facility managers to provide demand response resources to the grid (Nezamoddini and Wang, 2017), which may impact worker schedules as production output would be lower or completely curtailed when providing these services. The exact combinations of electricity generation resources and market pricing structures can introduce opportunities for more frequent adjustments to worker schedules around the availability of low-cost energy, which can exacerbate existing challenges with work–life balance.

Social science perspectives on good and bad jobs

Many studies of employment and job characteristics emphasize the impact that jobs can have on the health and well-being of workers, their families, and their communities. Bad jobs can increase rates of poverty, perpetuate gender inequality, and constrain social mobility (Carré et al., 2012; Adamson and Roper, 2019). The mechanisms that cause negative impacts from bad jobs can vary. While traditional employment models imply that workers are able to control the hours they work, in practice there are often mismatches in worker schedules, with many workers feeling overemployed because of long work weeks or undergoing temporary periods of over- and under-work reflecting other market conditions. This mismatch induces a feast-or-famine approach to employment, especially in industrial manufacturing sectors (Bluestone and Rose, 1997; Reynolds, 2004; Reynolds and Aletraris, 2006; Reynolds and McKinzie, 2019). Disparities between the hours workers would like to work and the hours they are scheduled to work can induce different types of stress: economic stresses if they are working fewer hours than they would like to work, and additional difficulties in balancing non-work family obligations if they are scheduled for more (or different) hours than they would ideally work (Reynolds, 2014). Beyond the number of work hours, not all combinations of work hours have the same benefits to workers; working non-standard schedules that include evenings, nights, or rotating schedules pose health risks and social costs (Presser, 2003).

While there is significant evidence that bad jobs have negative outcomes, determining what constitutes a good job has been harder to define. Many of the definitions of good jobs also align with particular branches of social science. Economic research typically focuses on wages and other compensation, while sociologists may focus on the intrinsic quality of work and public health researchers focus on the impact of work schedules and work–life balance. Warhurst et al. identified six key dimensions of job quality across different disciplines that study job quality: pay and other rewards, intrinsic characteristics of work, terms of employment, health and safety, work–life balance, and representation and voice (Warhurst et al., 2017). For each of these dimensions, they emphasize the importance of both objective and subjective measures of job quality. Objective measures focus on the ability of a job to meet workers' needs, while subjective measures account for individual preferences for job features.

Discussion

Although all six dimensions of job quality have a role in a just transition to a decarbonized economy, three may be directly influenced by the technological changes necessary to decarbonize the industrial sector. The intrinsic characteristics of a job may change as the new technologies and energy sources require different combinations of skills from workers, and potentially introduce further automation or oversight that can impact worker autonomy and variety of their jobs. However, the introduction of new manufacturing processes may also require more middle-skilled tasks, counteracting some of the polarization into high- and low-skill jobs common when manufacturing becomes more automated (Combemale et al., 2021). Transitioning to decarbonized manufacturing processes could also impact the meaningfulness and fulfillment workers gain from their jobs if they believe they are making significant contributions to larger societal goals. Understanding which skills may persist or grow in demand in decarbonized manufacturing jobs and which skills are no longer useful will help to determine how workers are trained for these positions. Additional study of how workers in a decarbonized economy feel about the meaningfulness of their work can also help to clarify what job attributes increase their overall satisfaction.

Work–life balance may also be affected by a decarbonization transition. The use of variable renewable energy may introduce more uncertainty into worker schedules, and adjusting manufacturing schedules to utilize least-cost energy sources where prices vary hourly may require different worker schedules. Energy-intensive processes are likely to be the most exposed to these changes, and we should aim to measure the working hours, reliability, and percentage of non-social working hours on worker schedules to ensure that these jobs are attractive enough to maintain the workforce necessary to support these industries. Technology transitions to decarbonize industrial processes may also impact the health and safety of workers; alternative processes may reduce the operating temperatures and pressures, instead utilizing catalysts or electrical potentials to create the thermodynamic conditions necessary for the chemical reactions that drive production processes. While reducing the high temperature and pressurized environments workers are exposed to may reduce the potential for some accidents, additional risk analysis of new processes should consider the potential for multiple risk pathways.

Other job quality dimensions, such as rewards and pay, terms of employment, and representation and voice are very frequently found in discussions of the dimensions of good jobs in the decarbonization transition. While these dimensions can be used to compensate for potential adverse effects from the technological transition to decarbonized manufacturing, they cannot overcome the job quality dimensions that are built-in by manufacturing technologies. As has been the case in other industries, if these job characteristics are too incompatible with workers' lives, then even increasing pay and improving employment terms are inadequate to ensure there is a sufficient workforce (Viscelli, 2016; Zabin et al., 2020). While much of the research focus for industrial decarbonization has focused on technical solutions, sociotechnical solutions may be better poised to address the additional challenge of ensuring a trained and willing workforce to participate in decarbonized industrial production. Metrics to determine the quality of jobs created in developing these jobs should consider how the jobs created affect multiple dimensions of job quality, in addition to ensuring adequate pay and worker rights, and metrics to assess the quality of technologies developed should consider more holistic metrics beyond utilization of capital and other non-labor resources. Failing to consider each of these job characteristics could mean that there are an insufficient number of workers available to sustain a decarbonized industrial sector at the pace necessary to meet climate targets.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=22-AEO2023&cases=ref2023&sourcekey=0; https://www.bls.gov/web/empsit/ceseeb1a.htm.

Author contributions

RC contributed to the conceptualization and writing of the manuscript.

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Conflict of interest

RC declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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Accomplishments and challenges of metrics for sustainable energy, population, and economics as illustrated through three countries

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The global Sustainable Development Goals require meeting multiple objectives on energy, population, economics, and ecosystems. Development and economic growth as defined by current metrics requires energy inputs, yet energy growth can also increase negative impacts on natural systems. To achieve sustainable development goals, policymakers and technologists will need energy system solutions that consider not only cost and efficiency but also population, quality of life, natural ecosystems, and culture that accommodates different starting points and transition timelines of various countries. To explore possible approaches, this perspectives paper summarizes energy in the context of economic growth and population, illustrating concepts through the diverse status and direction of three countries—Japan, the United States, and Bangladesh—as potential views into a post-growth sustainable future. Four fundamental questions on long-term energy development are identified, related to optimal energy use per capita, sustainable global energy demand, managing an energy transition with stable population, and the need for generalizable approaches across countries.

KEYWORDS

sustainable energy, sustainable development goals (SDG), metrics, Japan, Bangladesh, United States

1. Introduction

Access to energy is a fundamental requirement for life, from sunlight for plants to heat for human homes. Energy for human civilization has been under continuous transition, especially over the past 200 years, as societies expand beyond plant and animal power to include electricity, fuels, and advanced materials (Smil, 2004; Bashmakov, 2007). Energy demand growth and expansion of energy types has often been at the expense of the environment and human health (Smith et al., 2013). Thus, in recent decades, the emphasis has been to "ensure access to affordable, reliable, sustainable and modern energy for all," as stated in Sustainable Development Goal (SDG) 7 (United Nations, 2015).

Most energy technology researchers and developers are technologists thus their emphasis has been on developing new modern energy sources and advancing their reliability across delivery systems. Similarly, energy business and policy experts have focused on affordability (cost) and access for all. Energy cost, reliability, and access are quantitative and measurable objectives trackable at the system, country, and global scale (International Energy Agency, 2022; REN21, 2022; BP, 2023). As such, energy decisions have been largely economic and resource based with varying levels of cultural and political influence. Additionally, the provision of energy has been viewed as essential for absolute economic growth [measured by gross domestic product (GDP)] with variable strengths of this relationship emerging as countries develop and grow their industrial processes and their populations (Georgescu-Roegen, 1975; Stern, 2011). Even though they are measurable, it has been observed that current metrics to assess energy access and energy use, such as energy use per capita (which is lowest in low-income households), have proven inadequate to ensure the energy transition progresses or is measured in a just and equitable way (O'Sullivan et al., 2020; von Platten et al., 2020; Sovacool et al., 2021).

The remaining SDG 7 metric is sustainability, which has been variably defined vis-à-vis energy as clean, renewable, advanced, net-zero, and other versions of these terms (United Nations, 2015; Engel-Cox and Geocaris, 2023). Without an agreed upon qualitative definition, the energy community has not reached consensus on quantitative metrics defining sustainable energy, especially across global resources, supply chains, and cultures. Technoeconomic and life cycle assessment tools provide insights into the cost and to a lesser extent environmental impacts of energy technologies. However, quantitative metrics of the relationship between society and energy that can be measured, reported, and generalized for decision making on energy technologies do not seem to exist (Engel-Cox et al., 2022). One approach may be to evaluate energy technologies relative to the other SDGs (such as food, water, work, innovation etc.); yet, while the SDGs can complement each other, they can also conflict and may not be comprehensive across all possible sustainability measures of energy (Fader et al., 2018; Wiedmann et al., 2020).

The challenge of measuring sustainable energy is also tied to challenges of the concept of green growth and the ability to grow an economy while reducing environmental impacts. This requires a decoupling of a country's GDP from its energy and other resource use, which economic analysis has found to be persistently elusive (Parrique et al., 2019; Hickel and Kallis, 2020; O'Neill, 2020). While energy efficiency and a change from fossil to renewable energy reduces greenhouse gas emissions and other types of pollution per unit of energy generated, an overall increase in energy consumption has resulted in continued growth of the use of fossil fuels as well as other energy minerals for the transition (REN21, 2022). This is consistent with the finding that the primary accelerator of global environmental impacts is per capita consumption (Wiedmann et al., 2020).

A relationship between economics and sustainability in development has also been proposed using the Environmental Kuznets Curve (EKC), which suggests that a nation's level of development will also affect environmental quality, ultimately turning positive as per capita income increases. By utilizing an aggregated ecological footprint, researchers confirmed the EKC hypothesis, but found that GDP growth is not consequential for all aspects of the ecological footprint, suggesting some decoupling here (Kostakis and Arauzo-Carod, 2023). Further, it has been identified that while the EKC hypothesis is generally confirmed in 276 metropolitan areas around the globe for the residential and industry sectors, this was not the case for the energy sector (Fujii et al., 2018). Both EKC studies mentioned here suggest that support flowing from developed toward developing nations alongside additional renewable energy deployment will be critical to enable developing nations to proceed past their EKC tipping points.

Ultimately, some economists and scientists have proposed that meeting global climate objectives and other sustainability goals may require de-growth of consumption, higher resource efficiency, circular economy, and/or reduced population levels (Van Vuuren et al., 2018; Hickel and Kallis, 2020; UN Department of Economic, 2021). For some nations the linkage between labor per capita and economic growth has not been shown to be significantly related, in contrast to accepted classical growth models, and the stimulation of improving labor force participation, particularly for women, and encouraging better education and training opportunities may lead to economic growth in these cases (Taha et al., 2023).

To achieve objectives around sustainable energy, policymakers and technologists need to seek multiple energy system solutions that consider not only cost and efficiency but also population, quality of life, meaningful work, natural ecosystems, and a respect for culture. Global objectives for sustainability require a generalizable approach that also accommodates different starting points and transition levels of various countries. Using three countries as illustrations of different types and stages of sustainable development, this paper identifies challenges for future sustainable energy in the context of economics and population. Through these examples, the paper provides perspectives on measuring and addressing challenges for post-growth countries, growing countries, and the range of options in between. The overall objective is to advance the conversation of sustainable energy beyond technology and economics toward more holistic future-focused solutions.

2. Illustrative examples: Japan, USA, Bangladesh

Three countries with different baselines of energy consumption, population, and economic growth were chosen to illustrate similar and differing approaches. Specifically, these include:

- Japan: declining energy consumption and high energy access with declining population and low economic growth rate.
- United States: flat energy consumption and high energy access with a slightly increasing population and moderate economic growth rate.
- Bangladesh: increasing energy consumption and low energy access with a growing population and high economic growth rate.

Relevant facts about each country are described in this section with insights and comparisons presented in Section 3.

2.1. Japan

Due to a post-World War II baby boom, Japan's population increased year on year up until around the year 2010, since which the population has been in decline causing an aging, shrinking population with a median age of 48.4 in the year 2020 (United Nations, 2023). It is estimated that the median age in Japan will continue to increase as the population decreases in the foreseeable future. Although a population decrease may logically lead to an overall lower carbon footprint for the nation, it has been identified that as households with fewer and more elderly members increase, energy related household emissions also increase (Huang et al., 2019; Shigetomi et al., 2019). The overall peak for greenhouse gas emissions in Japan was predicted to have occurred in 2020, and as demographics shift in response to aging and shrinking, the contribution of lower income, older households is becoming more pronounced (Shigetomi et al., 2020).

The Japanese government recognizes this challenge and aims to usher in a new approach which they call Society 5.0 (Cabinet Office of Japan, 2023). Under the auspices of Society 5.0, the Japanese Government hopes to balance economic advancement with the resolution of social problems, with a special focus on the needs of the elderly and disparities caused due to the depopulation of rural areas. On the energy side, energy diversification and local production will be employed to ensure a stable energy supply with reduced emissions, and social innovations including robotics and automation are expected to support agriculture, manufacturing, and the elderly, specifically regarding aged care.

Japan is a relatively homogeneous society with very limited immigration when compared to other developed nations, while also highly dependent on imports of fossil fuels. This is also likely to be the case in terms of imported energy moving forward, particularly if a hydrogen economy is realized, perhaps meaning that emissions are avoided (or created) in other nations (Chapman et al., 2020). If Japan is to become a successful post-growth economy, will Society 5.0 ideals be sufficient to engender the transition such that energy goals and quality of life can be maintained long term?

2.2. United States

Similar to Japan, the United States (U.S.) is an industrialized country with a high GDP and well-developed energy infrastructure. However, unlike Japan, the U.S. population continues to grow, from growth rates of nearly 2% per year in the 1950s to a lower but still growing average annual rate of about 0.75% from 2010 to 2020 (United States Census Bureau, 2021b). U.S. population growth consists of both immigration and births with significant but variable contributions from both. It is notable that 2021 was a historic low in U.S. population growth (0.1%) and that the contribution from immigration exceeded births for the first time, although both were very low, a trend accelerated by the COVID-19 pandemic (United States Census Bureau, 2021a). The history of immigration has made the U.S. a highly diverse country, with about 14% of the current population born outside of the U.S. (United States Census Bureau, 2021c).

Energy use per capita in the U.S. is high, as is CO_2 equivalent emissions per capita, although both peaked about the year 2000 [U. S. Energy Information Administration, 2023]. Total energy use has been essentially flat and total CO_2 emissions have declined since 2000 even with continued population growth, largely driven by advances in energy efficiency and conversion of a portion of the electricity sector from coal to natural gas and renewables. Since U.S. GDP and GDP per capita grew significantly over the same time period, it indicates that the U.S. may be at least partially decoupling its energy resources use from economic and population growth.

While the U.S. electricity demand is expected to grow based on policies toward electrification of buildings and transportation, it is less clear if this will result in a change in overall total energy demand or merely a shift from fuels to power, with increased systemic efficiency. At the same time, U.S. population may stabilize or even start to decline based on immigration policy and economic advancement in other countries. The question for the U.S. is can it continue to improve its sustainability, reduce its resource use, and increase its efficiency to be more in-line with the energy intensity of Europe and Japan, while maintaining economic strength?

2.3. Bangladesh

Bangladesh is a rapidly growing, developing nation with an increasing appetite for energy, with energy consumption growing by 4.5% a year, alongside 6.9% annual economic growth (Enerdata, 2023). As Bangladesh aims to improve the quality of life of its populace, access to electricity is rapidly increasing, from approximately 55% in 2010, to 96% in 2020; however, grid reliability and resilience remains an issue and access to clean fuels for cooking is still limited to just 25% of households (Rose et al., 2020; Our World in Data, 2021).

Bangladesh is a young, rapidly growing nation, experiencing what some describe as a "demographic dividend", whereby the working age population is growing rapidly. In order to benefit from this dividend before population stabilizes, rapid digitalization and increased energy intensity are anticipated to provide employment opportunities for this burgeoning sector, whose impacts on the achievement of environmental goals is uncertain (Hosan et al., 2022). Recognizing this challenge, technological innovation will be critical in Bangladesh; further, the ability to learn from other nations in terms of the stimulation of innovation through conducive policy making will also be critical. As it has been shown that research and development, environmental taxes, and a growing GDP all have a positive long run relationship toward technological innovation, Bangladesh could shorten its energy transition timeline and more rapidly achieve its sustainable development goals through those approaches (Karmaker et al., 2021).

One concern for Bangladesh in its energy transition is the strong relationship between economic activity, GDP growth, and urbanization, which are all increasing, and energy consumption—intrinsically linked to carbon emissions in a heavily fossil fuel dependent nation (Rahman et al., 2021). The shift to renewable energy is of critical importance to Bangladesh. There is strong evidence from global energy transition evaluations that the shift toward renewable based electricity will pay dividends for lower income nations such as Bangladesh in terms of employment, health, and energy access (Chapman et al., 2021). A remaining question is at what point in the sustainable development of countries like Bangladesh is it reasonable to transition to new energy technologies and to aim to decouple energy consumption from economic growth?

3. Insights on sustainable energy development

While the literature has focused primarily on economics of energy and population, better metrics are needed from the perspective of sustainable energy development. Classic sustainable development means giving equal weight in decision-making to people, ecosystems, and economy, while providing for inter-generational equity for current and future generations. The challenge for sustainable energy is providing sufficient energy for quality of life for current and future humanity when it results in environmental impacts, no matter the energy source employed.

Consider the three countries described above and their economies as measured by GDP per capita (a proxy metric for economic growth). As seen in Figure 1, Japan's GDP per person is slightly increasing, even while Japan's overall GDP and population have remained flat for some 30 years. The U.S. continues to experience GDP growth both per capita and overall, as well as an increasing population. Bangladesh's GDP is currently comparatively very low but beginning to rise. Bangladesh's population has rapidly grown over the assessed period.

If GDP continues as a key economic measure, an emphasis on GDP per capita could be a better measure of benefit to individuals with less dependency on population growth and its environmental impact. However, increasing individual consumption at levels well beyond meeting quality of life indicators may raise GDP per capita without a corresponding environment benefit or worse. Multiple alternative economic metrics to replace GDP have been proposed and used in limited circumstances (Fleurbaey, 2009; Giannetti et al., 2015), although a full review beyond the scope of this paper. However, none have been accepted on a global scale. GDP per capita with all its flaws is a small step to a more nuanced metric but far from adequate, with new economic measures that encourage sustainability needed.

Energy represents a specific type of material consumption that can be generated from multiple sources with varying impacts and conserved through means of efficiency yet nevertheless results in similar utility outcomes. Considering consumption in terms of energy, Figure 2 explores power use over time for the three nations. Japan's moderate and flat electricity use per capita represents a middle path between the high but flat to declining power use of the U.S. and the low power use of Bangladesh, yet to reach an adequate level for its growing population. Japan residents have a high quality of life, so countries such as Bangladesh aspiring to energy use per capita at the U.S. scale may not be necessary yet the question remains, is the electricity consumption by Japan sufficient or also excessive? There is no consensus to what is the "right" amount of electricity per capita nor may there even be a single universal answer given the widely varying cultural, geographic, and infrastructure differences in each country.

Additionally, the decline in U.S. electricity demand per person represents a success in the advancement of energy efficiency in buildings, industry, and equipment. Yet, as electrification increases, the decline may be reversed although it may also be compensated for by a commiserate decline in direct fuel use. Similarly, Bangladesh may increase its use of electric cooking and other domestic activities, decrease fuel use, and potential grow its transportation options to include both electricity and fuels. Thus, while electricity access and use per capita is a key metric, its variability may depend on multiple end use factors in each country.

The ultimate challenge of these and similar metrics is defining measures of sustainability and the role of energy in achieving sustainable nations and energy transitions across a range of demographics and economics. The fundamental questions which need further research and insight include:

1. **What is the optimal level of energy use per capita for each country for a decent quality of life?** Energy use per capita should be a key metric, yet inter-country comparisons may need to be normalized or avoided. While this issue has been studied recently (Smil, 2004; Jackson et al., 2022), each country will have a different optimal energy use based on the country's size, natural resources, industrialization, culture, and climate. Energy use will need to include electricity, fuels, and direct heat, for transportation, buildings, industry, and other applications. Trade of materials and fuels may result in indirect transfer of energy use between countries, distorting use per capita. While imports and exports could be calculated in terms of energy use, a simpler approach would be to measure countries according to their own baseline. Significant multi-disciplinary analysis is needed to model energy use in consideration of human society and ecological impact, as well as the policies to achieve consensus objectives.
2. **What is the absolute global energy demand that is sustainable for the planet?** Another measure would be a total energy use metric for the planet, thus taking into consideration both demand and population. However, every type of energy engenders different environmental impacts, but they are often challenging to compare across energy types. A simplified metric of greenhouse gas emissions related to climate change has been used to represent a "cap" on energy and other emission sources, yet this misses a variety of other effects, including material extraction, air and water pollution, land use, etc. Additional inter-comparable measures of environmental impact beyond GHG emissions are needed to identify concepts around sustainable global energy capacity, which may include water demand and land use per energy unit, life-cycle efficiency, and recoverability or circularity.
3. **How can societies manage an energy transition with a stable or declining population?** As countries develop, the trend has been toward stable and then declining populations. When combined with more systemic energy efficiency, this could result in dramatic decreases in energy production. A reduced population could also provide unique opportunities for adaptation to the effects of climate change, including rewilding for natural buffer zones along coasts, increasing land conservation to address drought, and rebuilding communities at risk. Energy planning and larger economic measures rely on growth, yet quality of life should ideally remain high even if absolute growth declines. While economists are working on new metrics to replace GDP, an understanding and vision of an energy transition that reduces consumption overall and enables adaptation that benefits communities are essential. Policies and incentives that reward countries,

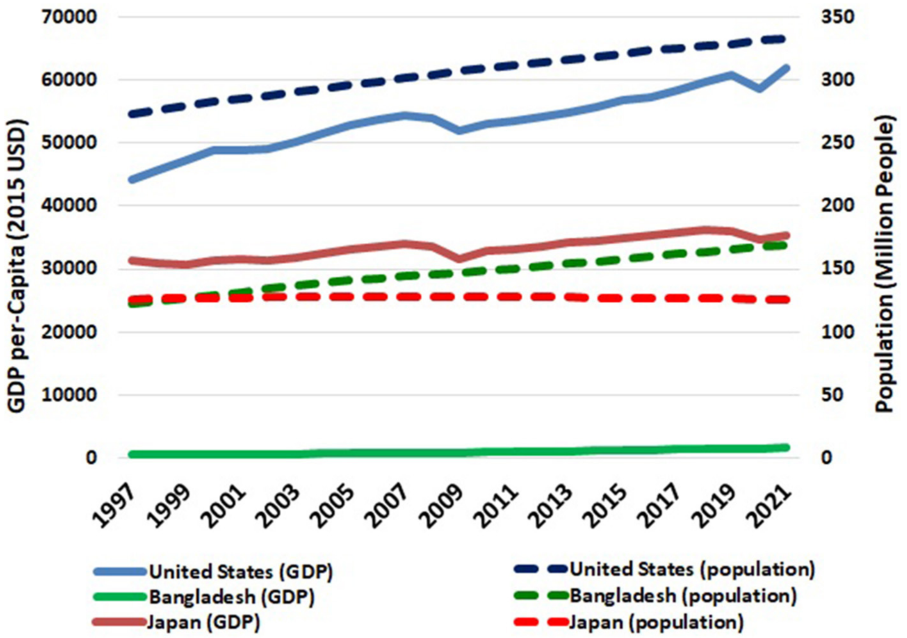

FIGURE 1
GPD per-capita (left-axis), and population (right axis) for the United States, Bangladesh, and Japan from 1997 to 2021.

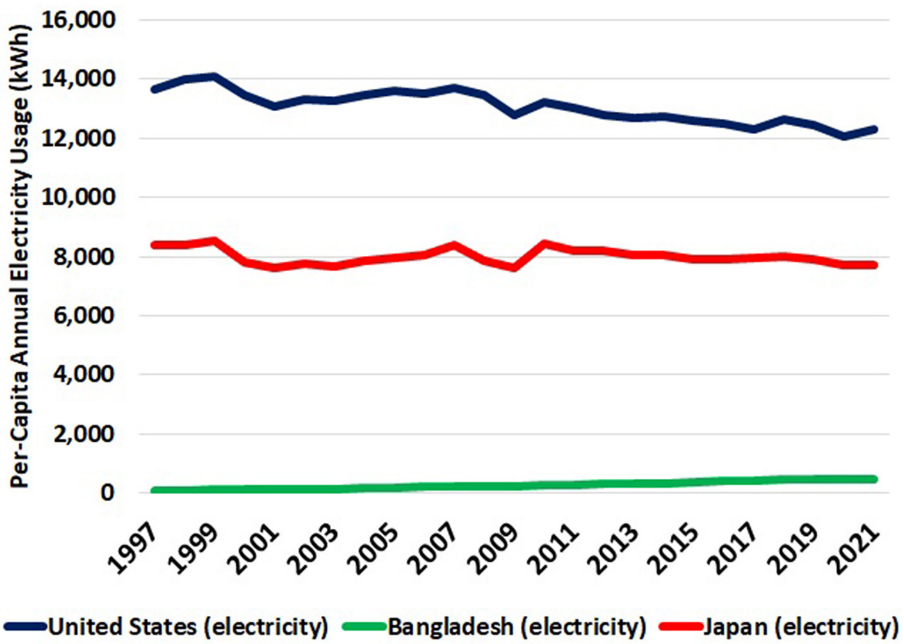

FIGURE 2
Electricity use per capita for the United States, Bangladesh, and Japan, 1997 to 2021.

industries, utilities, and individuals for reduced energy consumption, lower emissions, and increase efficiency in sourcing energy could incentivize investment and innovation even as demand declines.

4. **What generalizable approaches for sustainable energy could be used across cultures?** Every country is at a different stage of growth, with some still striving for energy access and others transforming and shrinking their energy footprints. A convergence of energy per capita between countries is overly simplistic and the narrative that energy development must go from coal to natural gas to renewables overlooks opportunities to speed up technological development and

deployment. New approaches are needed for countries to develop and maintain a high quality of life without economic and ecological disruption, no matter their starting point. Metrics that include more than just averages but also measure range of access to and quality of available energy would be important, since they focus more on the impact of energy on society rather than the sources of energy, which may vary significantly based on cultural and geographic resources.

When considering these insights and the three countries described, Japan may represent a harbinger of a near-future condition for the United States and eventually in coming decades for countries like Bangladesh. With a declining and highly urbanized population, a post-growth economy (representing lower levels of consumption), and recent growth in its renewable and low-GHG energy portfolio, Japan may be moving toward sustainability balanced across multiple development goals. Its concept of Society 5.0 with an emphasis on automation and technology is an experiment in how human society may need to proactively address socioeconomic trends that will become global in the next 50–100 years.

The U.S. might leverage its higher levels of natural resources and cultural diversity into energy and technology innovation as it seeks to reduce its global environmental impact. Bangladesh may leverage its demographic dividend and advance energy development quickly, ideally through technology leapfrogging, seeking to achieve a high quality of life without the higher energy demand experienced in other economies. Both may watch how Japan manages its current energy, technology, and demographic transition to better measure and develop their own sustainable futures.

In terms of all three nations, there are some existing approaches which may be applied to solving complex yet interrelated issues, one of which is the concept of energy justice, and the measurement of inequalities and their amelioration through energy poverty-based approaches. Multi-dimensional energy poverty measures are of particular interest here, as they not only use a variety of factors to measure energy poverty (energy access, fuel type usage, participation, pollutant loads, housing stock, climate variation etc.), they also recognize inherent differences both between nations, and within nations (Halkos and Aslanidis, 2023). Considering the resolution of SDG 7, the assessment and alleviation of energy poverty considers metrics across the facets of energy availability (energy consumption and access), affordability (income, GDP and device ownership), and efficiency (taking into account access to clean fuels and emissions) (Che et al., 2021).

Specifically, for Japan the development of a multidimensional index which takes into account housing construction and age, income and family structure identified that energy poverty is increasing in Japan since the 2020′s and single mother and single-elderly households are at high risk of energy poverty (Okushima, 2017). Further, as households which are suffering from energy poverty are less likely to be engaged in the energy transition, dealing with this issue is likely to engender multiple benefits (Chapman and Okushima, 2019).

For the U.S., the lack of a formal definition for energy poverty at the Federal level has been found to limit the effectiveness of the national response, in spite of the recognition of the issue and resource allocation toward its amelioration (Bednar and Reames, 2020). In addition, it has been clarified that there are racial disparities in energy poverty in the US, and that while low-income African-American households are particularly vulnerable to energy poverty, White households experienced the greatest level of energy poverty growth between 1990 and 2015. These outcomes were also found to hinge upon the types of energy used, demand levels, regions, socio-economic aspects and climate (Wang et al., 2021).

Bangladesh, often compared to its peers in South Asia, has a slightly higher level and intensity of multi-dimensional energy poverty than other South Asian nations, and the determinants of this energy poverty go beyond income and include family size (i.e., larger households experience higher levels of energy poverty), the reliance on traditional cooking fuels, and the age and gender of the primary breadwinner (Abbas et al., 2020). Interestingly, moving beyond demographic and socio-economic aspects, it was identified that increased financial inclusion and economic development in South Asian nations including Bangladesh led to energy poverty alleviation (Li et al., 2022), suggesting some crossover with EKC findings detailed in the literature review portion of this paper.

4. Conclusions

The next century will continue to be a time of transformation for society and the natural world. The past 200 years of industrial and information revolutions have resulted in an astonishing change in human culture, much of it bringing increased levels of comfort and benefit to many people. However, it has also resulted in increasing inequity between regions and countries, as well as caused a global decline in natural ecosystems, from species extinction to climate change. Energy technology advancements were a driver and key enabler of these transitions. Therefore, the sustainability revolution in the next 50–100 years toward more efficient, cleaner, and fewer energy resources requires new measures of sustainability to engender a better energy future for all. Multi-disciplinary cross-cultural collaboration between technologists, economists, sociologists, and political scientists from a diverse set of countries is needed to develop clear, measurable, and effective metrics for sustainable and equitable energy as human population begins to stabilize and continues to diversify.

Data availability statement

Publicly available datasets were analyzed in this study. The datasets utilized in this study derived from the World Bank World Development Indicators, a publicly available resource at https://databank.worldbank.org/source/world-development-indicators.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Brown-out of policy ideas? A bibliometric review and computational text analysis of research on energy access

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Introduction: The target of universal access to affordable, reliable, and modern energy services—key for individual, social, and economic well-being—is unlikely to be achieved by 2030 based on the current trend. Public policy will likely need to play a key role in accelerating progress in this regard. Although perspectives from the field of policy studies can support this effort, to what extent they have been employed in the literature on energy access remains unclear.

Methods: This study analyzed nearly 7,500 publications on energy access through a combination of bibliometric review and computational text analysis of their titles and abstracts to examine whether and how they have engaged with public policy perspectives, specifically, policy process research, policy design studies, and the literature on policy evaluation.

Results: We discovered 27 themes in the literature on energy access, but public policy was not among them. Subsequently, we identified 23 themes in a new analysis of the 1,751 publications in our original dataset, mentioning "policy" in their title or abstract. However, few of them engaged with public policy, and even those that did comprised a rather small share of the literature. Finally, we extracted phrases pertaining to public policy in this reduced dataset, but found limited mention of terms related to the policy process, policy design, or policy evaluation.

Discussion: While to some extent this might reflect the multidisciplinary nature of the research on energy access, a manual review of the abstracts of select publications corroborated this finding. Also, it shed light on how the literature has engaged with public policy and helped identify opportunities for broadening and deepening policy relevant research on energy access. We conclude that, despite their relevance to energy access, public policy perspectives have infrequently and unevenly informed existing research on the topic, and call on scholars in both communities to address this gap in the future.

KEYWORDS
bibliometric review, energy access, natural language processing, policy design, policy evaluation, policy process, sustainable development goal on energy (SDG 7), topic modeling

1. Introduction

Access to energy is important for individual, social, and economic well-being. Affordable, clean, and modern energy, while probably not sufficient, is essential for—among other objectives—alleviating poverty, reducing hunger, improving public health, broadening education, and fostering economic development. To cite just one instance, it is estimated that replacement of open fires and outdated stoves with clean cooking technologies could save 800,000 children, who die due to hazardous indoor air pollution, annually (SEforALL, 2023). The significance of energy access has been duly noted by international organizations as well. Illustratively, in 2014/2015, the United Nations (UN) included universal access as part of its Sustainable Development Goal on Energy (SDG 7) (UN DESA, 2023a).

The first target of SDG 7 (i.e., SDG 7.1) is: "By 2030, ensure universal access to affordable, reliable, and modern energy services" (UN DESA, 2023b). The focus of this target is on both access to electricity as well as access to clean cooking. However, the progress thus far has been inadequate to reach this target, and shows signs of slowing down further. According to UN DESA (2023b), the number of people without access to electricity decreased significantly from 1.2 billion in 2010 to 733 million in 2020. However, based on the current rate of progress, nearly 650 million people will still lack access to electricity by 2030. Further, 2.4 billion people —31 percent of global population—continue to use inefficient and high pollution cooking fuel. Based on the current trend, the increase in clean cooking will barely keep up with population growth and only 72 percent of the world is likely to have access to clean cooking even by 2030 (IEA et al., 2021).

The problem of energy access has a strong regional dimension as it mostly concerns the Global South, especially South Asia and sub-Saharan Africa. Over 98 percent of the population of Eastern Asia, Southeastern Asia, and Latin America has access to electricity (IEA et al., 2021). While electrification was low even in South Asia at the start of the previous decade, the region has made rapid progress since then. Presently, three of four people without access to electricity live in sub-Saharan Africa and the number of people without electricity access has in fact been increasing recently (IEA et al., 2021). Further, more than half the people without access to clean cooking fuel and technology live in Asia, but low-income countries in Africa have amongst the lowest rate of access to clean cooking in the world (UN DESA, 2023b). The challenge has been worsened by the COVID-19 pandemic; the number of people without access to electricity and to clean cooking is estimated to have actually increased between 2019 and 2021 due to a pause in implementation, shift in government priorities, rise in energy prices, and increase in poverty (IEA, 2021).

1.1. Addressing energy access from a policy perspective

Various interventions are required in different parts of the energy system in order to address the energy access problem. The expansion of energy infrastructure (whether centralized or decentralized), for example, is key for providing energy access in the long-term. For communities situated close to the electricity grid or gas pipeline, extension of the infrastructure is a plausible solution. However, such an approach can be more challenging to implement in a short-term in areas with no or little infrastructure. In this case, decentralized or stand-alone infrastructure or technologies can be necessary. Countries such as Bangladesh, Kenya, and Uganda have—in fact—successfully integrated grid, minigrid, and off-grid electrification to significantly increase electricity access over the previous decade (IEA et al., 2021), but many others have not.

Financing is another key intervention necessary for improving energy access. It is estimated that an annual investment of approximately USD 50 billion is necessary in order to achieve universal electricity access and USD 4 billion to achieve universal access to clean cooking (Climate Policy Initiative, 2019). In contrast, only USD 13 billion was mobilized—approximately 25 percent of the requirement—to increase electricity access and only USD 32 million—less than one percent of the requirement—was raised to provide clean cooking access (Climate Policy Initiative, 2019). Further, India and Bangladesh accounted for over 60 percent of the total tracked financing on energy access (Climate Policy Initiative, 2019). More financing will be especially important for countries in sub-Saharan Africa, which witness low and, in some cases, even declining investment in energy access.

Public policy at different levels of government also can, and—in all likelihood—will need to, play a significant role in accelerating progress toward SDG 7.1. Broadly, the literature on public policy has identified four categories of policy instruments (Hood, 1983), each of which is relevant for the energy access problem. First, governments can collect and/or provide reliable information, for example, in order to shed light on the status of energy access and to increase willingness to adopt clean cooking fuels and technologies (IEA et al., 2022). Second, governments can create regulations and/or standards, for example, that ensure interoperability of off-grid, minigrid, and grid technologies, help phase-out of high polluting fuels in the medium- or long-term, and create a social safety net for marginalized or vulnerable communities in order to increase their purchasing power. Third, governments can use economic incentives, for example, to promote fuel switching through better targeting of fossil fuel subsidies and to stimulate private investment for energy access (Zinecker et al., 2018; IEA, 2021). Finally, governments can mobilize their organizational machinery to build infrastructure, create new partnerships, and provide new services to the public.

1.2. Analyzing research in the policy realm for energy access

The academic field of *policy sciences* or *policy studies* has shed light on various dimensions of public policy(-making) which can help advance energy access. Here, we highlight three perspectives that are applicable in this effort.

First, the achievement of universal energy access will likely require the mobilization of policy relevant knowledge in the policy process in order to alter policy priorities, introduce new policy alternatives, foster policy innovation, or enhance policy implementation. The research on policy process addresses questions such as why and how specific issues come on the policy agenda (Kingdon, 1995); why specific alternatives are considered or favored to solve policy issues (Voß and Simons, 2014) and how they are calibrated (Haelg et al., 2020); why and how policies change (Sabatier, 1988; Hall, 1993; Baumgartner et al., 2018); how and when policies spread from one polity to another (Marsh and Sharman, 2009; Graham et al., 2013; Goyal, 2021); and how policies are implemented on the ground (and why they often change in the process) (Pressman and Wildavsky, 1984; Grin and Loeber, 2007). It can, therefore, help in understanding geographic and temporal variation in the processes and substance of public policy regarding energy access.

Second, the policies adopted to increase energy access will need to be cognizant of, if not coordinated or integrated with, policies at different levels of government that address other—potentially even competing—objectives of the energy system, such as energy security or environmental sustainability. The literature on policy design can aid the formulation of effective, forward-looking policies by addressing questions such as what the likely effects of different types of policy instruments and their calibrations in accomplishing policy objectives are (Olejniczak et al., 2020); how the different instruments in the policy "mix" interact with one another; to what extent are the various objectives and instruments in the policy mix consistent, coherent, and congruent with one another (Howlett and Rayner, 2013); whether the policy mixes at different levels of government are synergistic, additive, or counterproductive (Howlett and How, 2015); how the policies use procedural policy instruments to steer the policy process (Howlett, 2000); and whether the policy design is in line with policy capacities of the jurisdiction (Mukherjee et al., 2021).

Third, given the place of energy access on the international agenda, the evaluation of past policies or policies in other countries can facilitate lesson drawing and enable course correction through policy learning. The research on policy failure, policy success, and program evaluation has created useful knowledge in this regard. The key insights of this literature include: (i) a distinction among and appraisal of formal or government-driven, information or society-driven, and hybrid evaluation (Weiss, 1993; Hildén et al., 2014; Schoenefeld and Jordan, 2017); (ii) the need to distinguish among programmatic success, process success, and political success (Bovens et al., 2001; Vedung, 2006; Bovens, 2010; Marsh and McConnell, 2010a,b); (iii) criteria for assessing success (or failure) along each dimension (McConnell, 2010); (iv) the recognition that success along each dimension can vary over time (Goyal, 2021a); and (v) anticipation of policy success based on policy process or policy design characteristics (Bali et al., 2019; Goyal, 2021a).

While existing studies have conducted reviews of the research on energy access, to what extent and how the literature has engaged with public policy—specifically, perspectives on policy process, policy design, and policy evaluation—as a central theme is unclear. This study aims to address this gap through a review and computational text analysis of the bibliographic records of research on energy access.

2. Research methods

In this study, we combine bibliometric review and computational text analysis to examine whether and how scientific research has examined energy access and, within that area, to what extent policy questions have been pre-eminent.

Bibliometrics involves the—usually, quantitative—analysis of bibliographic records of scientific publications. A bibliographic record is an entry in a bibliographic database (such as Scopus or Web of Science) that contains identifying information as well as metadata of scientific publications. The fields in a bibliographic record include information on the authors, year, publication title, source, abstract, authors' keywords, and so on. A bibliometric review can shed light on the state of research on a topic and has previously been used in both energy research and policy studies (Goyal, 2017, 2021b; Goyal and Howlett, 2018; Goyal et al., 2022). We conducted the bibliometric analysis using the *bibliometrix* package in the R programming language (Aria and Cuccurullo, 2017). Bibliometrix is an open-source library with functions for mapping scientific activity and examining the relationships among different publications in a bibliographic dataset. Here, we focused on the following to obtain an overview of the dataset: (i) annual scientific production; (ii) most prolific authors, institutions, and countries; (iii) sources actively publishing in this research area; and (iv) publications with the most citations till date.

We use the following search query to identify publications relevant to energy access: "affordable energy" OR "clean cooking access" OR "electricity access" OR "energy access" OR "rural electrification" OR "SE4All" OR "sustainable energy for all" OR ["universal access" AND (cooking OR electricity OR energy OR fuel OR power)]. The search is conducted on both Scopus and the Web of Science, among the most widely used bibliographic databases, on 8 February 2023. On Scopus, it returned 6,541 publications while on the Web of Science it returned 5,432 publications. We used the Scopus of Science package (*version 0.0.4*) in Python (*version 3.10.10*) to combine publications from the two databases, resulting in 7,783 unique publications (4,190 publications were duplicated). After removing publications with no abstract, our complete dataset contains 7,498 publications. For analysis of policy-related research on energy access, we use a subset of 1,751 publications (hereafter, the policy subset) whose title or abstract mention the term "policy" (including its plural, "policies") in their title or abstract.

Subsequently, we conducted topic modeling—on publication titles and abstracts—to identify the key themes in the general literature (complete dataset) as well as the policy-related literature (policy subset). Fewer than 300 publications in the complete dataset were not in English, and even these contained a title and abstract in English. Topic modeling is a computational text analysis technique for "discovering" latent themes in a document collection based on mathematical/statistical analysis (Blei et al., 2003). While several topic modeling algorithms have been proposed over the past decade (Rosen-Zvi et al., 2004; Blei and Lafferty, 2007; Wang et al., 2007; Blei, 2012; Roberts et al., 2014), we use BERTopic for this study. BERTopic creates coherent topic representations using a novel approach based on state-of-the-art techniques in machine learning and natural language processing (Grootendorst, 2022). This involves document embedding using a pre-trained transformer model, dimensionality reduction, clustering, and identification of key terms within each cluster. The number of themes in the dataset is initially determined by the algorithm; we go through these manually and combine themes with over 80–85 percent similarity in order to obtain the final list of themes for our dataset. We repeated the bibliometric review and the topic modeling analysis for the policy subset to compare and contrast the findings in the general literature on energy access with the policy-related literature.

Subsequently, we examined the number of occurrences of key phrases pertaining to "policy" in order to delve deeper into the

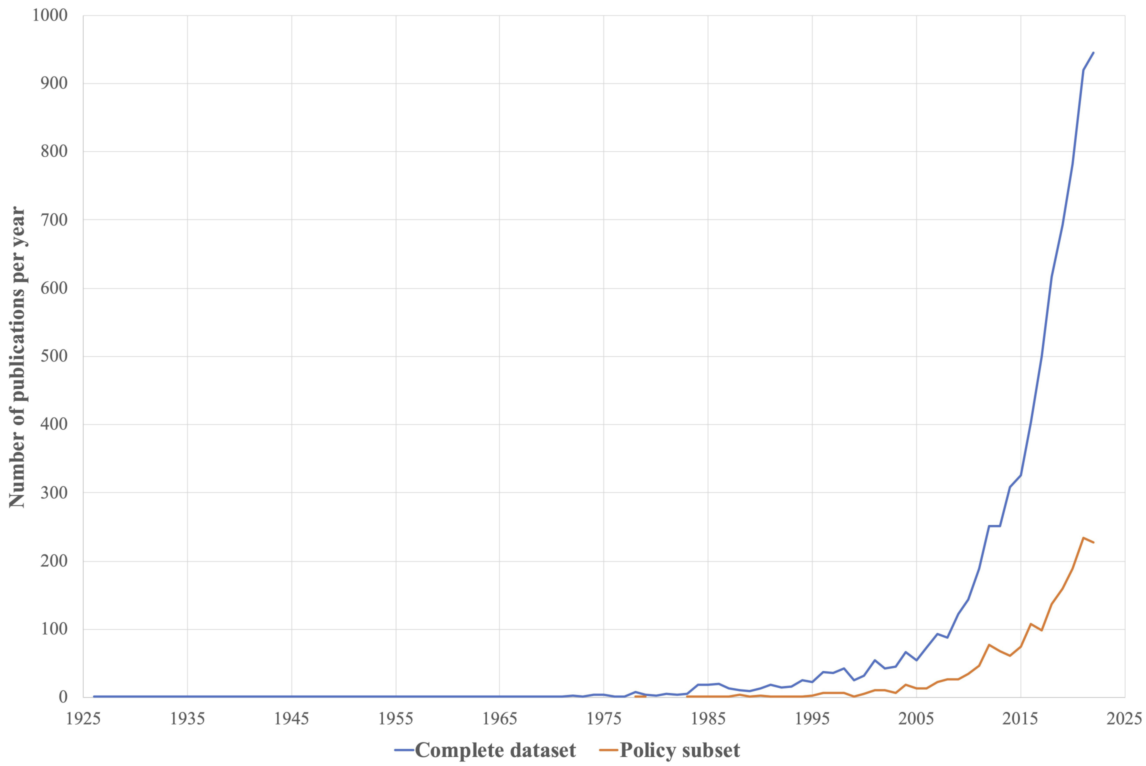

FIGURE 1
Number of publications on energy access per year.

mention of public policy within this dataset. This analysis of term occurrence used the KeyphraseVectorizer package in Python. KeyphraseVectorizer extracts key phrases matching specific parts of speech (in our case a noun phrase) in a document collection and counts their occurrences per document in the collection (Schopf et al., 2022). The phrases relevant to policy process, policy design, or policy evaluation were then identified and classified based on our knowledge of public policy. It is, of course, plausible that in a multidisciplinary research field—such as that of energy access—authors do not use the terminology of policy sciences or policy studies even though they engage with the notions of policy process, policy design, or policy evaluation (especially in the abstract). Therefore, we also reviewed abstracts of 10 percent of the policy subset, selected randomly, to check whether our findings regarding the volume of research on policy processes, policy design, and policy evaluation were robust. In addition, a close reading of abstracts of this randomly selected subset led to the inclusion of generic phrases that might also help identify work pertaining to the policy process (e.g., "coalition" or "policy direction"), policy design (e.g., "policy feature" or "policy scenario") or policy evaluation (e.g., "effective policy" or "policy lessons"). The abstracts of the publications selected through this process were reviewed manually to check to what extent and how the literature has delved into the policy process, policy design, or policy evaluation.

Our research design suffers from at least two limitations. First, while a manual review of select abstracts allows us to corroborate the centrality of policy process, policy design, or policy evaluation to the publication, it does not capture several other types of engagement with policy studies. These include, for example, a review of the research in policy sciences to inform the research question, the use of methods of policy analysis to design the study, and a discussion of policy relevant literature to inform recommendations for public policy and future research. Second, by limiting our search to Scopus and the Web of Science, we miss out on relevant publications not indexed by these. This is likely to be especially true for research on energy access that may have been published in more localized sources, for example, for higher policy impact.

3. Results

3.1. Overview of the datasets

As mentioned earlier, our complete dataset consists of nearly 7,500 bibliographic records. The earliest publications in this field are Post (1926), Keepper (1938), and Landis (1938), all focusing on rural electrification in the United States. However, the number of publications before 1970 was fewer than 10 and before 1980 was fewer than 50 (Figure 1). Energy access only started receiving more attention in the 1980s with over 100 publications in that decade alone. The field has grown exponentially since then, witnessing over 250 publications in the 1990s, nearly 700 publications in the 2000s, and over 3,500 publications in 2010s. This decade has seen even more activity; for example, in 2022 over 750 publications were published on the topic. Meanwhile, policy-related research has

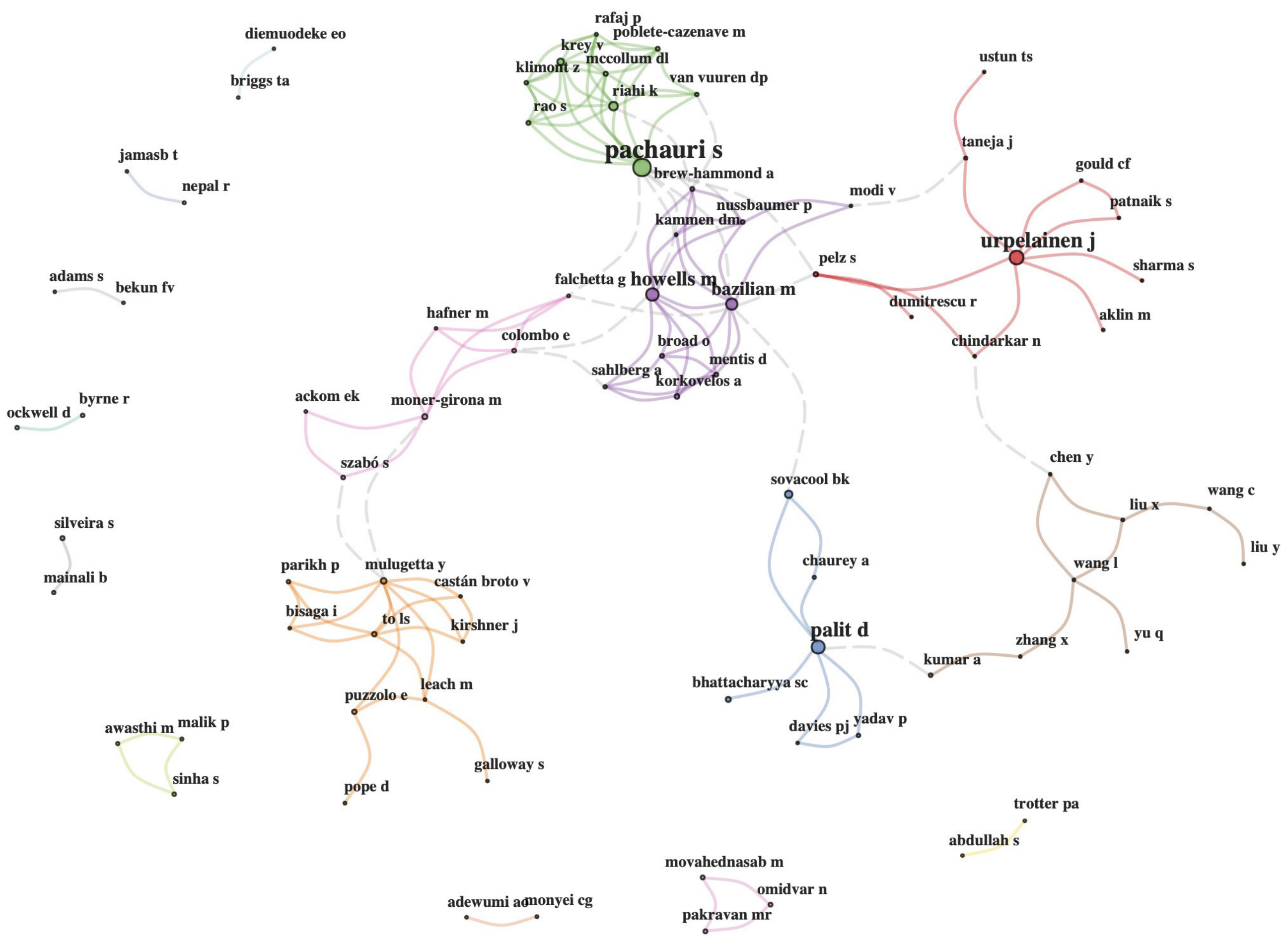

FIGURE 2
A co-authorship network of the 100 most prolific authors on energy access. A node in the graph depicts an author. The color of the node indicates its cluster, calculated based on the structure of the collaboration network. A link connecting two nodes indicates a co-authorship relationship. A link between nodes within the same cluster is depicted using a solid line while a link between nodes from different clusters is depicted using a dashed line. The size of the node as well as the label is indicative of the degree of the node (i.e., the number of co-authorship relationships).

grown significantly since around 2011, with over 100 publications in 2016 and more than 200 since 2021. The exponential growth in the volume of scientific research on energy access is possibly an indication of the increase in attention to the problem as well as the success of the Millennium Development Goals (MDGs) and the SDGs in raising its profile.

Research on energy access has involved over 15,000 authors, with an average of 3.4 co-authors per publication. About 600 authors have written five or more publications in this field while about 150 authors have 10 or more publications. A co-authorship network of the 100 most prolific scholars in this field is shown in Figure 2. J. Urpelainen is the most prolific author in this field with 67 publications on energy access (Table 1). Other authors who have published frequently in this field include A. Kumar (n: 45), D. Palit (n: 43), S. Pachauri (n: 41), and E. Colombo (n: 38). J. Urpelainen (n: 28), D. Palit (n: 27), and S. Pachauri (n: 25) appear in the list of the most prolific authors in the policy subset as well, along with M. Bazilian (n: 17) and B. Sovacool (n: 17).

Based on the institutional affiliation of the corresponding author, the countries with the most publications in the complete dataset are: the United States (n: 587), India (n: 416), the United Kingdom (n: 383), China (n: 382), Germany (n: 181), South Africa (n: 168), Spain (n: 141), Italy (n: 128), Sweden (n: 104), and Australia (n: 103). This suggests that the Global South has played a more prominent role in this research area than in areas such as the energy transition (Goyal et al., 2022). A comparison with the policy subset reveals that institutions in the United Kingdom, Australia, and Germany have a relatively high ratio of publications in the policy subset (38 percent, 34 percent, and 30 percent, respectively), while institutions in Spain and China have a relatively low ratio (15 percent and 19 percent, respectively).

A close look at institutional activity—based on the number of authorships—shows that Politecnico Di Milano (n: 157), KTH Royal Institute of Technology (n: 125), the University of California (n: 121), the International Institute for Applied Systems Analysis (n: 109), North China Electric Power University (n: 106), and the University of Cape Town (n: 103) have all published over 100 documents in this field (Table 2). Amongst the 15 most prolific institutions in this field, the International Institute for Applied Systems Analysis, University College London, the University of

TABLE 1 The most prolific authors on energy access.

Complete dataset		Policy subset	
Author	*N*	Author	*N*
J Urpelainen	67	J Urpelainen	28
A Kumar	45	D Palit	27
D Palit	43	S Pachauri	25
S Pachauri	41	M Bazilian	17
E Colombo	38	BK Sovacool	17
L Ferrer-Marti	35	M Howells	16
Y Li	35	SC Bhattacharyya	11
Y Liu	35	Y Mulugetta	9
M Bazilian	32	K Riahi	9
SC Bhattacharyya	31	A Kumar	8

TABLE 2 The institutions with the most authorships on energy access.

Institution	Complete dataset	Policy subset	Policy relevant ratio (%)
Politecnico Di Milano	157	25	16%
KTH Royal Institute of Technology	125	49	39%
University of California	121	25	21%
International Institute of Applied Systems Analysis	109	83	76%
North China Electric Power University	106	20	19%
University of Cape Town	103	19	18%
University of Oxford	81	9	11%
University College London	74	35	47%
Imperial College London	72	28	39%
Columbia University	70	29	41%
Delft University of Technology	70	6	9%
University of Cambridge	64	28	44%
Indian Institute of Technology	60	11	18%
Tsinghua University	57	15	26%
University of Strathclyde	57	12	21%

Cambridge, and Columbia University have a relatively high ratio of policy relevant publications (76 percent, 47 percent, 44 percent, and 41 percent, respectively).

While publications on energy access thus far have appeared in over 2,500 sources, there is a relatively low average of approximately three publications per source. Indeed, a majority of these sources have only one publication in this research area and 100 sources have 10 or more documents published. The sources with the most publications include: Energy Policy (n: 302), Renewable and Sustainable Energy Reviews (n: 298), Energy for Sustainable Development (n: 224), Renewable Energy (n: 222), Energies (n: 177), Energy Research and Social Science (n: 172), Energy (158), Applied Energy (n: 89), Sustainability (Switzerland) (n: 77), and the Journal of Clean Production and Sustainable Energy Technologies and Assessments (n: 63 each). The prominent presence of these sources even in the policy subset—with only a slightly different ranking in some cases—indicates that the importance of public policy for addressing energy access is acknowledged by the key avenues and communities in this field. It is, however, striking to note the absence of journals focusing on public policy broadly in this literature. Among prominent journals in public policy, only Global Policy (n: 3), the Review of Policy Research (n: 3), the Journal of Asian Public Policy (n: 2), the Journal of Public Policy (n: 1), and Policy and Society (n: 1) have a presence in the complete dataset.

3.2. Themes in the research on energy access

A list of the globally most cited publications within this dataset provides a preview of the themes that have been discussed in this research area (Table 3). Here, we observe significant emphasis on different technological alternatives in the context of energy access. Owusu and Asumadu-Sarkodie (2016), for example, highlight energy access as an opportunity associated with renewable energy. Similarly, other studies emphasize the potential of small hydropower (Paish, 2002), sustainable hydrogen production (Navarro Yerga et al., 2009), waste sludge (Tyagi et al., 2013), bioenergy (Creutzig et al., 2015), and DC microgrid technology (Kumar et al., 2017) in providing affordable and clean energy for all. Meanwhile, Zarfl et al. (2015) caution that significant increase in hydropower capacity alone will be insufficient for closing the electricity gap. In contrast, Shiu and Lam (Shiu et al., 2004) show that electricity consumption has a positive effect on economic growth and call for accelerating rural electrification in China. Two studies mention energy access in the context of the ongoing energy transition: Newell and Mulvaney (2013) contend that energy access is a key aspect of a just transition to a low carbon economy while Pachauri and Jiang (2008) note a significant difference in the share of households with electricity access between China and India.

While total citation count is one measure of the broad impact of a publication, it does not necessarily indicate the impact of the publication within the research area of energy access. The local citation count of a publication (i.e., the number of documents within this dataset that cite the publication) can shed some light here (Table 4). In general, we observe three broad strands of research that have high local citation count. The first includes studies that delve into the economic or social impact of energy access, for example, in the form of a gain in labor productivity (Kirubi et al., 2009), increase in female employment (Dinkelman, 2011), and higher literacy rate (Kanagawa and Nakata, 2008). The second, once again, focuses on alternatives—often based on renewable energy—for increasing energy access, spanning off-grid, micro- or mini-grid, and grid extension (Deichmann et al., 2011; Palit and Chaurey, 2011; Szab et al., 2011; Alstone et al., 2015;

TABLE 3 The globally most cited publications on energy access.

Study	Citations	Citations per year
Owusu and Asumadu-Sarkodie (2016)	1179	147
Zarfl et al. (2015)	1155	128
Paish (2002)	657	30
Shiu et al. (2004)	542	27
Navarro Yerga et al. (2009)	463	31
Tyagi et al. (2013)	421	38
Creutzig et al. (2015)	414	46
Kumar et al. (2017)	411	59
Newell and Mulvaney (2013)	401	36
Pachauri and Jiang (2008)	360	23

TABLE 4 The locally most cited publications on energy access.

Study	Local citations	Global citations	LC/GC ratio (%)
Kirubi et al. (2009)	140	258	54.26
Dinkelman (2011)	122	356	34.27
Kanagawa and Nakata (2008)	112	286	39.16
Szab et al. (2011)	103	196	52.55
Mandelli et al. (2016)	102	252	40.48
Palit and Chaurey (2011)	101	194	52.06
Alstone et al. (2015)	94	242	38.84
Cook (2011)	83	163	50.92
Deichmann et al. (2011)	81	203	39.9
Bhattacharyya (2006)	78	193	40.41

Mandelli et al., 2016). The third includes studies with a more explicit message for public policy: Cook (2011) highlights the need to focus on livelihoods rather than on cost recovery in order to increase rural electrification while Bhattacharyya (2006) stresses the importance of looking beyond rural electrification (in India) due to the low share of electricity in the rural energy mix.

To obtain a more systematic account of the literature, we identify 27 key themes in the research on energy access based on a topic modeling analysis (Table 5). The theme on "rural electrification" focuses on issues such as off-grid vs. grid extension, the role of local communities and cooperatives, and providing electricity to remote areas (Santiago and Roxas, 2012; Yosiyana and Simarangkir, 2015). Some themes also pertain to other policy objectives related to energy access. For example, the theme on "energy security" delves into topics around geopolitics, price dynamics, and providing energy in a changing climate (Kemfert, 2010; Panpuek and Teetong, 2016). Similarly, the theme on "energy poverty" focuses on issues surrounding the measurement of energy poverty, the relationship between poverty and energy access, and energy poverty and climate vulnerability (Bartiaux et al., 2018; Awan et al., 2022; Yadava and Sinha, 2022). Closely related to this, the theme on "energy justice" situates energy access in different settings such as low carbon development, post capitalism and post liberalism, and in the aftermath of crises or disasters (Luque-Ayala, 2018; Lacey-Barnacle et al., 2020; Hesselman et al., 2021). In a different vein, the criticality of energy access has also been discussed in the case of a "wireless network" (Xing et al., 2016; Zhou et al., 2020; An and Park, 2022).

As anticipated previously, various themes in the literature focus on technology alternatives for energy production. The theme on "solar energy", for example, discusses the technical and economic potential of solar energy, the different solar energy technologies, and the impact they can create on society (Diniz et al., 2006; Al-Shetwi et al., 2016; Kadri and Hadj Abdallah, 2016). Closely related to this, the theme on "solar home system" sheds light on aspects such as the financing, adoption, and evaluation of solar energy for household energy services (Ondraczek, 2011; Pode, 2013; Hellqvist and Heubaum, 2023). Similarly, the theme on "hydropower" delves into whether and how small-, micro-, and pico- hydropower can play a role in electrification (Koirala et al., 2017; Bhandari et al., 2018; Ariyabandu, 2020). Meanwhile, the theme on "bioenergy" examines the potential of different fuel sources and technologies in supplying energy (Okure et al., 2018; Andriatoavina et al., 2021; Kamalimeera and Kirubakaran, 2021). In addition, the literature has studied the production of hydrogen and other materials for energy in the theme on "energy materials" (Navarro et al., 2009; Nawaz et al., 2021) as well as the manufacturing, performance, and life cycle assessment of small "wind energy" (Masud, 1998; Mukulo et al., 2014; Rama Prabha et al., 2017).

Several themes are centered around the role of standalone alternatives for improving energy access. The most prevalent theme, that of "hybrid energy", focuses largely on the feasibility and performance of systems that combine renewable energy, fossil fuel-based energy, and/or storage (Nigussie et al., 2017; Rehman et al., 2020; Thirunavukkarasu and Sawle, 2021). The theme on "minigrid", for example, discusses the role of microgrids and minigrids in providing electricity in remote, low-density areas in an adjustable and expandable manner (Moner-Girona et al., 2018; Adefarati and Bansal, 2019; Mudaheranwa et al., 2023). With a more specific focus on system design, the theme on "system optimization" explores the balance among parameters such as the net present cost, the cost of electricity, the share of renewable energy, and the reliability of supply within a (hybrid) microgrid or minigrid system, and the role of an energy management strategy therein (Das et al., 2021; Mustafa Kamal et al., 2022; Sharma et al., 2023). Rather than prioritizing technical optimization, the theme on "multicriteria analysis" uses techniques such as analytic hierarchical process, the best worst method, and multi-objective optimization to also consider environmental and social objectives in microgrid design (Kumar et al., 2019; Juanpera et al., 2020; Elkadeem et al., 2021). In contrast, the theme on "DC microgrid" is primarily concerned with the technological design and feasibility of a direct current microgrid or nanogrid system in providing sustainable energy (Nasir et al., 2019; Kothari et al., 2022; Kumar and Bhat, 2022). Relatedly, the theme on "energy storage" studies different battery technologies in hybrid, microgrid, or more general stationary energy systems (Dhundhara et al., 2018; Jing et al., 2019; Kebede et al., 2021).

TABLE 5 Themes in the literature on energy access.

#	Theme	Key terms	N
1	Hybrid energy	Hybrid, diesel, system, wind, homer, battery, pv, kwh, techno, cost	487
2	Rural electrification	Electrification, rural, projects, electricity, local, countries, social, program, programs, communities	415
3	Minigrid	Microgrid, microgrids, minigrids, minigrid, load, grid, demand, design, off_grid, cost	307
4	Financing	Finance, sector, ssa, african, access, financing, continent, region, development, investment	290
5	Solar energy	Photovoltaic, solar, pv, pumping, cells, solar_photovoltaic, systems, program, water, modules	284
6	Solar home system	Solar, home, shs, lighting, bangladesh, households, products, kerosene, systems, lamps	264
7	Hydropower	Hydropower, hydro, turbine, micro, river, pico, water, head, plants, flow	260
8	Household energy	Cooking, lpg, household, households, charcoal, fuels, fuel, use, wood, firewood	215
9	Grid stability	Distribution_network, method, new, power, operation, scheduling, planning, model, multi, voltage	208
10	Bioenergy	Biomass, engine, waste, biogas, production, gas, crop, wood, fuel, agricultural	194
11	DC microgrid	Dc, voltage, control, microgrid, converter, architecture, power, microgrids, distribution_network, bus	178
12	Energy security	Energy_security, global, oil, affordable, climate_change, security, emissions, supplies, policy, gas	178
13	Energy planning	Gis, planning, data, spatial, satellite, geospatial, electrification, demand, information, electricity	178
14	Energy impact	Agricultural, irrigation, employment, farmers, labor, household, farm, households, rural, electrification	173
15	Energy poverty	Energy_poverty, household, multidimensional, income, households, poor, modern, poverty, access, indicators	149
16	Multicriteria analysis	Multicriteria, criteria, decisionmaking, decision, evaluation, alternatives, hierarchy, design, best, microgrids	133
17	Electricity distribution	Voltage, distribution, lines, phase, line, transmission, single, carrier, earth, return	117
18	Smart grid	Internet, smart, smart_grid, things, intelligent, monitoring, computing, networks, data, network	108
19	Wireless network	Information, harvesting, transfer, channel, sensor, transmission, radio, communication, network, powered	98
20	Energy materials	Hydrogen, materials, density, water, ion, synthesis, affordable, properties, high, promising	97
21	System optimization	Optimization, swarm, sizing, objective, optimal, hybrid, technique, algorithms, genetic, multi	87
22	Energy storage	Energy_storage, battery, batteries, charge, acid, ion, lead, storage, life, controller	84
23	Wind energy	Wind, wind_turbine, speed, small, speeds, manufacturing, resource, design, turbine, coastal	80
24	Economy and environment	Growth, long_run, consumption, emissions, panel, gdp, co2, sdg, economic, carbon	74
25	Energy justice	Energy_justice, justice, post, right, social, low_carbon, rights, energy_poverty, law, climate	63
26	Energy and gender	Women, gender, empowerment, energy_justice, entrepreneurs, equality, productive, access, equity, social	61
27	Energy Union	European, european_union, prices, decarbonization, policy, targets, affordable, security, consumers, markets	50

N denotes the number of publications clustered within the theme.

While much of the research focuses on energy production alternatives, some themes also address distribution and end-use. The theme on "grid stability" discusses topics linked to the integration of distributed energy and renewable sources with the electricity grid, such as intermittency, scheduling, and dispatch (Dou et al., 2014; Li et al., 2022; Wang, 2022). Meanwhile, the theme on "smart grid" highlights the role of a dynamic, interactive grid for building an electricity network of the future and tapping into the potential of demand response, real-time monitoring, and short-term forecasting through big data and machine learning (Nizar et al., 2008; El-Hawary, 2014; Zhang et al., 2017). Relatedly, the theme on "electricity distribution" examines technological challenges as well as solutions—such as the single-wire earth return system—in the distribution network for reducing the cost of electricity (van Niekerk and Hofsajer, 2000; Hosseinzadeh et al., 2011). In a different vein, the theme on "household energy" delves into barriers to clean energy adoption at the household level, with an emphasis on cooking. Studies within this theme emphasize alternatives such as income generation—for example, through off-farm employment—provision of social security, and targeted subsidization for influencing household behavior (He et al., 2016; Puzzolo et al., 2016; Sharma and Dash, 2022).

Some themes pertain to a more macro-level discussion on energy access. For example, the theme on "financing" underlines the need to mobilize financing, including climate financing and development financing—especially in Sub-Saharan Africa—in order to promote sustainable energy for all (Chirambo, 2018; Michaelowa et al., 2021). A key issue here is the strengthening of institutions in order to tap into diverse sources of investment (Sheba and Bello, 2020). The theme on "energy planning", meanwhile, delves into topics such as the use of satellite data to measure electrification, the estimation of electricity demand, and geospatial planning of transmission and supply infrastructure (Mentis et al., 2015, 2016; Dominguez et al., 2018). With a regional

TABLE 6 Themes in the policy-related literature on energy access.

#	Theme	Key terms	*N*
1	Energy behavior	Energy_poverty, income, household, multidimensional, inequality, households, modern, access, urban, poor	128
2	Solar energy	Solar, home, photovoltaic, solar_photovoltaic, systems, shs, off_grid, rural, market, diffusion	120
3	Hybrid energy	Hybrid, optimal, system, microgrid, optimization, power, techno, wind, battery, diesel	98
4	Household energy	Cooking, lpg, fuel, charcoal, household, firewood, fuels, fuelwood, households, use	72
5	Bioenergy	Biomass, biogas, food, rice, waste, materials, fast, potential, production, oil	68
6	Minigrid	Minigrids, minigrid, grid, electrification, off_grid, microgrids, rural, remote, villages, distribution	62
7	Energy transition	Coal, bangladesh, wind, indian, country, renewable, power, growth, generation, primary_energy	60
8	Energy Union	European, affordable, commission, european_union, gas, new, natural_gas, heating, external, federal	60
9	Economy and environment	Growth, asian, long_run, consumption, carbon, trade, economic, sdg, environmental, co2	59
10	Community electrification	Electrification, rural, electric, local, infrastructure, program, institutional, public, communities, social	59
11	Financing	Finance, climate, financing, financial, ssa, investment, capital, risks, private, power	57
12	Energy and sustainability	Renewable, nigerian, african, development, sustainable, potentials, review, sector, hydro, potential	45
13	Energy security	Oil, energy_security, global, foreign, international, strategic, supplies, secure, affordable, security	43
14	Governing electrification	Electrification, projects, sustainability, rural, project, communities, framework, program, programs, resilience	43
15	Energy and gender	Gender, women, men, firm, labor, gendered, enterprise, enterprises, entrepreneurial, empowerment	38
16	Hydropower	Hydropower, hydro, small, development, schemes, installled_capacity, stations, small_scale, plants, micro	38
17	Energy justice	Justice, housing, social, energy_justice, energy_poverty, community, rights, transport, material, socio	37
18	Energy for agriculture	Agricultural, irrigation, farmers, food, water, livelihood, crop, production, farm, security	30
19	Slum electrification	Water, pandemic, covid, healthcare, slum, facilities, space, health, sanitation, people	28
20	Energy governance	Governance, hydrogen, political, actors, communities, african, policy_making, initiatives, sector, recent	24
21	Energy planning	Satellite, planning, settlement, geographic, grid, burkina_faso, tool, data, electrification, spatial	24
22	Measuring access	Regular, farm, evidence, households, household, electricity, likely, supply, points, availability	22
23	Politics of access	Energy_justice, urban, democratic, uneven, political, change, infrastructural, spatial, local, relations	21

N denotes the number of documents clustered within the theme.

focus, the theme on "Energy Union" focuses on topics such as the role of renewable energy in providing affordable energy; EU level policies on energy, including the fuel quality directive and the renewable energy directive; and the requirements and implications of a resilient Energy Union (Zhang et al., 2017; Mexhuani et al., 2022).

The remaining themes engage with energy access in the wider context of the economy, environment, and society. The theme on "economy and environment" examines the influence of energy access on characteristics such as economic growth, ecological footprint, and greenhouse gas emissions (Vidyarthi, 2015; Balsalobre-Lorente et al., 2021; Arnaut and Dada, 2022). The theme on "energy and gender", meanwhile, studies the linkages among climate change, energy access, and renewable energy development on the one hand and entrepreneurship, gender (in)equality, and social inclusion on the other hand (Mohideen, 2012, 2021; Pueyo et al., 2020). Finally, the theme on energy impact analyzes the relationship between electrification and various socio-economic indicators, such as those pertaining to agriculture, child nutrition, household labor supply, and reproductive behavior (Saha, 1994; Lahiri, 2005; Rolland et al., 2013). Nearly 2700 documents are classified as miscellaneous as they do not distinctly match any of these themes.

3.3. Themes in the policy-related research on energy access

A topic modeling analysis of this subset results in 23 themes in the policy relevant literature on energy access (Table 6).

An examination of these themes shows that many of them correspond to the themes in the complete dataset. Even in the policy relevant literature, several themes delve into technological alternatives for generating energy, including "solar energy", "bioenergy", and "hydropower." Similarly, the prospect of "hybrid energy" and "minigrid" is also advanced in this research area. Further, the demand or end-use perspective on energy has been has been discussed in the theme on "household energy." In terms of policy objectives, the focus on "energy security" is retained in this subset. Meanwhile, the themes on "financing", "energy planning", and "Energy Union" capture energy access at a more macro level. In addition, two of the themes study the relationship of energy to the economy, the environment, and the society: "economy and environment" and "energy and gender."

A comparison of the themes prominent in the complete dataset and those prominent in the policy subset is shown in Table 7. As one might expect, the more technologically oriented themes in the complete dataset are not prominent in the policy relevant literature. These span energy generation ("wind energy" and "energy materials"), system configuration ("DC microgrid", "system optimization", "multicriteria analysis", and "energy storage"), energy distribution ("grid stability", "smart grid", "electricity distribution") and application area ("wireless network").

On the other hand, several themes pertaining to policy objectives are more prominent in this subset. The theme on energy poverty, for example, is captured partially by the theme on "energy behavior" and partially by the theme on "measuring access." While the theme on "energy behavior" examines the energy preferences of households for cooking, lighting, and other energy services (Klasen et al., 2005; Louw et al., 2008; Olang et al., 2018), the theme on "measuring access" establishes the status of energy access among households, communities, or public facilities such as primary health centers (Pelz and Urpelainen, 2020; Mani et al., 2021; Pelz et al., 2021). Similarly, the objective of rural electrification is discussed in the themes on "community electrification" and "governing electrification"; while the former focuses more on the role of civil society organizations and remote communities in improving energy access (Torero, 2016), especially in the case of last mile connectivity in Latin America, the latter focuses more on the role of the government in electrifying villages, especially in the context of Asia (Zomers and Gaunt, 2010; Derks and Romijn, 2019; Pandyaswargo et al., 2022). Even energy justice is covered by two themes in this subset, with one more inclined toward geographies in the Global North and concerns of affordability (Bartiaux et al., 2018; Evensen et al., 2018; Ozarisoy and Altan, 2021) and the other toward geographies in the Global South and issues of inequity and "politics of access" (Castán Broto et al., 2018; Cotton et al., 2021; Smith et al., 2022).

The policy relevant literature also delves into themes that are less prominent in the complete dataset. The theme on "energy transition", for example, discusses the challenge of transitioning away from fossil fuels as much as the opportunity of deploying renewable energy (Ghose, 2009). In addition, it emphasizes the need for effective governance in promoting a sustainable energy transition (Karim et al., 2019). Closely related to the theme on "energy transition", the theme on "energy and sustainability" highlights the role of the (renewable) energy system in promoting sustainable development—mainly in the context of Africa—and the need for effective governance therein (Kenfack et al., 2014; Sheba and Bello, 2020; Yetano Roche et al., 2020). The theme on "energy for agriculture", meanwhile, examines issues such as the role of energy access in facilitating access to groundwater for irrigation, the influence of different electricity pricing mechanisms on groundwater conservation, and the impact of tubewell irrigation on crop production (Bhandari, 2001; Evans et al., 2012; Sidhu et al., 2020). The lack of access to amenities (including electricity) in urban slums—often despite their proximity to the electricity grid—are highlighted in the theme on "slum electrification" (van Leeuwen et al., 2017; Yaguma et al., 2022). Finally, the theme on "energy governance" addresses issues such as the lack of local level capacity for the devolution of energy governance, the role of energy communities in energy governance, and the influence of politics on electricity access reform in low- and middle-income countries (Gore et al., 2019; Gebreslassie et al., 2022; Volkert and Klagge, 2022).

The themes in this subset can be broadly classified as mainstream, emerging, marginal, and declining in the context of energy access based on their relative importance over time (Figure 3). Themes with a high number of publications as well as a large share of publications in the past 5 years, for example, can be considered as mainstream and growing in importance (i.e., top right quadrant of Figure 3). These include the themes on "hybrid energy", "household energy", "energy behavior", and "solar energy." Further, themes such as "bioenergy", electrification, "energy transition", "Energy Union", and "minigrid" appear to be mainstream, but steady. Meanwhile, the themes with fewer publications but a high share of publications in the recent past are more likely to be emerging: "economy and environment", "energy and gender", "energy justice", "financing", "energy and sustainability" and—to some extent–"slum electrification", "energy planning", "measuring access", "energy governance", and the "politics of access." In contrast, the themes on "energy security", "hydropower", and "energy for agriculture" appear to be declining in their relative importance in the recent past.

While the themes in this subset are more policy relevant, whether even this strand of the literature has paid sufficient attention to public policy remains unclear. First, as noted above, several themes in this subset are common to the broader literature on energy access. On the one hand, this indicates that different themes in the broader literature have been addressed from a policy perspective; however, on the other hand, it raises the question whether their treatment of public policy has been cursory rather than in-depth. Second, although various themes address policy objectives, none of the themes are centered around public policy, with the possible exception of "energy governance" and "politics of access" to some extent. This is also reflected in the terms associated with the themes, which are predominantly domain-specific and terms such as governance, institution, law, policy making, politics, and program are prominent in only five of the 23 themes. Third, the themes that, prima facie, signal the most engagement with public policy—such as "energy governance" and "politics of access"—constitute a rather small share (less than five percent) of the policy relevant literature on energy access, as seen in Figure 3.

In the next section, we examine the use of terms related to public policy in further detail to understand whether and how the policy relevant literature has engaged with public policy.

4. Analysis: where is the policy?

The term policy (including its plural, policies) has been mentioned more than 2,800 times in the titles or abstracts of the policy relevant literature on energy access. However, as noted above, the mentions of phrases involving policy are relatively few. Apart from the phrase "energy policy" (n: 413), only the phrase "policy maker(s)" (n: 318) has over 100 occurrences in this dataset. Even phrases such as "policy implication(s)" (n: 75) or "policy recommendation(s)" (n: 51) are mentioned infrequently. In addition, "policy analysis" occurs on only 14 occasions in this dataset. We analyze the occurrence of phrases related to the policy process, policy design, and policy evaluation in more detail (Table 8). In total, 429 of the 1,751 policy-related studies mention any of these phrases, indicating that less than 6 percent of the

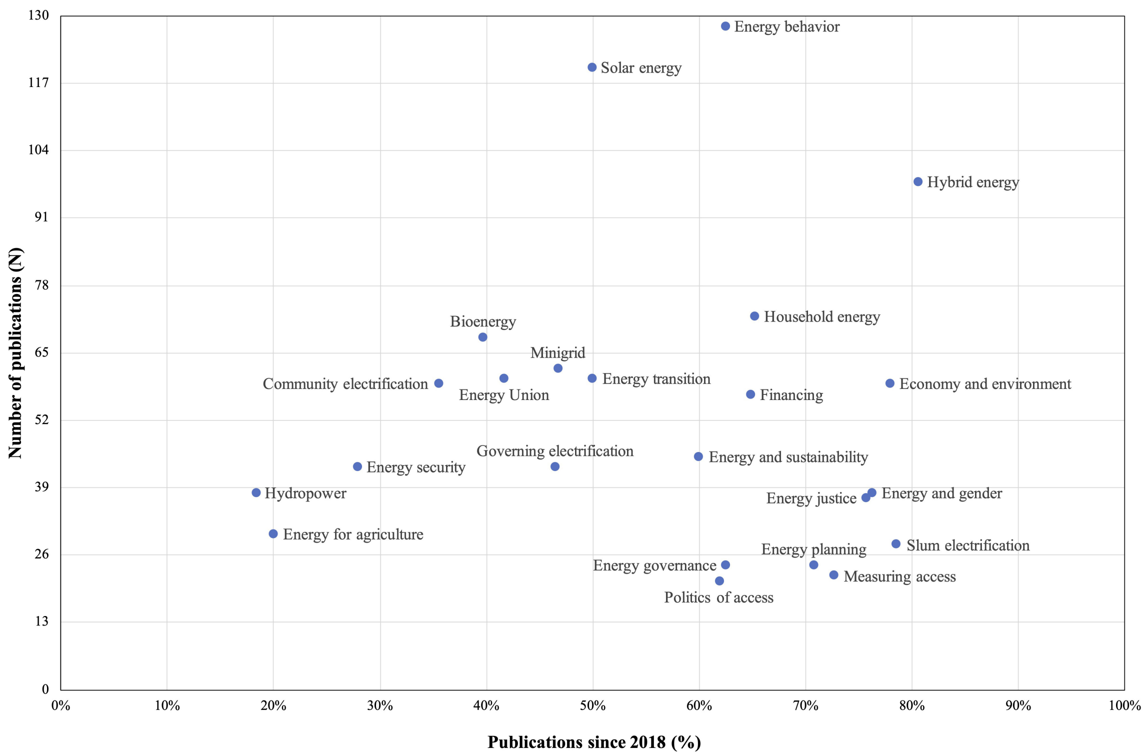

FIGURE 3
Theme-wise volume and recency of activity in policy-related literature on energy access.

overall literature and less than 25 percent of the policy-related literature has delved into policy processes, policy designs, or policy evaluation concerning energy access.

We observe that concepts related to the policy process have been mentioned in approximately 150 publications in the policy-related literature on energy access. These can approximately be classified based on the likely stage of the policy process in which they could be the most relevant. The phrases pertaining to agenda setting ("policy agenda(s)", "policy attention", "policy discourse", and "policy issues") have been mentioned approximately 30 times in this dataset. Meanwhile, phrases relevant to policy formulation ("policy development", "policy discussion", "policy formulation", and "policy planning") occur approximately 35 times. The phrases related to decision-making ("policy change(s)", "policy decision(s)", "policy initiatives", and "policy reform"), meanwhile, are mentioned about 50 times in this literature. Finally, the phrase "policy implementation" occurs only 14 times in this subset.

A closer look at publications that mention some of these phrases indicates that they are largely used in a descriptive or normative sense. For example, the term policy agenda is most commonly used to state that energy poverty is not on, or is only beginning to appear on, the policy agenda (Sareen et al., 2020; Castaño-Rosa and Okushima, 2021), or to propose a policy agenda for the issue (Amin et al., 2022; Thomson et al., 2022). An analysis of variation in energy access on the policy agenda—illustratively, over time or across geographies—is rarely done. Similarly, policy change is typically used in a descriptive manner in existing research (Kelkar and Nathan, 2021; Patel et al., 2021). Studies that examine the policy process have created insights on various dynamics in this area, such as the consensus and conflict among different discourses or narratives—including energy access or energy for all—in the energy transition (Mohan and Topp, 2018; Shukla and Swarnakar, 2022; Wibisono et al., 2023); the importance of domestic and international politics in influencing policy activity on energy access (Byrne et al., 2018; Gore et al., 2019; Dye, 2021; Newell and Daley, 2022); the role of policy entrepreneurship in placing the issue on the agenda (Goyal et al., 2020); the challenges that access policies face during implementation, including complexities, corruption, discrimination, and resource logistics (Geall and Shen, 2018; Zaman and Brudermann, 2018; Aklin et al., 2021); and the potential of social movements in changing policy (Delina, 2022).

Terms that might be relevant for policy design are more frequent, and have received attention in about 250 publications on energy access. Broadly, these can in turn be viewed as terms indicating policy means, policy ends, or combinations of means and ends. The various phrases that could describe policy means (such as "policy instrument", "policy intervention", "policy measure", and "policy option") have been mentioned about 110 times in this dataset. Conservatively, the phrases that could describe policy ends ("policy focus", "policy goal", "policy objective", and "policy priority") have about 60 occurrences in this dataset. Meanwhile, phrases that could describe a combination of means and ends ("policy design", "policy framework", "policy mix", "policy scenario", and "policy strategy") collectively occur about 80 times in this dataset.

TABLE 7 A comparison of themes in the literature on energy access vs. those in the policy-related literature on energy access.

Theme	Complete literature	Policy-related literature
Hybrid energy	Yes	Yes
Rural electrification	Yes	Yes, split across "Community electrification" and "Governing electrification"
Minigrid	Yes	Yes
Financing	Yes	Yes
Solar energy	Yes	Yes
Solar home system	Yes	Yes, captured within "Solar energy"
Hydropower	Yes	Yes
Household energy	Yes	Yes
Grid stability	Yes	No
Bioenergy	Yes	Yes
DC microgrid	Yes	No
Energy security	Yes	Yes
Energy planning	Yes	Yes
Energy impact	Yes	No
Energy poverty	Yes	Yes, split across "Energy behavior" and "Measuring access"
Multicriteria analysis	Yes	No
Electricity distribution	Yes	No
Smart grid	Yes	No
Wireless network	Yes	No
Energy materials	Yes	No
System optimization	Yes	No
Energy storage	Yes	No
Wind energy	Yes	No
Economy and environment	Yes	Yes
Energy justice	Yes	Yes, split across "Energy justice" and "Politics of access"
Energy and gender	Yes	Yes
Energy Union	Yes	Yes
Energy transition	No	Yes
Energy and sustainability	No	Yes
Energy for agriculture	No	Yes
Slum electrification	No	Yes
Energy governance	No	Yes

As in the case of the policy process, mention of policy design is often in a descriptive context (Trotter et al., 2017; Ndiritu and Engola, 2020). Yet, several (types of) studies in the policy-related literature have clear relevance for policy design. First, some studies assess economic, social, or technological viability of alternatives and shed light on feasible policy designs for promoting energy access (Thapar, 2022). Second, studies also model energy systems and create knowledge on possible policy pathways for achieving medium- or long-term objectives, typically, in a dynamic environment (Gebremeskel et al., 2023). Third, other studies examine the synergies and trade-offs among different policy objectives, such as energy access, climate change mitigation, and gender (Antwi, 2022).

Research incorporating a policy studies perspective shows how the above work can be enriched to make it more policy relevant. For example, Minogue (2013) and Chindarkar (2017) emphasize the need to address not only the technological but also the political and the social context through policy design and also ensure administrative, financial, and technical capacity for implementation of the design. Similarly, Kern et al. (2017) and Malhotra (2022) underscore the importance of considering the interaction among various objectives and instruments in a policy "mix" for effective policy design, especially as various energy policies often address potentially competing policy objectives (see also Trotter and Brophy, 2022). Finally, Barnett et al. (2020) exhibit the necessity of accounting for path dependence and the existing policy landscape for policy designing by showing that a policy mix can, paradoxically, weaken due to internal contradictions created by layering or patching policy through the addition of new policy instruments over time.

The number of publications that matched the phrases for policy evaluation was about 50. The phrase "policy evaluation" (or even associated phrases such as "policy failure", "policy success", "program evaluation", "program failure", or "program success") have been mentioned on less than five occasions in the policy relevant literature on energy access. The terms closest to evaluation in this subset are "successful implementation" (n: 14), "effective policy" (n: 13), "policy lesson(s)" (n: 7). However, successful implementation or effective policy have been generally used to refer to technical implementation (Kirchhoff et al., 2016) or to make a case for a specific policy recommendation (Landi et al., 2013; Khan et al., 2022) rather than to an empirical evaluation of policy.

Research that has undertaken some form of policy evaluation has shed light on different dimensions of policy-making for energy access. These include the role of public policy in reducing multidimensional energy poverty in Ghana (Crentsil et al., 2019), the influence of deregulation on the electricity system in low- and middle-income countries (Mutale and Mensah-Bonsu, 2009), and the positive effect of renewable energy policy in the Economic Community of West African States (ECOWAS) on energy access, primary energy supply, and energy intensity (Moustapha, 2022). In one example of the potential of lesson drawing in this area, Soyemi et al. (2021) assess the implementation of energy access policies in several countries to provide policy recommendations for Nigeria. Meanwhile, some studies have highlighted the several challenge(s) of providing universal energy access: the potential trade-offs among different policy objectives associated with energy access (Kansakar et al., 2009), the need for technical expertise in policy designing and policy implementation (Ndiritu and Engola, 2020), the necessity of close collaboration between the private sector and the public sector (Landi et al., 2013), the limitations of economic competition in "small" electricity systems (Nepal et al., 2018), and the continued need for subsidization as well as the "competition" between off-grid

TABLE 8 Occurrence of terms pertaining to public policy in the policy-related literature on energy access.

Policy concept	Term: frequency			
Policy process	Policy making: 37	Policy formulation: 15	Policy decisions: 15	Policy initiatives: 15
	Policy implementation: 14	Policy development: 10	Policy reform: 10	Policy agenda: 8
	Coalitions: 7	Policy issues: 7	Policy attention: 6	Policy changes: 6
	Policy planning: 6	Policy discussion: 5	Policy agendas: 5	Policy change: 5
	Policy discourse: 5	Policy decision: 5		
Policy design	Policy framework: 40	Policy measures: 33	Policy interventions: 29	Policy frameworks: 21
	Policy options: 21	Policy goals: 21	Policy objectives: 18	Policy design: 18
	Policy instruments: 17	Policy mix: 12	Policy scenarios: 11	Policy intervention: 9
	Policy barriers: 9	Policy strategy: 9	Policy priority: 8	Policy scenario: 6
	Policy focus: 6			
Policy evaluation	Successful implementation: 14	Effective policy: 13	Policy lessons: 7	Effective policies: 6

and on-grid energy for furthering access (Hellqvist and Heubaum, 2023).

A review of the abstracts of 176 randomly selected publications—i.e., 10 percent of the policy-related literature—corroborated the findings of the computational text analysis. We found that approximately 25 percent of this subset engaged with the policy process, policy design, or policy evaluation. Only three publications in this subset focused on some aspect of the policy processes, and none of them engaged with the literature on policy studies explicitly. Further, 34 publications paid attention to policy design in their problematization, analysis, or recommendations. Finally, 10 publications evaluated policy, program, or process in some form.

5. Discussion

To ensure universal access to affordable, reliable, and modern energy services by 2030 is a key target (SDG 7.1) for the sustainable development goal on energy (SDG 7). Despite the significant progress on increasing access to clean cooking and electricity over the past decade, the COVID-19 pandemic—among other reasons—has caused a slowdown and even backsliding in this effort. At the current pace, SDG 7.1 will not be achieved for either clean cooking (likely attainment: approximately 70 percent of the global population) or electricity (likely attainment: approximately 90 percent of the global population). As public policy can help accelerate the progress toward universal energy access, this study examined whether and how perspectives from *policy sciences* or *policy studies*—specifically, policy process research, policy design studies, and the literature on policy evaluation—have been used in nearly 7,500 publications on energy access indexed either by Scopus or the Web of Science.

Using topic modeling, we identified 27 themes in the literature on energy access. While some of these focused on policy objectives—such as "rural electrification", "energy security", "energy poverty", and "energy justice"—many focused on technological alternatives for increasing access—such as "solar energy", "solar home system", "hydropower", "bioenergy", "wind energy", and "energy materials"—or configuration of the energy system, such as "hybrid energy", "minigrid", "DC microgrid", "multicriteria analysis", "system optimization", and "energy storage." In addition, some themes discussed energy distribution or end-use ("grid stability", "electricity distribution", "smart grid", "household energy") while others emphasized more macro-level themes ("financing", "energy planning", "Energy Union") or the relationship of energy to the economy, environment, and society ("energy impact", "economy and environment", "energy and gender"). This analysis revealed public policy was not a key theme in the literature on energy access.

Subsequently, we examined the themes in the more policy-related literature on energy access (i.e., publications mentioning policy in their title or abstract) to see whether the situation in this literature was different. The themes discovered in this analysis were quite similar to those in the broader literature on energy access. However, some of the more technologically oriented themes spanning energy generation ("wind energy" and "energy materials"), system configuration ("DC microgrid", "system optimization", "multicriteria analysis", and "energy storage"), energy distribution ("grid stability", "smart grid", "electricity distribution") and application area ("wireless network") were not prominent here. Instead, themes pertaining to policy objectives stood out more clearly, with "energy behavior" and "measuring access" addressing energy poverty, "community electrification" and "governing electrification" speaking to rural electrification, and "energy justice" and "politics of access" engaging with energy justice in different geographies. In addition, themes surrounding "energy for agriculture", "slum electrification", "energy transition", "energy and sustainability", and "energy governance" were also discovered. Yet, with the possible exception of "energy governance" and "politics of access"—which were a small part of the literature—the themes in this literature also showed limited engagement with public policy.

We analyzed the occurrence of terms related to policy process, policy design, and policy evaluation in the policy-related literature on energy access. We found hardly any mentions of phrases pertaining to policy, with even phrases such as "policy implication(s)", "policy recommendation(s)", and "policy analysis" receiving much fewer than 100 mentions in our dataset. Further, phrases pertaining to the policy process (such as "policy agenda", "policy change", "policy implementation"), policy design (such as "policy design", "policy mix", "policy objective", "policy instrument"), or policy evaluation (such as "policy evaluation", "policy failure", "policy success") were hardly mentioned or mentioned in a cursory or descriptive manner. Sophisticated research based on the *policy sciences* or *policy studies* was uncommon despite its relevance for energy access.

It is plausible that a larger volume of the literature has, in fact, engaged with topics concerning the policy process, policy design, and policy evaluation, but used generic phrasing and terminology for a multidisciplinary audience. Although we cannot rule this possibility out completely, our manual review of randomly selected abstracts of 10 percent of policy-related literature too indicated that only 25 percent of the studied engaged with the policy process, policy design, or policy evaluation in some form. Most of these, too, focused on policy design, few on policy evaluation, and almost none on the policy process. Further, even among these, hardly any engaged explicitly with the policy studies literature. This could inhibit knowledge cumulation or energy access and instead create fragmentation among different bodies of research.

A manual review of publications mentioning terms relevant to the policy process, policy design, or policy evaluation revealed uneven treatment of these perspectives. While several studies had clear relevance to policy design, this strand of research on energy access could benefit further from insights from policy studies such as (i) the importance of accounting for the political and social context as well as policy capacity in policy design(ing); (ii) the potential interaction among different policy objectives and policy instruments that could be synergistic or conflicting; and (iii) the need to account for path dependence and the existing policy landscape in policy analysis. On the other hand, policy evaluation has received much less attention in the field of energy access. Here, there is scope for much more breadth as well as depth, shedding light on policy failures and successes around the world, incorporating process and political assessment of public policy in evaluation, and studying when and how policies help achievement of universal access to energy. Finally, the policy process has received the least attention in this literature even though policy design is affected significantly by policy-making dynamics. Research examining why some governments adopt policies concerning energy access, whether and how vested interests influence policy design, and how energy access policies are implemented can create useful knowledge for explaining and altering the status quo.

The reasons for the observed structure of knowledge in this research area could be several. First, publications on technological and economic assessment seem to dominate research on energy access and other social science perspectives may have received less attention within this scholarly community. Second, the *policy sciences* or *policy studies* community has likely focused primarily on the Global North (especially North America) and concerns of the Global South (such as energy access) have not found traction among scholars in this field. Third, there might be limited opportunities for scholarly exchange between the two communities of researchers. Fourth, public policy education—although growing rapidly—is still not mainstream in the Global South with most degree programs, departments, and schools being less than two decades old (El-Taliawi et al., 2021). Fifth, such research requires access to fine-grained socioeconomic indicators (including metrics for energy access), policy documents, and people involved in the policy process, all of which might pose a high barrier.

An examination of the dataset—and, especially, the publications that have engaged with the policy process, policy design, and policy evaluation—reveals how these factors might be at play. First, many of the studies that engage with the policy process, for example, are published in just one source: *Energy Research and Social Science*. At the same time, journals focusing on public policy have published little on the topic of energy access, possibly resulting in a dearth of avenues for this kind of research. Second, studies that engage with the policy design literature appear to have been written by scholars who have co-authored with researchers in the policy studies community, indicating that more opportunities for an exchange of perspectives is likely to be fruitful. Third, several studies on policy evaluation, for example, are based on countries where English is an official or semi-official language, suggesting that the ability to access or interpret data might indeed pose a challenge to diversify the policy-relevant research on energy access. Future research could investigate whether these findings are specific to the literature on energy access and whether the findings differ in the case of research on energy justice or energy poverty, for example. If so, these research areas could serve as a bridge between the literature on energy access and the research on public policy.

To conclude, future research activity on public policy in and for energy access is much needed if the backsliding on SDG 7.1 is to be reversed and progress toward the achievement of the SDGs is to be made. This study proposes different perspectives through which this can be done and demonstrates how the few studies that have done so have created useful scholarly knowledge for addressing the energy access challenge.

Data availability statement

The raw data from Scopus and Web of Science is subject to license. The authors will share the processed data used for the analysis upon request.

Author contributions

NG and MH contributed to conception of the study. NG designed the study, organized the database, conducted the analysis, and wrote the first draft of the manuscript. MH wrote sections of the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Contextual factors in local energy policy choices: comparative case of solar energy policy in two cities

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Numerous recent calls have been made for policy design research to embed itself throughout the policy process and explore avenues for matching tools and targets. These calls have argued that policy design research, while emphasizing the content and the choice of design, has been under-leveraged, particularly in exploring rationales for effectiveness. In this paper, we conduct a comparative case study to explore variation in participation rates for two similarly categorized solar policies across two mid-sized cities. In this regard, three contextual factors are examined, including the population characteristics, the existing configuration of policies, and the physical environment, which all contribute to shaping policy effectiveness. We argue that policy design is situated within an explicit context and that without capturing the context, the effectiveness of policies may not translate if diffused.

KEYWORDS
policy design, contextual factors, solar policy, rooftop solar, community solar

1. Introduction

The growing interest in policy design has focused on demonstrating that specific design features influence how target participants perceive the policy and its effectiveness (Howlett, 2018; Curley et al., 2020). Most current research in policy selection is being conducted from rational and/or behavioral perspectives. Rational policy design integrates an analysis of the problem, information about the instruments used for intervention, and the barriers and values addressed by the potential intervention. The behavioral approach to policy selection argues for appropriately matching specific individuals or households with policy tools (Howlett, 2019). The effort to match tools to targets can be viewed as an enhanced rational policy tool choice effort because it considers the sociodemographic context in which the policy is enacted. While much research exploring these phenomena utilizes binary data to measure policy presence, there have been more recent efforts to develop measures for nuance and variation in design features (see Siddiki and Curley, 2022 for further discussion).

Despite these changes to measuring policy design content, the incorporation of context has been mainly limited to studies of implementation. Policy enactment, for example, has made great strides in understanding the implications of the context of a successful implementation process (Braun et al., 2011). Policy enactment refers to the idea that administrators interpret and translates policy into the current implementing environment. Ball et al. (2011) refer to four elements of context in policy enactment: "situated contexts, professional cultures, material contexts, and external contexts and expectations from broader policy context" (p.21). In policy enactment research, the focus is often on the context of the implementing body in a local environment that determines and shapes policy implementation. In most instances, context is treated as a limitation to the generalizability of policy research. These elements combined suggest that we need to better understand the role of context, this paper focuses on the characteristics of the target population, the configuration of existing policies, and the physical environment in which the policy will be implemented. We do this with an explicit effort to understand the how context of a policy design might influence policy effectiveness.

This paper utilizes a comparative case analysis of solar (or photovoltaic, PV) policy selection in two mid-sized cities to demonstrate the benefit of taking a more holistic and contextualized approach to policy design and tool choice. Through this exploratory study, we discover four key takeaways for understanding the context in a policy design necessary for research. In order to identify these key takeaways, we lean on the literature to identify three contextual factors critical to understanding the success of policy designs for solar PV policy: population characteristics, the configuration of existing institutions and policies, and the physical characteristics of the environment within each community. While these contextual factors in policy design might be moderately different depending on the policy topic, we suppose that these are relevant contexts for solar policy design and effectiveness.

2. Literature overview: solar policy

Previous research on U.S. solar policy has included both state-level policy design and incentives (Sarzynski et al., 2012; Yi and Feiock, 2012; Shrimali and Jenner, 2013; Cheng and Yi, 2017; Koski and Siddiki, 2022) and local solar policy tools such as green purchasing projects (Simcoe and Toffel, 2014), adopting solar arrays for governments [EERE (Office of Energy Efficiency and Renewable Energy), 2020], land use and zoning for renewables (Becker, 2019), expedited permitting (Li and Yi, 2014), education and outreach initiatives (Li and Yi, 2014), and financial incentives to residents (Li and Yi, 2014). The financial incentives bucket of policy tools includes rebates, direct grants, direct loans/low-interest loans (Kelly, 2016), feed-in-tariffs (FIT), productions-based incentives (other than FIT), interest rate buy-downs, property tax credits and abatements (Borenstein and Davis, 2016; Matisoff and Johnson, 2017), and sales tax incentives. Financial policy tools aim to make accessing solar technology easier by reducing the cost barrier (Li and Yi, 2014). These solar policies are often part of more extensive sustainability efforts (e.g., climate action plans). Local governments are motivated to adopt climate action plans and solar policies due to political factors (Yi and Feiock, 2012), citizen demands (Devine-Wright, 2011; Graff et al., 2018), economic opportunities or costs (Sawhney and Rahul, 2014), and related regional policy adoption (Simcoe and Toffel, 2014). In response to these pressures, local policymakers develop consumer-focused solar policies to increase rooftop solar and/or community solar farms (Hsu, 2018; Peters et al., 2018).

Rooftop PV is the installation of solar panels on the roof of a building. These types of panels may be purchased or leased. This strategy allows individuals to generate electricity using the area on their roofs. Net-metering is a commonly used policy to incentivize rooftop PV. This practice allows customers to offset their electricity consumption and possibly earn money from 'selling' their overproduction back to the utility.

Community solar farms are large arrays of PV panels, sited on public or private lands, from which customers purchase energy. Four primary models for community solar exist: utility-sponsored model, on-bill crediting, special purpose entity model, and non-profit "buy a brick" model [SEIA (Solar Energy Industries Association), 2020]. Unlike rooftop PV, the community solar farm approach does not typically allow individuals to earn money from overproduction.

In Section 3, we detail the solar policy instruments present in our case study cities. To inform our analysis of these policy instruments, in the following sections, we identify and explore existing research on contextual variables that have been demonstrated or hypothesized to relate to policy design and effectiveness. Specifically, we discuss characteristics of the target population and the physical environment, as well as the compatibility of existing policy instruments. This research was foundational to our inductive analysis of the specific solar policies in place in Tallahassee and Fort Collins with a focus on the relation between contextual variables and policy design and effectiveness.

2.1. Context of policy design

Policy design research has unfolded in two primary avenues; the first is designing the policy itself, while the second is exploring the designed policy's content (Siddiki and Curley, 2022). The process of designing has often centered on the choices of designers. This might include exploring political motives (May, 1991) and emphasizing tool choice and the characteristics of those tools (Hood, 1983; Salamon, 2002). These tools have also been connected to expectations regarding behavior change of the targeted population (Capano and Howlett, 2020). Similarly, research into policy bundling and mixes suggests that some tools can complement or limit another tool's effectiveness (Rogge and Reichardt, 2016; Howlett and Mukherjee, 2017). Despite this, there is little known about well-designed policy mixes. This may be partly due to the difficulty of distinguishing the impact of design attributes from the contextual environments that enable them to succeed. While the implementation gap has been clearly noted as a mechanism for designs to fail, policy design research has yet to unpack context's role in the success (or failure) of policy as designed. The following sections explore the potential for the target population's characteristics, the configuration of existing institutions and policies, and the physical environment to influence the efficacy of policy design.

2.1.1. Configuration of existing institutions and policies

Policymakers utilize a mix of policy tools when attempting to affect the behavior of the target population. Policy tools can be used to regulate and alter the behavior of actors on both the supply and demand sides of a market. Regulations achieve their objective by requiring or banning certain activities (Krause et al., 2019); they typically are not favored among the target population because they operate by constraining choice. In contrast, incentives influence behavior by increasing the marginal cost of undesirable activities or goods and decreasing the cost of desirable ones while continuing to offer target populations a choice (Krause et al., 2019).

Policy mixes are often needed because one tool alone cannot achieve the desired public good (Krause et al., 2019). However, the tools included in a policy mix can have interactive effects (Yi and Feiock, 2012)—they can intentionally or unintentionally compete with (Kern et al., 2017) or complement (Rogge and Reichardt, 2016) one another. This can occur due to silos within the organization, and to the piecemeal accumulation of policies over time. Additionally, the political self-interest of a policymaker can lead to the selection of a policy tool motivated by the political payoff, with little to no care given to whether it will be effective or how it may interact with existing policies (Flanagan et al., 2011). In extreme cases, policymakers may intentionally stunt effective policy to serve their political self-interests.

Despite efforts to understand cohesion in policy tools (Howlett and Rayner, 2007), the ability to identify policies that work together or against one another is limited (Gasteiger, 2018; Capano and Howlett, 2020). Extant research on policy mixes emphasizes the temporality of adoption (Rayner et al., 2017; Halász, 2019), tool interactions that enhance (Lecuyer and Bibas, 2012) or interfere with (Grabosky, 1995) policy outcomes, and the rationality of patching and packaging policies (Howlett and Rayner, 2007; Kern et al., 2017). However, existing efforts to compare policy mix effectiveness do not consider the impact of contextual factors beyond the policies within the mix, such as alternative policy arrays, political or physical environments, and social contexts (such as Kern et al., 2017). Thus, this previous research assumes that the effectiveness of policy mixes does not vary as a function of their context.

2.1.2. Characteristics of the target population

Target populations are considered an element of rational policy design (Schneider and Sidney, 2009). Research on target populations unpacks the distribution of burdens and benefits based on existing social constructions. This body of work, highlighted in a review by Pierce et al. (2014), includes income (Brucker, 2007; Gollust and Lynch, 2011), race (Sidney, 2001, 2005; Garrow, 2012), immigration status (Yoo, 2001, 2008; DiAlto, 2005), employment sectors (Schroedel and Jordan, 1998; Patterson and Keefe, 2008; Ingram and Schneider, 2011), age (Campbell, 2003; Lockhart et al., 2008; Bushouse, 2009; Hudson, 2013), homeownership (Hunter and Nixon, 1999), sexual orientation (Donovan, 1993, 1997), offender status (Miller, 2012), and gender identity (Bensonsmith, 2005). Research in this area often focuses on who gets what – after the policy is designed and selected. However, recent work from Krause et al. (2019) suggests that community characteristics relating to the social construction of the targeted groups, including “race, political leaning, income, and population,” influence and shape which policy tool is selected (p. 477). Krause’s work connects the previous studies on targets with the argument that targets are intentionally and rationally chosen to achieve a specific goal. While targets may be deliberately selected, tools may be chosen based on the perceived deservingness of those targets; more pointedly, the social construction of the target population may determine the distribution of benefits and burdens via tool choice (Capano and Lippi, 2017; Krause et al., 2019). This implies that the targets and the larger context of community characteristics and the community’s perception of the target population likely influence the policy’s design and the efficacy of the match between tool and target.

Policy tool selection is a process that includes anticipating the target population’s barriers to participation, response to the specific tool, and a resulting behavioral change in line with desired policy goals (Howlett and Ramesh, 2003). Despite the importance of policy targets in the policy tool selection process (Howlett, 2018; Maor, 2020; Paddeu and Aditjandra, 2020), relatively little is known about what motivates targets (Capano and Howlett, 2020). Howlett (2018) characterized the process of matching the policy tool to the target population as “calibrating incentives and disincentives to achieve expected levels of compliance and outcomes” (pp. 6). However, this often proves more difficult than policy actors expect (Howlett, 2018), suggesting that they need to develop a greater understanding of the target audience’s motivations rather than relying on intuition.

2.1.3. Physical environment

Physical environments can both affect and be affected by public policy. Possible relevant physical characteristics include the existing built environment, the slope of the land, the presence of natural structures such as bodies of water and trees, and local climate considerations. For any policy that is dependent (directly or indirectly) on land use and weather-related factors, the regional physical characteristics of the environment may have implications for success. For example, health policies that incentivize walking or riding bikes as alternate transit may be less effective in locations that receive frequent rain or snow. If policymakers do not consider the physical environment during policy design and selection, the policy is unlikely to have the desired effect.

Policies such as land use and zoning (Wilson et al., 2003), streets and sidewalks (Lopez and Hynes, 2006), public park formation (Simis et al., 2016), and even site selection for power plants (Czarnowska and Frangopoulos, 2012) directly impact the physical environment. Moreover, through their influence on the physical environment, these policies can influence health (Lopez and Hynes, 2006; Wilson et al., 2008b), the ability to work (Guthrie et al., 2019), and overall happiness (Cloutier et al., 2018) of individuals in that environment. For example, the field of environmental justice research links the built environment to outcomes such as healthy behaviors (Wilkie et al., 2018), education access (Shirazi and Keivani, 2017), racial justice (Wilson et al., 2008a), and pollution exposure (King, 2015). Each policy that shapes the physical environment has long-standing ramifications for the ability of new policies to be effective. However, the link between historical policy decisions and other policies’ ability to be effective is less well understood (Li et al., 2017; Capano and Howlett, 2020). In addition, changes in the physical environment can hold important implications for the transferability of effective policy tools between locations, particularly when seeking to manage common Pool resources (Ruddle, 1998; Khan, 2005). Therefore, it is surprising that the physical environment’s role in policy outcomes has received scant attention in the policy choice (selection and design) literature.

2.1.4. Summary

In theory, a policy is designed to meet the needs of a given community, but every community’s needs will differ according to the contextual environment, which suggests that policies cannot transfer into a new environment without considerable alteration. This argumentation suggests that policy designs themselves should be developed based on the context of the community. In other words, a policy should be intentionally re-designed by altering the design according to a series of factors. The current rationale for re-designing policy is that the context of the tool (i.e., target population, local environment, politics, technology, and the policy mix) has changed and is limiting its effectiveness (Edmondson et al., 2019). However, there is little evidence that these contextual factors – community populations, configurations of the existing policy, and physical environment – are considered during policy design (Chapman et al., 2016) and tool selection. The following section overviews existing solar policy research to provide background for our exploratory comparative case study of solar policy effectiveness in two communities.

3. Methodology

Given our emphasis on understanding how context informs outcomes, we utilize a comparative case-study approach (Yin, 2003). Case studies are essential in building "context-dependent knowledge" (Flyvbjerg, 2006, pg. 6), and qualitative comparative case studies are considered helpful in theory development (Baxter and Jack, 2008). Our goal is not to draw large-scale generalizations but to demonstrate how energy policy effectiveness depends on the context of policy choices. Our comprehensive case studies include an exhaustive review of documents published on government websites related to existing policies and solar program participation data gathered through a partnership with the respective utilities.

Our case cities are Fort Collins, Colorado, and Tallahassee, Florida. We selected two cities with council-manager forms of government and similar population sizes, both of which are served by a municipally owned electric utility (MOU). These factors combine to suggest that the city governments should have similar levels of control and capacity to offer solar programs. Furthermore, by focusing on two cities with MOUs, we can ensure that they have the same internal capacity related to the programming and do not face investor-owned utilities' barriers (Homsy, 2016; Curley et al., 2021).

Both communities have solar power policy bundles to promote participation in rooftop solar and community solar farms. However, the utilities differ based on electric distribution and generation status: Fort Collins is a non-generating, distributive utility, whereas Tallahassee is a generating and distributing utility. Previous research suggests that utilities experience different barriers to implementing renewables if they are distributive but non-generating (Krause, 2011). Appendix A1 provides further details about the MOUs (City of Tallahassee Utilities, TU; City of Fort Collins Utilities, FCU).

4. Case description

The following sections detail participation in solar programs in Tallahassee and Fort Collins and the contextual factors that may account for observed differences across the two cases. Specifically, we report on the contextual factors in these two cities regarding their solar policies, population characteristics, and physical environments as they might relate to solar policy design, selection, and effectiveness.

4.1. Policy descriptions: rooftop PV

4.1.1. Tallahassee

Tallahassee Utilities expanded its low-interest loan program to allow residential customers to borrow up to $20,000.00 to install rooftop PV systems. To qualify for the solar loan program, Tallahassee Utilities requires that all solar installers are FSEC certified, and that the customer participates in a Tallahassee Utilities energy audit before installing the loan item. TU offers net metering but does not allow a customer's bill below zero dollars. Any additional credits can be transferred to the next month but expire at the end of the year (defined by the net metering anniversary date).

4.1.2. Fort Collins

Fort Collins' solar policy toolkit for rooftop PV includes Fort Collins' Solar Rebate Program (SRP), solar loans, and net metering (bill credits; City of Fort Collins, 2019a). The city's solar installation sizing limitation is relevant to each, dictating that the size may not exceed 120% of the typical annual use. Through SRP, residential customers can receive rebates for their solar installation, with rebate amounts calculated based on $0.50/Watt of generation capacity and total rebates possibly varying each year (City of Fort Collins, 2019b,c). These rebates are in addition to federal incentives. The loan program allows customers to receive a loan for 100% of the project cost for solar installations. Participants repay their loans through their monthly utility bills (City of Fort Collins, 2019c). Finally, the FCU net metering program provides bill credits that vary based on Time-of-Day pricing. Thus, solar energy reduces the customer's bill by the rate at that time of day, with excess generated solar energy credited at a slightly lower rate (City of Fort Collins, 2019c); there is no direct cap on the credits; however, the sizing limitations of existing solar installations ultimately set an upper limit on the credits.

4.2. Policy descriptions: community solar

4.2.1. Tallahassee

Tallahassee has two solar farms that provide customers with community solar. Solar farm #1 became operational in 2018 and was installed at roughly $33.2 million. It spreads over 120 acres near Tallahassee Airport (Hamlin, 2018). Solar farm #1 is 20 megawatts (American Cities Climate Challenge, 2020). The utility offered three enrollment levels; customers can use solar for 25, 50, or 100 percent of their monthly electricity consumption. In addition, they provide a fixed 0.05 cent fuel charge for 20 years instead of the natural gas fuel charge (035 cents), which fluctuates over time. Solar farm #2, which became operational in January 2020, is a 40-megawatt facility (American Cities Climate Challenge, 2020) and spans 240 acres by the Tallahassee Airport (Woolson, 2020). The solar farm operation guidelines are documented in the city ordinances via Sec. 21–24. More information regarding these and other solar-related policies is discussed in Appendix A.3.

4.2.2. Fort Collins

The Fort Collins community solar program began in 2015. Customers participating in the Community Solar Program receive bill credits based on their subscription level, associated solar array production amount, and time-of-day pricing, ranging from 5.23 cents per kilowatt-hour to 22.92 cents per kilowatt-hour (City of Fort Collins, 2020b). The city of Fort Collins Utility has priced these 305-watt panels, including a 1$ per watt rebate, paired with federal incentives, bringing the panel cost down to $484.95 (Ferrier, 2015). There is an operation and maintenance fee of 9.38375% for the net solar credits generated by the array (City of Fort Collins, 2020e). The

Riverside Community Solar Array was installed as a pilot program in partnership with the Clean Energy Collective. The 0.632-megawatt (632 kW) PV facility spans 6 acres (Braun, 2017). Thus, the community solar arrays in Tallahassee generate nearly 100 times as much electricity as the array in Fort Collins.

4.3. Program participation

Figure 1 documents actual participation rates in the respective programs for each city. Participation in the Solar Rooftop PV programs is much higher in Fort Collins than it is in Tallahassee. However, we see the opposite pattern for Community Solar.

The first solar farm reached maximum capacity in Tallahassee before it was active. Upon opt-in, participants per kWh rate increased by 43% (from 0.035 to 0.05). This means that participants are actively charged more, with no ability to engage in net metering, to participate in the Tallahassee Community Solar program. Despite this, demand for solar energy in the city was still high, and Tallahassee had a waitlist for the next solar farm rollout in Tallahassee. Tallahassee had enough participation in the community solar programs to reach total capacity for solar subscriptions at the end of 2019 before the second solar farm was operational.

Interest in community solar is also strong in Fort Collins. There is a waitlist to join the Fort Collins Community Solar Program (City of Fort Collins, 2020a). Participation in community solar is limited by capacity constraints, although community solar capacity growth is motivated by customer interest and demand. However, the community solar program in Fort Collins requires upfront participant buy-in. This means that people essentially buy a panel for a specific amount of money and are then credited for the power those panels produce. Both of these programs are labeled as community solar; however, they operate functionally differently. This is likely due in part to the nature of Fort Collins Municipal utility as a distributional, non-generating utility; as a result, Fort Collins Utility likely faces additional barriers in expanding its community solar program.

We see that residential customer subscriptions are much higher in Tallahassee than in Fort Collins, and there has been a significant increase in Tallahassee's community solar program in a much shorter time than the Fort Collins program. In Fort Collins, the participation rate for rooftop solar programs is much higher than that seen in Tallahassee. Given the interest in Tallahassee for the community solar program, it suggests that the interest is present within the community for increasing rooftop solar participation. The following sections will explore the contextual factors that might help to explain the variation in participation rates despite the perceived demand for solar-focused programs.

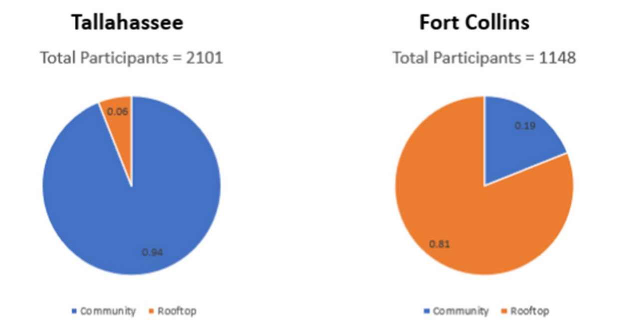

FIGURE 1
Policy participation comparison.

5. Assessing contextual factors

The following section will explore the three factors that we identified through the literature overview as potentially relevant to defining appropriate context for policy design. The existing solar policies at the state level that promote the residential use of solar energy in each community are described in Sections 3.1.2.1 through 3.1.2.3. These policies are summarized and compared in Appendix A.1. Complimentary policies are described in Section 3.1.2.4. In addition to state policies, the federal government offers an additional 30% tax credit on purchasing solar electric systems (City of Fort Collins, 2019c; Solar Energy Industries Association, 2021). After the configuration of existing policies (section 4.1), the target population characteristics (section 4.2), and the physical environment (section 4.3) are assessed below. These sections are then summarized and used to provide key takeaways in section 5.

5.1. Configuration of existing policies

5.1.1. Existing solar policy – state level

5.1.1.1. Florida

Each city's desire and ability to adopt solar programs is likely shaped by state-level policy, as suggested in our literature review above. Florida was ranked 8th in 2018 (3rd in 2017) for its total solar generation, with 252,597 homes powered by solar, and roughly 1% of the state's electricity use comes from solar. Florida does not have a renewable portfolio standard. However, as of 2019, Florida had eight renewable energy incentives (DSIRE, 2020d). This includes a) a sales tax exemption, which provides relief from the financial burden of purchasing solar systems by decreasing the overall cost, and b) a property tax exemption for certain eligible technologies, including solar water heaters, solar PV, wind, and geothermal heat pumps (DSIRE, 2020a). The tax incentive amount is 100% of the added property value of the technology for residential installations and 80% for non-residential. Several regulations oversee all solar systems (approved by the Florida Solar Energy Center), and installing contractors meet licensing requirements. Florida also instituted rules that prevent homeowners' associations from limiting the ability of homeowners to install rooftop solar on their properties.

5.1.1.2. Colorado

When Colorado adopted its Renewable Energy Standards (RES) in 2004, it was the first state in the U.S. to institute such initiatives due to a public vote. Colorado's RES requires a percentage of utility power to be generated by renewable sources. Specifically, investor-owned utility power should be 30% renewable, while cooperatives and municipal utility's renewable share depends on facility size, ranging from 10 to 20% (National Conference of State Legislatures, 2019). At the time of this study, Colorado residents were exempt

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from 100% of the sales and use taxes that result from residential solar system installations. Colorado also offers property tax incentives for residential, commercial, industrial, and agricultural properties. For residential solar, owners are exempt from paying taxes on any increase in property values added by installing solar technology and other renewable energy technologies are exempt as well (DSIRE, 2020a,b,c). Colorado was ranked 8th in solar energy generation in 2014 (12th in 2018), with roughly 3% of total electricity use powered by solar and about 215,974 homes utilizing solar. As of 2019, Colorado had 13 renewable energy incentives (DSIRE, 2020e). Appendix A.2 provides additional context and synthesis of state-level policy offerings.

5.1.2. Complementary policies

Both cities have a webpage dedicated to sustainability and the activities undertaken to achieve sustainability. Fort Collins has a single department-the Sustainability Services Area-dedicated to environmental sustainability and addresses economic and social sustainability (City of Fort Collins, 2020d). This department reports to one of the Deputy City Managers and operationalizes sustainability as the synergy that results from economic health, environmental protection, and intentional equitable policy; each of these has a dedicated budget line and a total of 28 full-time equivalents between them (City of Fort Collins, 2019a). The City of Tallahassee has a sustainability director and emphasizes community preservation (City of Tallahassee, 2020a). Still, it does not have a dedicated sustainability department (City of Tallahassee, 2019a) or associated budget (City of Tallahassee, 2019c).

Differences in policies regulating the built and natural environmental elements that influence solar panel feasibility, placement, and productivity will impact solar uptake. Specific examples include land use policies limiting the placement of solar panels, building codes specific to roofing regulations, and urban tree policies and programming.

5.1.2.1. Solar zoning ordinances

The siting of rooftop (residential) and community solar panels is regulated at the city and county levels for Tallahassee and Fort Collins. The county and city ordinances combined primarily define panel installation classifications, height and setback requirements, approved zoning districts, the application process, and the pricing structure for energy produced for each city. There are multiple notable differences between the zoning ordinances, both in design and stipulations, that may impact the adoption of solar. Appendix A.3 gives a complete list of each city's requirements in the ordinance's original language and a detailed narrative of the differences and their implications for solar adoption.

In Tallahassee, Leon County takes on most responsibility for the ordinance structure, with the city outlining the energy production pricing structure. Tallahassee has three ordinances covering price, and Leon County has one solar ordinance that details the rest. In contrast, a Fort Collins municipal code search returns 44 codes and regulations that mention solar. In Fort Collins, the structure of the zoning code relevant to solar panels results in the applicable ordinances being scattered throughout the city codes, which increases complexity and introduces a potential barrier to adoption.

In addition to differences in the complexity of the codes, there are differences in their content. For example, the communities differ in their attention to protecting access to sunlight for solar energy production. Whereas Tallahassee provides a statement about the ability to obtain a solar easement, Fort Collins devotes more effort and specificity to protecting solar access. This solar access provision removes barriers to rooftop/residential PV and community solar adoption in Fort Collins.

Additional ordinances that impact community solar adoption include the set-back, fencing, and landscaping requirements that protect viewsheds and land quality while promoting safety. Height limits for rooftop PV, set-back requirements, and the permit process appear to be more stringent in Fort Collins. Implementation influences how these code differences will impact solar uptake. Greater stringency may enhance solar adoption by guaranteeing appropriate installation and placement or act as a barrier to adoption due to challenges in achieving compliance. One area where Tallahassee's code is stricter is the Leon County Ordinance No 2020–01 specification that building-mounted solar systems must endure a wind load of 120 miles per hour, which adds a requirement to the permitting process. Community solar may face further obstacles in Tallahassee, given additional restrictions against placement in agricultural/silvicultural/conservation or preservation areas. However, while such regulations may impact the ability to develop a community solar farm, they do not have implications for resident participation in a community solar program once established. Table 1A in Appendix A.3 compares the solar zoning ordinances of Leon County/Tallahassee and Fort Collins.

5.1.2.2. Building regulations

Neither city specifies roofing regulations; however, the building codes for Florida and Colorado provide a list of allowed roofing materials. Each state lists the following allowable materials: asphalt shingles, concrete and clay tile, metal roof shingles, mineral-surfaced roll roofing, slate shingles, wood shingles, wood shakes, and photovoltaic shingles (International Code Council, 2020; UpCodes, 2020). Colorado also provides one additional allowable material, metal panels. The variety of acceptable materials may suggest that city building regulations do not appear to hinder solar adoption. However, restrictions set forth by Homeowners' Associations may add an extra level of complexity to rooftop solar installations in both locations.

5.1.2.3. Tree protections

The city of Tallahassee has clear guidelines about protected tree status and appears to have stricter rules around tree protection. Within Tallahassee's tree canopy ordinance, each tree has a critical protection zone to prevent root damage from digging and soil compaction during construction. The ordinances also outline a tree credit system based on the size of the tree, which is applied when the removal of a tree is subject to reforestation requirements. These protections extend to essentially any tree greater than 4 inches in diameter, particularly in areas of development. In addition, certified arborists in Tallahassee can grant tree protection beyond those currently listed. These regulations act as additional burdens to land selection for solar development; this is particularly important for community solar.

The City of Fort Collins' ordinance also establishes a process to protect trees during development. It designates a 6-inch or greater diameter to establish protection; however, Fort Collins does not appear to have as many protections as Tallahassee. The tree protection plan in Fort Collins does establish protection and dictates tree replacement but does not utilize a point system as presented in the City of Tallahassee. Fort Collins appears to have fewer protections and greater built-in flexibility than Tallahassee.

5.1.2.4. Forestry programs

The city of Tallahassee houses an Urban Forestry focus within its Planning Department. The 2018 Urban Forest Master Plan guides the department's conservation of the current tree canopy and implements strategies to help it grow. Canopy protection occurs through community education and outreach efforts, the Leon County Canopy Roads committee, and the Adopt-A-Tree program's implementation, allowing Tallahassee residents who live along a city-or county-maintained roadway to have a tree planted for free.

The parks department houses Fort Collins' forestry focus. The department summarizes its primary activities as follows: pruning the urban forest, conducting a risk assessment for community trees, tree replacement, identifying and controlling insects and disease, using industry standards and licensed arborists, collaborating with developers and landscapers to preserve plant diversity, and engaging in public outreach and information campaigns (City of Fort Collins, 2020c).

TABLE 1 Comparing city demographics.

	Tallahassee	Fort Collins
Population	189,907	161,175
Municipal utility electricity customers	122,000 total customers; 102,480 residential	70,500 total customers; 63,000 residential
65 and over %	8.1%	8.8%
% White alone	57.4%	89%
% Black African American	35%	1.2%
% Foreign-born	8.2%	6.4%
Median value home	$177,900	$265,900
Own occupied housing	39.6%	53.9%
High School Grad	92.5%	96%
Bachelors or higher	47.5%	52.5%
Registered Democrats (County)	53.7%	27.7%
Support Renewable Energy	67%	68%

5.2. Population characteristics

Table 1 offers an overview of population characteristics for Tallahassee and Fort Collins. They are both similarly sized cities with universities and a population with high levels of education; however, Tallahassee tends to be more racially diverse with lower levels of owner-occupied housing than Fort Collins. In addition, the county-level voter registration data suggests that Tallahassee is more Democratic than Fort Collins; however, each city appears to have the same degree of support for renewable energy as measured by the Yale Climate Opinion Map 2020 for renewable energy support (Howe et al., 2015). The remaining data for Table 1 comes from the U.S. Census quick facts website (Census Bureau, 2019), the MOUs website for each city, and the departments of state websites for voter registration (Colorado Secretary of State, 2021; Florida Department of State, 2021).

This section demonstrates that each city likely has unique population characteristics that might shape their ability to engage in the policies. Lower rates of home ownership in Tallahassee means the eligible number of participants in a policy design that requires homeownership will already be lower than can be observed in Fort Collins.

5.3. Physical environment

The following Sub-sections focus on the role of climate and tree cover as they are relevant to solar policy. We recognize that the context of the physical environment can refer to a much broader field of elements relevant to the specific policy issue itself.

5.3.1. Climate

Florida has a subtropical climate characterized by heat and humidity. Temperatures frequently exceed 90°F during 6 months of the year and are accompanied by a relative humidity of 50% or greater. These conditions result from abundant sunlight (particularly April through November), an average of nearly 60 inches of rainfall per year, and proximity to large bodies of water. Tallahassee is in Northern Florida and is moderately cooler than more Southern parts of the state, experiencing an average of 18 days below freezing from November through March (Black, 2003). The average temperature in Tallahassee is 67°F, with an average high of 81°F in the hottest month (July) and an average low of 51°F in the coldest month (January; Climate Data, 2020b). The city's average wind speeds range from 5 to 7.5 miles per hour (Florida Climate Center, 2020). However, Tallahassee can also be subject to strong winds from tropical storms and hurricanes. Hurricane season officially begins in Florida in June and ends in November. Depending on the storm category, wind speeds during hurricanes can range from 74 to 157 miles per hour or higher (Collins et al., 2017).

Fort Collins is a cold semi-arid climate (Climate Data, 2020a). The warmest month is July, with an average high temperature of 85°F, and in January, the coldest month, the average low temperature is 13°F. The annual average precipitation is 15.08 inches, and the average annual snowfall is 47 inches, with the highest average snowfall of 10.2 inches in March (Western Regional Climate Center, 2020).

5.3.2. Tree cover

As of 2015, based on LIDAR data, Tallahassee has an overall tree canopy coverage of 55% (City of Tallahassee, 2020c). Based on a 2020 analysis of 2016 LIDAR data, Fort Collins has tree canopy coverage of 21.62% (Rasmussen, 2020). The canopy coverage difference of approximately 33% is evident in the aerial images shown in Figures 2A,B, these images come from Google Maps (2018, 2019).

5.4. Summary of contextual factors

The discussion above unpacks some evident variation in existing environments that likely contribute to variation in policy participation. First, the current policy bundle for solar panels is more extensive in Fort Collins than in Tallahassee, presumably increasing participation rates in rooftop solar for Fort Collins. Second, variation across population characteristics (i.e., homeownership, median income) suggests that rooftop solar policy participation is more likely in Fort Collins. Lastly, tree cover is higher in Tallahassee, which means that conditions for rooftop solar may be less conducive, and siting community solar may be more complicated than in Fort Collins.

Residential solar installations often require tree removal to maximize generation from the PV array. The necessity for tree removal could discourage some homeowners from pursuing rooftop PV because of the resulting loss of cooling and aesthetics. Given the denser tree canopy and higher number of cooling days in Tallahassee, this would appear to be a greater issue. Thus, the physical environment may help explain variation in participation rates and address alternative policy designs that could increase solar installation. Table 2 below compares how these contextualizing factors might shape policy participation.

In addition, potential costs associated with weather events, such as hurricanes and possible wind damage to the panels, may limit residential willingness to invest in solar panels in Tallahassee. Unlike Tallahassee, Fort Collins does not have frequent significant wind or hurricane events. However, Fort Collins does experience strong wind events and hailstorms that can result in replacing roofing, requiring the removal and re-installment of solar systems to do so. While most insurance companies will treat solar panels as part of the home structure, some insurance policies may not cover roofs or the attached solar panels once installed (Hurtibise, 2016). In addition, most insurance companies increase insurance rates to protect solar panels. The increasing financial burden and risks of placing solar panels on one's roof in Tallahassee may decrease participation. Given the barriers to involvement in rooftop solar in Tallahassee, it is no wonder that community solar provides opportunities for participation without the additional costs related to hurricane losses, increasing insurance costs, tree removal, etc. Despite having similar levels of demand for the policy and the existence of solar incentives, the contextual environment (i.e., characteristics of the population, configuration of policy bundles, and physical environment) influence the designed policy from being equally effective in both cities. Alternative policy mechanisms, such as city or state insurance coverage for solar panels and reimagining rooftop solar ownership (rather than community solar), may be considered by policymakers to help overcome the barriers of instituting an effective rooftop solar program in Tallahassee.

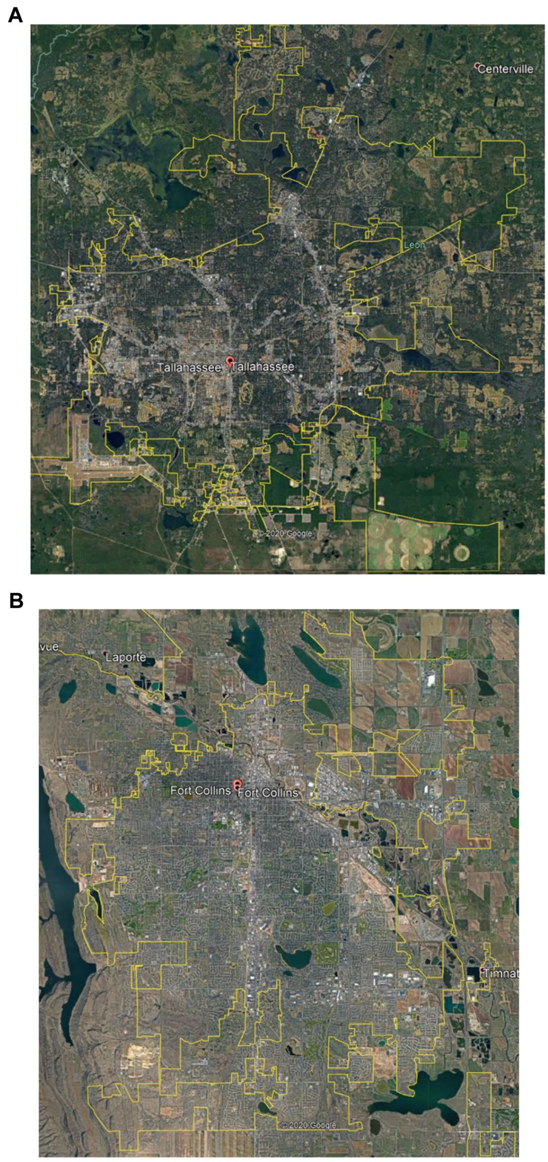

FIGURE 2
(A) Tree cover in Tallahassee. Tallahassee: 10/11/2018; 24.73miles up. **(B)** Tree cover in Fort Collins. Fort Collins: 7/17/2019; 24.12miles up.

6. Discussion

6.1. Alignment between context and effectiveness

Some key factors contribute to lower rooftop PV participation in Tallahassee than Fort Collins. First, the existing solar and complementary policy configuration suggests that Tallahassee will have fewer participants in the rooftop PV program than Fort Collins. More specifically, the financial incentives are smaller for Tallahassee residents, and participants are not allowed to net meter beyond zero (the utility does not pay the household for credits). The second is that tree protection and forestry programs shape the physical environment; Tallahassee has an older canopy that suggests that homes are heavily shaded and not ideal for rooftop PV installation. However, Fort Collins, which is more newly developed, has a younger tree canopy in many residential spaces which might make rooftop PV more appealing. Third, the community characteristics suggest that home ownership and racial homogeneity are higher in Fort Collins, consistent with previous findings that white, upper-middle-income, and highly educated individuals appear to participate in these programs at higher rates than other groups (Wolske, 2020). The collective impact of the above contextualizing factors suggests that rooftop PV would likely be a more effective policy in Fort Collins than in Tallahassee. The contexts described above for Tallahassee, such as shaded roofs, zoning rules, lower homeownership rates, and a lower median

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TABLE 2 Contextual factor supports which policy: community or rooftop?

Context category	Factor	Fort Collins	Tallahassee
Population characteristics	Home Ownership Rate: Higher in Fort Collins	Rooftop	Community
	Income: Higher in Fort Collins	Rooftop	Community
Policy bundle	State policy: Colorado has more resources for Rooftop available	Rooftop	Community
	Solar Zoning Ordinance: More complex and stringent in Fort Collins	Depends on Implementation	Rooftop
	Solar Zoning Ordinance: Wind Load Rating Requirement in Tallahassee	Rooftop	Community
	Solar Zoning Ordinance: Solar Access Protection is greater in Fort Collins	Rooftop	Community
	Tree Protections: More stringent in Tallahassee	Limited Impact	Limits Rooftop
	Forestry Program: Conservation and canopy growth	Limited Impact	Limits Rooftop
Physical environment	Tree Cover: Tallahassee urban tree canopy	Limited Impact	Limits Rooftop
Policy effectiveness (participation) more likely for		Rooftop	Community Solar

income, are likely to limit the effectiveness of large-scale rooftop solar incentives.

6.2. Contextualizing policy design

Based on the case comparison conducted above, we have identified specific factors that are likely relevant to policy design effectiveness. This section outlines those specific features and offers a series of takeaways that should be explored in alternative policy contexts for their generalizability. These takeaways explicate the potential avenues in which policy design should consider community context prior to implementation. Doing this will likely help target scarce resources into more effective policy.

6.2.1. Population characteristics

refer largely to the potential Pool of participants. Contextualizing this group means understanding the limitations and considerations of the potential targets. In this case, elements of the population's financial capabilities and homeownership are likely to directly impact participation based on the proposed policy design. Therefore, communities with higher rates of homeownership and higher median income are likely more able to engage in residential rooftop solar policies. Given that we see higher rates of homeownership and more expensive homes in Fort Collins, we could expect higher rates of participation in programs that require more upfront Capital and access to the property. This suggests that matching the characteristics of the community to the policy tool is likely important for design effectiveness.

Takeaway 1: Considering population characteristics in tool selection will help to increase policy effectiveness.

6.2.2. Existing policy configuration

refers to the idea that policy design can be hindered or amplified by existing policy within a community. This means that prior to selecting a design preference, the configuration of potentially impactful policies is needed. In the case of the policies described here, Tallahassee, Florida does not have the same degree of benefits that can be offered to incentivize residents of Fort Collins, Colorado. This makes it more likely that an additional inducement in Fort Collins is likely to have a significant impact on adoption rates and that owning solar panels might be a more relevant factor than simply green energy. This seems to be evident in the design of their community solar program which still centers solar panel ownership, which likely activates state-level benefits as well.

Takeaway 2: The full slate of existing policies is likely to interact, potentially in complementary ways that increase the effectiveness of a policy design.

However, policy configurations can also limit the effectiveness of a particular policy. We see this through the included building regulations and tree protections that are put into place. Specifically, in Tallahassee where building codes related to roofing and higher protections for trees might limit the ability of solar rooftops to be effective, we might suspect lower participation in rooftop PV programs.

Takeaway 3: The existing configurations of related policies are likely to interact with the proposed policy design, potentially in conflicting ways that decrease the effectiveness of the proposed policy design.

6.2.3. Physical environment

refers to the actual characteristics of the geographic location where the policy is being considered. In this case, we are looking at two different communities, one in Northern Florida and the other in Colorado. The weather and physical conditions of the locality are relevant for considering policy design. In the state of Florida there are hurricane events that can lead to unstable insurance markets, Colorado has the potential for blizzard conditions. While technology can be installed to help melt snow from the solar panels, large-scale wind events (such as hurricanes) can create additional risks for solar panel installation, particularly with the need for additional insurance riders in complicated insurance markets. Another potentially complicated physical environment constraint is tree cover. Roof-top solar power requires homes to have spaces with high degrees of shade, however, the city of Tallahassee has a very strong tree protection policy compared to Fort Collins (as discussed above). This suggests that both elements like available sunshine, lack of shading, and weather might act as potential barriers for policies that emphasize individual ownership of rooftop PV.

Takeaway 4: The physical environment, such as tree cover and weather, influences the ability of some policy design strategies to be limited in their effectiveness.

6.2.4. Putting it all together

The above discussions suggest that there are four factors that contextualize the ability of specific policy designs to be effective. We see evidence in this case that elements such as characteristics of the population, existing policies, and the physical environment can interact and contribute to varied levels of policy effectiveness. In the City of Tallahassee, we see population characteristics such as lower house values and homeownership rates, combined with strong tree protections, fewer policy incentives, and high rates of tree cover and more risk from severe weather limit the effectiveness of rooftop PV programs. However, the demand for solar energy still exists, it simply needs to be met through more innovative policy design or alternative policy solutions, which we see through high rates of participation in community solar. Alternatively, Fort Collins experiences higher levels of home ownership and larger incentives, with fewer physical environment barriers, which appears to be related to much higher levels of increased participation in their rooftop solar program and much lower levels of participation and engagement in community solar.

6.3. Implications for policy design

In this paper, we compare two solar policies across two communities to identify what contextual factors influence the effectiveness of solar policy design. This comparative case study specifically demonstrates that policy participation and effectiveness are impacted by the relevance of design choices related to contextual factors of population characteristics, existing policy configurations, and physical environments. The interaction of these factors, coupled with the program's design features, are likely to inform and potentially predict policy effectiveness in a more complete way than is typically captured by current research. These factors significantly affect research on policy adoption, design, and implementation.

Given the apparent relevance of contextual factors identified in this paper, policies may diffuse in ways that are inconsistent with their ability to be effective. Policy transfer research hints at this, that contexts of communities are relevant for policy effectiveness, however, if these contextual factors were considered during the design stage inappropriate policy transfer could be avoided. This suggests that there should be a role for integrating design features, these contextual factors, and the theoretical lenses of diffusion to best understand which policy (or design feature) is most appropriate for any given community. While these factors emphasize the need of policy adoption, policy enactment predominately emphasizes the organizational and situational needs for implementing policy; however, this research might argue that successful implementation depends on having a clear understanding of the potential contextual factors that might act as barriers to participation. These contextual factors can help to alter policy design or encourage the adoption of additional strategies to overcome ineffective design transfer.

Although studies on policy implementation (enactment), policy learning (failure), and policy transfer may consider some of the factors explicitly addressed here, their inclusion in policy design, especially rational policy tool choice research, is limited. In this study, we have laid out a series of key takeaways for how we might expect these contextual factors to be relevant to policy design. However, the present study is limited by its exploratory nature, and future research should examine the quantitative impact of these contextual features on policy choices and effectiveness more systematically. Integrating these elements in the study of policy design, particularly policy choice, may enable policymakers and scholars to enhance policy effectiveness, improve equity in distributing and delivering public goods and services, and decrease inefficiencies in government spending.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

This was a collaborative project across two institutions that were working with different municipally-owned utilities. The outcome data demonstrated very clear differences. CC and her student NH put together an initial draft manuscript that explored the potential reasons for those differences. PA-Y helped to refine the manuscript and make edits to the paper. Other co-authors read a draft of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor SS declared a past co-authorship with the author CC.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsuep.2023.1180830/full#supplementary-material

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Linking energy policy, energy insecurity, and health outcomes

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Energy insecurity poses a global challenge with far-reaching social equity and health implications. This paper provides a comprehensive perspective on the relationship between energy insecurity and health outcomes in developed countries. Existing research has identified associations between energy insecurity and various physical and mental health outcomes. Moreover, climate change can exacerbate the adverse health consequences of energy insecurity, disproportionately affecting vulnerable populations. Based on a review of existing literature, this paper identifies several knowledge gaps, proposes future research directions, and discusses data challenges faced by researchers in measuring energy insecurity and assessing the health impacts of existing programs that tackle energy insecurity. Furthermore, the paper highlights the importance of fostering collaboration among different governmental agencies and other sectors to enhance energy insecurity program management and data collection for program evaluation.

KEYWORDS

energy insecurity, energy justice, health, energy policy, climate change

1. Introduction

Energy insecurity is a pressing issue globally. It can be broadly defined as the inability to meet basic household energy needs (Hernández, 2016).[1] This multidimensional issue is deeply intertwined with larger structural challenges that reflect and reinforce the inequalities based on socioeconomic status, race, ethnicity, and other social dimensions, all of which may contribute to adverse health outcomes (Hernández, 2016; Bednar and Reames, 2020). A growing body of literature has explored the interconnections between energy insecurity and health (Cook et al., 2008; Hernández, 2016; Simcock et al., 2017; Oliveras et al., 2021; Pan et al., 2021; Liu et al., 2022). In response, many developed countries have implemented various energy and housing policies to address household energy insecurity. However, given the complex interplay of structural challenges with energy security, the mechanisms through which energy insecurity affects various health outcomes remain inadequately understood (Hernández, 2016). Additionally, little is known about whether and how existing policy tools that tackle energy insecurity effectively address its related health risks, impeding informed future program design. This paper synthesizes the knowledge accumulated over the past decade regarding the relationship between energy insecurity and health, with a focus

1 While similar terms like "energy poverty," "energy access," and "energy vulnerability" are used in the literature to describe domestic energy deprivation (Brown et al., 2019), we adopt "energy insecurity" in this paper because the definition of "energy insecurity" we follow (Hernández, 2016) is broad enough to capture various levels of energy difficulties that different households face in the developed country context. This spectrum of challenges ranges from the lack of access to basic modern energy services (i.e., "energy poverty") to the lack of access to affordable, reliable, and sustainable energy (i.e., "energy access").

on developed countries. By examining existing literature from energy and health journals, we identify knowledge gaps and propose future research directions and practical interventions to address the health risks associated with energy insecurity.

2. Adverse health consequences of energy insecurity

Energy insecurity poses significant health risks to individuals, stemming from two major causes as discussed in the literature: (1) a household's inability to afford enough energy to meet essential needs (Hernández and Siegel, 2019; Bednar and Reames, 2020; Cong et al., 2022), and (2) lack of access to reliable and resilient power infrastructure (Ji et al., 2016; Brown et al., 2019). Below we summarize how they may affect individual health in the context of developed countries based on previous research.

2.1. Household's inability to afford essential energy needs

Low-income households often struggle to pay utility bills and may fall into arrears, leading to difficult choices like sacrificing necessary expenses for medication or food to cover energy costs (Bhattacharya et al., 2011; Cong et al., 2022; Shan et al., 2022). In the United States, for example, 25.8 million low-income households face a high energy burden (i.e., spend more than 6% of income on energy bills), and 15.4 million of them experience a severe energy burden (i.e., spend more than 10% of income on energy bills) (Drehobl et al., 2020). Moreover, specific demographic groups, such as pensioners, the unemployed, and those with disabilities or young children, are more susceptible to domestic energy deprivation due to their unique energy needs to keep essential medical services or equipment (Bouzarovski and Petrova, 2015). These households usually have higher-than-average energy demand, exceeding their limited income and increasing the risk of utility shut-offs. Consequently, these vulnerable households may live in unhealthy or unsafe indoor temperatures or be unable to sustain essential medical services and equipment.

Energy insecurity due to households' inability to afford essential energy needs can adversely affect physical and mental health, increasing the likelihood of acute diseases and worsening chronic health conditions. Previous studies in developed countries have found energy insecurity is associated with respiratory and mental health outcomes, including asthma, pneumonia, diabetes, hypertension, depressive disorders, and poor-quality sleep (Shenassa et al., 2007; Cook et al., 2008; Liddell and Morris, 2010; Hernández and Siegel, 2019; Jessel et al., 2019; Memmott et al., 2021; Oliveras et al., 2021).

2.2. Lack of reliable and resilient power infrastructure

Energy insecurity can also arise from the lack of reliable and resilient power grid infrastructure, which may impact health negatively (Bouzarovski and Petrova, 2015). While the link between inadequate grid infrastructure and health risks has been evident and prevalent in developing countries (Jenkins et al., 2016; Banerjee et al., 2021; Nawaz, 2021; Pan et al., 2021; Zhang et al., 2021; Li et al., 2022), this issue manifests as unequal access to reliable power infrastructure in developed countries, disproportionately affecting low-income and minority communities (Bouzarovski et al., 2016; Bouzarovski and Tirado Herrero, 2017).

Research using county-level data or household-level data has demonstrated that lower-income and racial minority communities experience more frequent and prolonged power outages in the US (Mitsova et al., 2018; Xu and Tang, 2020; Azad and Ghandehari, 2021; Nejat et al., 2022). These disadvantaged groups and families with young children tended to have lower tolerance for service disruptions after recent hurricanes or storms in Florida, Louisiana, Purto Rico, and Texas and experienced more hardship during power outages, such as difficulties with getting access to healthcare services and medication (Mitsova et al., 2018, 2021; Coleman et al., 2020). However, these studies only establish associations between energy insecurity and access to medical services, and more rigorous analyses are needed to determine the direct link between the lack of reliable power supply and broader physical and mental health impacts.

3. Climate change exacerbates the adverse health consequences

The increasing frequency of extreme weather events and natural disasters due to climate change can exacerbate the negative health impacts of energy insecurity on vulnerable and socially marginalized populations as it can affect both causes of energy insecurity identified in Section 2 (Shonkoff et al., 2011; Smith et al., 2013; Reames, 2016; Bouzarovski and Simcock, 2017; Benevolenza and DeRigne, 2019; Longden et al., 2021). At the household level, extreme temperatures, either too cold or warm, create additional energy burdens for low-income households as they need to increase the usage of their heating/cooling devices, which leads to higher energy bills. Vulnerable households may have health risks like heatstroke or hypothermia as they limit energy consumption to cope with tight income constraints (Jessel et al., 2019; Thomson et al., 2019; Cong et al., 2022; Shan et al., 2022).

Furthermore, the impact of more frequent extreme weather events and energy service disruptions due to inadequate energy infrastructure, disproportionately affects specific vulnerable groups, such as the poor, the elderly or disabled, family with young children, and substance abusers (Mitsova et al., 2018; Benevolenza and DeRigne, 2019; Azad and Ghandehari, 2021; Nejat et al., 2022; Rodríguez et al., 2022). Exposure to energy service disruptions increases their levels of mental, emotional, and physical stress. Consequently, climate change is likely to reinforce existing socioeconomic disparities, leaving low-income, minority, and other marginalized groups burdened with greater economic and health challenges unless proactive policies are implemented to address equity concerns (Shonkoff et al., 2011).

4. Discussion

Existing literature has been trying to establish the connection between household energy insecurity and adverse physical and mental health outcomes and calls for proactive policies to address energy insecurity and its associated health risks. However, little is known about the effectiveness of policies or programs that have been implemented to address energy insecurity and there lack of studies on the health impacts of these initiatives. Furthermore, while previous research has identified associations between energy insecurity and health risks, there is a need for more rigorous causal analyses to fully comprehend the mechanisms through which energy insecurity affects various health outcomes. To bridge these research gaps, we propose several future research directions and recommend improvements for practices.

4.1. Challenges and opportunities for future research

4.1.1. Developing a comprehensive definition and measurements of energy insecurity

Energy insecurity is a complex issue intertwined with broader aspects of inadequate housing, material and infrastructure deprivation, and neighborhood disadvantages (Hernández, 2016). To conduct a more thorough investigation of energy insecurity, it is crucial to establish a comprehensive definition that captures its multiple dimensions and guides the development of appropriate measurements.

Notably, considerable efforts have been made toward creating a holistic definition and framework of household energy insecurity (Bouzarovski and Petrova, 2015; Gouveia et al., 2022; Scheier and Kittner, 2022). For example, Thomson et al. (2019) developed a conceptual diagram encompassing vulnerability to excessive indoor heat while considering related aspects like house features, adaptability to extreme weather, and sensitivity to adverse consequences. Additionally, there has been ongoing work to develop indices and map vulnerability, capturing various facets of energy insecurity in the US and European countries. The Structural Energy Poverty Vulnerability (SEPV) index by Recalde et al. (2019) summarizes structural determinants of energy poverty in the European Union, revealing geographical patterns and their impact on health. The census tract level data provided by the Climate and Economic Justice Screening Tool,[2] presents an opportunity to create a similar index for energy insecurity in the US, considering structural factors while connecting them to climate change and health outcomes.

However, the limited availability of large-scale high-resolution energy data is still a significant roadblock for researchers to measure some dimensions of energy insecurity. Most research so far has focused on measuring energy affordability using household energy burden or ability to pay (Memmott et al., 2021). There has been scant research on energy-limiting behaviors, measured as the time of use or the energy consumption change in response to outdoor temperatures (White and Sintov, 2020; Oliveras et al., 2021; Cong et al., 2022). Availability of data for energy-limiting behaviors and other measurements of ability to pay, such as utility disconnections or bill arrears, is often restricted due to proprietary ownership by utilities or household-level survey data not disclosing high-resolution geographical information (e.g., the US Residential Energy Consumption Survey or other protected survey data collected by researchers). To facilitate research on energy insecurity and its related outcomes, it would be helpful for researchers, utilities, and government agencies to collaborate and seek better data-sharing or open-data practices in the future.

In addition to household-level energy affordability, the lack of access to reliable and resilient power infrastructure is an important dimension of energy insecurity, as discussed in previous sections. To measure this dimension, web scraping outage data from utility live outage maps (Shan et al., 2022) may present an opportunity for researchers to obtain geolocation-specific power outage and recovery data during extreme weather events and normal operations.

4.1.2. Assessing the impacts of energy justice programs on health outcomes

Another area requiring future research is the assessment of health impacts associated with a diverse range of energy programs aimed at addressing various aspects of energy insecurity. For example, within the current policy landscape of the US, these initiatives are implemented by different government agencies and utilities. They encompass utility bill assistance, financial incentives for adopting energy efficiency, clean energy, and upgrades that improve resilience to extreme weather, as well as dissemination of energy information and regulatory measures (Brown et al., 2019). There has been research evaluating participation in some of these programs and their effectiveness in reducing energy burden. Integrating relevant health outcome data, future research can further investigate their efficacy in enhancing low-income households' physical and mental health and examine whether and how they complement each other to mitigate the health risks stemming from energy insecurity.

However, accessing high-resolution health data also poses challenges, as it is collected and managed by hospitals or health departments at various levels of government with restricted public access. Therefore, establishing better data-sharing mechanisms between researchers, health departments, and hospitals is essential to facilitate such program evaluation.

4.2. Implications for practice: forging collaboration to enhance program management and data collection across government agencies and sectors

Addressing energy insecurity and its health impacts requires collaboration among various departments, including housing, health, human services, energy, and emergency management (Middlemiss and Gillard, 2015). These departments are managing various energy and housing programs separately, which increases

2 https://screeningtool.geoplatform.gov/en/methodology#energy-burden

the difficulty of data collection for program evaluation. To facilitate data collection for program evaluation, interdepartmental partnerships can be established. For instance, in the US context, the Centers for Disease Control and Prevention (CDC), the Department of Housing and Urban Development (HUD), and the Department of Energy (DOE) can work together to establish and enforce energy efficiency standards for HUD-subsidized housing. They can also collaborate to develop programs like the Enterprise Green Communities Criteria and Certification,[3] which provides a framework to ensure that low-income housing is healthier, more efficient, and incorporated into the fabric of communities, promoting resident well-being and sustainability. In the program design phase, collaborative data management arrangements should be developed to collect program implementation and performance data for future evaluation.

Another area requiring collaboration is integrating climate change mitigation and adaptation programs. By connecting natural disaster mitigation initiatives with efforts that promote energy efficiency and carbon reduction, we may better address the disproportionate economic and health impacts of climate change on vulnerable populations. Achieving this objective requires collaboration between emergency management and energy/environmental departments at different levels to formulate and implement proactive policies that address both disaster resilience (e.g., building retrofitting to mitigate natural disaster risks) and energy insecurity (e.g., building energy efficiency upgrades). Community-based organizations, advocacy groups, and residents' input are also vital in this process. These collaborative efforts will streamline data gathering and management for effective program implementation and evaluation.

3 https://www.greencommunitiesonline.org/introduction

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TT and HK conceptualized the research, conducted the literature review, and wrote the paper. HK collected the data. TT edited the paper. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) TT declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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A bibliometric review of energy justice literature

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Introduction: Academic literature on energy justice sits at the intersection of a complex ecosystem of technologies, geographies, disciplinary traditions, terminologies, frameworks, theories, and methods. Its recent and rapid growth suggests it is of interest to a large number of stakeholders. However, these same features make aggregation and summarization a considerable undertaking.

Methods: This article uses advanced bibliometric analytics to synthesize this disparate and varied metadata to characterize trends in the treatment of energy justice in academic literature. The review covers 4,196 articles published between 1983 and 2023 with methods appropriate to the number and diversity of publications and associated subfields.

Results: We document distinct uses of similar terminologies across subfields in literature, inequitable ratios of global research compared to absolute levels of energy poverty, and the large but under-recognized contribution of cooking to the energy justice literature.

Discussion: In summarizing this voluminous literature and analyzing thematic changes over time, we provide scaffolding for more detailed reviews to place themselves within the larger interconnected literature network.

KEYWORDS

energy justice, energy equity, energy poverty, energy democracy, energy insecurity, energy burden, fuel poverty, bibliometric review

1. Introduction

Energy justice literature has seen rapid growth over its short history and has the potential for a large academic and practical impact in the future. This review presents the largest, most systematic, and most comprehensive review of the energy justice field to date, summarizing an ever-expanding network at the intersection of energy and social justice.

> *Energy justice refers to the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those historically harmed by the energy system* (Baker et al., 2019).

As both a goal and an emerging academic field, energy justice is incredibly multifaceted. Literature on energy justice evaluates the justice implications of a wide range of technological fields (solar, wind, fossil fuels, buildings, transportation, grids, etc.) on many different levels of demographic and social vulnerability (minorities, gender, income, health, etc.). In addition, energy justice questions encompass geographies all around the world, upstream and downstream effects, from the mining of rare earth minerals to waste cycles, different time scales of impact, whether injustices occur in the "access to" or "realization of" the energy technology or quality, and whether energy benefits or burdens are being distributed, in addition to many other issues.

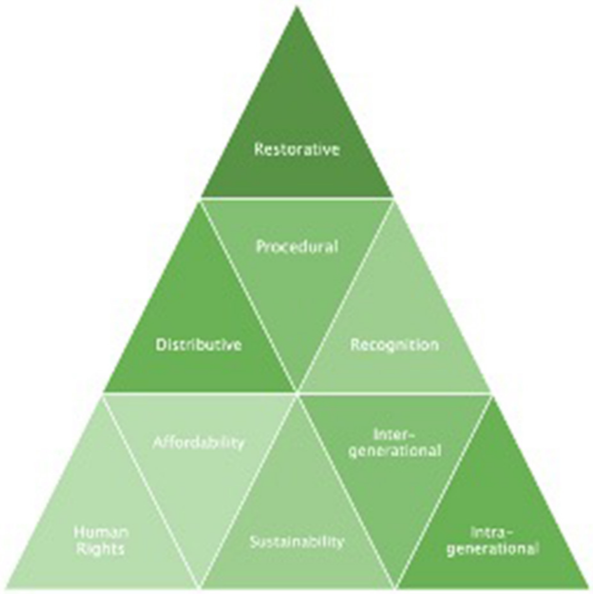

FIGURE 1
Theories of energy justice.

This multifaceted field houses a plurality of frameworks and theories. In a 2016 conceptual review of the field, Jenkins et al. (2016) proposed a framework that includes distributive, procedural, and recognition justice as the three core tenets. Distributional energy justice evaluates the allocation of the benefits and burdens of energy. Procedural energy justice is the equitable engagement of all stakeholders in decision-making and requires "participation, impartiality, and full information disclosure." And finally, recognition of energy justice calls for fair representation and the offering of complete and equal political rights to all individuals (McCauley et al., 2013). These three tenets, which are placed in the middle tier of the theory pyramid in Figure 1, are often accompanied by restorative justice (Heffron and McCauley, 2017). Restorative justice is an approach adopted from criminal justice—articulated in Zehr's (1990) book *Changing Lenses—A New Focus for Crime and Justice*—that involves all the stakeholders involved in a crime to address the harms, needs, and obligations arising from the crime by putting right and enabling healing to the greatest extent possible. Restorative justice is placed at the top of the pyramid to acknowledge the prior and ongoing harm to low-income communities and communities of color that create unequal baselines and endowments.

In addition to the three tenets framework, Sovacool et al. promote a framework approach consisting of many core principles. Their list has included human rights concerns, availability, affordability, due process, good governance, transparency and accountability, sustainability, intra- and intergenerational equity, responsibility, resistance, and intersectionality (Sovacool and Dworkin, 2015; Sovacool et al., 2016, 2017). Five of these principles form the foundation of the theory pyramid in Figure 1.

TABLE 1 Energy justice terminology.

Term	Definition	Source
Energy justice	The goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those by the energy system	Baker et al. (2019)
Energy equity	Achieving energy equity entails giving groups different types of tools such that they can equally take advantage of opportunities or reach a desired goal	Cong et al. (2022)
Energy democracy	The notion that communities should have a say and agency in shaping and participating in their energy future	Baker et al. (2019)
Energy insecurity	The inability to meet basic household energy needs due to the high costs of energy	Baker et al. (2019)
Energy burden	Amount of overall household income spent to cover energy costs	Baker et al. (2019)
Energy poverty	A lack of access to basic, life-sustaining energy	Baker et al. (2019)
Fuel poverty	When a household is unable to afford adequate energy services in the home on their present income. Includes all uses of energy, not just heating. Focuses on what is needed, not what is being achieved	Boardman (2012)

Finally, the field has a long dictionary of overlapping terminologies (see Table 1). The Initiative for Energy Justice (IEJ) created a workbook that discusses the range of terms associated with 'energy justice' broadly and how these terms are used by both academics and practitioners (Baker et al., 2019). Their list of common terms includes *energy justice*, *energy equity*, *energy democracy*, *energy insecurity*, *energy burden*, and *energy poverty*, of which each has different associations. To this list, we have added the related term *fuel poverty*, which most closely parallels the meaning of *energy insecurity* and appears earlier in the literature.

The core intellectual roots of energy justice are composed of literature on environmental and climate justice as well as discussions of inequality and justice from political philosophy and ethics (Baker et al., 2019). While energy justice builds on these longer-established disciplines, the field itself is quite new, only emerging academically in 2017. The multiple facets, the plurality of theories, and the large dictionary of terms not only offer the field the opportunity for wide reach and transcendence of many issues but also demonstrate its scattered nature. In the most comprehensive review prior to this article, Jenkins et al. (2021) note that "efforts are generally more multidisciplinary than interdisciplinary, and it is a potentially 'corruptible concept', highly vulnerable to a range of political agendas".

This complex and voluminous literature requires scalable approaches to synthesize insights and trends. We leverage advances in systematic literature review approaches and visualization to address this gap. Bibliometric methods are uniquely suited to the systematic and comprehensive review of the diverse academic literature composing the field of energy justice. By adopting this approach, we describe the superstructure within the energy justice field, showing interlinkages and thematic evolutions, and providing a scaffolding that will support future research.

2. Methods

Bibliometrics is the use of statistical methods to review and map scientific literature through systematic, transparent, and reproducible processes. Bibliometrics is a particularly suitable scientific mapping technique for voluminous, fragmented, and controversial research fields because it provides objective and reliable analyses. It can provide structured analysis to a large body of information, infer trends over time and themes researched, identify shifts in the boundaries of the disciplines, detect the most prolific scholars and institutions, and present the "big picture" of a field of research (Aria and Cuccurullo, 2017).

This article performs a bibliometric review of academic energy justice publications primarily using the R-package biblometrix described by Aria and Cuccurullo (2017). Their flexible, open-source tool allows scholars to follow the complete scientific mapping workflow using substantial and effective statistical algorithms and data visualization tools.

While Jenkins et al. (2021) review was systematic and comprehensive of their stated scope, by using time-intensive manual methods, they reviewed 155 academic articles published between 2008 and 2019. In addition to Jenkins et al. (2021) highly cited review, we identified three other articles that applied bibliometric analysis methods, to varying degrees, to subsets of the energy justice literature. First, Brown et al. (2020a) in *Energy Research & Social Science* used bibliometric methods to examine the persistence of energy burdens (high proportion of income spent on energy bills) in the United States. Their article presents an ecosystem of energy energy-burden stakeholders and then visualizes thematic clusters and trends over time. Second, later in 2020, several of the authors from Brown et al. (2020a) published a second review in *Progress in Energy* that takes a more qualitative and narrative approach to reviewing the "magnitude, causes, correlates, and impacts of the energy burden currently experienced by low-income households in the U.S (Brown et al., 2020b)." They expand on the design and cost-effectiveness of programs designed to reduce energy poverty in the United States. Third, Li et al. (2015) offered bibliometric results on energy poverty (referred to as the lack of modern energy services, primarily related to developing countries) and fuel poverty (referred to generally as the lack of ability to afford adequate warmth in the home, primarily pertaining to households in Europe). This quantitative review focused on reporting numbers and terms rather than on insights.

The computational methods used in this analysis allow for the expansion of the time span, search terms, and types of publications to review 4,196 academic publications published and available on the Scopus Database on or before 5 July 2023. Table 2 compares the scope and search criteria of this review to those of Li et al. (2015), Brown et al. (2020a), and Jenkins et al. (2021).

The primary difference is the dramatic expansion of the review's search terms in this analysis. Instead of narrowing the search to only articles that include one term explicitly in the title, abstract, or keywords, the search was broadened to include all of the terms that Table 1 identifies from the social science and legal literature (Baker et al., 2019) in addition to *fuel poverty*. All terms were searched, as well as synonyms to each of the terms, and their plural forms. By using an asterisk wildcard character as a simplified form of regular expression, the search term "energy *justice*" was used to find documents that included *energy justice*, *energy injustice*, *energy justices*, or *energy injustices*. This analysis did not explicitly include *energy security* as this term generally refers to a different, well-established literature at the intersection of electric power systems, risk, and global energy governance. Still, our search results identified several articles that discussed energy insecurity on a national scale rather than on a household scale. Since "energy justice", broadly speaking, is a fragmented and multidisciplinary field, a narrow selection of search terms risks missing large portions of the literature.

Several additional steps were taken to ensure review relevance. Nearly 160 articles were removed that used a definition of *energy burden* from the fields of biology, microbiology, zoology, and ecology which refers to metabolic energy burden on an organism scale or societal systems scale. We removed duplicate articles using the unique accession numbers for each entry as well as manual methods. The computational review of all publications was supplemented by human scanning of all titles for relevance.

The starting date of this search is not limited in order to capture the full history of this field. This allows us to include six publications prior to 1985, such as a *Harvard Environmental Law Review* article from 1983 titled "Energy Equity for the Poor: The Search for Fairness in Federal Energy Assistance Policy" by Manaster (1983), and an article in the *Journal of Economic Psychology* titled "Social Policy Options and Fuel Poverty" by Bradshaw and Hutton (1983). Manaster (1983) discussed the financial burden of high energy costs placed on Americans since the 1973 oil embargo. Bradshaw and Hutton used data from three national surveys to evaluate policy options for relieving fuel poverty, defined as the inability to afford adequate wealth in the home (Bradshaw and Hutton, 1983). We do not assume that these were foundational articles to fuel poverty research, as both seem to imply prior research, but that they were some of the earliest articles accessible in the Scopus database. While the earliest article found for this review was published in 1979, there were only 15 (0.36%) results published before 2000 and only 87 (2%) results between 2000 and 2007. Therefore, expanding the review's temporal scope does not significantly change the following analyses. Nonetheless, the date range was expanded for comprehensiveness.

This analysis searched the Scopus database for depth, standardization of documentation, and integration with the bibliometrix R-package. Scopus is one of the largest abstract and citation databases of peer-reviewed literature including scientific journals, books, and conference proceedings. Their curated collection contains the contents of over 25,800 unique peer-reviewed scholarly journals covering disciplines across social sciences, physical sciences, health sciences, and life sciences.

TABLE 2 Scope and search criteria of existing systematic energy justice reviews.

Characteristic	Jenkins et al. (2021)	Brown et al. (2020a)	Li et al. (2015)	This review
Search terms	"Energy justice" in the title, abstract, and keywords	(Energy efficiency and solar energy) and (low-income households and poverty) and (data analysis and evaluation) in keywords. Further, at least one author from the US	Searched topic for: "energy poverty" or "energy poor" or "fuel poverty" or "fuel poor"	"Energy *justice*", "energy *equit*", "energy democracy", "energy insecurity", "energy burden*", "energy poverty", or "fuel poverty" in the title, abstract, or keywords, where * acts as a wildcard character
Time span	1 January 2008–31 December 2019	2010–2019	1981–21 January 2014	Before 5 July 2023
Databases	ScienceDirect, Project MUSE, HeinOnline, SpringerLink, Taylor and Francis Online, Wiley Online Library, Sage Journals, Annual Reviews	Web of Science	Scientific Citation Indexing (SCI) and Social Sciences Citation Index (SSCI) databases from Web of Science	Scopus
Document types	Full-length articles and review articles that were peer-reviewed and published in English	Peer-reviewed and gray literature	Only specified to "Scientific publications"	Full-length articles, review articles, perspectives, conference articles, books, and book chapters. All, not limited to English
Total publications	155	183	269	4,196

Forty-two percent of the energy justice literature in this review is published in only nine journals: *Energy Research and Social Science* ($n = 371$), *Energy Policy* ($n = 320$), *Energies* ($n = 130$), *Sustainability* ($n = 121$), *Energy Economics* ($n = 113$), *Energy and Buildings* ($n = 99$), *Renewable and Sustainable Energy Reviews* ($n = 77$), *Applied Energy* ($n = 66$), *Energy for Sustainable Development* ($n = 66$), and *Energy* ($n = 62$). Source clustering through Bradford's law identifies these 10 of the 1,298 total sources as core sources, or the nucleus of journals particularly devoted to this subject.[1]

Since this database has complete coverage of these most popular journals, the use of this single database is sufficient for the following analysis. As a verification step, the search terms from Jenkins et al. (2021) were reproduced in the Scopus database, resulting in 187 academic articles, which is larger than, and broadly inclusive of, their 155-article review. This may be due to later steps by the authors to remove articles they found not to be relevant to the overall review even though the articles fit the explicit search criteria. As found in this review, the articles that fit the name of the search criteria but not their spirit may have focused on energy security as in national security risk or may be published in a language other than English.

The acceptable document types were finally expanded to include articles, reviews, proceedings, books, and book chapters. Book reviews, corrections, notes, letters, and editorial materials were all excluded as they were largely repetitive of the original content provided in the included document types. This review also did not limit the language of publication. Not limiting publications to just those published in English added 87 results published between 1979 and 2023. Many of these articles defined *energy poverty* for different local contexts, such as in Italy, Mexico, or Argentina, and all metadata (most importantly, the title, abstract, and keywords) were written in English. By including these diverse global perspectives, this review prioritizes equity in its methods as well as its subject matter.

2.1. Methodological limitations

This review has three key limitations. First, similar to all bibliometric analyses, this review does not use the full text of articles, only the extended metadata. The metadata includes the title, abstract, authors, journal, research area, publication date, keywords, citations, times cited, and funding information, among others. While the full text of many of the included articles is open access, many others remain behind journal paywalls. The crucial contribution of this bibliometric review to the field lies in its reproducibility, breadth, and ability to reveal superstructures. Therefore, this analysis does not pursue the large additional methodological and computational burden that compiling and digitizing the full texts entails.

Second, the broad search terms result in the inclusion of a small number of publications where energy justice, as defined earlier, is not the primary focus. For example, publications that examine technology and are described as having 'the potential to reduce energy insecurity' or are motivated by 'overcoming worldwide energy poverty and climate change'. Their limited presence is acknowledged but not removed at present from the much larger analysis. *En masse*, the strength of the systematic methods outweighs the limited presence of outliers. As detailed earlier, several steps were taken to ensure overall review relevance including removals of biological literature and manual human scanning of all publications.

Using a scientific publication database excludes the important energy justice grassroots and activist perspectives in gray literature.

1 Bradford's law states that "if the journals are arranged in descending order of the number of articles they carried on the subject, then successive zones of periodicals containing the same number of articles on the subject for the simple geometric series $1 : n_s : n_s^2 : n_s^3$." Bradford called the first zone, the nucleus of journals particularly devoted to the given subject.

Compiling and extending similar methods to this extensive gray literature provide a promising opportunity for future research. Fuller and McCauley's (2016) article titled "Framing Energy Justice: Perspectives From Activism And Advocacy" provides an excellent starting point by developing an analytical framework for assessing the emergence of energy justice in the activist and advocacy areas through a survey of organizations in Philadelphia, Paris, and Berlin. The Energy Justice Workbook expanded upon Fuller and McCauley's (2016) work in Section 1.1 on energy justice in practice (Baker et al., 2019). In this section, the authors reviewed statements of practitioners and advocates, finding that they rely less on the terms *energy justice* and more on *energy equity* or *energy democracy*. Carley et al. (2021) provide a non-comprehensive review of energy justice programs in the United States on which future work can be built. However, these cross-cutting energy justice issues are faced by communities around the world; therefore, a focus on any one country may leave out key themes.

Table 3 describes the resulting contents of this review.

TABLE 3 Descriptive summary of this review's contents.

Characteristic	Value
Time span of publications	1979 to 5 July 2023
Number of sources (journals, books, conferences, etc.)	1,298
Number of documents	4,196
Average years from publication	4.5
Average document citations	20.63
Number of unique references	221,922
Document types	2,958 articles; 273 reviews; 380 conference articles; 120 perspectives (editorials, notes, and short surveys); 82 books; and 383 book chapters
Keywords	11,868 Keywords Plus; 7,923 author keywords
Authors	8,895 authors; 701 authors of single-authored documents
Collaborations	886 single-authored documents; 3.1 average authors per document; 24.93% international coauthorships

3. Results

3.1. Dramatic growth

The energy justice field has grown quickly since 2009, with a compound annual growth rate of 14.65%. Jumps in productivity in 2018 and 2021 (measured by the slope of scientific production) indicate turning points in the field (Figure 2). As of 5 July 2023, there were already 409 articles published, further indicating that the field has a strong growth trajectory.

3.2. Prolific authors and highly cited publications

In a similar fashion to Li et al. (2015), published 8 years ago, we find that Benjamin K. Sovacool is by far the most prolific author in this field, even when considering fractional coauthorship. In contrast to traditional publication measurement where all authors gain one publication no matter the number

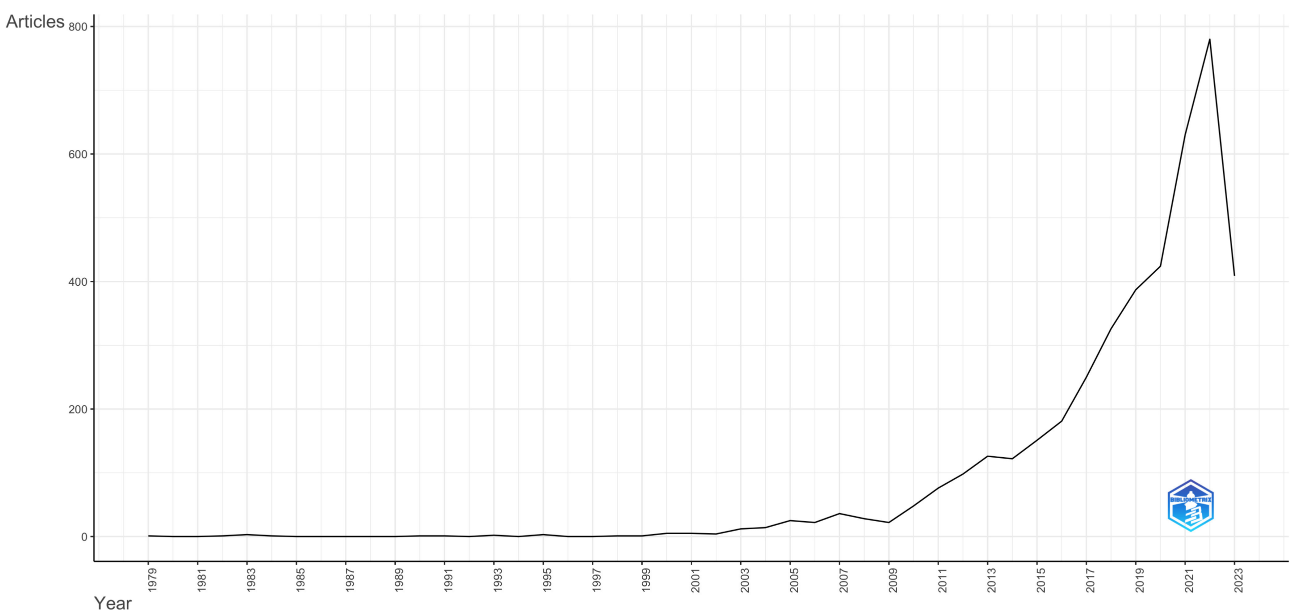

FIGURE 2
Annual scientific production, 1979–July 2023.

of coauthors, fractional coauthorship divides the contribution of each publication between the number of coauthors (i.e., 2 co-authors on one publication each are attributed 0.5 fractionalized authorship). Sovacool authored 82 publications in this review, equivalent to a fractionalized authorship of 37.35, more than three times higher than the next most prolific author. The domination of this academic literature by one author indicates both their core contribution to the growing field and the field's immaturity as an academic dialogue. The lack of a more diverse authorship is surprising for this global, ethical topic. While energy justice is a rapidly growing field that has gained much academic interest, it may not yet have matured into a thriving intellectual exchange among many researchers. Notable other authors ranked by their number of publications include Bouzarovski ($n = 33$), McCauley ($n = 29$), Heffron ($n = 26$), Gouveia ($n = 20$), Pachauri ($n = 20$), and Simcock ($n = 20$).

To distinguish impact within the energy justice field from larger academic import, this article separates global and local citations. Global citations measure citations from documents in the entire database, reflecting the more common interpretation of a publication's citation count. Local citations measure the citations a document has received from within the analyzed review. Therefore, while global citations reveal publications of interest to the entire academic community, local citations indicate the importance of the review itself. The list of local citations also includes articles that are not in the original review but are highly cited by it, further overcoming issues surrounding the inclusion of specific keywords. Figure 3 shows the 10 most cited documents globally (top) and locally (bottom).

The example of the most globally cited article immediately demonstrates the importance of evaluating local citations instead of global citations in a bibliometric review process. Jacobson and Delucchi (2011) article titled "Providing All Global Energy With Wind, Water, and Solar Power, Part I: Technologies, Energy Resources, Quantities and Areas of Infrastructure, and Materials" has the most global citations, with 1,030, but only 17 local citations. Upon inspection, this article was included in this review because of its use of the term *energy insecurity* in the first sentence of the abstract. *Energy insecurity* was used twice more throughout the text of the article but only as a motivator as in the sentence "Climate change, pollution, and energy insecurity are among the greatest problems of our time." Therefore, within this field, it has little relevance, even though it has the most overall citations.

Jenkins et al.'s (2016) review titled "Energy Justice: A Conceptual Review" is the most locally cited article and the second-most globally cited article. Therefore, it has significant import both to the larger academic community, as well as the energy justice community. Their review introduces the previously mentioned three tenets approach of distributional, recognition, and procedural justice and proposes a research agenda for the field.

Next, we compare the source of publications between documents in the review and documents cited by publications in the review. Documents in this review were most often published in *Energy Research and Social Science* (8.8%), but cited documents were most often published in *Energy Policy* (6.2%). Both of these Elsevier journals, as well as another, published prescient special issues on energy justice that encourage the academic development of the field. *Energy Policy* published the special issue "Exploring the Energy Justice Nexus" in 2017 (McCauley et al., 2017), *Energy Research and Social Science* published "Energy Demand for Mobility and Domestic Life: New Insights From Energy Justice" in 2016 (Simcock and Mullen, 2016), and *Applied Energy* published 'Low Carbon Energy Systems and Energy Justice' in 2019 (McCauley et al., 2019).

Overall, there are significant similarities between the most globally cited documents and the most locally cited documents indicating the strong links between energy justice and related fields. Table 4 provides a brief synopsis of the ten most locally cited documents in this review and summarizes the key texts recognized within this diverse interdisciplinary field.

Summarizing these 10 most locally cited articles provides an indicative map of the field. For example, four of the articles take a global perspective of their energy justice issue (Bouzarovski and Petrova, 2015; Sovacool and Dworkin, 2015; Day et al., 2016; Jenkins et al., 2016), four focus primarily on issues in the United Kingdom (Liddell and Morris, 2010; Boardman, 2012; Moore, 2012; Walker and Day, 2012), and the final two examine issues in the developing world (Nussbaumer et al., 2012; González-Eguino, 2015).

Figure 4 begins to investigate this (lack of) geographic diversity by visualizing the authors' affiliation locations around the world. An author's affiliation country does not necessarily represent the article's study location, but it may be indicative. The disproportionately small presence of sub-Saharan Africa in both the focus of the 10 most locally cited articles and the geographic distribution of authors serves as a stark contrast to the large absolute levels of measurable energy poverty in the sub-continent. There were no articles published in any African language. These results suggest that (1) academic research into energy justice, broadly defined, is not commensurate with absolute need and (2) individuals from the studied countries are often not involved in the formal publication process. Although these problems are not unique to energy justice, it is particularly pertinent for energy justice to center and involve the voices of those directly affected.

The examples of publications from countries in Central and Latin America reveal further disconnects between the absolute energy poverty burden of individuals, the proportion of research on those locations, academic affiliations in those locations, publications in the local languages, and inclusions in the Scopus database. Of the 87 articles not published in English in this review, 42 were published in Spanish or Portuguese; however, only 11 of these have authors with affiliations in Central or Latin America. The proportion of publications and affiliations in Central or Latin America inadequately represents the long history of 'pobreza energética' legal work and activism (Montoya, 2020). For instance, Indigenous organizing in Mexico against displacement from large-scale land grabs for wind farms (Baker, 2016) significantly influenced Director Shalanda Baker's path toward bringing energy justice into the U.S. Department of Energy system (Baker, 2021). As described by Montoya (2020), definitions of *energy poverty* for Latin America

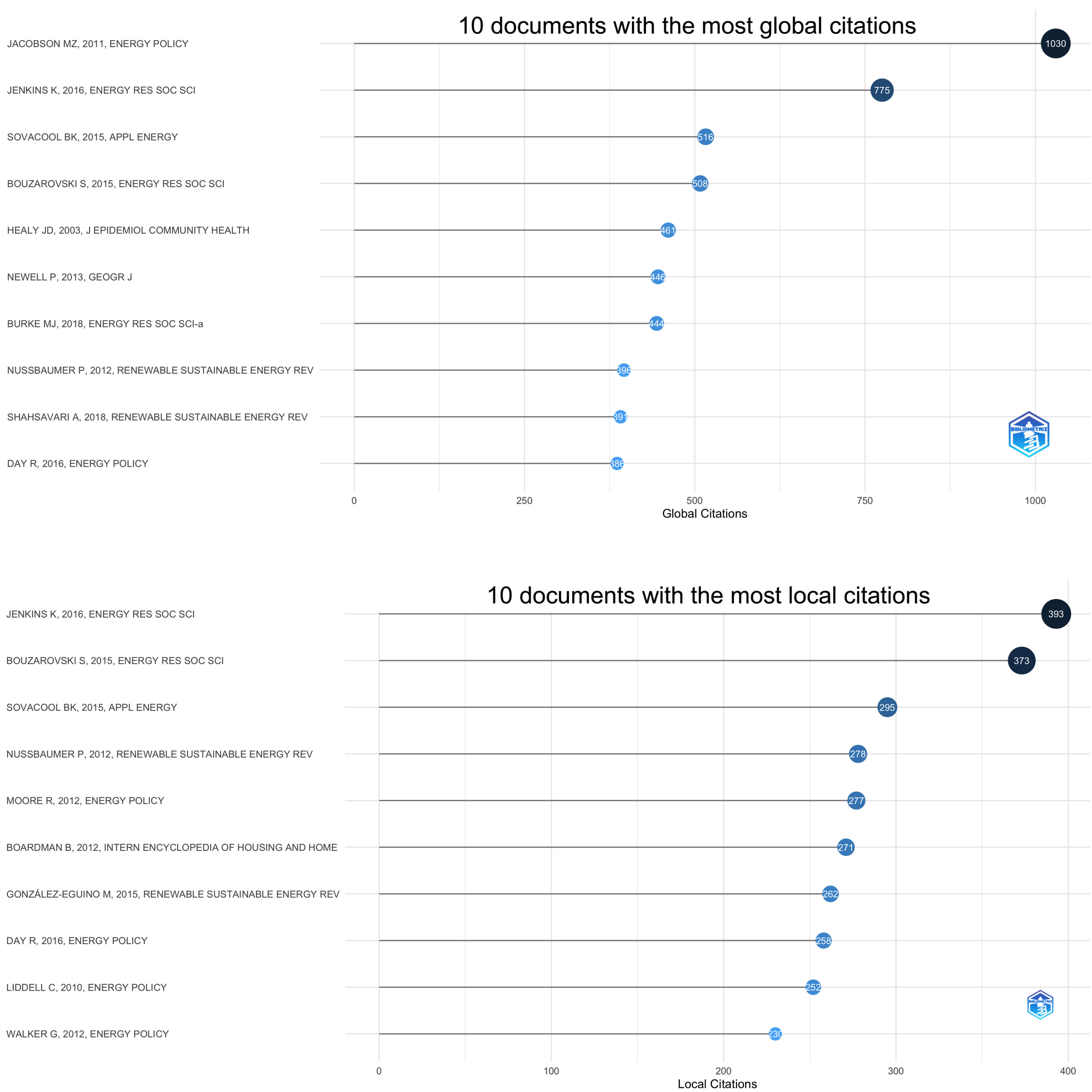

FIGURE 3
Most cited documents, globally **(top)** and locally **(bottom)**.

often appear more expansive and comprehensive than those commonly used in the United Kingdom and Europe. Latin American definitions often consider "more complex factors recognizing not only weather and geographical differences in the region but also the variety of cultural and social perceptions over energy needs and consumption" (Montoya, 2020). Scopus searches using "pobreza energética" or related terms in Spanish or Portuguese revealed no new articles, indicating that the Scopus database is more limiting than the inclusion of search terms in different languages. Bridging language barriers and inequities in global publication systems would allow for larger exchanges of ideas, perceptions, and frameworks to overcome these global issues.

Eight of the ten most locally cited articles focus on "energy" or "fuel" poverty as defined by the inability of households to meet their basic energy needs (Liddell and Morris, 2010; Boardman, 2012; Moore, 2012; Nussbaumer et al., 2012; Walker and Day, 2012; Bouzarovski and Petrova, 2015; González-Eguino, 2015; Day et al., 2016). Three of these focus on different measurement techniques (Moore, 2012; Nussbaumer et al., 2012; González-Eguino, 2015), reflecting the importance of quantification to energy poverty scholars. However, none of these articles addresses the efforts

TABLE 4 Synopses of the 10 most locally cited documents in this review, in decreasing order of local citations.

Articles	Synopsis
Jenkins et al. (2016)	• Provides a conceptual review of energy justice and proposes a research agenda. • Introduces three core tenets theory approach: distributional, recognition, and procedural justice. • Context: global context of energy production and consumption.
Bouzarovski and Petrova (2015)	• Integrated conceptual framework for research and amelioration of energy deprivation/poverty. • Context: inability of households to meet their energy needs in developed and developing countries.
Sovacool and Dworkin (2015)	• Presents energy justice framework informed by concepts from justice, philosophy, and ethics. • Details energy justice as a conceptual, analytical, and decision-making tool. • Context: academic framework building for a global problem.
Nussbaumer et al. (2012)	• Reviews methods for measuring energy poverty and proposes a new composite index (Multidimensional Energy Poverty Index). • Context: households in several African countries.
Moore (2012)	• Discusses and compares definitions of fuel poverty in the UK and their implications for policymaking and targets. • Context: UK and European policy.
Boardman (2012)	• Defines fuel poverty as pertaining to an encyclopedia for housing. • Context: Primarily UK-focused.
González-Eguino (2015)	• Reviews energy poverty defined by the lack of energy access, its measurement techniques, and implications. • Context: lack of electricity access and use of wood-burning stoves in the developing world.
Day et al. (2016)	• Applies Sen and Nussbaum's capabilities framework to energy use, proposing a new, multidimensional definition of energy poverty. • Context: philosophical conceptualization, joining global North and South approaches.
Liddell and Morris (2010)	• Reviews literature on the health impacts of fuel poverty. Addresses physical and mental health impacts for adults, caregivers, and children. • Context: Studies mostly in the UK, others in New Zealand and the US.
Walker and Day (2012)	• Considers how fuel poverty can be aligned with prior social and environmental justice topics. • Addresses fuel poverty through distribution, recognition, and procedures theories. • Context: the UK.

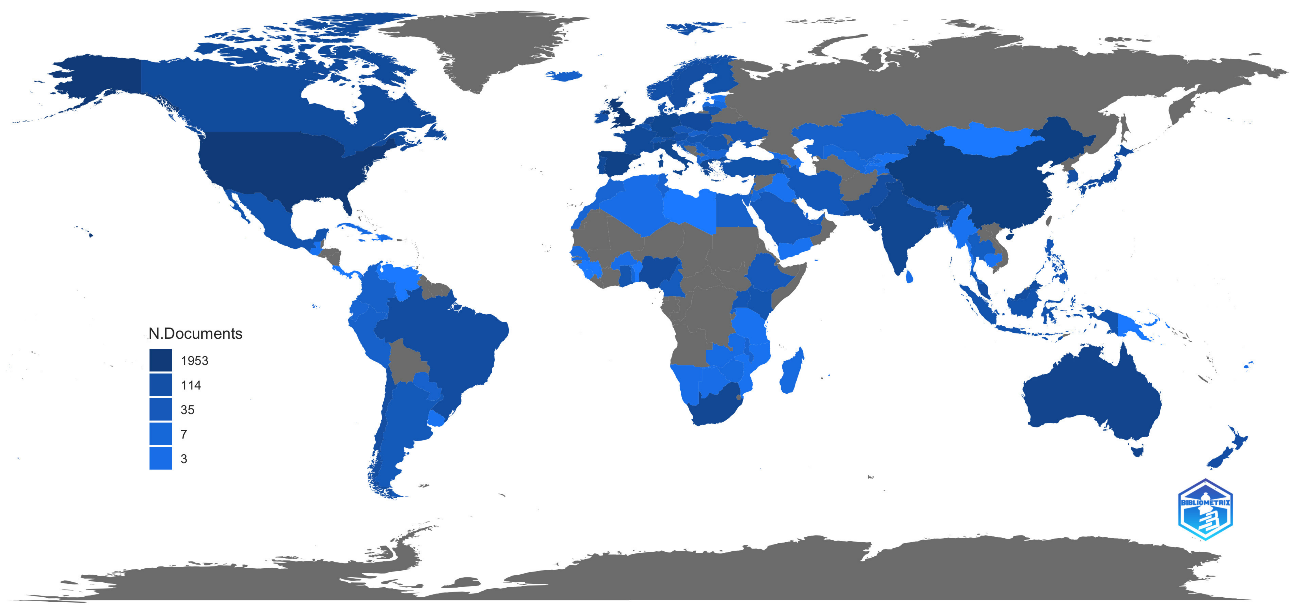

FIGURE 4
Country Scientific Production: number of documents with at least one coauthor's affiliation located in each country.

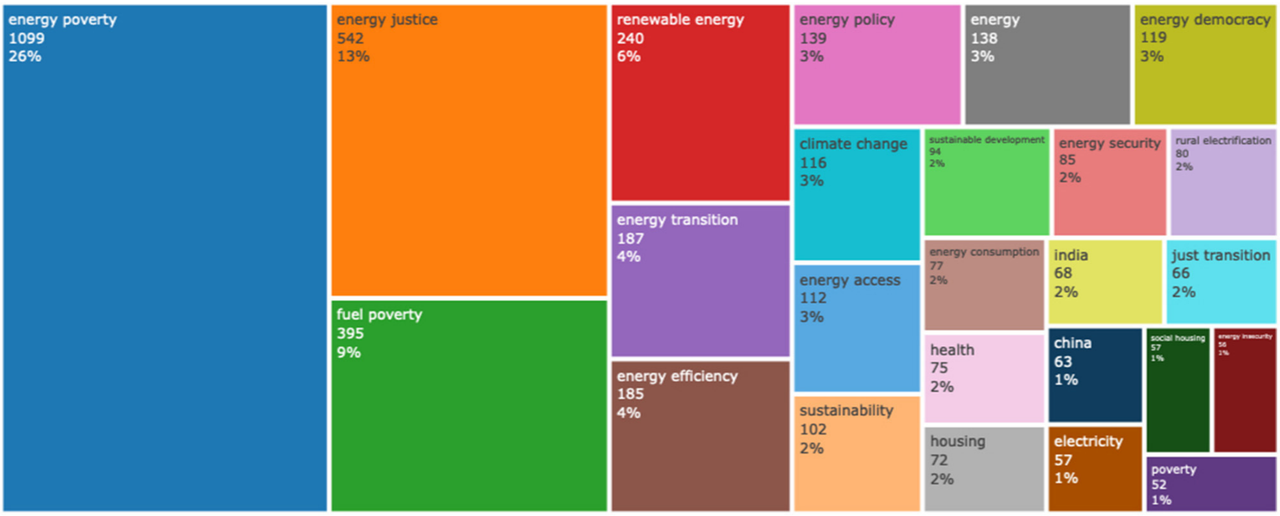

FIGURE 5
Overall frequency of the top 25 keywords listed by authors.

and perspectives of grassroots advocates, activists, or individuals working in or experiencing energy poverty for decades. This observation is in alignment with the Initiative for Energy Justice Workbook's note that, in general, practitioners and advocates make explicit references to centering the voices of low-income communities and communities of color, while academics tend to take a more measured approach by not explicitly centering the voices of the studied communities (Baker et al., 2019). While not ranking in the top 10, Fuller and McCauley (2016) article (which has nearly 100 local citations) fills part of this gap by articulating an energy justice frame from the perspective of advocates and activists in select locations such as Philadelphia, Paris, and Berlin.

Finally, we acknowledge the dominance of new theory frameworks presented in these articles. Nearly half of the articles introduce novel theory frameworks or conceptual approaches to energy justice or energy poverty. This finding reflects the importance of framing to unite such a complex and diverse discipline. It also indicates the importance of these particular framings, published at most 13 years ago, to make bringing the experiences of energy justice felt globally for centuries into the academic sphere.

3.3. Themes and trends

In Figure 5, the representation of author keyword frequency across all 2,290 publications confirms the dominance of the 'energy poverty' branch of energy justice. Authors explicitly included 'energy justice' in only 13% of publication keywords, while 'energy poverty' was found in 26% of publication keywords. Not only are energy poverty and energy access clear energy (in)justice issues, but they also compose the majority of articles in the field. Prior reviews rarely take into account the varied terminology of this field, thereby missing these large contributions. This result also speaks to the need for studies on energy access and energy poverty to acknowledge their role in the energy justice field at large.

Of the seven search terms (*energy justice/equity/democracy/insecurity/burden/poverty*, *fuel poverty*), six appear in the top 50 keywords. *Energy poverty* ranks first, *energy justice* ranks second, *fuel poverty* ranks third, *energy democracy* ranks ninth, and *energy insecurity* ranks twenty-fourth.

Because this review largely draws on academic social science and law literature, one would expect similar findings to the Energy Justice Workbook in terms of terminology usage. While the frequency rankings of *energy justice*, *energy equity*, *energy democracy*, and *energy insecurity* are largely in line with their findings, this article finds significant differences in the usage of *energy burden* and *energy poverty*. Baker finds *energy burden* to be commonly used by social sciences and infrequently used in law but *energy poverty* to be rarely used by social sciences and infrequently used by law. While *energy poverty* appears in the keywords of 26% of publications in this review, *energy burden* appears in <0.6%. These results indicate that although energy poverty has a recognized prominent role in the development of the energy justice field, the burden of that poverty has not been equally explored. Authors may opt for terminology such as *energy poverty* as a proxy for energy burden; however, this could indicate that the field under-acknowledges the nature of that poverty, only acknowledging it as a metric rather than a burden that affects individuals across and within households differently. Nuances in language and terminology are crucial in the development of any field but particularly for a field dedicated to the justly characterizing injustice.

Beyond keyword counts, we find a much larger diversity and interconnectedness of definitions and implied contexts for each of our selected terminologies than indicated by prior reviews. For instance, when in the context of publications based in the United Kingdom or Europe, *fuel poverty* largely refers to the inability of households to affordably warm their homes (Boardman, 2012), whereas the inability of households to affordably cool their homes in the United States falls under *energy burden* (Cong et al., 2022). In literature from developing countries, *fuel poverty* may refer to diverse topics such as a poverty of options for energy needs, the burden of collecting firewood for cooking and heating fuel, or poor reliability (Ferrall et al., 2022) and/or affordability (Gill-Wiehl et al., 2021) of existing options. Overall, *energy justice* and *energy equity* are often used interchangeably; however, *energy justice* is much more common. *Energy justice* may imply a larger focus on more progressive frameworks, such as procedural and restorative justice, than *energy equity*, which generally relies on distributive justice. However, when referring to energy inequities, differences in distributions are frequently measured in reference to the equality of some energy good or service, rather than other more expansive theories of a just distribution such as a capabilities approach or basic-minimum approach. *Energy insecurity* is either used in the context of national-scale oil crises, or household-scale uncertainty and precarity surrounding meeting energy needs. In literature from the United States and Europe, *energy burden* often has a narrower definition of a percentage of income spent on energy; however, energy burdens come in many non-income forms, including development, health, and the environment. Insights from literature from Latin America may serve to expand our definitions of energy burdens to include contextual factors such as geography and weather, as well as cultural preferences and health effects. Similar to *fuel poverty* and *energy burden*, *energy poverty* often has more expansive definitions in literature from developing countries and refers more narrowly to the unaffordability of electricity in literature from developed countries. Related literature on energy access often falls under energy poverty but generally refers only to the use of electricity rather than energy more holistically. Therefore, without understanding the larger context of how terminologies are used across subfields and geographies, energy justice researchers may miss relevant insights from related articles using different terms.

This plurality of definitions does not necessarily represent a weakness of the field. On large and small scales, communities must ultimately decide for themselves what justice in their energy systems will mean now and in the future. However, when decided locally, these differing priorities and frameworks for justice may create contested fields where competing definitions of just energy futures conflict.

An evaluation of author keyword occurrences over time shows that *energy poverty* has a much longer publication history and remained the most popular author keyword through 2021. The use of *energy justice* as a keyword only started in 2016 and has grown quickly since. The stark difference in growth over time between *fuel poverty* and *energy access* compared to *energy poverty* and *energy justice* reinforce the disconnect in acknowledging a lack of access as a justice issue.

We next adapt the method adopted by Cobo et al. (2011) to design a conceptual structure map using a multiple correspondence analysis methodology to cluster all publications in the review into six groups based on author keyword co-occurrence and a factorial analysis (Figure 6). The origin of the map represents the average position of all articles, therefore the center of the research field. The proximity between keywords corresponds to the shared usage among articles in our review: keywords are close in the conceptual structure map when a large proportion of articles treat them together; keywords are distant when only a small fraction of articles use these words together. The intuitive literature clusters are clearly separate. For example, the purple cluster represents rural electrification in developing countries, the brown cluster focuses on thermal comfort and buildings, the blue cluster is framework and justice-focused, while the red cluster is health- and poverty-focused. The brown "buildings" cluster is farthest from the plot's origin, indicating its peripheral nature within the rest of the literature.

This multiple correspondence analysis methodology clearly outlines silos that have emerged in the field. For instance, rural electrification (the purple cluster) and health/poverty (the red cluster) are starkly distinct even though the following longitudinal analysis depicts the historic merging of cooking into fuel poverty at large (which would include electrification). The literature seems to delineate between energy–poverty–climate nexus (Casillas and Kammen, 2010) and energy–poverty–health nexus, which are not mutually exclusive (Gill-Wiehl and Kammen, 2022). It is equally important for these types of sub-literature to be in communication while also not overlooking entire subfields in their consolidation. The importance of this is evidenced by the absence of cooking, our first energy use as a species, as a keyword within the map at all.

To analyze the thematic evolution of the field longitudinally, we adapt the previously described clustering method by dividing the research set into subperiods, rerunning the clustering methodology of keyword co-occurrences within each time frame, and then examining how the sub-clusters progress over time. We divide the subperiods based on the major turning points in the literature identified in the scientific productivity chart (Figure 2): 2010, 2017, and 2020. These themes are represented by the colored vertical bars in which height represents the relative amount of literature in that theme. Flows between subperiods represent how literature in a previous subperiod would be recategorized in the following subperiod, indicating the relationships between themes across time. This unique longitudinal analysis in Figure 7 allows us to highlight the tendencies of topics to merge or split into several themes.

Early literature in this energy justice review focused primarily on households and cooking (categorized under fuel or energy poverty). These themes merged into focuses on poverty, fuel poverty, and rural electrification between 2011 and 2017. New themes such as energy consumption and food security also emerge here. The varied themes for the 2011–2017 period merge and are clarified between 2018 and 2020 into groups labeled electricity, fuel poverty, renewable energy, and policy. Justice only strongly emerges in the last subperiod, which includes 2021 through 2023 but builds out of the literature on renewable energy and policy from 2018 through 2020. Fuel poverty (aka energy poverty) is the strongest theme across all subperiods, touching nearly all other themes.

In particular, we analyze the merging of the dominant themes of cooking and households between 1979 and 2010 into fuel poverty and rural electrification by 2011. Although electric cooking is expanding, even by 2022, it is not on track to be the most prominent clean cooking option for households currently without access, nor has it provided the gains in access seen elsewhere

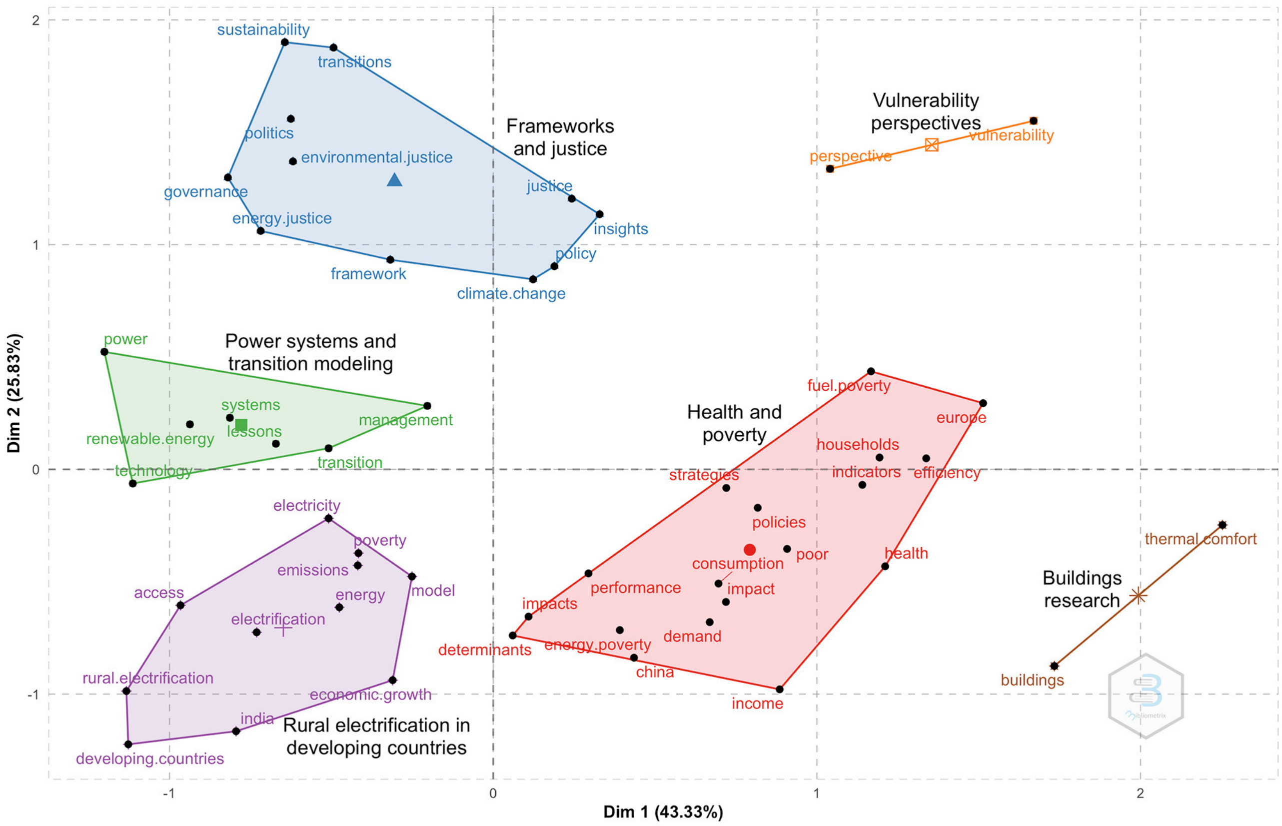

FIGURE 6
Conceptual structure word map on Keywords Plus generated using multiple correspondence factorial analysis. Moving clockwise from top-center, literature clusters include: vulnerability perspectives (orange), buildings research (brown), health and poverty (red), rural electrification in developing countries (purple), power systems and transition modeling (green), frameworks and justice (blue).

(Gill-Wiehl and Kammen, 2022). These trends over time speak to the household level role of cooking in the early development of the energy justice literature and the larger field's shift away. The salience of energy justice's shift away from clean cooking is illustrated by the large energy justice implications of different clean cooking solutions for individuals, and the gendered inequities across individuals within households. Many of these implications for health, spending, and time are not captured when cooking is grouped with all other forms of household energy. For example, the established metrics used to indicate fuel poverty (e.g., 10% of the monthly household expenditure) rarely distinguish the 5% threshold that the Energy Sector Management Assistance Program set for cooking fuel (Boardman, 2012; Bhatia and Angelou, 2015; Gill-Wiehl et al., 2021). This consolidation, while logical for contexts of national-level grid access to electricity, leads the literature to fail to acknowledge the energy justice implications of the other more prominent clean cooking options, namely, liquified petroleum gas. The current structure of the field would also miss the justice implications of other emerging clean options such as ethanol or biomass pellets in specific advanced gasifiers. Our results indicate a growing gap in the literature on the energy justice implications of clean cooking, despite the fact that this theme was foundational to establishing the field.

4. Discussion and conclusion

In summary, this article used advanced bibliometric analytics to synthesize disparate and varied metadata to characterize trends in the treatment of energy justice in academic literature. In the largest and most comprehensive review of the field to date, this review covered 4,196 articles published between 1979 and 2023 at a scale appropriate to the number and diversity of publications. Our quantitative methods offer the ability to review this wealth of information in a truly systematic, comprehensive, replicable, and unbiased manner.

We found that energy justice literature has seen rapid growth over its short history and has the potential to have a large academic and practical impact in the future. It has a multitude of facets, a plurality of theories, and a long dictionary of terminology. However, it houses distinct siloed subfields and remains somewhat removed from longer-established social theories of justice. Furthermore, we documented distinct uses of similar terminologies across subfields in the literature, inequitable ratios of global investigation to absolute levels of energy poverty, and the large but under-recognized contribution of cooking to energy justice literature.

While prior reviews were able to examine both a larger proportion of the published literature and each article in more

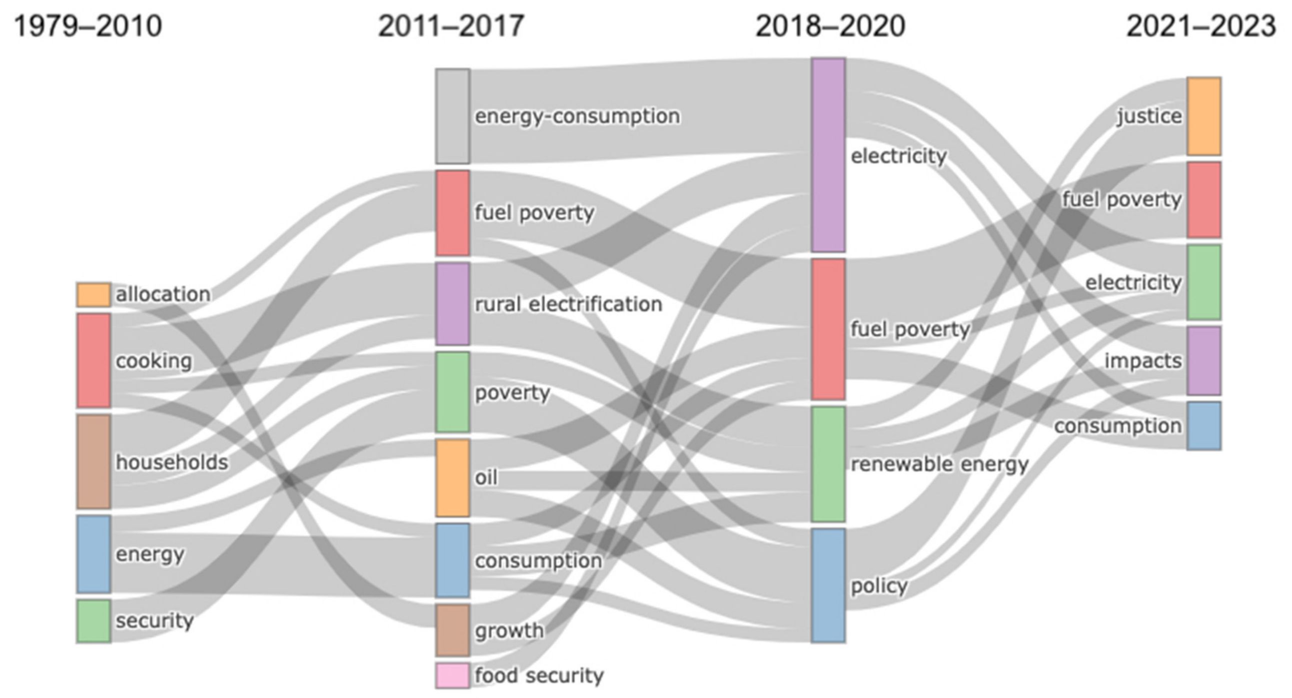

FIGURE 7
Thematic trends in energy justice literature.

depth, the field's rapid growth and expansion will make similar tasks increasingly impossible. Bibliometric methods allow for the synthesis of larger-scale themes and trends, and their interconnections so that more focused reviews can understand their context in the larger discipline. This article expanded on earlier bibliometric reviews on energy burden and energy poverty by including highly related literature on fuel poverty, energy insecurity, and energy equity and justice.

We also found that prior reviews understate the proportion of energy justice literature dedicated to household energy poverty and the role of subfields in the development of the larger energy justice field. For example, less than five studies in Jenkins et al.'s (2021) review are related to cooking, yet our results speak to the foundational nature of cooking articles in energy justice. Energy poverty research in terms of rural electrification and clean cooking has made significant contributions to the field overall in terms of number of articles and intellectual import. Yet, our results seem to speak to a shift in the field that consolidates cooking into fuel poverty and rural electrification. We advocate that energy justice scholars adopt a new term, "cooking poverty," to acknowledge the cooking-specific justice issues that are distinct from lighting and heating and are currently not sufficiently discussed under the umbrella of fuel poverty. We also suggest that future research explicitly investigates the energy justice implications of different clean cooking-fuel options. To date, the current literature only has a few energy justice articles solely focused on cooking. To assume that renewable electrified cooking is the only pathway to a just transition only deprives justice for the most vulnerable in the interim.

We found distinct, siloed subfields such as energy poverty in low- and middle-income countries (LMICs) and heating/thermal comfort, mostly in high-income countries. We believe that the field could benefit from increased learning across related subfields and geographic locations of study. For instance, even in LMICs, households often use their polluting cook stove as a source of heat, a benefit that disappears with a clean stove. Yet, our results show that thermal comfort is rarely discussed in relation to health and poverty or rural electrification. Heating, like cooking, is often grouped with lighting, electric appliances, transport, and cooking under energy poverty.

Even within the subfields, there are silos. Specifically, within the energy justice subfield of household energy in LMICs, there is distinct literature on rural electrification and separately on health/poverty. We advocate for researchers to bridge, but not consolidate, those fields to acknowledge justice implications of the energy–poverty–health nexus.

Sufficiently recognizing prior contributions and integrating common frameworks, theories, and methods will allow energy justice scholars to build from past literature to reach a more universal understanding of energy justice and not overlook key topics. Doing so will allow the literature to truly contribute toward achieving equity in both the social and economic participation in energy systems while also remediating the burdens of those historically harmed.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

IF-W led the conceptualization, implementation, writing, and revisions of this study. AG-W contributed to crucial data acquisition and substantial revisions on the role of energy poverty and cooking literature. DK supported the research and funded this analysis. All authors contributed to manuscript revision and approved the publication of the content.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

IF-W declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsuep.2023.1175736/full#supplementary-material

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How can quantitative policy analysis inform the energy transition? The case of electrification

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Quantitative analyses may aim to provide actionable answers to policy questions and to generate tools or insights for decision-making. Given the deep uncertainties involved in any realistic reckoning of policy questions, this study argues that only the second of these goals is achievable. Here, this argument is illustrated by considering analyses of how the electrification of an activity changes the damage from the air pollution emissions that occur because of that activity. The sources of uncertainty in such an analysis include the long life of the technologies being studied. Consequently, the structure and operation of the electricity grid might change because of the new technology and independent of it. Analysts must make subjective choices about what to include in their analysis and what to exclude. For example, policies modeled in isolation may, in reality, be bundled with other policies; interactions between technologies may be missed if the analysis focuses on only one technology; and certain benefits or costs may be neglected because they lie outside the scope of the analysis and the expertise of the analyst. Quantitative policy analysis must aim to be part of the broader discussions in society that ultimately determine what policies get implemented.

KEYWORDS

decarbonization, electrification, policy analysis, energy transition, lifecycle analysis

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Introduction

Morgan et al. (1992) identify a variety of motivations for policy analysis: from the desire to inform a policy decision to the development and demonstration of new methods and tools. Morgan et al. (1992) call the former of these motivations "substance-focused." Within this category, motivations range from "answering" policy questions in a form that leads to direct implementation to "illuminat[ing] and provid[ing] insight on a general area of policy concern for a variety of interested parties." From this perspective, it is extraordinarily difficult for analysts to answer complex policy questions based solely on quantitative analysis. Even very careful analyses must satisfy themselves with providing broad insights and developing tools that might inform broader policy discussions.

This argument is illustrated by considering analyses of how the electrification of an activity changes the damage from the air pollution emissions that occur because of that activity. *Electrification* is defined as a switch to using electricity to power activities that currently require the distributed combustion of fossil fuels. Examples of such activities include light transportation (Michalek et al., 2011; Holland et al., 2016; Yuksel et al., 2016) and space heating in homes (Hanova and Dowlatabadi, 2007; Vaishnav and Fatimah, 2020; Deetjen et al., 2021). This fuel switch is seen by analysts as an essential decarbonization strategy (Davis et al., 2018).

Attributional and consequential analyses of electrification

Whether or not electrification actually reduces greenhouse gas emissions—and Harms from emissions of short-lived pollutants—depends on how much pollution is produced in generating electricity for the application in question.

A recent National Academies of Science Engineering and Medicine (NASEM, 2022) report argues that, when assessing policies that induce a change—such as a shift from a fossil fuel to electricity—analysts must account for the change in harms *induced* by the change in fuel.

The NASEM report argues that, in practice, this means that it is incorrect to simply use the average emissions intensity, expressed in the mass of pollutants per unit of electricity produced, based on the current operation of the electricity system. Using average emissions is an attributional approach: it should be used only to apportion the harms from the current operation of the power system among current uses. Almost by definition, this makes attributional approaches unsuitable for studying the effects of electrification.

Instead, for small changes in demand, analysts must model how the operation of the current electricity system will change if more electricity is demanded. This amounts to asking which of the existing generators will produce more to meet the new demand. The NASEM (2022, p. 190–194) report outlines four key approaches to performing this analysis: regression based on past operations of the power system, modeling of the current or future operation of the power system, the use of proxies (e.g., non-baseload generation), and inferences based on data about the real-time operation of the power system. Each approach has significant limitations.

For large changes in demand, analysts must model how new demand will change the composition, structure, and operation of the power system. This consequential analysis is not straightforward. Analysts must make many assumptions—about policies, about the relative costs of different technologies, and about the often volatile prices of commodities—to produce estimates of emissions from future systems.

Average emissions from the existing power system are a physical quantity that can (and is) directly measured. The notion of changes in marginal emissions from current and future systems is a conceptual construct that is not directly related to any physical quantity. Using a consequential approach to answer questions that are of interest to policymakers presents three challenges.

Challenge 1: uncertainty induced by long-lived technologies

Modern personal vehicles in the United States are projected to last nearly 20 years (Zhu et al., 2021). Electric appliances such as heat pumps may have similar lifetimes (Staffell et al., 2012). An analysis that assumes unchanging marginal emission factors from the electricity grid ignores the possibility of better performance over the lifetime of a new technology than in its first year of operation. Some studies approximate this improvement in performance by assuming that electricity grid marginal emission factors fall in line with average emission factors (Vaishnav and Fatimah, 2020; Deetjen et al., 2021). However, studies of historical regression-based emissions factors have shown that this improvement has not occurred in the United States (Holland et al., 2022b). A response to this study questioned the appropriateness of using marginal emissions factors designed to reflect small, short-term changes to the grid to study the effect of changes that are neither small nor short term (Gagnon et al., 2022).

An alternative approach is exemplified by the Cambium data set assembled by the National Renewable Energy Laboratory (Gagnon et al., 2023). Cambium calculates long-run marginal emission factors by comparing two alternative runs: one with a baseline level of demand and another in which demand in each hour is perturbed by a substantial amount. In each of these runs, a capacity expansion model (CEM) and an economic dispatch model are both run. The CEM captures the fact that new generators and transmission capacity may need to be built in response to large and persistent changes in demand. The Cambium modeling approach also adjusts the generation mix to ensure that existing state and national renewable portfolio standards are met.

This approach differs from current approaches in two ways. First, it accounts for structural rather than operational changes. Second, it offers a way of modeling the effects of changes that occur *alongside* a large change in demand but not entirely *because* of it. This could be especially relevant to policymakers, who may want to account not only for the fact that the operation and structure of the grid will change because of the new demand a policy induces but that also, in the long term, the power system will undergo changes unrelated to the new demand.

There is, nonetheless, "an inescapable degree of subjectivity" (Holland et al., 2022a) in how short- or long-term consequential emissions are modeled. While it is theoretically possible to put bounds on the consequences of those subjective choices, the computational requirements and barriers to entry in terms of the depth of expertise needed for such analyses are substantial.

Challenge 2: uncertainty induced by choices related to the system boundary

An important source of uncertainty is the choice of system boundary, wherein some aspects of the consequences of a policy may be left out of the decision. Here, three examples are discussed.

First, an analysis may ignore that policies may not be implemented in isolation from each other but as bundles with other unrelated policies. For example, utilities may require that owners of electric vehicles switch to time-of-use rates (DTE Electric Company, 2023). Therefore, a policy to encourage the adoption of electric vehicles may have the unintended (and unmodeled) effect of switching users to dynamic rates, which may affect how they use other electricity-consuming appliances. An analyst must grapple with the diversity in utility responses to electrical vehicle adoption and the diversity of user responses.

Second, there might be current or future synergies between different technologies, which may not be accurately modeled. For example, a heating ventilation and air-conditioning contractor might advise a client that installing an electrical heat pump is financially more attractive if the client also installs rooftop solar panels and improves the insulation of their home. Vehicle-to-grid and vehicle-to-home technologies might allow users or service providers to manipulate household electricity load profiles in ways that meaningfully change the impact of electric vehicles on the power system.

Third, deploying a technology might produce benefits that are either unrelated or indirectly related to energy or the environment. For example, Michalek et al. (2011) quantify the ways in which electric vehicles might reduce geopolitical risk, military spending, and volatility in fuel costs. Analyses of weatherization often focus on energy, cost, or air pollution benefits (or harms); (Fowlie et al., 2018) but often ignore the significant health benefits associated with better-insulated homes (Howden-Chapman et al., 2007; Tonn et al., 2021). In advocating for ambitious technical targets for batteries for aviation, Viswanathan et al. (2022) note that the effort to achieve these targets will have spillover benefits for electric road vehicles. Deploying technologies might produce learning effects, which might shift the balance of benefits and costs in ways that are seldom captured in models; for example, significant learning, defined as the reduction in cost for every doubling of deployed capacity, has been observed for electric vehicles (Taylor et al., 2005; Rubin et al., 2015; Malhotra and Schmidt, 2020). The deployment of technologies can catalyze the construction of supporting infrastructure, which, in turn, can make the technology more attractive. Li et al. (2017) demonstrate this positive feedback loop in the case of electric vehicles and charging infrastructure, arguing that investing in charging infrastructure is more cost-effective than subsidizing EVs (electric vehicles) directly.

Challenge 3: reconciling present and future perspectives

The 2022 NASEM report notes that attributional LCA (ALCA) "estimates emissions as they are *or could be in some projected future state* (emphasis added)" (20). In a future where the electricity grid is substantially—if not fully—decarbonized, an ALCA would show that widespread electrification is unambiguously better than the continued use of fossil fuels. Nonetheless, a consequential analysis performed from today's perspective might suggest that many changes made in the direction of that future increase environmental harms.

The first solution to this conundrum is to identify those strategies that reduce harms even in the short term and prioritize them, while continuing to deploy fossil fuels in applications where they do less harms given the current and near-future electricity grid (Williams et al., 2012). A criticism of this approach is that any continued reliance on fossil fuels risks creating lock-ins and stranded assets (Bertram et al., 2015). A second criticism is that a managed, sequential deployment of technology presumes more control over how the energy transition unfolds than is realistic. A third criticism is that any detailed recommendations about the correct sequencing could suffer from false precision. All the sources of uncertainty described earlier mean that detailed recommendations based on small differences between alternatives run the risk of being an artifact of what the analyst chose to include (or not) in the analysis (Lave, 1996).

A second solution is to take a heuristic approach. In this view, what matters in most contexts[1] is that a combination of electrification and grid decarbonization offers a pathway to net zero emissions, whereas the distributed combustion of fossil fuels does not. While eschewing detailed recommendations based on differences that are smaller than the surrounding uncertainty, analysts may restrict themselves to hot-spot analyses that identify great potential harms (or benefits) that might be ignored in policies that are focused on energy or greenhouse gas emissions. For example, an early study of electric vehicles with lead–acid batteries found that the harms from excess emissions of lead from smelters would far exceed any benefits from reduced greenhouse gas emissions (Lave et al., 1995). A criticism of the heuristic approach stems from the fact that the extent of warming is a function of cumulative greenhouse gas emissions (IPCC, 2021). A trade-off exists between the indirect decarbonization benefits of policies that increase greenhouse gas emissions in the near term (e.g., through learning to reduce costs and accelerate full adoption) and their contribution to the cumulative stock of atmospheric greenhouse gases. The analysis must grapple with this trade-off. A second criticism of a heuristic approach is that resources—including money, attention, and political will—are finite. Failing to allocate them optimally can carry potentially large opportunity costs (Tengs et al., 1995).

What can policy analysts say about electrification?

The net-zero emissions energy systems study by Davis et al. (2018) identified sectors, including load-following electricity, as difficult to decarbonize. Sectors such as light transportation and the residential sector were, however, flagged as straightforward to decarbonize. What makes assessing the effects of electrification complicated is that the straightforward-to-decarbonize sectors are coupled with load-following electricity, which is hard to decarbonize. Arguably, the overall goal of studies of the environmental consequences of electrification is to elucidate the evolving nature of that coupling.

In doing so, analysts studying electrification must recognize that different approaches and assumptions might be legitimate, given subtle differences in the specifics of the decision that the analysis is seeking to inform. For example, if only the near-term implications of an electrification policy are of interest, it may be appropriate to ignore structural changes to the grid that result from that electrification or that occur alongside it.

For the analysis to have broader relevance, it must be repeated using different approaches (e.g., short- or long-range marginal emissions or average emissions from a future grid), and differences in the results must be discussed. Analysts must identify what assumptions are the most consequential and give users of the analysis the means to easily substitute their own assumptions instead.

1 There are some applications (e.g., aviation) where it is not clear that full electrification is feasible.

Finally, consumers of analysis must ensure that there is a match between the question they are trying to answer and the question that a study has answered. They should pay attention to differences in time scale (e.g., short vs. long term), goals (e.g., reducing short-term harms vs. long-term transformation), and scope (e.g., a standalone intervention vs. numerous intertwined changes). Where these differences are large, they should be cautious about basing policy on the conclusions of the study.

What can policy analysts say about policy choices?

Quantitative policy analyses in service of the energy transition should comply with guidance on how to conduct good policy analysis in general. Morgan et al. (1992) identify "Ten Commandments" for good policy analysis: (1) do your homework with literature, experts, and users; (2) let the problem drive the analysis; (3) make the analysis as simple as possible but not simpler; (4) identify all significant assumptions; (5) be explicit about decision criteria and policy strategies; (6) be explicit about uncertainties; (7) perform systematic sensitivity and uncertainty analysis; (8) iteratively refine the problem statement and the analysis; (9) document clearly and completely; and (10) expose the work to peer review.

While it is difficult to meet all these strictures fully, analysts and decision-makers should grow warier of analyses as they veer further away from these commandments. Policy analysis can provide clear answers to scientific questions, provided there is "unambiguous data or well-founded theoretical insight" (Morgan, 1978, p. 971). If it becomes too difficult to track all assumptions or adequately characterize sensitivities and uncertainties, one must question the reliability of any conclusions. Consequential analyses of the effects of electrification must yoke together multiple models from domains as diverse as epidemiology and power system analysis. Arguably, they make it extraordinarily hard for analysts to obey Morgan et al. (1992) commandments. Conclusions from these analyses must be presented with a corresponding degree of humility and even skepticism.

In his critique of benefit analysis, Lave (1996) described the method as foremost a means of structuring complex problems, arguing that "the option identified as having the largest net benefit does not have a strong claim to being the best social choice" (129). In the same vein, given the depth of uncertainty associated with decisions pertaining to electrification, quantitative analysis ought to be identified as one (but not the only) tool to aid decision-making rather than a means of generating optimal policy prescriptions. This approach has been described as "modeling for insights" (Huntington et al., 1982).

John Stuart Mill defined representative democracy as government by discussion. Quantitative policy analysis must accept that it forms part of a discussion (Mill, 1861; Harris, 1956) and must—if at all possible—seek to make that discussion more productive.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

PV: Writing—original draft, Writing—review and editing.

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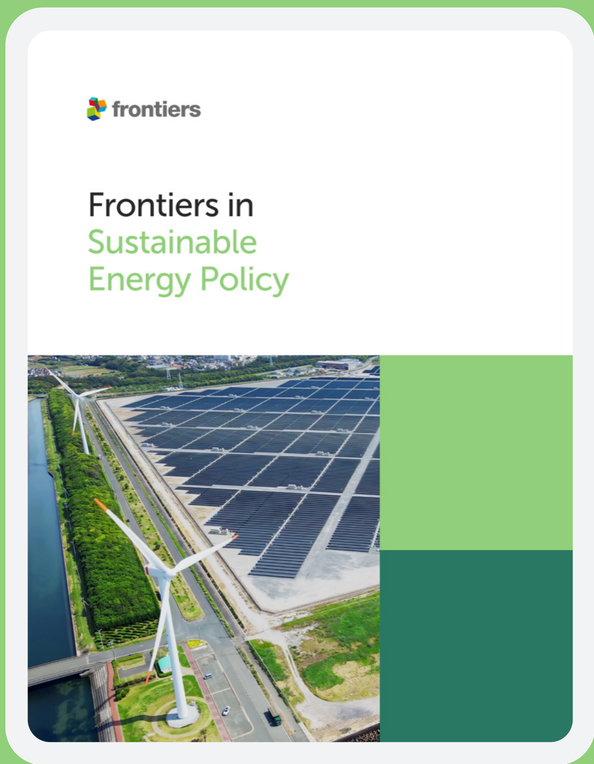

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