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Entrepreneurship in the renewable energy sector: A systematic literature review of types, characteristics, and sustainability impacts

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ABSTRACT

Despite the potential impact and critical nature of entrepreneurship on decarbonization and energy justice, interdisciplinary research in this field is still scarce. Start-ups in the renewable energy sector require special academic attention due to their significant impact on sustainability and the challenges these ventures face, which are deeply rooted in the complex and high-barrier nature of the sector. Using a systematic approach, an initial sample of over 2600 academic articles was collected and narrowed down to 142 relevant articles focused on entrepreneurship in the renewable energy sector, which were analyzed in detail. Based on this comprehensive review, the entrepreneurship literature has been categorized into three types, each characterized by its unique features and sustainability implications. The in-depth content analysis revealed that the literature deals extensively with developing and implementing new decarbonization technologies, but transformative approaches are neglected, depending on the type of entrepreneurship. This review shows that numerous success factors for entrepreneurship in the renewable energy sector have been identified, and their targeted promotion and implementation are crucial for further development. The results form the basis for a new framework that highlights antecedents, success factors, and outcomes of technology entrepreneurship in the renewable energy sector. This cross-disciplinary review contributes to the existing literature by providing a comprehensive research agenda for this emerging field to pave the way for future empirically based entrepreneurship studies in this sector.

Abbreviations

AI	Artificial Intelligence
API	Application Programming Interface
ENT	Entrepreneurship
GIS	Geographic Information Systems
GPT-4	Generative Pre-trained Transformer 4
GW	Gigawatt
IEA	International Energy Agency
IoT	Internet of Things
NGOs	Non-Governmental Organizations
PM2.5	Particulate Matter with a diameter under 2.5 μm
R&D	Research and Development
SDGs	Sustainable Development Goals
SJR	SCImago Journal & Country Rank (Index)

1. Introduction

Innovation in the energy sector is crucial to the transition to sustainable, secure, and affordable energy, which is essential for tackling climate change, enables global growth, and is an element of the United Nations' Sustainable Development Goals (SDGs) [1,2]. Entrepreneurship is a key driver of innovation in this sector, supporting the introduction and development of new sustainable technologies and business models [3,4]. Start-ups introduce new business models, foster innovation, and drive economic growth by challenging traditional paradigms and leveraging emerging technologies to meet evolving market demands [5,6]. Such entrepreneurial ventures significantly contribute to advancements within the renewable energy sector by promoting the development and adoption of innovative energy solutions and playing a crucial role in the transition towards a more sustainable energy future [4,7].

Interdisciplinary research between management, entrepreneurship,

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and renewable energy technologies has increased significantly in recent years, as research at this interface integrates different expertise and enables the development of technically pioneering solutions that represent a new way of accomplishing business. For instance, Richter [8] highlighted that transitioning to sustainable power generation will require significant changes in the structure of the electricity sector. In practical terms, utility companies must adapt their business models to maintain competitiveness within the transforming energy market. Therefore, several scholars focus on developing novel business models in the renewable energy sector, demonstrating a clear shift towards more innovative, sustainable, and efficient energy solutions [9,10]. Research also addresses the barriers that sustainable business models in the energy sector face due to regulatory risks and emphasizes the importance of adaptable and robust strategies [11]. The renewable energy sector's challenges and opportunities are not homogenous, and significant differences exist between developing and industrialized countries regarding entrepreneurship within this field [12]. Existing research emphasizes how the socio-economic context, existing knowledge, regional traditions of entrepreneurship, and government support can influence the development and success of ventures in the renewable energy sector. Studies show that start-ups in low-carbon energy technologies can accelerate decarbonization [13]. Moreover, the literature indicates that rural entrepreneurship provides access to energy for the first time in many regions as part of electrification efforts, thereby promoting energy justice in these areas [14,15].

The existing literature provides valuable insights, particularly on emerging new business models within the sector. These models are systematic approaches designed by new ventures to generate, deliver, and capture value, thus enabling strategic positioning and competitive advantages in dynamic markets [12,13]. Beyond new business models, entrepreneurship encompasses a broader spectrum, including identifying, assessing, and exploitung opportunities, often through innovative practices and establishing of new businesses [14]. It involves an entrepreneurial mindset focused on uncovering and pursuing potential ventures, frequently leading to the initiation of start-ups [15]. Due to rapid advances in entrepreneurship research within the renewable energy sector and its growing significance for sustainability, a systematic literature review is crucial. It identifies key topics, highlights the role of start-ups in decarbonization, and outlines future research directions. Resulting frameworks and guidelines can also provide practice-relevant insights that help more clearly identify success factors for start-ups in the renewable energy sector and promote their practical implementation in sustainable business models [16]. This review, therefore, focuses on answering the following questions. (1) What is the current state of entrepreneurship in the renewable energy sector, and how do contextual factors shape its characteristics and outcomes? (2) What are the implications for future research, entrepreneurs, and policy design to promote innovation and sustainability in the renewable energy sector through entrepreneurial activity?

2. Theoretical background

Entrepreneurship encompasses recognizing, evaluating, and exploiting opportunities, leading to founding new businesses [17]. Moreover, these entrepreneurial processes, driven by a willingness to take risks and a commitment to innovation and proactivity, are combined with effective resource management to secure a competitive advantage and facilitate business growth in a dynamic market [18,19]. The underlying cause of this process is the determination of individuals to conceptualize and implement innovative business concepts, which enables the creation and development of novel businesses [20]. Building on this entrepreneurial thinking, start-ups emerge as key players in promoting economic growth by acting as catalysts, bringing innovation and competition to the market [21]. They disrupt traditional market structures and challenge incumbents to innovate, raising economic productivity and technological standards [22]. Moreover, start-ups promote market efficiency by exploiting inefficiencies in existing markets and introducing business models that better meet consumer needs [23]. Their agility allows them to adapt quickly to changing market conditions and consumer preferences, often faster than larger, more established companies [24]. In R&D-intensive sectors, start-ups accelerate the introduction of new technologies by using their lean structures [25].

While start-ups are a significant driver of innovation across various industries, their success is often contingent upon the specific market dynamics of their chosen field. In this context, the renewable energy sector facing several urgent challenges, including climate change and energy security, offers a unique environment where start-ups can contribute. This study utilizes the International Energy Agency's (IEA) definition of the renewable energy sector, which encompasses electricity generation from renewable energy sources such as solar, wind, hydro, geothermal, and bioenergy [26]. The continuous global expansion of renewable energy sources is evident with capacity additions estimated at 507 GW, an increase of almost 50 % over the previous year [27]. This considerable expansion illustrates the dynamism of the sector and the opportunities that are becoming available for start-ups. The core of their significance lies in their ability to develop and implement novel technologies and business models central to promoting a more sustainable future [28]. However, in the renewable energy sector, start-ups face unique and significant challenges distinguishing them from new ventures in other industries. These challenges are deeply rooted in the sector's characteristics and the inherent nature of start-ups and require detailed consideration. Financing is one of the major challenges in energy innovation, as the development and integration of new energy technologies require significant initial investments [29]. At the same time, uncertainty about the return on investment, combined with the long time frame for market entry, increases the risk for potential investors [30]. The difficulty of raising capital is further increased because many energy start-ups are still at an early stage and often need to be sufficiently commercially or technologically validated to take advantage of traditional financing options [31]. Introducing and scaling new technologies in the renewable energy sector presents technical and operational difficulties. The complexity of the energy system, including the need to integrate with or replace existing infrastructure, requires start-ups to have a high level of technical innovation capability, a comprehensive systemic understanding, and operational excellence [32].

In addition to the financial and technological hurdles, energy start-ups face a complex and frequently changing regulatory landscape. The energy industry is highly regulated, and the legal framework varies between countries and regions. The ability to operate in this multilayered regulatory environment, where policy decisions can significantly impact the viability and profitability of business models, is crucial. This regulatory uncertainty can significantly delay or even prevent the introduction of new technologies or services to the market and thus represents another barrier for start-ups in the renewable energy sector [11].

Given these substantial financial, technological, and regulatory hurdles, energy start-ups must adopt innovative strategies to address and overcome the challenges they face effectively. Their approach focuses on innovative business models, adopting digital technologies, and strategic integration into the broader energy sector ecosystem. Government loan programs for research and development support energy start-ups' survival and growth and provide the groundwork for subsequent venture capital investment [29]. In addition, corporate venture capital investment is a key component in the financial ecosystem for renewable energy start-ups and serves as a crucial funding source [33]. While previous studies focus only on venture capital or barriers, this paper aims to provide a comprehensive overview of success factors beyond funding, addressing a broader range of determinants for start-up success.

3. Research methodology

To ensure a systematic and comprehensive approach to the literature review, the methodology developed by Webster and Watson [34] and Denver and Tranfield [35], commonly used in energy and entrepreneurship research, was followed to collect the dataset of relevant articles (Fig. 1) [9,36–38].

3.1. Literature research

The literature search involved the targeted selection of relevant sources, particularly the choice of appropriate databases and the definition of adequate search terms. Therefore, Scopus was selected as primary database for the initial development of the literature base for this review [9]. When selecting keywords, the systematic literature review needed to focus on literature dealing with entrepreneurship and start-ups in the renewable energy sector. The leading search terms "entrepreneur*" and "energ*" were extended to include keywords derived from the definition of the renewable energy sector.

The approach was aligned with the definitions provided by the International Energy Agency (IEA) [26]. Accordingly, the search string used the following keywords: "entrepreneur*", "energ*" and one of the following to describe renewable energy: "batter*", "biofuel", "biogas", "clean", "geothermal", "hydro", "ocean", "renewable", "solar", "storage", "tide", "wave", "wind". To ensure that the reviewed literature also addresses aspects of systems engineering within the renewable energy sector, additional terms such as "system design", "modeling", and "optimization" were included. These terms help identify research discussing the effective implementation of renewable energy systems. In a subsequent search string, as part of the studies focus on business development,

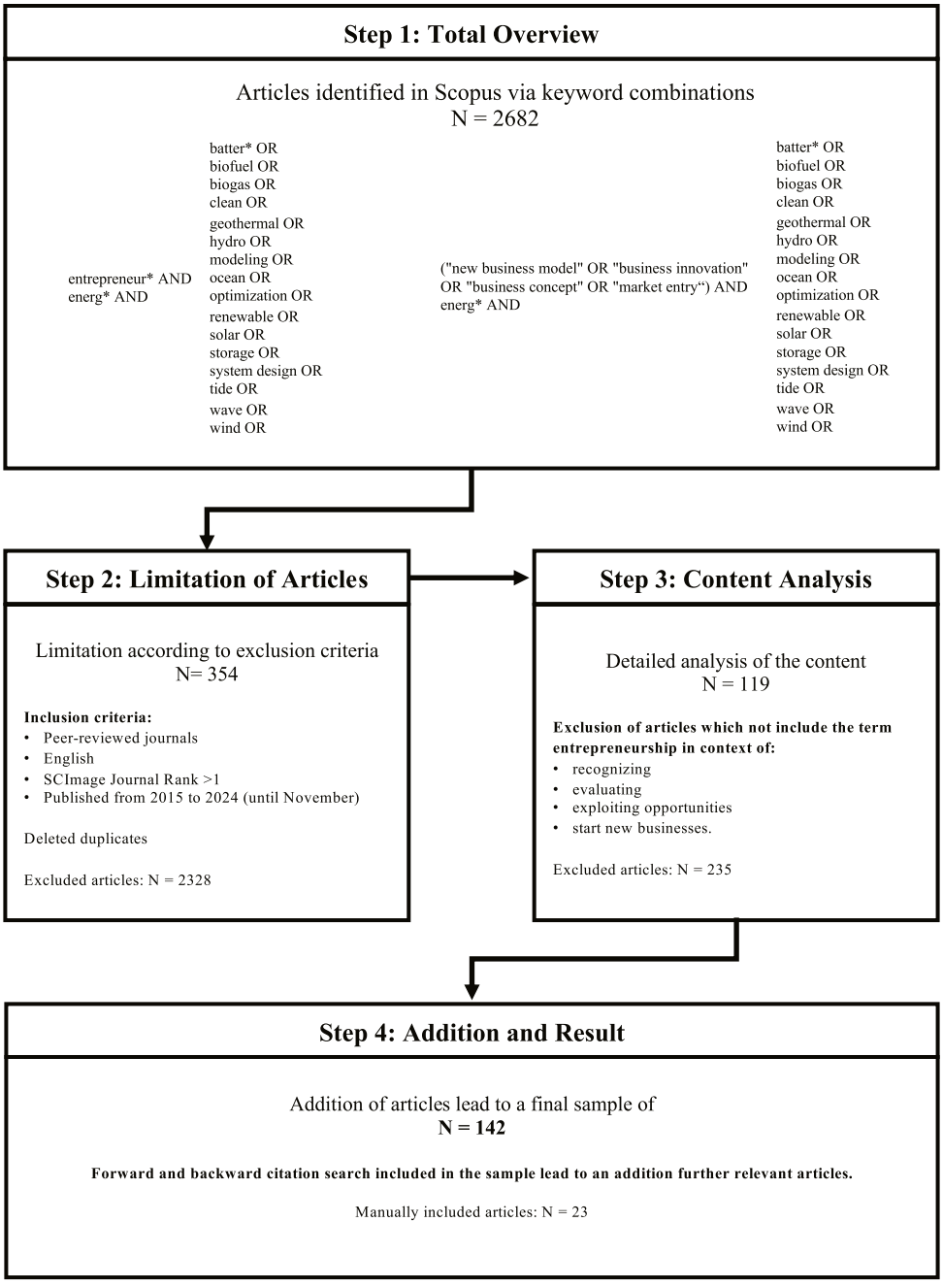

Fig. 1. Flow diagram describing the systematic literature review process, including all steps from identifying the earliest sample to analyzing the final sample.

Table 1
Classification of analyzed literature by type of entrepreneurship.

Type of Development	Type of Entrepreneurship	Key Characteristics	Studies
Renewable Energy Innovation	Technology Entrepreneurship	Development and adoption of new renewable energy technologies (radical and incremental), economic growth, and positive impact on carbon emission efficiency	Abdul et al. [45], Aguiar-Hernandez and Breetz [46], Ahlgren Ode and Lagerstedt Wadin [47], Ahtikoski et al. [48], Bajak [49], Ball and Kittler [5], Bharti et al. [50], Baquero and Monsalve [51], Bednarz and Broekel [52], Calvo et al. [10], Chavez et al. [53], Chen et al. [54], Chou et al. [55], Cicchiello et al. [56], Cojoianu et al. [57,58], Colombelli and Quatraro [59], Criscuolo and Menon [60], Cumming et al. [61], de A. Dantas et al. [62], Dhayal et al. [63], Doblinger et al. [64,65], Dobrovolska et al. [66], Dodd et al. [67], Doh et al. [68], Dong et al. [69], Donner et al. [70], Engels and Münch [71], Fuentes et al. [72], Gaddy et al. [73], Gao [74], Gasbarro et al. [75], Ghosh et al. [76], Gitelman et al. [77], Goldstein et al. [78], Guerin [79], Günzel-Jensen and Rask [80], Hall et al. [45], He et al. [81], Islam et al. [31], Jolly et al. [82], Kanda et al. [83]Karimi et al. [84], Kedron and Bagchi-Sen [85], Khezri and Hasan [86], Kirch Kirkegaard et al. [87], Knuth [88], Kokkonen and Ojanen [89], Korberg et al. [90], Lam and Law [91], de Lange [92], Leisen et al. [11], Malen and Marcus [93], Maiti [94], Marcus and Cohen [95], Mathiesen et al. [96], Mazzucato and Semieniuk [97], Midttun and Piccini [98], Mohammadi Lanbaran et al. [99], Moya-Clemente et al. [100], Mrkajic et al. [101], Nadkarni et al. [102], Norouzi et al. [103], Oguanobi and Joel [104], Pacheco and Khoury [105], Patrizio and Chinese [106], Peng and Liu [107], Pinkse and Groot [12], Rahbauer et al. [108], Rena et al. [109], Röder et al. [110], Romme et al. [111], Ruggiero et al. [112], Saura et al. [113], Sawulski et al. [114], Singh et al. [115], Skare et al. [116], Sovacool et al. [117], Slimane and Rousseau [118], Thomas and Maine [119], Toroslu et al. [120], York et al. [121], Yuan and Zhang [122]
Formation of Community	Community Entrepreneurship	Combining community-driven initiatives with sustainable energy solutions, local communities take charge of their energy needs and innovative environmental protection	Allain and Madariaga [123], Anfinson [124], Becker et al. [125], Curran [126], Graziano et al. [127], Gui and MacGill [128], Herbes et al. [129], Huang et al. [130], Jolly and Raven [131], Lebo [132], Lehtonen and Okkonen [133], Mah [134], Mahzouni [135], Meena et al. [136], Mininni [137], Mitzinneck and Besharov [138], Morrison and Ramsey [139], Nastasi and Mazzoni [140], Papazu [141], Parreño-Rodriguez et al. [142], Pastore et al. [143], Piterou and Coles [144], Roby and Dibb [145], Sperling [146], Süsser et al. [147], Vernay and Sebi [148], Zohar et al. [149]
Access to energy	Rural Entrepreneurship	Affordability of energy, infrastructure for energy production, distribution, and consumption	Aklin et al. [150], Amankwah-Amoah and Hinson [151], Asante et al. [152], Bandi et al. [153], Baruah [154], Domegni and Azouma [14], Gabriel et al. [155,156], Gabriel and Kirkwood [157], Gatto and Drago [158], Groenewoudt and Romijn [159], Haldar [160], Heuër [161], Hossain et al. [162], Irfan et al. [163], Jain and Koch [164], Kanyarusoke [165], Kennedy et al. [166], Mahto [167], Li and Shen [168], Mishra et al. [169], Moore and Collins [170], Namugenyi et al. [171], Narwane et al. [172], Ngowi et al. [173], Njoh [174], Pailman et al. [175], Plutshack et al. [176], Robert et al. [177], Sengupta et al. [178], Surie [4], Udemba et al. [179]

the keyword "entrepreneur*" was replaced with the keyword query ("new business model" OR "business innovation" OR "business concept" OR "market entry"). This approach ensured the inclusion of papers that, while not explicitly using the term "entrepreneur*," aligned conceptually with the definition of entrepreneurship.

The literature search was conducted following a systematic process (Fig. 1). First, (1) the selected database was searched for article titles, abstracts, and keywords using the specified keyword queries. Second, (2) the documents were filtered according to inclusion criteria. Only peer-reviewed journal articles in English with a SCImago Journal and Country Index (SJR) > 1 published from 2015 to 2024 (until November) were included in the literature analysis, resulting in 354 articles. The SJR index is an international, citation-based metric for evaluating scientific journals [39]. In addition to the formal inclusion criteria, (3) an informal criterion was applied, and the content of all articles was analyzed.

Articles that did not use the term entrepreneurship as recognizing, evaluating, and exploiting opportunities to start new businesses [17] were excluded, reducing the sample size to 119 articles. Following the content exclusion analysis, (4) significant citations of the articles included in the sample were analyzed, which led to the addition of 23 further relevant articles. This extended the final data set to 142 articles that address entrepreneurship in the renewable energy sector.

3.2. Data extraction and coding

The pre-screening of the articles showed that these could be categorized into main categories according to their characteristics and outcomes of entrepreneurial activities, following the coding approach outlined by Webster and Watson [34]. This systematic coding process enabled identifying and classifying key themes among different types of entrepreneurship within the literature [40–43]. The primary objective of this literature review was to address the renewable energy sector, which is characterized by unique characteristics, challenges, and impacts on sustainability that are not adequately represented by standard classifications in entrepreneurship literature. Consequently, sector-specific categorizations were developed in the study rather than strictly adhering to conventional classifications. Drawing from insights gained through the comprehensive literature review, the categories of technology entrepreneurship, community entrepreneurship, and rural entrepreneurship were established.

To ensure high accuracy in classification, a combined approach was utilized, leveraging the efficiency of automated processes alongside meticulous manual review. A customized large language model based on OpenAI's GPT-4 was employed to classify the articles in the sample into three predefined categories [44]. This process involved carefully analyzing at least two articles from each category manually, and these analyses were used to train the GPT model. The customized GPT then assigned all 142 articles to one of the three categories. To further enhance the accuracy of this classification, all GPT's suggestions were manually verified.

4. Findings and analysis

Research on entrepreneurship in the renewable energy sector was classified into three categories, each supporting sustainable growth and social progress (Table 1). Specifically, 83 of 142 articles were categorized as technology entrepreneurship, 27 as community entrepreneurship, and 32 as rural entrepreneurship. Technology entrepreneurs drive economic growth, improve carbon efficiency, and support the transition to a greener economy through technological innovation. Their ability to adapt quickly and implement innovative solutions makes them valuable to the global transition to a greener economy.

In contrast to technology entrepreneurship, community entrepreneurship produces less radical technological innovations but still aims to improve and apply environmentally friendly technologies [41]. Community entrepreneurship in the renewable energy sector focuses on initiatives that combine sustainable energy solutions with local ownership. Entrepreneurs create platforms for local communities to meet their own energy needs, leading to innovative approaches to environmental protection. Rural entrepreneurship in the renewable energy sector improves access to affordable and reliable energy [43]. This is particularly evident in underserved and rural areas, where innovative business models and technologies can expand access to energy and increase local economic performance.

To illustrate the distribution of renewable energy sources in the entrepreneurial context, Fig. 2 shows the number of articles analyzed in depth dealing with various renewable energy sources. There is a strong emphasis on solar energy, particularly in community entrepreneurship (81 % of the analyzed papers related to community entrepreneurship address solar energy) and rural entrepreneurship (91 %). There is also a notable number of articles that focus on wind energy. In contrast, other types of renewable energy sources, such as bioenergy, geothermal energy, energy storage, and hydropower, arerelatively under-represented in the literature, especially in the context of community and rural entrepreneurship. In sections 4.1 to 4.4, each finding is comprehensively analyzed independently within the context of its respective type of entrepreneurship.

4.1. Technology entrepreneurship

A significant number of the academic articles reviewed were categorized as technology entrepreneurship as they focus on developing and deploying new renewable energy technologies, economic growth, and the positive impact on carbon efficiency. This literature has been organized into a conceptual framework to provide better structure and clarity (Table 2). The individual components of this framework are explained in detail in sections 4.1.1 to 4.1.3.

4.1.1. Trends and antecedents

An important antecedent in the renewable energy sector is the development of decarbonization technologies and their deployment through the introduction and diffusion of innovative technologies, which is necessary due to climate change. Start-ups are essential in developing technologies to reduce CO_2 emissions and implementing decarbonization strategies [47,72,80]. The growth momentum for start-ups is driven by continuous technological innovation, which enables the application of modern technologies to develop efficient and effective solutions to the prevailing challenges in the energy market [72]. Start-ups actively promote decentralized energy models, exploring the use of technologies such as microgrids and local energy generation systems [72,110].

To strengthen the need, the United Nations Sustainable Development Goals (SDGs) are gaining importance as a critical framework for

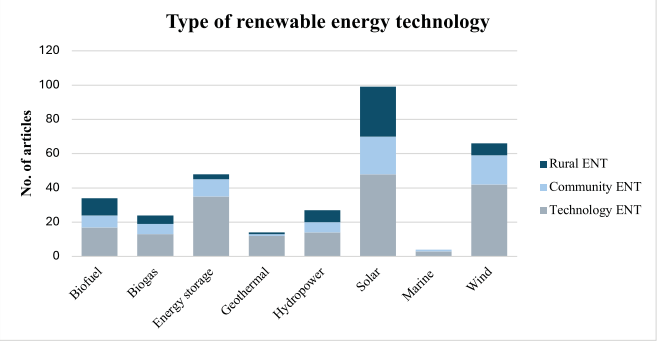

Fig. 2. Number of articles selected for this review in which the various types of renewable energy technology are thematically addressed. Multiple classifications are possible if the paper covers more than one type of technology.

Table 2
Conceptual framework about technology entrepreneurship divided into antecedents/trends, success factors, and outcomes.

	Antecedents/Trends	Success Factors	Outcomes
Decarbonization Technologies	• Advancements towards renewable technology adoption • Distributed systems • Electrification • Enhancement of Waste Management Practices • Future trends like AI and IoT • Implementation of decarbonization strategies	• Adequate funding for capital-intensive R&D projects • Efficient utilization of natural resources through advanced decarbonization technologies • Strong link between research and industry	*Energy Transition* • Emergence of environmentally relevant sectors by entrepreneurs, companies, political decision-makers • Innovative start-ups are driving the pace of the energy transition and serving as key indicators for its success in decarbonization. • Improving technological efficiency and performance • Localized and tailored decarbonization technologies for specific environments • Replacement of fossil fuels in the medium to long term *Practical Decarbonization Solutions* • Examples of critical technologies for decarbonization efforts: bioenergy, circular bioeconomy approach, photovoltaics, reduced air pollution, smart energy systems
Regulatory Frameworks and Energy Policy	• Policy measures • United Nations Sustainable Development Goals • Urgency of combating climate change • Warning from IEA	• Effective resolution of disputes over research policy • Overcoming regulatory barriers to foster innovation • Robust regulations supporting energy technology deployment, less volatility • Strong and proactive government and political support and high investment confidence through sectoral stability	*Regulatory Impact on Sustainable Development* • Achieving the SDGs due to reduced environmental pollution which leads to improved health and quality of life • Effective provision and strategic allocation of state subsidies within regulatory frameworks and energy policy
Market Conditions and Scaling	• Cost-effectiveness • Industry development • New Business Models	• Active knowledge exchange to enhance market integration and technology scaling • Improved access to financial resources • Increased investment confidence by reducing sectoral uncertainty • Successful market penetration and seamless international expansion of cleantech technologies • Support from tech venture builders to create scalable business models	*Market Transformation* • Enhancing market competitiveness through the reduction of electricity costs • Reduction of market entry barriers • Value creation to change traditional industry standards *Market Strategy* • Customized strategic approaches driven by market-demand-based research and development • Strengthening of international cooperation *Financing* • Financing via crowdlending platforms • Investments through green venture capital
Socio-Economic Impact of Energy Entrepreneurship	• Critical infrastructure • Extreme weather events • Fundamental human needs	• Alignment of mentalities and adaptation to conservative contexts for better market integration and technology acceptance • Cultivating entrepreneurial spirit • Strong customer and needs-orientation to effectively address societal demands	*Entrepreneurial Thinking* • Entrepreneurs' decisions are significantly shaped by social, regional, and institutional contexts. • Founders' network as a decisive factor • Increased diversity of perspectives, experience, and skills in development • Personal characteristics are decisive for entrepreneurial behavior *Social Impact* • Innovative value propositions are used to change social beliefs and overcome social norms and cultural-cognitive barriers • Stronger focus on scientific education, creation of new employment opportunities

promoting sustainable entrepreneurship [2,100], affecting policy. The literature emphasizes that the International Energy Agency (IEA) has also warned that the world will only be able to tackle climate change cost-effectively by developing and utilizing novel energy technologies [63]. The impact of energy start-ups goes beyond environmental considerations. It recognizes the natural antecedent for their activities [1]. As a result, start-ups in the renewable energy sector play a central role in democratizing access to reliable and economical energy sources, thereby promoting social justice [167]. The transition to renewable energy requires technological innovation and new business models to maximize efficiency and profitability, making these technologies scalable and economically viable through integrated approaches. Integrating smart grids, power-to-x solutions, micro-smart grids, distributed energy, and shared energy storage demonstrates how integrative approaches can unlock the full potential of renewables [103,112,143].

Wind and solar energy, for instance, are variable energy sources that pose specific challenges to the energy system due to their variability. Traditionally, the focus has been on integrating renewable energies into the electricity system, however, it is increasingly argued that a combined approach involving the electricity, heating, and transport sectors is essential [143]. Utilizing various storage options, such as thermal, electrical, or gaseous storage, creates the flexibility to integrate more considerable amounts of these variable energy sources efficiently. A sole focus on intelligent electricity grids would limit the potential for integrating variable renewable energies [71]. Power-to-x technologies play a crucial role in this context. They enable the conversion of renewable electricity into other forms of energy, thereby allowing cross-sectoral use and storage of energy. Power-to-heat systems have proven

cost-efficient strategies for increasing self-consumption rates in renewable energy communities and electrifying end-use consumption [143]. Another trend is the development of micro smart grids. These decentralized energy systems combine renewable energy generation, energy storage, and intelligent control to ensure sustainable and efficient local energy supply. Micro smart grids represent the shift towards a decentralized energy infrastructure and provide numerous opportunities for innovation and business development for start-ups [71].

As the energy market evolves, new dynamics emerge, creating disruptive change opportunities. The introduction and implementation of innovative business models in the renewable energy sector are being driven by technological innovation, with start-ups serving as a pivotal catalyst in this transformation. For example, digital technologies are a dominant trend that start-ups use to develop transformative solutions and revolutionize traditional business models [72,98]. By developing digital platforms that efficiently connect buyers and sellers, they reduce barriers to entry and increase the overall efficiency of the sector. Moreover, artificial intelligence (AI) is revolutionizing the energy sector. AI optimizes energy efficiency, grid management, and the integration of renewable energies through forecasting and real-time analysis [99]. Geographic Information Systems (GIS) and the Internet of Things (IoT) also present new opportunities for start-ups to develop scalable business models. Using GIS technology, companies in the renewable energy sector can conduct site analysis and infrastructure planning more efficiently, improving scalability and competitiveness [104]. Building on the trends and antecedents discussed, the following section examines the success factors critical to technology entrepreneurship in renewable energy.

4.1.2. Success factors

Various factors can influence the success of technology entrepreneurship in the renewable energy sector. Securing adequate funding is a critical factor influencing the success of technology entrepreneurship. Start-ups in the renewable energy sector face significant challenges, as innovation is often highly capital-intensive. Developing and scaling new energy solutions based on advanced technologies requires substantial initial investments, typically directed toward research and development, the construction of production facilities, and market introduction [61,73]. To illustrate the development of funding for start-ups in the renewable energy sector in recent years, Fig. 3 shows the number and volume of funding records in this field over the past ten years (data source Crunchbase, November 2024). The data indicates that investments in renewable energy start-ups have developed significantly despite the mentioned challenges. These trends reflect a growing interest from investors in sustainable technologies and underscore the importance of funding for the success of technology companies in the renewable energy sector.

Given that venture capitalists and other investors are often hesitant to invest in these technologies due to their high risks and long-term return horizons, the ability of start-ups to raise the necessary capital

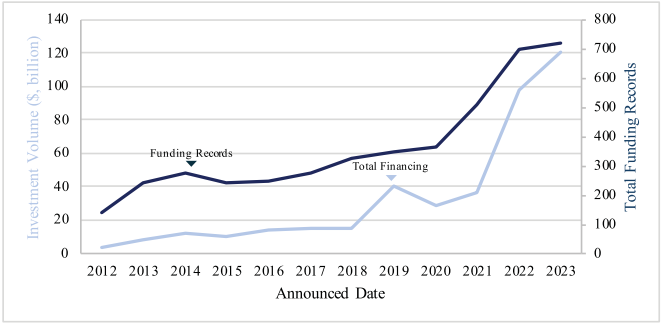

Fig. 3. Number of funding records and investment volume in the renewable energy sector (2012–2023). Data source: Crunchbase, own illustration.

becomes a decisive determinant of their success. Green venture capitalists provide high-risk capital to eco-innovative companies that offer financial returns and contribute to sustainable development. This type of capital is crucial for renewable technology and renewable energy start-ups, as they are often outside the interest of traditional funding sources [72]. Governments can impact the financing of energy start-ups by formulating policies that reduce barriers to entry. This is mainly done by reducing uncertainty and creating a clear and stable regulatory environment attractive to investors [61]. Instruments like feed-in tariffs increase investor confidence and create an incentive framework to establish new companies despite significant initial investments and market uncertainties [5,57]. This includes incentives such as subsidies, tax breaks, and regulatory frameworks that encourage investment in green technologies [73]. Simplifying licensing procedures and regulations, including the procedures for obtaining necessary licenses and certifications, can release valuable resources and time, thereby facilitating the entry and success of new market participants [144]. In addition to government legislation, funding initiatives such as the Advanced Research Projects Agency-Energy (ARPA-E) program, established by the US Department of Energy in 2009, provide financial support for start-ups that private investors often neglect [78]. This program focuses on high-risk technologies that have difficulty securing initial funding. ARPA-E currently manages 52 programs, encompassing a range of technical categories involving start-ups and other institutions, especially universities (Fig. 4) [180]. The ARPA-E programs indicate a focus on key areas such as "Generation," "Resource Efficiency," "Grid," and "Manufacturing Efficiency," suggesting a strategic interest in enhancing energy production, optimizing resource use, and modernizing infrastructure. The distribution of programs also highlights that ARPA-E is focused on energy generation and the application of these technologies, ensuring that advancements are practical and scalable. The ARPA-E programs foster innovation that supports a more balanced and resilient energy ecosystem by allocating significant resources across these technical domains. Despite its success in stimulating innovation and patent activity, ARPA-E's impact on long-term commercial success and market scalability remains limited. During the critical "valley of death" transition from development to market, further support is critical to ensure the commercial viability of these technologies [78].

Success factors for technology entrepreneurship in the renewable energy sector are closely linked to overcoming market barriers and promoting scalability. These barriers [181,182] hinder the introduction of new renewable technologies and their growth, primarily due to market barriers that impede scalability and innovation, especially for start-ups focused on sustainable solutions [12]. Previous studies categorized these barriers into three different types [182–184]. Inefficiency-based barriers arise from the non-excludable nature of environmental benefits, leading to underinvestment in clean technologies and insufficient competitive pressure on large firms to address inefficiencies [12,182,183]. Externality-based barriers include negative externalities, such as the environmental damage caused by fossil fuel production, which is not adequately reflected in market costs, and positive externalities, like undervalued ecosystem services, deter investment in preservation. Government policies, including subsidies for fossil fuels, further distort market dynamics [12,182,184]. Additionally, information-based barriers stem from a need for more awareness among consumers and producers about the benefits of clean energy technologies and complexities within supply chains that hinder the adoption of sustainable practices [12,182,184]. Addressing these barriers involves the careful development of business models that are both sustainable and competitive [10]. Start-ups in the renewable energy sector can overcome these barriers by using innovative financing, forming strategic alliances, and engaging in policy dialogues to foster a favorable market environment. Collaborating with established firms and policymakers can help address externalities by aligning incentives with environmental benefits, gradually reducing power imbalances compared to established companies [12].

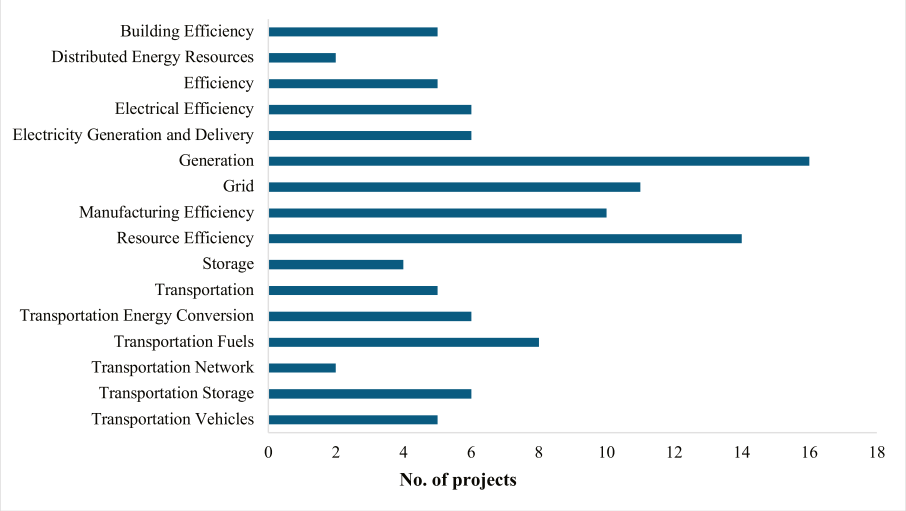

Fig. 4. Distribution of ARPA-E programs across technical categories. Source: ARPA-E Programs, own illustration [180].

Another critical success factor for start-ups in the renewable energy sector is the capacity to navigate the heterogeneity of local markets. Each region and country has distinct regulatory requirements and individual needs [47], which must be considered. These differences often require changes to business models. Such adaptations underline the need to view business models as flexible and dynamic entities tailored to local conditions. Customer preferences, regulatory requirements, and environmental factors vary significantly from one market to another. The ability to respond quickly to change and commercialize technological innovation gives start-ups an advantage over slower, traditional energy companies. A compelling aspect of these business models is their ability to operate in resource-constrained environments [167]. Here, start-ups use innovative approaches to turn scarcity into abundance by changing supply and demand dynamics. This illustrates how start-ups challenge market leaders with their disruptive business models and act as catalysts for broader social and economic change. However, a holistic approach is necessary, and agility must be complemented by factors like cost competitiveness, market timing, and the ability to guide external pressures to ensure long-term success [185].

A key success factor for scaling innovations is the iterative development and refinement process that enables local technology adaptation [47]. The continuous transnational exchange of knowledge promotes the scaling of start-ups and enables these ventures to expand more quickly into new markets. Collaborating with technologically advanced countries and adopting their best practices strengthens the ability to innovate and scale in technologically lagging countries [114].

Renewable energy sector start-ups face significant societal challenges, primarily socio-political acceptance and cultural-cognitive barriers, so the success of start-ups in the renewable energy sector is contingent upon a robust customer and demand orientation, enabling them to meet social requirements effectively. In conservative contexts, where traditional energy solutions are often favored over innovative approaches, the lack of social support makes it challenging to introduce new technologies [75,87]. This highlights the mismatch between traditional consumption patterns and innovative, sustainable solutions to combat climate change. To gain the necessary acceptance and support, start-ups must adapt to conservative attitudes and invest in community engagement and stakeholder management. Start-ups in the renewable energy sector interact with multiple stakeholders who can act as antecedents for their success and development. These stakeholders include investors, governments and regulators, customers and end users, research organizations, and universities. They need to be carefully managed to avoid any limitation of entrepreneurial flexibility and adaptive learning critical to a start-up's success in the dynamic renewable energy sector [80]. In addition, limited knowledge sharing among stakeholders, as evidenced by discussions on the need for open innovation and collaboration with external parties, and outdated knowledge among key stakeholders are significant barriers for start-ups [10,75].

4.1.3. Outcomes

Energy Transition Practical Decarbonization Solutions. Renewable energy start-ups play a pivotal role in promoting environmental sustainability. By driving innovative approaches, these new ventures are significantly contributing to reducing global CO_2 emissions and minimizing other environmental impacts [47,72,80]. New ventures are contributing to reducing greenhouse gas emissions and strengthening local economic cycles by, for instance, efficiently using local biomass resources [70]. Utilizing waste, energy start-ups significantly contribute to developing a circular economy to reduce air pollution and greenhouse gas emissions [70,110]. Studies indicate that green start-ups could have a positive impact on the environment. Cojoianu et al. suggest a potential correlation between green start-ups and reductions in urban air pollution. The study analyzed data from 12,834 cities (2010–2019) to assess the impact of green start-ups on reducing air pollution (PM2.5) and highlights that cities with a higher density of green start-ups, particularly those operating in areas such as smart grids, energy efficiency, and wind energy, may experience improvements in air quality [58]. However, further research is needed to understand and substantiate these connections fully. The study acknowledges limitations in establishing strict causality or regional variations, raising concerns about the generalizability of the findings and emphasizing the need for further research to confirm these results [58]. Ghosh et al. provide valuable insights into how landfills, often considered environmental burdens, could be transformed into energy resources through innovative technologies [76]. According to the Global Methane Pledge, landfills are a significant source of methane emissions, accounting for approximately 20 % of global anthropogenic methane emissions [186]. The paper indicates that modern gas capture systems could recover up to 80 % of this methane, converting it into biogas for electricity and heat generation. Digital tools, including blockchain and IoT-based sensors, could monitor methane emissions and optimize waste stream management, as suggested in the study. While the paper primarily offers indications rather than definitive evidence, it underscores the significant potential of start-ups and technology-driven solutions in addressing methane emissions and enhancing landfill sustainability [76]. Further research and practical implementation are essential to validate and realize these opportunities fully. Another example highlighting the transformative

potential of start-ups in the renewable energy sector is their role in advancing and deploying hydrogen as an alternative energy source [51]. Start-ups play a pivotal role, particularly in pioneering technologies such as hydrogen energy, by substantially contributing to environmental improvement through innovative approaches to social entrepreneurship and actively influencing the transition to more sustainable forms of energy. Nevertheless, the study underscores that this transition faces significant challenges, including high production and infrastructure costs, insufficient regulatory support, and the complexity of coordinating efforts among industry, government, and academia [51].

Start-ups have a crucial contribution to the energy transition, not only by developing innovative new technologies but also by improving existing technologies and making them more accessible. For instance, start-ups are working to improve the efficiency and longevity of solar panels while making them easier to install and maintain. Such innovations contribute to an increase in energy yield and actively promote the dissemination of this technology, which plays a pivotal role in a low-carbon future [72].

Regulatory Impact on Sustainable Development. Start-ups in the renewable energy sector contribute to social sustainability by developing and implementing innovative approaches and technologies for renewable and affordable energy. Therefore, this sector's social dimension is of the most significant importance in achieving the seventh goal of sustainable development as defined by the United Nations [100].

Market Transformation and Strategy. The adaptability and flexibility of start-ups in the energy sector enable them to introduce and disseminate innovative business models. Consequently, they could have the potential to alter traditional market dynamics and achieve significant economic results [115]. The business model transformation process exemplifies this, a critical mechanism that enables rapid adaptation to changing market conditions and regulatory frameworks, particularly in the dynamic renewable energy industry [47]. For instance, energy start-ups continue to innovate the industry by introducing circular business models based on new technologies and the efficient use of resources [70]. In addition, new technologies such as artificial intelligence for grid optimization and creating digital energy marketplaces illustrate the types of innovation that start-ups drive [72]. Such technological advances enable more efficient and transparent energy distribution and lower barriers to entry, thereby increasing competitiveness. However, the potential of these innovative business models is not assured. A thorough assessment of the nature and level of stakeholder engagement and the necessary flexibility and learning capacity is required to ensure long-term viability and success [80].

Energy start-ups contribute to a broader ecosystem of factors driving cost reduction, with innovative technologies and materials contributing to these decreases [187]. For example, developments in photovoltaics initiated by start-ups have helped to improve material efficiency and reduce the cost per unit of energy produced, making solar energy more competitive [49,72]. However, alongside these developments, external factors such as large-scale production capacities and financial investments, particularly from countries such as China, have also impacted cost reduction, which illustrates the complexity of the cost dynamics in the solar energy sector [185]. Similarly, Tesla has reduced costs and increased production through improved manufacturing methods and scaling, accelerating the time to market for its technologies [119].

Energy start-ups use internationalization and networks to expand their market position and increase their economic performance [10,72,115]. Expanding into international markets enables start-ups to scale their solutions and increase competitiveness. Adapting to international needs fosters innovation and supports sustainable business growth. Networks facilitate market entry and provide access to critical resources such as technology and expertise. Partnerships enable start-ups to overcome challenges such as local regulations more effectively and grow faster [10].

Financing. As an outcome of entrepreneurship in the renewable energy sector, the literature suggests a shift toward more innovative approaches and financing mechanisms to address the sector's unique challenges. These alternative mechanisms could provide valuable complements to traditional venture capital, broadening access to funding and helping to address the persistent financing gap. Government support remains a cornerstone of entrepreneurial success in this sector. Stable and predictable policy frameworks, including subsidies, renewable energy standards, and carbon emission caps, foster green venture capital [61]. Crowdlending and public-private partnerships also offer additional financing channels when start-ups have difficulty accessing traditional financing options [47,118]. Projects in the renewable energy sector often have social and environmental benefits, which motivates investors in other ways. However, Slimane and Rousseau also identify specific sector characteristics that influence success in crowdlending campaigns. Renewable energy projects are risky and can quickly become obsolete due to new technologies. Therefore, investors usually assess the projects' feasibility and market opportunities. This increases the information asymmetries and, thus, the risks for investors [118].

Entrepreneurial Thinking. Energy start-ups profoundly impact individuals, providing personal and professional development opportunities while sharing and diversifying knowledge among stakeholders [49,59,114]. Employees of these start-ups can broaden their knowledge by learning new technical skills and collaborating across disciplines, which enhances their personal and professional development [50]. Fostering the individual characteristics of the founders, such as risk-taking, creativity, self-confidence, and the ability to evolve, is crucial for realizing entrepreneurial intentions. At the same time, external social, regional, and institutional contexts significantly impact decision-making by shaping the perception and behavior of potential entrepreneurs within their communities and the broader social and political environment [89].

Social Impact. Energy start-ups also play a crucial role in driving technology adoption by providing energy supply solutions. They directly contribute to the local diffusion of new technologies by setting up in different communities, including less affluent areas. The presence of start-ups leads to an immediate increase in technology adoption in their immediate neighborhood. It promotes the growth of the renewable energy market in the long term [188]. Moreover, by creating jobs and stimulating local economies, energy start-ups further enhance the adoption of these technologies. Beyond contributing to economic performance, these jobs also significantly contribute to social development, providing opportunities for disadvantaged communities and helping to reduce social inequalities [51].

4.2. Formation of community through entrepreneurship

Community entrepreneurship in the renewable energy sector represents a dynamic intersection of community-led initiatives and sustainable energy solutions. It entails local communities taking responsibility for their energy needs, pursuing alternative energy sources, and fostering self-sufficiency. This approach empowers communities to shape their energy futures and advances environmental sustainability through renewable energy projects and innovative ecological protection strategies [40,41]. Community entrepreneurship in the renewable energy sector is a multifaceted entrepreneurial activity that varies depending on the actor, such as environmental NGOs, parliamentarians, businesses and local communities, and the location. This diversity is reflected in how they collaborate in developing and implementing innovative and sustainable energy solutions [148].

Previous research highlights different aspects of community entrepreneurship in the renewable energy sector. It shows how the commitment of communities, the creativity of entrepreneurs, and the support of political and social institutions work together to drive change towards a more sustainable energy future. The literature suggests that ideas of ecological modernization have considerable influence at institutional and social levels [126,133]. As dynamic renewable energy sector actors,

energy communities can adapt to existing energy systems and either enter into a symbiosis with established energy players or compete directly with them [148]. These initiatives are particularly effective at the local level, yet their impact can extend beyond local boundaries [125]. Community entrepreneurship accomplish this while transforming centralized energy systems into more distributed and decentralized structures [128]. Previous research on bricolage, middle-out mechanisms, and collective resource building shows that community entrepreneurship is a versatile strategy for promoting a low-carbon energy transition and positively impacts market entry, particularly in less densely industrialized areas [105,141,149].

Research on community entrepreneurship in the energy sector is often illustrated by case studies. The literature review shows a growing diversity of approaches and technologies worldwide. Case studies from different countries and with different technological focuses provide deep insights into how communities initiate and implement renewable energy projects and promote local development. Most case studies examine European community projects. The case studies analyzed in this review illustrate how community energy projects adapt to local conditions and significantly contribute to regional energy transformation. For example, the Samsø Renewable Energy Island in Denmark demonstrates how integrating different renewable energy sources can achieve complete energy self-sufficiency [146]. The success of the Samsø Renewable Energy Island project demonstrates how such initiatives depend on the interplay of external and internal conditions. External factors, including government support and establishing a clear guiding vision, created a conducive framework for the project. Internal factors, such as the strong sense of community, cooperative traditions, and the involvement of dedicated local actors, were critical for its successful implementation. Crucially, the project aligned external requirements with local interests through flexible adaptation and active population participation, ensuring social acceptance, financial involvement, and long-term commitment to the initiative [146]. Similarly, the Eno Energy Cooperative in Finland demonstrates the successful use of locally sourced biomass for district heating, which promotes local economic development while reducing dependence on fossil fuels [133]. In addition, the case study of rural energy projects in Ireland highlights how integrating multiple renewable energy technologies increases the stability of local energy systems while strengthening social cohesion within communities [139].

However, community entrepreneurship also faces challenges that can limit its effectiveness in fostering local development. These include limited access to financial resources and expertise, which can hinder the planning and execution of initiatives. Institutional and governance issues, such as fragmented policies and regulatory complexities, often create additional barriers. Economic uncertainties and logistical constraints further complicate the process, while social and cultural dynamics, including resistance to change and competing interests, can affect community engagement [40,127].

4.3. Rural entrepreneurship

Entrepreneurship is essential for rural areas' economic and social development and provides innovative solutions to traditional and emerging challenges, including energy access. It increases the affordability of energy and the infrastructure for its generation, distribution, and consumption in areas where an extension to the national grid is difficult, expensive, or impractical due to geographical challenges [162,165]. Access to energy in rural areas provides necessities (such as lighting), strengthens social security, and promotes income-generating activities that are otherwise impossible without electricity [175]. Two distinct forms of entrepreneurial activity can be identified in the context of entrepreneurship in rural areas. The first type of venture facilitates access to energy, while the second category encompasses new entrants who benefit from the potential for energy access. Entrepreneurial ventures have emerged as a direct result of access to electricity and emphasize the critical role of energy in stimulating and supporting local economic activity [162,173].

This review of the relevant literature indicates that solar energy is the predominant focus of studies about entrepreneurship in rural areas, with 91 % of the analyzed studies dealing with rural entrepreneurship discussing this technology. Solar energy is considered a cost-effective and reliable solution, particularly in rural areas where access and implementation are relatively straightforward. In comparison, other renewable energy technologies receive considerably less attention: 31 % of the studies mention biofuels, 22 % reference hydropower, and wind energy, and 16 % address biogas. Technologies such as energy storage (9 %), geothermal energy (3 %), and ocean energy (0 %) appear to be rarely discussed in the literature. The frequent mention of solar energy highlights its practicality and broad applicability, particularly in rural contexts. The limited focus on other renewable technologies indicates that these alternatives receive different research attention, potentially pointing to an underexplored opportunity for diversifying rural energy solutions.

However, entrepreneurs in the renewable energy sector also face several challenges in developing countries [151,156,172–174]. Rural entrepreneurship is mainly constrained by limited access to institutional finance, inadequate political support, and underdeveloped physical infrastructure, which collectively lead to elevated costs and logistical difficulties. Additionally, the dominance of established fossil fuel industries, combined with a shortage of qualified workforce and insufficient knowledge transfer, creates further obstacles. Cultural barriers and a lack of awareness regarding the benefits of renewable energy also hinder its widespread adoption in rural areas. These challenges impede the capacity of entrepreneurs to effectively establish and expand their businesses, thereby influencing the comprehensive transition to sustainable energy systems in these regions. Prior research indicates that a unified strategy between the national innovation framework and entrepreneurial activities is crucial to cultivating a conducive ecosystem for the growth and sustainability of renewable energy start-ups [4,156].

4.4. Case studies

In practice, several exemplary start-ups fulfill many of these success factors. These cases illustrate how various types of entrepreneurship can be effectively implemented to contribute to sustainable development within the renewable energy sector.

Redwood Materials: Redwood Materials exemplifies technology entrepreneurship by creating a closed-loop supply chain for battery materials. By developing advanced recycling technologies for lithium-ion batteries, Redwood Materials aims to minimize the environmental impact of electronic waste while ensuring a sustainable supply of materials for future battery production [189]. This approach addresses both the economic and environmental dimensions of sustainable development by reducing dependence on raw material extraction and promoting the efficient use of resources.

Gokin Solar: Gokin Solar contributes to the renewable energy sector and technology entrepreneurship by focusing on producing efficient solar panels and photovoltaic solutions, utilizing advanced monocrystalline silicon technology to enhance performance and efficiency [190].

Arcadia: As shown in the results, innovation in the energy sector goes beyond advancements in hardware, extending to digital solutions that leverage data integration for sustainability, as demonstrated by Arcadia. The company provides a platform that uses API-based products to aggregate energy consumption and cost data, enabling businesses to optimize energy services and pursue electrification and decarbonization initiatives. Additionally, Arcadia manages one of the most extensive community solar programs in the United States, allowing consumers to benefit from solar energy without needing private installations [191].

SOURCE: This start-up serves as a model of rural entrepreneurship by addressing water scarcity through the deployment of solar-powered

hydro panels. These panels harvest water vapor from the atmosphere to provide clean drinking water in regions experiencing critical water shortages [192]. By harnessing energy to fulfill essential human needs, SOURCE contributes to the broader goal of social sustainability.

HUSK: HUSK Power Systems also demonstrates rural entrepreneurship by delivering renewable energy solutions to off-grid African and Asian communities. The company constructs and operates solar-hybrid microgrids that generate affordable and reliable electricity for rural households, businesses, and public services. HUSK Power Systems integrates solar power with biomass and battery storage, creating sustainable energy infrastructure in areas lacking access to the national grid [193].

5. Discussion

5.1. Summary of findings and future research

The renewable energy sector is characterized by a dynamic environment in which various types of entrepreneurship are central to promoting sustainable growth and social progress. At the same time, its unique characteristics and challenges require innovative solutions. This review analyzed three distinct types of entrepreneurship individually to understand their respective contributions comprehensively. This literature review has indicated that these types of entrepreneurship differ considerably in their contribution to sustainable growth and are, therefore, highly dependent on their context, such as the legal framework in their respective regions. Entrepreneurs drive economic growth, improve carbon efficiency, and advance the green economy through technology entrepreneurship. Furthermore, community entrepreneurship improves green technologies and embeds sustainability locally, while rural entrepreneurship emphasizes the social aspects of sustainability.

A significant ratio of the reviewed literature pertains to technology entrepreneurship, prompting the focus of the research on developing a comprehensive conceptual framework. This framework outlines the trends, antecedents, success factors, and outcomes associated with technology entrepreneurship in advancing renewable energy technologies, fostering economic growth, and enhancing carbon efficiency. Identifying numerous success factors for technology entrepreneurship underscores this sector's complexity and multifaceted nature. However, although numerous start-ups have made substantial contributions to advancements in renewable energy, their efforts are frequently impeded by regulatory barriers, high capital requirements, and socio-cultural obstacles.

Future research should use secondary datasets to enhance the existing research framework and enable a thorough and accurate assessment of start-ups' effectiveness and potential drawbacks in the renewable energy sector. This approach would allow for a detailed examination of outcomes and other dimensions within the conceptual framework. This could provide a unique opportunity to analyze an ongoing transition and open a new perspective on how this can influence immediate outcomes and long-term change. In the literature on start-ups in the renewable energy sector, studies have already described sustainable business performance in terms of environmental performance. For example, studies establish a link between new businesses and the reduction of urban air pollution, showing that green start-ups improve air quality [57]. However, detailed analyses of these impacts across different technologies remain limited. As the urgency of climate change and societal expectations increase, understanding these impacts will be critical for managers and policymakers to make sustainability-focused decisions.

Community entrepreneurship is important in transforming centralized energy systems into decentralized, resilient models that promote energy independence, sustainability, and local economic growth. Despite their potential, these initiatives face considerable challenges, including financial and technical limitations, regulatory complexities, and social resistance. Addressing these barriers requires targeted strategies such as improved governance and inclusive stakeholder engagement to ensure their effectiveness and scalability.

The literature on community entrepreneurship in renewable energy is characterized mainly by case studies that illustrate how local circumstances, cultural contexts, and policy frameworks shape project outcomes. While these studies provide valuable insights, their limited generalizability highlights the need for future research to take a more holistic approach that considers the diversity of actors and methods in the field. Future research should further explore the collaborative and competitive dynamics between community entrepreneurs and established energy companies, with a focus on overcoming barriers and aligning objectives with broader market demands and policy frameworks.

This research shows that rural entrepreneurship is central to economic and social development in these areas, especially in improving energy access. Entrepreneurship manifests in two distinct forms: ventures that facilitate access to energy and new entrants that capitalize on the potential created by energy access. The current research and entrepreneurial focus on solar energy overlooks the potential of other renewable technologies like biomass, biogas, hydropower, and wind energy. Exploring these underrepresented areas could uncover opportunities for diversification and address specific local energy needs. Future research should investigate barriers to adopting these technologies and develop strategies to promote a more varied and resilient rural energy portfolio.

5.2. Implications

This research shows that success in all the types of entrepreneurship defined in this review is highly dependent on the external environment. One of the key challenges for renewable energy entrepreneurs is dealing with the changing regulatory environment. Entrepreneurs should keep abreast of current and future regulations in order to identify opportunities and risks at an early stage. Active participation in policy processes can help to create favorable conditions and secure access to financial incentives. This requires a proactive approach to policymakers and strong networking within the industry. Another important aspect is to adapt business models to the local context. A thorough market analysis enables entrepreneurs to understand a region's specific energy needs and cultural attitudes. Based on this understanding, solutions can be developed that are functional and culturally acceptable. These measures can help build local acceptance and strong community relations, particularly important when implementing infrastructure projects. In addition, strategic partnerships and networks are essential for renewable energy entrepreneurs. Working with universities, established companies, and fellow entrepreneurs can provide access to valuable resources and expertise. These connections help to build credibility and facilitate market entry through collective engagement.

To effectively promote the transition to renewable energy, policymakers must create a supportive environment through regulatory stability, targeted economic incentives, and improved access to capital. First, a stable regulatory environment is essential. Policymakers should focus on developing transparent and predictable policies and long-term commitments that reduce uncertainty for investors. Simplifying permitting procedures and ensuring regulatory consistency are important measures to encourage greater private sector involvement and sustainable investment in renewable energy projects. In addition, the design of targeted economic incentives is crucial in promoting growth in the renewable energy sector. By introducing subsidies, tax credits, and grants targeted explicitly at renewable energy initiatives, policymakers can lower barriers to entry and encourage market development. Facilitating access to capital is critical for renewable energy projects. Policymakers can set up government funding programs. Examples include ARPA-E in the United States and African Rural Energy Enterprise Development (AREED) in Africa, both of which support renewable

energy initiatives. Government funding, such as grants or low-interest loans, can help bridge financing gaps, while risk mitigation policies can attract private capital and support start-ups with high up-front costs.

5.3. Limitations

Although a systematic approach was followed, the study has certain limitations. Firstly, like other research, the International Energy Agency's definition of renewable energy was used in the study [9]. However, other synonyms or broader terms exist, such as "clean energy". Given this diversity of terms, relevant articles that could have enriched the discussion may have yet to be included in the final dataset. Secondly, a large sample of 142 articles was coded for this study. Methodological rigor was emphasized to counteract potential bias, with the results regularly reviewed by the author group. Additionally, a hybrid approach was employed, combining the efficiency of automated processes with meticulous manual review to refine the classification further. Thirdly, the analyzed literature was divided into different categories. However, it is important to note that these categorization options are neither fully exhaustive nor always mutually exclusive. Other approaches to categorizing the studies may also be helpful and offer different perspectives.

6. Conclusion

This study conducted a systematic literature review on entrepreneurship in the renewable energy sector. Using a comprehensive analytical approach, 142 articles were analyzed in detail and categorized into three distinct types of entrepreneurship: technology entrepreneurship, community entrepreneurship, and rural entrepreneurship. The study's findings indicate that these new businesses play a central role in promoting sustainability through decarbonization initiatives and innovative solutions for energy access. The study's analysis shows that technology start-ups in the renewable energy sector require strategic approaches due to the complex challenges and numerous success factors. Transparent, long-term regulatory frameworks are crucial to encourage investment in technology-driven start-ups, lower barriers to market entry, and strengthen collaboration between community entrepreneurs and established companies. Moreover, there is also a need for a comprehensive approach to promoting rural entrepreneurship in the renewable energy sector, including financial and policy support and targeted investments in a broader range of technologies.

CRediT authorship contribution statement

D. Bendig: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. **L. Brüss:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – review & editing. **F. Degen:** Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT-4 to classify articles within their sample. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] Chu S, Majumdar A. Opportunities and challenges for a sustainable energy future. Nature 2012;488:294–303. https://doi.org/10.1038/nature11475.
[2] United Nations. Resolution adopted by the general assembly on 25 september 2015 - transforming our world: the 2030 agenda for sustainable development. https://www.unfpa.org/sites/default/files/resource-pdf/Resolution_A_RES_70_1_EN.pdf. [Accessed 28 August 2024].
[3] Eitan A, Rosen G, Herman L, Fishhendler I. Renewable energy entrepreneurs: a conceptual framework. Energies 2020;13:2554. https://doi.org/10.3390/en13102554.
[4] Surie G. Creating the innovation ecosystem for renewable energy via social entrepreneurship: insights from India. Technol Forecast Soc Change 2017;121:184–95. https://doi.org/10.1016/j.techfore.2017.03.006.
[5] Ball C, Kittler M. Removing environmental market failure through support mechanisms: insights from green start-ups in the British, French and German energy sectors. Small Bus Econ 2019;52:831–44. https://doi.org/10.1007/s11187-017-9937-8.
[6] Hoogendoorn B, van der Zwan P, Thurik R. Goal heterogeneity at start-up: are greener start-ups more innovative? Res Policy 2020;49:104061. https://doi.org/10.1016/j.respol.2020.104061.
[7] Schaltegger S, Wagner M. Sustainable entrepreneurship and sustainability innovation: categories and interactions. Bus Strateg Environ 2011;20:222–37. https://doi.org/10.1002/bse.682.
[8] Richter M. Utilities' business models for renewable energy: a review. Renew Sustain Energy Rev 2012;16:2483–93. https://doi.org/10.1016/j.rser.2012.01.072.
[9] Engelken M, Römer B, Drescher M, Welpe I, Picot A. Comparing drivers, barriers, and opportunities of business models for renewable energies: a review. Renew Sustain Energy Rev 2016;60:795–809. https://doi.org/10.1016/j.rser.2015.12.163.
[10] Calvo N, Monje-Amor A, Villarreal O. When your value proposition is to improve others' energy efficiency: analyzing the internationalization dilemma of eco-innovations in SMEs. Technol Forecast Soc Change 2022;185:122069. https://doi.org/10.1016/j.techfore.2022.122069.
[11] Leisen R, Steffen B, Weber C. Regulatory risk and the resilience of new sustainable business models in the energy sector. J Clean Prod 2019;219:865–78. https://doi.org/10.1016/j.jclepro.2019.01.330.
[12] Pinkse J, Groot K. Sustainable entrepreneurship and corporate political activity: overcoming market barriers in the clean energy sector. Entrep Theory Pract 2015;39:633–54. https://doi.org/10.1111/etap.12055.
[13] Krishna H, Kashyap Y, Dutt D, Sagar AD, Malhotra A. Understanding India's low-carbon energy technology startup landscape. Nat Energy 2023;8:94–105. https://doi.org/10.1038/s41560-022-01170-y.
[14] Domegni KMS, Azouma YO. Productive uses of energy: a solution for promoting energy justice in rural areas in West Africa. Renew Sustain Energy Rev 2022;160:112298. https://doi.org/10.1016/j.rser.2022.112298.
[15] Jenkins K, McCauley D, Heffron R, Stephan H, Rehner R. Energy justice: a conceptual review. Energy Res Soc Sci 2016;11:174–82. https://doi.org/10.1016/j.erss.2015.10.004.
[16] Kraus S, Mahto RV, Walsh ST. The importance of literature reviews in small business and entrepreneurship research. J Small Bus Manag 2021;61:1095–106. https://doi.org/10.1080/00472778.2021.1955128.
[17] Gartner WB. "Who is an entrepreneur?" Is the wrong question. Am J Small Bus 1988;12:11–32. https://doi.org/10.1177/104225878801200401.
[18] Covin JG, Slevin DP. A conceptual model of entrepreneurship as firm behavior. Entrep Theory Pract 1991;16:7–26. https://doi.org/10.1177/104225879101600102.
[19] Ireland RD, Hitt MA, Sirmon DG. A model of strategic entrepreneurship: the construct and its dimensions. J Manag 2003;29:963–89. https://doi.org/10.1016/s0149-2063(03)00086-2.
[20] Bird B. Implementing entrepreneurial ideas: the case for intention. Acad Manag Rev 1988;13:442–53. https://doi.org/10.2307/258091.

[21] Freeman J, Engel JS. Models of innovation: startups and mature corporations. Calif Manag Rev 2007;50:94–119. https://doi.org/10.2307/41166418.
[22] Slater SF, Mohr JJ. Successful development and commercialization of technological innovation: insights based on strategy type. J Prod Innov Manag 2005;23:26–33. https://doi.org/10.1111/j.1540-5885.2005.00178.x.
[23] Feder C. The effects of disruptive innovations on productivity. Technol Forecast Soc Change 2018;126:186–93. https://doi.org/10.1016/j.techfore.2017.05.009.
[24] Ries E. The lean startup. New York, NY: Crown Business Division; 2011.
[25] Wennekers S, Thurik R. Linking entrepreneurship and economic growth. Small Bus Econ 1999;13:27–56. https://doi.org/10.1023/a:1008063200484.
[26] International Energy Agency. World energy outlook 2013. https://www.iea.org/reports/world-energy-outlook-2013. [Accessed 27 September 2024]. Licence: CC BY 4.0.
[27] International Energy Agency. Renewables 2023. https://www.iea.org/reports/renewables-2023. [Accessed 26 September 2024]. Licence: CC BY 4.0: IEA; 2024.
[28] Rhodes A, Skea J, Hannon M. The global surge in energy innovation. Energies 2014;7:5601–23. https://doi.org/10.3390/en7095601.
[29] Zhao B, Ziedonis R. State governments as financiers of technology startups: evidence from Michigan's R&D loan program. Res Policy 2020;49:103926. https://doi.org/10.1016/j.respol.2020.103926.
[30] Ghosh S., Nanda R. Venture Capital Investment in Clean Energy Sector. Harvard Business School Entrepreneurial Management Working Paper No 11-020 2010. https://doi.org/10.2139/ssrn.1669445.
[31] Islam M, Fremeth A, Marcus A. Signaling by early stage startups: US government research grants and venture capital funding. J Bus Ventur 2018;33:35–51. https://doi.org/10.1016/j.jbusvent.2017.10.001.
[32] Palmié M, Boehm J, Friedrich J, Parida V, Wincent J, Kahlert J, et al. Startups versus incumbents in 'green' industry transformations: a comparative study of business model archetypes in the electrical power sector. Ind Mark Manag 2021;96:35–49. https://doi.org/10.1016/j.indmarman.2021.04.003.
[33] Hegeman PD, Sørheim R. Why do they do it? Corporate venture capital investments in cleantech startups. J Clean Prod 2021;294:126315. https://doi.org/10.1016/j.jclepro.2021.126315.
[34] Webster J, Watson RT. Analyzing the past to prepare for the future: writing a literature review. MIS Q 2002;26.
[35] Tranfield D, Denyer D, Smart P. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. Br J Manag 2003;14:207–22. https://doi.org/10.1111/1467-8551.00375.
[36] van Burg E, Romme AGL. Creating the future together: toward a framework for research synthesis in entrepreneurship. Entrep Theory Pract 2014;38:369–97. https://doi.org/10.1111/etap.12092.
[37] Zastempowski M. Analysis and modeling of innovation factors to replace fossil fuels with renewable energy sources - evidence from European Union enterprises. Renew Sustain Energy Rev 2023;178:113262. https://doi.org/10.1016/j.rser.2023.113262.
[38] Mauler L, Duffner F, Leker J. Economies of scale in battery cell manufacturing: the impact of material and process innovations. Appl Energy 2021;286:116499. https://doi.org/10.1016/j.apenergy.2021.116499.
[39] Vogel R, Hattke F, Petersen J. Journal rankings in management and business studies: what rules do we play by? Res Policy 2017;46:1707–22. https://doi.org/10.1016/j.respol.2017.07.001.
[40] Kubli M, Puranik S. A typology of business models for energy communities: current and emerging design options. Renew Sustain Energy Rev 2023;176:113165. https://doi.org/10.1016/j.rser.2023.113165.
[41] Johannisson B. Community entrepreneurship - cases and conceptualization. Entrep Reg Dev 1990;2:71–88. https://doi.org/10.1080/08985629000000006.
[42] Garud R, Karnøe P. Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship. Res Policy 2003;32:277–300. https://doi.org/10.1016/S0048-7333(02)00100-2.
[43] Bryant CR. Entrepreneurs in the rural environment. J Rural Stud 1989;5:337–48. https://doi.org/10.1016/0743-0167(89)90060-0.
[44] Bendig D, Bräunche A. The role of artificial intelligence algorithms in information systems research: a conceptual overview and avenues for research. Manag Rev Q 2024. https://doi.org/10.1007/s11301-024-00451-y.
[45] Abdul D, Wenqi J, Sameeroddin M. Prioritization of ecopreneurship barriers overcoming renewable energy technologies promotion: a comparative analysis of novel spherical fuzzy and Pythagorean fuzzy AHP approach. Technol Forecast Soc Change 2023;186(Part A):122133. https://doi.org/10.1016/j.techfore.2022.122133.
[46] Aguiar-Hernandez C, Breetz HL. The adverse effects of political instability on innovation systems: the case of Mexico's wind and solar sector. Technovation 2024;136:103083. https://doi.org/10.1016/j.technovation.2024.103083.
[47] Ahlgren Ode K, Lagerstedt Wadin J. Business model translation—the case of spreading a business model for solar energy. Renew Energy 2019;133:23–31. https://doi.org/10.1016/j.renene.2018.09.036.
[48] Ahtikoski A, Routa J, Repola J, Laitila J. The financial viability of artificial drying of forest chips, a case study from Northern Finland. J Clean Prod 2019;212:1454–61. https://doi.org/10.1016/j.jclepro.2018.12.110.
[49] Bajak A. Chile's chance to embrace science for the twenty-first century. Nature 2017;552:53–5. https://doi.org/10.1038/d41586-017-08385-0.
[50] Bharti K, Agarwal R, Satsangi A, Rajwanshi R. Analyzing the influence of university support and entrepreneurial culture on solar entrepreneurial intentions among Indian students. Int J Manag Educ 2024;22:100991. https://doi.org/10.1016/j.ijme.2024.100991.
[51] Baquero JEG, Monsalve DB. From fossil fuel energy to hydrogen energy: transformation of fossil fuel energy economies into hydrogen economies through social entrepreneurship. Int J Hydrog Energy 2024;54:574–85. https://doi.org/10.1016/j.ijhydene.2023.06.123.
[52] Bednarz M, Broekel T. Pulled or pushed? The spatial diffusion of wind energy between local demand and supply. Ind Corp Change 2020;29:893–916. https://doi.org/10.1093/icc/dtaa012.
[53] Chavez VA, Stinnett R, Tierney R, Walsh S. The importance of the technologically able social innovators and entrepreneurs: a US national laboratory perspective. Technol Forecast Soc Change 2017;121:205–15. https://doi.org/10.1016/j.techfore.2016.09.002.
[54] Chen S, Bai H, Wang B, Lin J-H. Social enterprise, renewable energy, and cap-and-trade under sustainable insurance. Energy Econ 2024;133:107535. https://doi.org/10.1016/j.eneco.2024.107535.
[55] Chou JC-P, Hu M-C, Tsung-Ying Shih T. Green transformation: lessons from the fuel cell innovation system in Taiwan. J Clean Prod 2019;240:118182. https://doi.org/10.1016/j.jclepro.2019.118182.
[56] Cicchiello AF, Gatto A, Salerno D. At the nexus of circular economy, equity crowdfunding and renewable energy sources: are enterprises from green countries more performant? J Clean Prod 2023;410:136932. https://doi.org/10.1016/j.jclepro.2023.136932.
[57] Cojoianu TF, Clark GL, Hoepner AGF, Veneri P, Wójcik D. Entrepreneurs for a low carbon world: how environmental knowledge and policy shape the creation and financing of green start-ups. Res Policy 2020;49:103988. https://doi.org/10.1016/j.respol.2020.103988.
[58] Cojoianu TF, Hoepner AGF, Hu X, Ramadan M, Veneri P, Wójcik D. Are cities venturing green? A global analysis of the impact of green entrepreneurship on city air pollution. Small Bus Econ 2024;62:523–40. https://doi.org/10.1007/s11187-023-00764-4.
[59] Colombelli A, Quatraro F. Green start-ups and local knowledge spillovers from clean and dirty technologies. Small Bus Econ 2019;52:773–92. https://doi.org/10.1007/s11187-017-9934-y.
[60] Criscuolo C, Menon C. Environmental policies and risk finance in the green sector: cross-country evidence. Energy Pol 2015;83:38–56. https://doi.org/10.1016/j.enpol.2015.03.023.
[61] Cumming D, Henriques I, Sadorsky P. 'Cleantech' venture capital around the world. Int Rev Financ Anal 2016;44:86–97. https://doi.org/10.1016/j.irfa.2016.01.015.
[62] de A, Dantas G, de Castro NJ, Dias L, Antunes CH, Vardiero P, Brandão R, et al. Public policies for smart grids in Brazil. Renew Sustain Energy Rev 2018;92:501–12. https://doi.org/10.1016/j.rser.2018.04.077.
[63] Dhayal KS, Giri AK, Esposito L, Agrawal S. Mapping the significance of green venture capital for sustainable development: a systematic review and future research agenda. J Clean Prod 2023;396:136489. https://doi.org/10.1016/j.jclepro.2023.136489.
[64] Doblinger C, Dowling M, Helm R. An institutional perspective of public policy and network effects in the renewable energy industry: enablers or disablers of entrepreneurial behaviour and innovation? Entrep. Reg Dev 2015;28:126–56. https://doi.org/10.1080/08985626.2015.1109004.
[65] Doblinger C, Surana K, Anadon LD. Governments as partners: the role of alliances in U.S. cleantech startup innovation. Res Policy 2019;48:1458–75. https://doi.org/10.1016/j.respol.2019.02.006.
[66] Dobrovolska O, Ortmanns W, Podosynnikov S, Halynskyi D, Miniailo A. Start-ups and entrepreneurship in renewable energy: investments and risks. Financial markets. Institutions and Risks 2024;8:213–40. https://doi.org/10.61093/fmir.8(2).213-240.2024.
[67] Dodd T, Orlitzky M, Nelson T. What stalls a renewable energy industry? Industry outlook of the aviation biofuels industry in Australia, Germany, and the USA. Energy Pol 2018;123:92–103. https://doi.org/10.1016/j.enpol.2018.08.048.
[68] Doh J, Budhwar P, Wood G. Long-term energy transitions and international business: concepts, theory, methods, and a research agenda. J Int Bus Stud 2021;52:951–70. https://doi.org/10.1057/s41267-021-00405-6.
[69] Dong W, Li Y, Lv X, Yu C. How does venture capital spur the innovation of environmentally friendly firms? Evidence from China. Energy Econ 2021;103:105582. https://doi.org/10.1016/j.eneco.2021.105582.
[70] Donner M, Gohier R, de Vries H. A new circular business model typology for creating value from agro-waste. Sci Total Environ 2020;716:137065. https://doi.org/10.1016/j.scitotenv.2020.137065.
[71] Engels F, Münch AV. The micro smart grid as a materialised imaginary within the German energy transition. Energy Res Soc Sci 2015;9:35–42. https://doi.org/10.1016/j.erss.2015.08.024.
[72] Fuentes R, Chen D, Felder FA. Systematically mapping innovations in electricity using startups: a comprehensive database analysis. Technol Soc 2023;74:102282. https://doi.org/10.1016/j.techsoc.2023.102282.
[73] Gaddy BE, Sivaram V, Jones TB, Wayman L. Venture Capital and Cleantech: the wrong model for energy innovation. Energy Pol 2017;102:385–95. https://doi.org/10.1016/j.enpol.2016.12.035.
[74] Gao X. The comparative impact of solar policies on entrepreneurship in the U.S. solar photovoltaic installation industry. Energy Pol 2021;156:112389. https://doi.org/10.1016/j.enpol.2021.112389.
[75] Gasbarro F, Rizzi F, Frey M. Sustainable institutional entrepreneurship in practice. Int J Entrep Behav Res 2018;24:476–98. https://doi.org/10.1108/ijebr-11-2015-0259.
[76] Ghosh A, Kumar S, Das J. Impact of leachate and landfill gas on the ecosystem and health: research trends and the way forward towards sustainability. J Environ Manage 2023;336:117708. https://doi.org/10.1016/j.jenvman.2023.117708.

[77] Gitelman LD, Kozhevnikov MV, Starikov EM, Gamburg AV. Technology entrepreneurship as a factor of sustainable energy in smart cities. WIT Trans Ecol Environ 2020;246:101–12. https://doi.org/10.2495/EPM200101.
[78] Goldstein A, Doblinger C, Baker E, Anadón LD. Patenting and business outcomes for cleantech startups funded by the Advanced Research Projects Agency-Energy. Nat Energy 2020;5:803–10. https://doi.org/10.1038/s41560-020-00683-8.
[79] Guerin TF. Business model scaling can be used to activate and grow the biogas-to-grid market in Australia to decarbonise hard-to-abate industries: an application of entrepreneurial management. Renew Sustain Energy Rev 2022;158:112090. https://doi.org/10.1016/j.rser.2022.112090.
[80] Günzel-Jensen F, Rask M. Combating climate change through collaborations? Lessons learnt from one of the biggest failures in environmental entrepreneurship. J Clean Prod 2021;278:123941. https://doi.org/10.1016/j.jclepro.2020.123941.
[81] He Y, Wu H, Wu AY, Li P, Ding M. Optimized shared energy storage in a peer-to-peer energy trading market: two-stage strategic model regards bargaining and evolutionary game theory. Renew Energy 2024;224:120190. https://doi.org/10.1016/j.renene.2024.120190.
[82] Jolly S, Spodniak P, Raven RPJM. Institutional entrepreneurship in transforming energy systems towards sustainability: wind energy in Finland and India. Energy Res Soc Sci 2016;17:102–18. https://doi.org/10.1016/j.erss.2016.04.002.
[83] Kanda W, Sakao T, Hjelm O. Components of business concepts for the diffusion of large scaled environmental technology systems. J Clean Prod 2016;128:156–67. https://doi.org/10.1016/j.jclepro.2015.10.040.
[84] Karimi MS, Doostkouei SG, Shaiban M, Easvaralingam Y, Khan YA. Investigating the role of entrepreneurship in advancing renewable energy for sustainable development: evidence from a System-GMM panel data approach. Sustain Dev 2023;32:3329–43. https://doi.org/10.1002/sd.2847.
[85] Kedron P, Bagchi-Sen S. Explanations of firm survival in renewable energy in the United States: a study of ethanol refineries. Eur Plan Stud 2018;26:2237–55. https://doi.org/10.1080/09654313.2018.1530150.
[86] Khezri M, Hasan QM. Exploring the impacts of entrepreneurship indices on renewable energy mix: a cross-country study. Renew Sustain Energy Rev 2024;199:114539. https://doi.org/10.1016/j.rser.2024.114539.
[87] Kirch Kirkegaard J, Cronin T, Nyborg S, Karnøe P. Paradigm shift in Danish wind power: the (un)sustainable transformation of a sector. J Environ Policy Plan 2021;23:97–113. https://doi.org/10.1080/1523908x.2020.1799769.
[88] Knuth S. "Breakthroughs" for a green economy? Financialization and clean energy transition. Energy Res Soc Sci 2018;41:220–9. https://doi.org/10.1016/j.erss.2018.04.024.
[89] Kokkonen K, Ojanen V. From opportunities to action - an integrated model of small actors' engagement in bioenergy business. J Clean Prod 2018;182:496–508. https://doi.org/10.1016/j.jclepro.2018.02.013.
[90] Korberg AD, Skov IR, Mathiesen BV. The role of biogas and biogas-derived fuels in a 100% renewable energy system in Denmark. Energy 2020;199:117426. https://doi.org/10.1016/j.energy.2020.117426.
[91] Lam PTI, Law AOK. Financing for renewable energy projects: a decision guide by developmental stages with case studies. Renew Sustain Energy Rev 2018;90:937–44. https://doi.org/10.1016/j.rser.2018.03.083.
[92] de Lange DE. Legitimation strategies for clean technology entrepreneurs facing institutional voids in emerging economies. J Int Manag 2016;22:403–15. https://doi.org/10.1016/j.intman.2016.06.002.
[93] Malen J, Marcus AA. Promoting clean energy technology entrepreneurship: the role of external context. Energy Pol 2017;102:7–15. https://doi.org/10.1016/j.enpol.2016.11.045.
[94] Maiti M. Does development in venture capital investments influence green growth? Technol Forecast Soc Change 2022;182:121878. https://doi.org/10.1016/j.techfore.2022.121878.
[95] Marcus AA, Cohen SK. Public policies in a regulated entrepreneurial setting. Bus Polit 2015;17:221–51. https://doi.org/10.1017/s1369525800001637.
[96] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. https://doi.org/10.1016/j.apenergy.2015.01.075.
[97] Mazzucato M, Semieniuk G. Public financing of innovation: new questions. Oxf Rev Econ Policy 2017;33:24–48. https://doi.org/10.1093/oxrep/grw036.
[98] Midttun A, Piccini PB. Facing the climate and digital challenge: European energy industry from boom to crisis and transformation. Energy Pol 2017;108:330–43. https://doi.org/10.1016/j.enpol.2017.05.046.
[99] Mohammadi Lanbaran N, Naujokaitis D, Kairaitis G, Jenciūtė G, Radziukynienė N. Overview of startups developing artificial intelligence for the energy sector. Appl Sci 2024;14:8294. https://doi.org/10.3390/app14188294.
[100] Moya-Clemente I, Ribes-Giner G, Pantoja-Díaz O. Configurations of sustainable development goals that promote sustainable entrepreneurship over time. Sustain Dev 2020;28:572–84. https://doi.org/10.1002/sd.2009.
[101] Mrkajic B, Murtinu S, Scalera VG. Is green the new gold? Venture capital and green entrepreneurship. Small Bus Econ 2019;52:929–50. https://doi.org/10.1007/s11187-017-9943-x.
[102] Nadkarni K, Lefsrud LM, Schiffner D, Banks J. Converting oil wells to geothermal resources: roadmaps and roadblocks for energy transformation. Energy Pol 2022;161:112705. https://doi.org/10.1016/j.enpol.2021.112705.
[103] Norouzi F, Hoppe T, Kamp LM, Manktelow C, Bauer P. Diagnosis of the implementation of smart grid innovation in The Netherlands and corrective actions. Renew Sustain Energy Rev 2023;175:113185. https://doi.org/10.1016/j.rser.2023.113185.
[104] Oguanobi VU, Joel OT. Scalable business models for startups in renewable energy- Strategies for using GIS technology to enhance SME scaling. Eng Sci Technol 2024;5:1571–87. https://doi.org/10.51594/estj/v5i5.1109.
[105] Pacheco DF, Khoury TA. Social movements and entrepreneurial activity: a study of the U.S. solar energy industry. Res Policy 2023;52. https://doi.org/10.1016/j.respol.2022.104621.
[106] Patrizio P, Chinese D. The impact of regional factors and new bio-methane incentive schemes on the structure, profitability and CO2 balance of biogas plants in Italy. Renew Energy 2016;99:573–83. https://doi.org/10.1016/j.renene.2016.07.047.
[107] Peng H, Liu Y. How government subsidies promote the growth of entrepreneurial companies in clean energy industry: an empirical study in China. J Clean Prod 2018;188:508–20. https://doi.org/10.1016/j.jclepro.2018.03.126.
[108] Rahbauer S, Menapace L, Menrad K, Decker T. Adoption of green electricity by small- and medium-sized enterprises in Germany. Renew Sustain Energy Rev 2016;59:1185–94. https://doi.org/10.1016/j.rser.2016.01.079.
[109] Rena Yadav S, Patel S, Killedar DJ, Kumar S, Kumar R. Eco-innovations and sustainability in solid waste management: an indian upfront in technological, organizational, start-ups and financial framework. J Environ Manage 2022;302:113953. https://doi.org/10.1016/j.jenvman.2021.113953.
[110] Röder M, Jamieson C, Thornley P. (Stop) burning for biogas. Enabling positive sustainability trade-offs with business models for biogas from rice straw. Biomass Bioenergy 2020;138:105598. https://doi.org/10.1016/j.biombioe.2020.105598.
[111] Romme AGL, Bell J, Frericks G. Designing a deep-tech venture builder to address grand challenges and overcome the valley of death. J Organ Des 2023;12:217–37. https://doi.org/10.1007/s41469-023-00144-y.
[112] Ruggiero S, Varho V, Rikkonen P. Transition to distributed energy generation in Finland: prospects and barriers. Energy Pol 2015;86:433–43. https://doi.org/10.1016/j.enpol.2015.07.024.
[113] Saura JR, Ribeiro-Navarrete S, Palacios-Marqués D, Mardani A. Impact of extreme weather in production economics: extracting evidence from user-generated content. Int J Prod Econ 2023;260:108861. https://doi.org/10.1016/j.ijpe.2023.108861.
[114] Sawulski J, Gałczyński M, Zajdler R. Technological innovation system analysis in a follower country – the case of offshore wind in Poland. Environ Innov Soc Transit 2019;33:249–67. https://doi.org/10.1016/j.eist.2019.07.002.
[115] Singh M, Jiao J, Klobasa M, Frietsch R. Making Energy-transition headway: a Data driven assessment of German energy startups. Sustain Energy Technol Assess 2021;47:101322. https://doi.org/10.1016/j.seta.2021.101322.
[116] Skare M, Gavurova B, Sinkovic D. Regional aspects of financial development and renewable energy: a cross-sectional study in 214 countries. Econ Anal Policy 2023;78:1142–57. https://doi.org/10.1016/j.eap.2023.05.006.
[117] Sovacool BK, Jeppesen J, Bandsholm J, Asmussen J, Balachandran R, Vestergaard S, et al. Navigating the "paradox of openness" in energy and transport innovation: insights from eight corporate clean technology research and development case studies. Energy Pol 2017;105:236–45. https://doi.org/10.1016/j.enpol.2017.02.033.
[118] Slimane FB, Rousseau A. Crowdlending campaigns for renewable energy: success factors. J Clean Prod 2020;249:119330. https://doi.org/10.1016/j.jclepro.2019.119330.
[119] Thomas VJ, Maine E. Market entry strategies for electric vehicle start-ups in the automotive industry – lessons from Tesla Motors. J Clean Prod 2019;235:653–63. https://doi.org/10.1016/j.jclepro.2019.06.284.
[120] Toroslu A, Herrmann AM, Chappin MMH, Schemmann B, Castaldi C. Open innovation in nascent ventures: does openness influence the speed of reaching critical milestones? Technovation 2023;124:102732. https://doi.org/10.1016/j.technovation.2023.102732.
[121] York JG, O'Neil I, Sarasvathy SD. Exploring environmental entrepreneurship: identity coupling, venture goals, and stakeholder incentives. J Manag Stud 2016;53:695–737. https://doi.org/10.1111/joms.12198.
[122] Yuan F, Zhang P. Are natural resources, sustainable growth and entrepreneurship matter endogenous growth theory? The strategic role of technical progress. Resour Policy 2024;96:105189. https://doi.org/10.1016/j.resourpol.2024.105189.
[123] Allain M, Madariaga A. Understanding policy change through bricolage: the case of Chile's renewable energy policy. Governance 2020;33:675–92. https://doi.org/10.1111/gove.12453.
[124] Anfinson K. Capture or empowerment: governing citizens and the environment in the European renewable energy transition. Am Polit Sci Rev 2023;117:927–39. https://doi.org/10.1017/s0003055422001034.
[125] Becker S, Kunze C, Vancea M. Community energy and social entrepreneurship: addressing purpose, organisation and embeddedness of renewable energy projects. J Clean Prod 2017;147:25–36. https://doi.org/10.1016/j.jclepro.2017.01.048.
[126] Curran G. Contemporary environmental entrepreneurs: from the alternative technology movement to ecologically modernised community energy. J Environ Policy Plan 2021;23:467–81. https://doi.org/10.1080/1523908X.2021.1880316.
[127] Graziano M, Billing S-L, Kenter JO, Greenhill L. A transformational paradigm for marine renewable energy development. Energy Res Soc Sci 2017;23:136–47. https://doi.org/10.1016/j.erss.2016.10.008.
[128] Gui EM, MacGill I. Typology of future clean energy communities: an exploratory structure, opportunities, and challenges. Energy Res Soc Sci 2018;35:94–107. https://doi.org/10.1016/j.erss.2017.10.019.
[129] Herbes C, Rilling B, Holstenkamp L. Ready for new business models? Human and social capital in the management of renewable energy cooperatives in Germany. Energy Pol 2021;156:112417. https://doi.org/10.1016/j.enpol.2021.112417.

[130] Huang P, Ma H, Liu Y. Socio-technical experiments from the bottom-up: the initial stage of solar water heater adoption in a 'weak' civil society. J Clean Prod 2018; 201:888–95. https://doi.org/10.1016/j.jclepro.2018.08.087.
[131] Jolly S, Raven RPJM. Collective institutional entrepreneurship and contestations in wind energy in India. Renew Sustain Energy Rev 2015;42:999–1011. https://doi.org/10.1016/j.rser.2014.10.039.
[132] Lebo FB. Evaluating a collaborative governance regime in renewable energy: wind power and the lake erie energy development corporation (LEEDCo). Environ Dev 2019;32:100449. https://doi.org/10.1016/j.envdev.2019.06.004.
[133] Lehtonen O, Okkonen L. Energy cost reduction creates additional socioeconomic benefits– the case of Eno Energy Cooperative, Finland. Energy Pol 2019;129: 352–9. https://doi.org/10.1016/j.enpol.2019.02.018.
[134] Mah DN-y. Community solar energy initiatives in urban energy transitions: a comparative study of Foshan, China and Seoul, South Korea. Energy Res Soc Sci 2019;50:129–42. https://doi.org/10.1016/j.erss.2018.11.011.
[135] Mahzouni A. The role of institutional entrepreneurship in emerging energy communities: the town of St. Peter in Germany. Renew Sustain Energy Rev 2019; 107:297–308. https://doi.org/10.1016/j.rser.2019.03.011.
[136] Meena NK, Yang J, Zacharis E. Optimisation framework for the design and operation of open-market urban and remote community microgrids. Appl Energy 2019;252:113399. https://doi.org/10.1016/j.apenergy.2019.113399.
[137] Mininni GM. The Barefoot College 'eco-village' approach to women's entrepreneurship in energy. Environ Innov Soc Transit 2022;42:112–23. https://doi.org/10.1016/j.eist.2021.12.002.
[138] Mitzinneck BC, Besharov ML. Managing value tensions in collective social entrepreneurship: the role of temporal, structural, and collaborative compromise. J Bus Ethics 2019;159:381–400. https://doi.org/10.1007/s10551-018-4048-2.
[139] Morrison C, Ramsey E. Power to the people: developing networks through rural community energy schemes. J Rural Stud 2019;70:169–78. https://doi.org/10.1016/j.jrurstud.2018.07.006.
[140] Nastasi B, Mazzoni S. Renewable hydrogen energy communities layouts towards off-grid operation. Energy Convers Manag 2023;291:117293. https://doi.org/10.1016/j.enconman.2023.117293.
[141] Papazu I. Entrepreneurial resource construction through collective bricolage on Denmark's renewable energy Island: an ethnographic study. Entrep Reg Dev 2021;33:837–62. https://doi.org/10.1080/08985626.2021.1964613.
[142] Parreño-Rodriguez A, Ramallo-González AP, Chinchilla-Sánchez M, Molina-García A. Community energy solutions for addressing energy poverty: a local case study in Spain. Energy Build 2023;296:113418. https://doi.org/10.1016/j.enbuild.2023.113418.
[143] Pastore LM, Lo Basso G, Ricciardi G, de Santoli L. Smart energy systems for renewable energy communities: a comparative analysis of power-to-X strategies for improving energy self-consumption. Energy 2023;280:128205. https://doi.org/10.1016/j.energy.2023.128205.
[144] Piterou A, Coles AM. A review of business models for decentralised renewable energy projects. Bus Strateg Environ 2021;30:1468–80. https://doi.org/10.1002/bse.2709.
[145] Roby H, Dibb S. Future pathways to mainstreaming community energy. Energy Pol 2019;135. https://doi.org/10.1016/j.enpol.2019.111020.
[146] Sperling K. How does a pioneer community energy project succeed in practice? The case of the Samsø Renewable Energy Island. Renew Sustain Energy Rev 2017; 71:884–97. https://doi.org/10.1016/j.rser.2016.12.116.
[147] Süsser D, Döring M, Ratter BMW. Harvesting energy: place and local entrepreneurship in community-based renewable energy transition. Energy Pol 2017;101:332–41. https://doi.org/10.1016/j.enpol.2016.10.018.
[148] Vernay A-L, Sebi C. Energy communities and their ecosystems: a comparison of France and The Netherlands. Technol Forecast Soc Change 2020;158:120123. https://doi.org/10.1016/j.techfore.2020.120123.
[149] Zohar T, Parag Y, Ayalon O. Of agency, action, and influence: the middle-out mechanism for promoting a low-carbon energy transition. Energy Res Soc Sci 2021;72:101900. https://doi.org/10.1016/j.erss.2020.101900.
[150] Aklin M, Bayer P, Harish SP, Urpelainen J. Economics of household technology adoption in developing countries: evidence from solar technology adoption in rural India. Energy Econ 2018;72:35–46. https://doi.org/10.1016/j.eneco.2018.02.011.
[151] Amankwah-Amoah J, Hinson RE. Scaling up and scaling out of darkness: elucidating the influences of institutional dysfunction in scaling up solar PV in Sub-Saharan Africa. World Dev 2024;183:106726. https://doi.org/10.1016/j.worlddev.2024.106726.
[152] Asante D, He Z, Mintah Ampaw E, Gyamerah S, Ankrah Twumasi M, Opoku-Mensah E, et al. Renewable energy technology transition among small-and-medium scale firms in Ghana. Renew Energy 2021;178:549–59. https://doi.org/10.1016/j.renene.2021.06.111.
[153] Bandi V, Sahrakorpi T, Paatero J, Lahdelma R. Touching the invisible: exploring the nexus of energy access, entrepreneurship, and solar homes systems in India. Energy Res Soc Sci 2020;69:101767. https://doi.org/10.1016/j.erss.2020.101767.
[154] Baruah B. Creating opportunities for women in the renewable energy sector: findings from India. Fem Econ 2015;21:53–76. https://doi.org/10.1080/13545701.2014.990912.
[155] Gabriel C-A, Kirkwood J, Walton S, Rose EL. How do developing country constraints affect renewable energy entrepreneurs? Energy Sustain Dev 2016;35: 52–66. https://doi.org/10.1016/j.esd.2016.09.006.
[156] Gabriel C-A. What is challenging renewable energy entrepreneurs in developing countries? Renew Sustain Energy Rev 2016;64:362–71. https://doi.org/10.1016/j.rser.2016.06.025.
[157] Gabriel C-A, Kirkwood J. Business models for model businesses: lessons from renewable energy entrepreneurs in developing countries. Energy Pol 2016;95: 336–49. https://doi.org/10.1016/j.enpol.2016.05.006.
[158] Gatto A, Drago C. When renewable energy, empowerment, and entrepreneurship connect: measuring energy policy effectiveness in 230 countries. Energy Res Soc Sci 2021;78:101977. https://doi.org/10.1016/j.erss.2021.101977.
[159] Groenewoudt AC, Romijn HA. Limits of the corporate-led market approach to off-grid energy access: a review. Environ Innov Soc Transit 2022;42:27–43. https://doi.org/10.1016/j.eist.2021.10.027.
[160] Haldar S. A landscape level analysis of entrepreneurship and sustainable energy transitions: evidences from Gujarat, India. Sustain Dev 2022;30:489–502. https://doi.org/10.1002/sd.2244.
[161] Heuër A. Women-to-women entrepreneurial energy networks: a pathway to green energy uptake at the base of pyramid. Sustain Energy Technol Assess 2017;22: 116–23. https://doi.org/10.1016/j.seta.2017.02.020.
[162] Hossain ML, Shapna KJ, Li J. Solar energy brightens lives and strengthens the resilience of geographically challenged communities in Bangladesh. Energy Sustain Dev 2023;74:79–90. https://doi.org/10.1016/j.esd.2023.03.016.
[163] Irfan M, Yadav S, Shaw K. The adoption of solar photovoltaic technology among Indian households: examining the influence of entrepreneurship. Technol Forecast Soc Change 2021;169:120815. https://doi.org/10.1016/j.techfore.2021.120815.
[164] Jain S, Koch J. Crafting markets and fostering entrepreneurship within underserved communities: social ventures and clean energy provision in Asia. Entrep Reg Dev 2019;32:176–96. https://doi.org/10.1080/08985626.2019.1640481.
[165] Kanyarusoke K. Problems of engineering entrepreneurship in Africa: a design optimization example in solar thermal engineering. Eng Sci Technol Int J 2020; 23:345–56. https://doi.org/10.1016/j.jestch.2019.05.002.
[166] Kennedy R, Numminen S, Sutherland J, Urpelainen J. Multilevel customer segmentation for off-grid solar in developing countries: evidence from solar home systems in Rwanda and Kenya. Energy 2019;186:115728. https://doi.org/10.1016/j.energy.2019.07.058.
[167] Mahto RV, Belousova O, Ahluwalia S. Abundance – a new window on how disruptive innovation occurs. Technol Forecast Soc Change 2020;155:119064. https://doi.org/10.1016/j.techfore.2017.09.008.
[168] Li C, Shen B. Accelerating renewable energy electrification and rural economic development with an innovative business model: a case study in China. Energy Pol 2019;127:280–6. https://doi.org/10.1016/j.enpol.2018.12.009.
[169] Mishra R, Shiradkar S, Werner K, Maria T, Kumar P, Venkateswaran J, et al. Dynamics of solar energy entrepreneurship in rural Bihar, India. Energy Sustain Dev 2023;76:101269. https://doi.org/10.1016/j.esd.2023.101269.
[170] Moore HL, Collins H. Decentralised renewable energy and prosperity for Lebanon. Energy Pol 2020;137:111102. https://doi.org/10.1016/j.enpol.2019.111102.
[171] Namugenyi I, Coenen L, Scholderer J. Realising the transition to bioenergy: integrating entrepreneurial business models into the biogas socio-technical system in Uganda. J Clean Prod 2022;333:130135. https://doi.org/10.1016/j.jclepro.2021.130135.
[172] Narwane VS, Yadav VS, Raut RD, Narkhede BE, Gardas BB. Sustainable development challenges of the biofuel industry in India based on integrated MCDM approach. Renew Energy 2021;164:298–309. https://doi.org/10.1016/j.renene.2020.09.077.
[173] Ngowi JM, Bångens L, Ahlgren EO. Benefits and challenges to productive use of off-grid rural electrification: the case of mini-hydropower in Bulongwa-Tanzania. Energy Sustain Dev 2019;53:97–103. https://doi.org/10.1016/j.esd.2019.10.001.
[174] Njoh AJ. A systematic review of environmental determinants of renewable energy performance in Ethiopia: a PESTECH analysis. Renew Sustain Energy Rev 2021; 147:111243. https://doi.org/10.1016/j.rser.2021.111243.
[175] Pailman W, Caprotti F, Bobbins K, de Groot J. The informality-energy innovation-finance nexus: sustainable business models for microgrid-based off-grid urban energy access. Energy Res Soc Sci 2024;118:103749. https://doi.org/10.1016/j.erss.2024.103749.
[176] Plutshack V, Sengupta S, Sahay A, Viñuales JE. New and renewable energy social enterprises accessing government support: findings from India. Energy Pol 2019; 132:367–78. https://doi.org/10.1016/j.enpol.2019.05.009.
[177] Robert FC, Frey LM, Sisodia GS. Village development framework through self-help-group entrepreneurship, microcredit, and anchor customers in solar microgrids for cooperative sustainable rural societies. J Rural Stud 2021;88. https://doi.org/10.1016/j.jrurstud.2021.07.013.
[178] Sengupta S, Sahay A, Hisrich RD. The social – market convergence in a renewable energy social enterprise. J Clean Prod 2020;270:122516. https://doi.org/10.1016/j.jclepro.2020.122516.
[179] Udemba EN, Philip LD, Emir F. Performance and sustainability of environment under entrepreneurial activities, urbanization and renewable energy policies: a dual study of Malaysian climate goal. Renew Energy 2022;189:734–43. https://doi.org/10.1016/j.renene.2022.03.024.
[180] Advanced Research Projects Agency - Energy U.S. Department of Energy; 2024. https://arpa-e.energy.gov/technologies/programs. [Accessed 15 November 2024].
[181] Patzelt H, Shepherd DA. Recognizing opportunities for sustainable development. Entrep Theory Pract 2011;35:631–52. https://doi.org/10.1111/j.1540-6520.2010.00386.x.
[182] Dean TJ, McMullen JS. Toward a theory of sustainable entrepreneurship: reducing environmental degradation through entrepreneurial action. J Bus Ventur 2007;22:50–76. https://doi.org/10.1016/j.jbusvent.2005.09.003.

[183] Pacheco DF, Dean TJ, Payne DS. Escaping the green prison: entrepreneurship and the creation of opportunities for sustainable development. J Bus Ventur 2010;25:464–80. https://doi.org/10.1016/j.jbusvent.2009.07.006.
[184] Cohen B, Winn MI. Market imperfections, opportunity and sustainable entrepreneurship. J Bus Ventur 2007;22:29–49. https://doi.org/10.1016/j.jbusvent.2004.12.001.
[185] Evro SR, Wade C, Tomomewo O S. Solar PV technology cost dynamics and challenges for US new entrants. Am J Energy Res 2023;11:15–26. https://doi.org/10.12691/ajer-11-1-2.
[186] Climate and Clean Air Coalition (CCAC). The imperative for methane action. https://www.globalmethanepledge.org/imperative-methane-action. [Accessed 25 November 2024].
[187] Udemba EN, Emir F, Philip LD. Mitigating poor environmental quality with technology, renewable and entrepreneur policies: a symmetric and asymmetric approaches. Renew Energy 2022;189:997–1006. https://doi.org/10.1016/j.renene.2022.03.060.
[188] O'Shaughnessy E, Forrester S, Barbose G. Supply sunspots and shadows: business siting patterns and inequitable rooftop solar adoption in the United States. Energy Res Soc Sci 2023;96:102920. https://doi.org/10.1016/j.erss.2022.102920.
[189] Redwood materials inc. https://www.redwoodmaterials.com. [Accessed 24 November 2024].
[190] Gokin Solar Co. Ltd https://gokinsolar.com/en; 2024. [Accessed 24 November 2024].
[191] Arcadia power Inc. https://www.arcadia.com; 2024. [Accessed 24 November 2024].
[192] Source. https://source.co. [Accessed 24 November 2024].
[193] Husk power systems. https://huskpowersystems.com. [Accessed 24 November 2024].