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Review

Sustainable energy experiments and demonstrations: Reviewing research, market and societal trends

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ABSTRACT

Research into the impact of innovative sustainable energy experiments and demonstrations is crucial to diversifying, scaling up, and accelerating the sustainable energy transition. Although there is vast research into sustainable energy experiments and demonstrations, research literature offers a fragmented collection of findings. A coherent overview of themes and insights regarding the transformative impact of innovative sustainable energy experiments and demonstrations on sustainable energy systems from the past, present, and near future is lacking and necessary to increase experiments and demonstrations' impact on the sustainable energy transition. The research in this study fills this knowledge gap by providing such an overview and yields novel insights into the organized function and impact of experiments and demonstrations. It spans a broad spectrum of sustainable energy technologies, the empirical domains where these are invented, developed and applied, and the stakeholders involved. The overview is the outcome of a Delphi study in which the insights of 47 international scientific research experts in sustainable energy experiments and demonstrations are bundled and explained. This study presents a thematic overview of the significant insights regarding past and current sustainable energy experiments and demonstrations and outlines a research agenda for the future. Policymakers, practitioners, and scientists can leverage this to inform their sustainable energy policies, business strategies, and research programs.

1. Introduction

Innovative sustainable energy technologies can be conceptualized as systems that capture a physical phenomenon or a collection of physical phenomena and use them [1] to generate, harvest, convert, store, transport, and operate power using "new or modified processes, techniques, practices, systems and products" [2,p. 100], adopted by humans [1], to "avoid or reduce environmental harms" [2,p. 100].

Research shows that innovative sustainable energy technologies often develop and become applied through experiments and demonstrations (E&Ds) that serve as first steps in sustainable energy technologies' production, consumption, and commercialization [3–5]. These E&Ds can be defined as settings wherein stakeholders like governmental bodies, academia, commercial firms, NGOs, customers, and societal groups cooperate to further experiment, test, understand, design, use, and improve new sustainable energy technologies before they may grow large and can be commercially exploited [6–12]. Examples of industrial sectors - and within these sectors, diverse stakeholders - implementing these sustainable energy technologies are construction, urban development, cleantech, retrofitting, transportation, automotive, production, agriculture, and maritime industrial sectors [13–15].

E&Ds are essential in developing, applying, and implementing new sustainable energy technologies in industry, market, and society. Over the past fifty years, the number of E&Ds for sustainable energy innovation has increased substantially, as has the research into the technological, organizational, market, and societal aspects of sustainable energy in E&Ds [7,13,16–18]. However, the research literature offers a fragmented collection of findings. A coherent overview of themes and insights regarding the transformative impact of innovative sustainable energy E&Ds on the sustainable energy systems from the past, present, and near future is lacking. The research in this study fills this knowledge gap by providing this overview. It advances the literature by yielding novel insights into the systemic function of E&Ds in the sustainable energy transition, insights necessary to increase sustainable energy E&Ds' impact on the speed and scale of the sustainable energy transition.

This research reports a Delphi study among 47 scientists researching E&Ds for sustainable energy innovation. It provides a succinct narrative of past and current research while also looking ahead by identifying avenues for future research in this field. Taking an E&D model that visualizes and describes basic concepts and relationships of the E&D process as a starting point, 47 scientists are asked to provide their past, current, and future insights about the 'E&Ds for new sustainable energy' phenomenon. In a Delphi study research design, all participating scientists provided core insights regarding the research question: *What is the situation regarding experiments and demonstrations (E&D) research for sustainable energy innovation, and what are the future themes and questions to be researched in this field?* The experts' insights are narrated in this study.

Following the approach above, this study touches upon various sustainable energy technologies as exemplary cases discussed by participating scientists, such as hydrogen and hydrogen fuel cells, photovoltaics (PV), carbon capture and storage (CCS), biofuels, electric vehicles (EVs), smart grids and microgrids, airborne wind power, energy storage, electrofuels, advanced heating ventilation, geothermal energy, energy saving windows, smart connectors, and hydropower [13,16]. The insights into the E&Ds that enable the development, application, and scale-up of these sustainable energy technologies in social, business, economic, governmental, market, and societal settings - consisting of various collaborating stakeholders - which contribute to avoiding and reducing environmental harm [13,16,18,19], provide input for a future research agenda in the field of E&Ds for sustainable energy innovation.

This study is structured as follows: Section 2 discusses the innovation management literature this research aims to contribute to and presents an E&D model that visualizes and describes E&Ds and the E&D process. It creates a starting point of shared vocabulary and understanding, supporting the 47 experts to start from a common conceptual framework. Section 3 presents the research design of the Delphi study that was conducted. Section 4 overviews past and current socio-technical research into E&Ds for sustainable energy innovation. Section 5 presents and discusses a future research agenda in the field of E&Ds for sustainable energy innovation. Section 6 closes off with the main conclusions of this study.

2. Literature on experiments and demonstrations in the sustainable energy innovation process

This section provides an overview of the innovation management literature streams in which E&Ds hold a position and function and to which this study aims to contribute. It then introduces the E&D model for sustainable energy innovation, which is a starting point for shared understanding and a conceptual framework in this study.

2.1. Experiments and demonstrations in various innovation literature streams

E&Ds and E&D processes are empirical phenomena in various innovation management literature streams (see Table 1), such as literature streams on sustainable energy experiments [7,13,16], adoption and diffusion of innovation [20–22], technology readiness level

Table 1
E&Ds in various innovation literature streams.

Literature stream	Basic principle	Function of E&Ds	Representative publications
Sustainable energy experiments	Engineering and design for innovative sustainable energy device development	E&Ds are test settings for sustainable energy innovations	[7,13,16]
Adoption and diffusion of innovations	Normal-distributed growth pattern of the use of innovations	E&Ds are settings that can ignite user acceptance and can become the starting point of market growth of innovations	[20–22]
Technology readiness levels	Nine levels of maturity in the development of science-based technological innovation	E&Ds are central in technology readiness levels (TRLs) 3, 4, 5, 6, and 7	[23–25]
Dynamic capabilities	Sensing, seizing, and reconfiguring capabilities of innovating organizations	E&Ds are used to develop prototypes of innovative products, services, and production and marketing processes	[26–28]
Stage-gating	Stage-by-stage path to develop innovative products, services, and processes	E&Ds are used to develop innovative products, services, and process specifications to create more certainty regarding market demand	[29–31]
The multi-level perspective	Innovation-based transitions as a three-level phenomenon consisting of niches, regimes, and landscapes	E&Ds and the innovations developed in them occur in market niches and can break out to become integrated into market/industrial/ societal regimes	[32–34]
Strategic niche management	Social dynamic processes leading to technological innovations breaking through from niches to regime levels	E&Ds enable the initiation and growth of social networks that support the growth of innovations	[35–37]
National systems of innovation	A government-academia-business triangle collaboration for innovation	E&Ds facilitate government-academia-business collaboration for nation-wide innovation	[38–40]
Technological innovation systems	Dynamics between functions in a nation that contribute to and drive technological and societal innovation	E&Ds facilitate collaborative learning processes for the development of innovative combinations of technologies and markets	[41–43]
Transition management	Society, government, industry, and markets collectively transform towards innovative forms of sustainable production and consumption	E&Ds result in social and technical innovations and transition paths	[44–46]

methodology [23–25], dynamic capabilities theory [26–28], the stage-gating model [29–31], the multi-level perspective [32–34], strategic niche management [35–37], national systems of innovation [38–40], technical systems of innovation [41–43], and transition management [44–46]. Although these literature streams vary in basic principles (see Table 1, second column), they have in common that E&Ds are the empirical settings where innovations are experimented with, innovations are technically developed, attention and recognition for innovations are generated among various stakeholder groups, and which act as drivers for further application, use, adaptation and scaling up of innovations (see Table 1, third column).

Although E&Ds are central to these innovation management literature streams, relatively little research is conducted into the nature, content, processes, organization, and strategy concerning E&Ds in the field of E&Ds for sustainable energy innovation [13,16–18]. In these theoretical streams, E&Ds are central as an empirical organizational form or instrument that facilitates innovation and can and should be used for that purpose [7,13,16,20–46]. However, in these literature streams, there is little theorization and empirical research into the form, function, and nature of E&Ds and the interrelationships between different E&Ds, for example, where different sustainable energy forms are developed, which are in different phases of development, are set up in different geographical areas, and where different stakeholders with different interests are involved [13,16–18]. Nevertheless, since E&Ds form the link between R&D and market and societal applications of innovations, which requires much time, attention, resources, knowledge, and stakeholder commitment, more knowledge and insight into E&Ds is crucial [3–5,7,11–18]. Based on different studies from various sub-fields of innovation management, this study contributes to the needed insights on E&Ds and their role in developing and scaling sustainable energy technologies, resulting in a comprehensive overview of research themes and insights that provide the basis for future research in this area.

2.2. *The experiment and demonstration process model*

The process model in the upper part of Fig. 1 outlines the development of innovative sustainable energy technologies in E&Ds. The model provides insights into the courses, sequences, iterations, versatility, multiplicity, and complexity of sustainable energy development processes in E&Ds. It provides a starting point for shared vocabulary and understanding.

2.2.1. *The experiment and demonstration process that follows research and development projects*

E&Ds follow up on inventions made in research and development (R&D) projects [5,47,48]. R&D projects mark the invention phase; in the upper part of Fig. 1 on the left side of the figure. New sustainable energy technologies are discovered and developed in various sequential and parallel R&D projects. This basic and initial applied R&D is mainly done by publicly funded and administered university researchers and concentrates on concept development and testing [49,50], which aims to transform 'hypothesized energy phenomena' into 'proof of concepts' into 'applicable sustainable energy options.' The R&D projects in this invention phase are often hidden from view and situated in one or more university laboratories [14,50,51].

2.2.2. *From technical to organizational experiments and demonstrations*

To transition from this invention phase to a product- and production development phase, 'open to the public E&Ds' are needed, whose characteristics are visualized in the upper part of Fig. 1, to the right of the invention phase [51–53]. In the product- and production process development phase, prototypical sustainable energy products- and production processes are developed based on the discoveries of sustainable energy technology and knowledge from the invention phase. First, prototypes of sustainable energy technology products and the

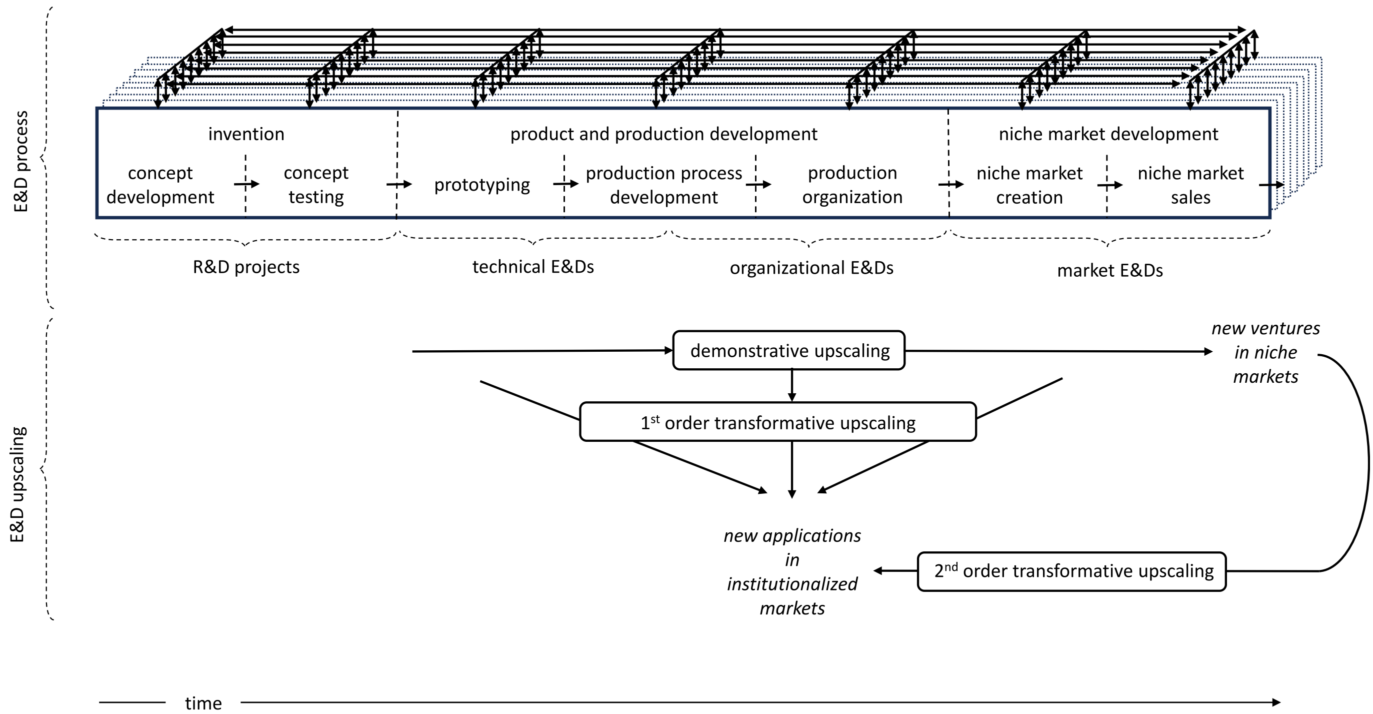

Fig. 1. The E&D process model for sustainable energy innovation [13,16–18], adapted].

production processes that can produce these prototypes on a larger scale are being developed. This is primarily done by collaborating public university laboratories and private corporate laboratories. Second, the prototypical production- and logistics processes are built to enable the production and delivery of the first commercial versions of the sustainable energy product prototypes. Third, the organizational facilities and arrangements are created to produce the commercial versions of the sustainable energy prototypes in increasingly larger quantities [7,9,51]. Halfway through this trajectory, the focus shifts from prototypical sustainability energy product development to prototypical sustainable energy production process and organization development. The first half of the process occurs in technical E&Ds and the second in organizational E&Ds, which are visualized on the right side of the technical E&Ds in the upper part of Fig. 1 [14,54–56]. This first and second half of the process are done by collaborating public universities and private companies, successively in university and firm laboratories and at physical production sites. The physical shift from university laboratories to corporate laboratories to production sites goes hand in hand with a gradual takeover of the leadership of the innovation process from public universities to commercial companies [15,57,58].

2.2.3. *From organizational to market experiments and demonstrations*

When both technical and organizational E&Ds have led to manufacturable and organizable new sustainable energy products, the moment comes when niche markets are explored. How sustainable energy products are put on the market is experimented with and demonstrated in market E&Ds; in the upper part of Fig. 1, this is the phase on the right side of the rectangle. The niche market development phase creates and grows a new market and focuses on developing the processes for commercialization and social embedding of new sustainable energy products in the market- and social niches [5,59–67]. In this phase, cooperating private companies – with decreasing involvement of public universities – organize and lead the sales, delivery, and after-sales service of sustainable energy products and accompanying services, all happening in the marketplace [15,58,68,69].

2.2.4. *Versatility, multiplicity, and complexity of the experiment and demonstration processes*

The model visualizes and describes an ideal-typical organization and forward flow of the E&D process. However, in practice, attention to other E&D aspects in a specific E&D phase is also possible and often present. Technical E&Ds, for example, pay explicit attention to the new sustainable energy technology but often also to the organizational and market aspects of the technology under development. The same applies to organizational and market E&Ds, of which organizational E&Ds may also pay attention to technical and market aspects and market E&Ds to technical and organizational aspects [70–72]. Furthermore, the E&D process shows an ideal-typical sequential progression. However, this does not imply that such progression is a golden standard or an all-covering representation of the intricate processes that sustainable energy technologies go through. Many variations in sustainable energy technology development are conceivable, demonstrable, and current practice, dependent on predictable but also on many unpredictable factors as many different stakeholders participate in or influence the course of events in E&Ds from their environment. Examples of variable events include setting up and running various E&Ds simultaneously, visualized in the upper part of Fig. 1 by the multiple ‘R&D-to-market’ dotted-line rectangles behind the ‘R&D-to-market’ rectangle in the forefront. Another variation is that collaborating innovating stakeholders go back and forth between the different types of E&Ds, i.e., iterative feedback and feedforward loops, within a given R&D-to-market trajectory and between different R&D-to-market trajectories, visualized in the upper part of Fig. 1 by the double-sided arrows going in and out of the (sub-)rectangles in the foreground and the dotted (sub-)rectangles behind it [18,73,74]. The E&D process model provides insights into the specific functions and types of E&Ds, their ideal-typical flow, the iterative feedback and feedforward relationships, and the multiplicity of the processes, emphasizing the versatile and complex characteristics of the E&D trajectory.

2.3. *Upscaling the outcomes from experiments and demonstrations*

The first outcome of collaborating universities and commercial firms that goes through these E&D processes - often supported by governmental subsidies, favorable or flexible regulations, and governmental policy - is first-generation technology development in a niche market [64,75–80]. Iteratively, going through the three types of E&Ds several times in multiple trajectories brings improved generations of technology to a niche market [49,50,70,72,81,82]. Endurance is necessary because sustainable energy technological innovation involves a long trajectory, requiring several years for first-generation technology and market development and several decades for follow-up generation technology and market development and upscaling [14,70–72,81–89]. Within and from these E&Ds, three primary forms of upscaling and growth can be distinguished: demonstrative upscaling, first-order transformative upscaling, and second-order transformative upscaling [18], visualized by the arrows in the lower part of Fig. 1.

2.3.1. *Demonstrative upscaling*

By organizing and completing technical, organizational, and market E&Ds, industrial actors and public and private partners create, develop, and improve sustainable energy products, services, production processes, and logistical processes, creating and serving small niche markets. By this, the organizations participating in these sustainable energy E&Ds develop new ventures and niche markets that did not yet exist [90–93]. The new ventures serve small niche markets, and this combination of venture creation, niche market development, and small market growth can be called demonstrative upscaling [18].

2.3.2. *First-order transformative upscaling*

In the meantime, the organizations that participate in the three types of sustainable energy E&Ds explore which newly developed sub-products or sub-processes they can immediately apply, preferably cost-neutral or as quality improvements, in their already existing, standardized production and service processes outside the sustainable energy E&Ds. This means that innovative sustainable energy sub-products, −services, or -processes from E&Ds can sometimes be transferred and integrated into existing industrial products, services, and processes of the firms participating in E&Ds [90,92–96]. This first-order transformative upscaling is characterized by a large, substantial scale of scaling up, leading to changes in existing, standardized production and consumption systems, patterns, and institutions [18].

2.3.3. *Second-order transformative upscaling*

Finally, when the small ventures and niche markets created by demonstrative upscaling continue to grow, they become more independent and autonomous, and this growth leads to the transformation of the small ventures and niche markets into large sustainable energy companies and markets [90–92], there is additionally transformative upscaling of a second order. In second-order transformative upscaling, the new ventures and niche markets that result from the demonstrative upscaling process grow large and develop and transform into new dominant and institutionalized sustainable energy companies [97], providing unique products and services to new large and dominant markets, which also drive stakeholders (e.g. suppliers, customers, competitors, and investors), patterns and institutions (e.g. production and consumption routines, regulations, client habits, and competitive dynamics) in the environments with which they interact to change [18].

2.3.4. *Time horizons*

The average time for technologies to develop from initial versions, when R&D and the first technical E&Ds have been completed, into versions that become established and upscaled in markets is often two decades or more [17,81–84,98,99]. Bento and Wilson [98] analyzed sixteen technologies retrospectively and found an average time of twenty-two years for these technologies to develop into dominant designs. In line with this, it is reported that the time for sustainable energy technologies, such as carbon capture and storage (CCS) [84] and biogas [99], to develop via upscaling from E&Ds into one of the potentially dominant technologies in traditional markets, takes twenty-five years or more [17,81–84,99]. Gibbins and Chalmers [83] stress that for CCS, the time between the development of the first production plants, leading to a second tranche of more user-oriented production plants, followed by a third stream of fully commercial production plants, is at least ten to fifteen years, and often takes much longer. Haszeldine [84] goes far beyond this and concludes that ten to fifteen years would not lead to fully developed and improved CCS technology. For CCS technology to completely mature, Haszeldine [84] substantiates and exemplifies that at least five partially sequential and partially parallel demonstration tranches are needed. This makes the period in which the CCS technology is improved, matured, and made cost-effective twenty-five years or longer. Junginger et al. [99] report a sort-like period of biogas E&Ds inside and outside Sweden. Within a basic structure of several subsequent and parallel tranches of demonstration projects, Junginger et al. [99] report that learning takes place in three systems: one for the building and infrastructure of the biomass plant, one for the operation of the plant; and one for the efficiency improvement of the plant. It takes considerable time to build and operate production facilities and learn from them via feedback and -forward loops. Junginger et al.'s [99] research focused only on the building and functioning of the plant, not the establishment and institutionalization of an emerging market. If large-scale and transformative scaling-up in the market is also considered, a period of twenty-five years can be regarded as short and can last much longer, up to fifty years [98,100]. To paint an even broader picture, for example, after the discovery of the photovoltaic effect in 1839, it took 115 years of R&D to make the first efficient solar cell, and then fifty years of E&Ds to deploy 3 GW of production capacity worldwide [101]. Almost two centuries later, there has been large-scale upscaling and acceptance of this technology, with still lots of efficiency and effectiveness improvements ahead [102–105].

3. Delphi study methodology and methods

The research in this study is based on the Delphi methodology and consists of two survey rounds.

3.1. *Delphi study*

This research is based on a Delphi study among 47 expert scientists who all research E&Ds for sustainable energy innovation [106,107]. Starting from the E&D process model, which visualizes and describes basic concepts and relationships of the E&D process and serves as a shared starting point of vocabulary and understanding regarding the 'E&Ds for new sustainable energy' phenomenon, all participating experts provided core insights regarding past and current research and research to be carried out in the (near) future, i.e., a research agenda.

The Delphi method is a frequently applied methodological basis for conducting surveys among scientific experts to provide an overview of a research field and formulate a research agenda in emerging research fields. It focuses on expert consensus through two or more rounds of surveys. Key features of the Delphi method used in this study include the anonymity of the participating scholarly experts during the research process to reduce the influence of dominant individuals, two rounds of surveys with controlled feedback after each round, and aggregation of the expert opinions using numerical summaries [106,107].

The anonymity of the participating experts during the Delphi study process was guaranteed by inviting all experts separately and communicating with them separately during both Delphi rounds. Not earlier than when the Delphi study was closed, all experts were informed of each other's participation. The Delphi study's timeframe is given in Table 2.

3.2. *Round one*

In the first round, a team of three researchers in E&Ds for sustainable

Table 2
Delphi study timeframe.

Activity	Date
Approached 69 experts	16-01-2024
Commitment to participate received from 47 experts	15-02-2024
Sent E&D model and open questions to 47 experts	22-02-2024
Received contributions from 47 experts to question 1 and from 46 experts to question 2	16-04-2024
First version of categorized, edited, and narrated document produced by researcher 1	17-05-2024
Second version of document, based on input from researcher 2, written by researchers 1 and 2	23-05-2024
Third version of document, based on input from researcher 3, written by researchers 1, 2, and 3	01-06-2024
Third version sent to 47 experts	05-06-2024
Amendments received from 47 experts and integrated in final document	21-06-2024
Final document ready and agreed by all three researchers and 47 experts	08-07-2024

energy innovation approached 69 scholarly experts for participation. The experts were sought by identifying frequently cited authors in the reference lists of three recent review articles on E&Ds for sustainable energy innovation [16–18] and approaching a number of those still working in the field at the time of the research. 47 experts accepted the invitation, ranging from two starting researchers in the field, 21 significant scientists with 1 to 5 Scimago Q1-publications in the E&D field, 10 influential scientists with 6 to 15 Scimago Q1-publications in the E&D field, and 14 very influential scientists with 16 or more Scimago Q1-publications in the E&Ds for sustainable energy innovation field. The researchers accounted for 673 Scimago Q1 publications in the field, averaging 14 publications per expert. All participating experts' research is at the interface between natural and social energy science, with 14 experts having a stronger focus on the design, engineering, and technological aspects of sustainable energy innovation and 33 experts focusing relatively more on the social science aspects of sustainable energy innovation and transition. Table 3 gives an overview of the dominant journal sources of the literature they refer to in this study, including journals that are referred to twice or more.

Table 3
Dominant journal sources.

Journal title	# References
Energy policy	18
Energy Research & Social Science	15
Journal of Cleaner Production	14
Environmental Innovation and Societal Transitions	13
Research Policy	9
Renewable and Sustainable Energy Reviews	9
Sustainability	8
Technology Analysis & Strategic Management	6
Energies	4
Renewable Energy	4
Technological Forecasting & Social Change	3
Sustainable Energy Technologies and Assessments	3
Technology Innovation Management Review	2
Science	2
Business Strategy and the Environment	2
Industrial Marketing Management	2
Clean Technologies and Environmental Policy	2
Journal of Environmental Policy & Planning	2
Cities	2
Industry and Innovation	2
Applied Energy	2
Nature Energy	2
European Planning Studies	2
One Earth	2
Political Geography	2

To provide a common starting point and conceptual framework, the participating scientific experts were provided with a document describing and visualizing the E&D process model as presented in Section 2. They were asked to respond to an open question by e-mail. The central question they were asked to reflect on was:

(a) What is the situation regarding experiments and demonstrations (E&D) research for sustainable energy innovation, and (b) what are the future themes and questions to be researched in this field?

Regarding the first part of the question, the experts were asked to describe in 200–500 words the current research situation regarding E&Ds for sustainable energy innovation and to refer to scientific research and examples that support this insight. This resulted in contributions from 47 participants, totaling 16,000 words. Regarding the second part of the question, all experts were asked to describe in 200–500 words the important research lines that should be part of a future research agenda regarding E&Ds for sustainable energy innovation, supported by references to scientific research. This resulted in contributions from 46 participants, totaling 12,500 words.

The participating experts were given the space to choose their focus, with the freedom to choose from a wide array of applicable sustainable energy technologies for E&Ds, an extensive collection of empirical domains in which these technologies are applied, and an extensive collection of stakeholders that influence the application of these technologies in these empirical domains. For an exemplary and non-exhaustive overview of E&D elements and aspects they could freely choose from, see Table 4.

The answers to the two parts of the question have a broad character, given the experts' freedom of choice in focusing on specific sustainable energy technologies, application domains, and stakeholders involved. The overviews of their answers can, therefore, be seen as indicative and guiding, not as prescriptive and directive.

3.3. Round two

In the second round, two researchers from a team of three simultaneously and independently from each other classified labels for the contributions received for both questions. One of the two researchers also summarized the texts within each label and transferred the labels and associated text summaries to the second researcher, who evaluated the labels and texts and proposed changes to the first researcher. Changes were implemented after a discussion and after a consensus was reached. The resulting document was then forwarded to the third researcher, who made a check based on the original submissions and proposed additional changes. These were implemented after a discussion with the team of three and after reaching a consensus.

This resulted in a document with three themes and seven sub-themes concerning the first part of the question and a document with 19 avenues for future research for the second part of the question. Both resulting texts were then sent to the 47 participating scholarly experts, requesting to indicate inaccuracies, errors, and improvements and whether they agreed or disagreed with the text's content. The team of three researchers implemented the additions, changes, and improvements that the experts indicated. All participating experts consented to the final document being the outcome of the Delphi study and agreed to be co-authors of the final document.

4. Results: Insights from past and current E&D research

As a research theme, E&Ds for sustainable energy have been on the research agenda for fifty years [13,16–18]. Attention to it has grown each year, and E&Ds are now a well-known and accepted research theme within the research field regarding the strategy and organization of sustainable energy innovation and transition. This section discusses three central themes that have played a leading role in research in recent years and today, distinguishing seven sub-themes. The themes and

Table 4
E&D elements and aspects.

Key E&D element or aspect	Type	Representative references
Sustainable energy technology	Hydrogen and hydrogen fuel cells Photovoltaics (PV) Carbon capture and storage (CCS) Biofuels Electric vehicles (EVs) Smart- and microgrids Airborne wind power Energy storage Electrofuels Advanced heating ventilation Geothermal energy Energy saving windows Smart connectors Hydropower	[7,13,16]
Empirical domain	Construction Urban development Cleantech Retrofitting Transportation Automotive Production Agriculture Maritime	[13–15]
Stakeholder	Customers Users Factories Governments Universities Knowledge centers NGOs Industry Capital investors Politicians Energy communities Suppliers Media Shareholders Employees Interest groups Lobbyists Banks	[7,13,16]

subthemes, including the number of experts that mentioned them and representative references, are presented in Table 5 and elaborated in the sections below.

4.1. Sustainable energy technology portfolios and missions

It is relevant to focus on portfolios containing multiple sustainable energy technologies and establish varied E&D programs. Well-thought-out missions can underpin these portfolios and programs.

4.1.1. Creating resilient sustainable energy technology portfolios: investments in economy, technology, governance, and people

Investments in economics, technology, governance, and people in E&Ds may remain necessary for further development and upscaling sustainable energy technology portfolios. E&Ds have a dual purpose: to promote continued sustainable energy portfolio innovation and to scale up. Both goals can be pursued. In the ambition to rapidly scale up and integrate portfolios with new sustainable energy technologies to address grand societal challenges, stakeholders may be at risk of locking themselves into specific low-carbon pathways [81,118]. While upscaling may remain essential to achieving climate targets, there is also a risk that a new sustainable energy portfolio is not resilient to future developments [110]. This means it is advisable to continue experimenting and demonstrating new and emerging sustainable energy technologies without compromising the already successful upscaling measures [54].

Economic and technical investments are needed in existing scaled-up sustainable energy technology and subsequent newer generations of sustainable energy technology. For example, regarding PV cells, in recent decades, economies of scale and technological innovations have significantly reduced the cost of silicon-based PV cells, making solar electricity competitive with conventional fossil fuel-based electricity. However, these silicon-based PV cells have reached their efficiency limit of around 27 % [119,120]. This limit arises from the spectral width of the solar spectrum, consisting of UV, visible, and infrared radiation that cannot be converted effectively by a single absorber material. Significant conversion efficiencies can be obtained using multi-junction technologies, incorporating different PV materials tailored to various parts of the solar spectrum. In this respect, metal halide perovskites have emerged as a promising new class of low-cost PV materials [121]. Under standard test conditions, this perovskite/silicon tandem type has already demonstrated 34 % efficiency at the laboratory scale. Other examples of technologies in an initial phase that need further E&D investments to develop and possibly scale up are low-carbon fuels like advanced biofuels and carbon-neutral synthetic fuels (or electrofuels), negative emissions technologies, and carbon dioxides removal options like bioenergy with carbon capture and storage or enhanced weathering [122].

In addition to a specific focus on the energy sector, E&Ds can also focus on related sectors. Attention is needed for E&Ds in industrial sectors with high energy use, such as the construction industry as a significant energy consumer during construction and use of buildings and construction materials with high embodied energy [62,69]. For example, switchable electrochromic films are being developed to increase the energy-saving capacity of windows and glass facades of existing buildings [123] and are being made ready for organizational demonstrations at existing buildings. Other construction-oriented examples of sustainable energy technologies currently being experimented with are deep geothermal energy and high-temperature aquifer thermal energy storage. Deep geothermal energy involves tapping into deep geothermal reservoirs to extract thermal energy for building use, currently in a demonstration phase at Delft University of Technology [124]. It includes a high-temperature aquifer thermal energy storage system that addresses seasonal fluctuations in thermal energy demand

Table 5
E&D research themes.

Theme	# Experts	Subtheme	# Experts	Representative references
Sustainable energy technology portfolios and missions	26	Creating resilient sustainable energy technology portfolios: investments in economy, technology, governance, and people	22	[11,87,108–110]
		Becoming multi-mission-oriented	10	
Experiments and demonstrations as inherent instruments for learning and market formation	34	Continuous experimentation and demonstration	10	[7,11,12,48,60,72,87,95,111,112]
		Remaining focused on knowledge transfer and joint learning: bottlenecks	18	
		Putting market formation central	27	
Concentrating transformative upscaling on new cross-sectoral systems and institutions	30	Building cross-sectoral systems	26	[109,113–117]
		Focusing on institutional change	11	

by storing excess thermal energy in underground aquifers during periods of low demand in the connected buildings [125]. Furthermore, being in the era of data and thanks to computational power improvements, various innovative ideas have emerged in designing, modeling, and controlling advanced energy systems, giving rise to the concept of smart buildings or, more generally, smart energy systems. Various experimental buildings with connected thermal storage options have been employed to evaluate and demonstrate the efficacy of advanced predictive and data-driven building energy management methods [126–128].

However, in addition to these technological developments, social dynamics can also be explored to advance the resilience of sustainable energy technology initiatives [129,130]. A recent study exploring the emergence, development and deployment of electric vehicles (EVs) focused on how governance regimes, e.g., a blend of local and national policies implemented over three decades and aimed at both industrial growth and vehicle demand growth, played a role in this evolution. This study also underscores the significance of advocacy groups and robust neighborhood networks in advancing EVs, along with shifts in consumer preferences [131]. It illustrates how the spread of EVs and their consequent societal uptake has been propelled by the synchronization of numerous processes at various levels. This involves interactions among diverse actors and social groups, each with distinct interests and visions of the future.

This is just a selection of current options, exemplary of a more extensive reservoir of options that need further development to create a flexible and resilient sustainable energy technology portfolio that can meet a voluminous energy demand under varying circumstances.

4.1.2. Becoming multi-mission-oriented

A mission-based approach to societal issues, in which governments implement an intended change based on policy, regulation, and stimulation to inspire and guide creativity and experiments from the practical field [132], also applies to the CO_2 reduction problem. The European Union has launched several missions regarding carbon reduction, as many countries have. However, E&Ds may not just be about carbon management but can include multiple aspects of sustainability in its mission. While the development of sustainable energy technology still has a substantive way to go, the question arises as to whether this single societal mission is sufficient to prevent and solve sustainability problems. As time passes, E&Ds for sustainable energy can become increasingly multi-mission driven, where multiple urgent strategic goals that require transformative systems change for sustainable development are combined [133]. In the Netherlands, for example, after many years of R&D and navigating through various phases of E&Ds, current renewable energy technologies such as wind, solar, and EV batteries have successfully penetrated the energy market. Even though these energy technologies have rapidly developed under the thorough support of the first mission for electrification, the question arose about how circularity criteria as a second and complementary mission can be integrated into the design of these technologies and how circularity strategies can be applied to minimize waste during the decommissioning of wind parks, batteries, or solar panels [134,135]. Circularity challenges like waste management, resource scarcity, and supply uncertainty have remained under-addressed and now pose significant threats to the energy system. This, for example, implies a critical role for experimentation and demonstration of life cycle assessment methodologies in identifying environmental impacts throughout the lifecycle of sustainable energy innovations, from production to end-of-life disposal [136]. It can be expected that a multi-mission approach will raise new questions and issues over time and lead to the inclusion of additional missions, such as justice in energy distribution, regulation of energy-consuming artificial intelligence (AI) and blockchain technology, reduction of virgin material use, and geopolitical aspects of the global energy market.

In this context of the higher complexity of the energy sustainability issue as merely carbon management, in a multi-mission approach, the question can be raised of how many E&Ds are needed to make different technologies viable to develop a resilient, sustainable energy technology portfolio [137,138]. This question is central to initial research into the required number of E&Ds for carbon dioxide removal technology, using fitted logistic growth curves [139] and large datasets of previous technologies developed in E&Ds [139]. An important issue related to this is the costs of integrating these new technologies from the moment they are ready to scale up within existing and new infrastructures. These integration costs, which can significantly increase the overall system cost, are a critical factor often missed in traditional cost calculations and grid parity assessments for, for example, PV technologies. Research indicates that integration costs represent approximately 15 % of the total PV system costs, a substantial component that cannot be ignored as PV technology scales up [103].

4.2. Experiments and demonstrations as inherent instruments for learning and market formation

E&Ds may be continuously needed to develop and scale up new sustainable energy technology, continue to learn its new possibilities, put what has been learned into practice, and create new supply and demand markets.

4.2.1. Continuous experimentation and demonstration

A continuous flow of E&Ds remains necessary to continue developing, testing, and demonstrating innovations, learning from them, and scaling up a number of them demonstratively and transformatively. Although transformative upscaling of sustainable energy technology is an important objective of E&D strategies in many industrialized countries, the dynamics of E&Ds, demonstrative applications, and small niche upscaling are also valuable. It requires participants who can jointly manage the E&Ds in which they collaborate, based on the principle that the experiment or demonstration can already be the aimed-for result [140–142]. Continuous experimentation and demonstration creates a growing reservoir of sustainable energy technologies, application options, and experience with these options and possibilities [143]. Experimentation and demonstration do not always aim to scale up transformatively but can be used to focus on monitoring, feedback processes, and reflexivity within the experimental or demonstrative setting [141,144]. The positive energy district (PED) is an example of such a setting, i.e., an area of buildings with zero carbon emissions and a surplus of sustainable energy production. PEDs are adding complexity with their district-level approach to energy positiveness, the smartness and governance needed to exchange energy [145,146], and its citizen's orientation [147]. The relatively large scale makes them suitable E&Ds to which experimental governance is applied. The European Union aims to have 100 PEDs in 2025, but with currently three in operation, the PED is still in the early E&D phase [148].

4.2.2. Remaining focused on knowledge transfer and joint learning: bottlenecks

An important goal of E&Ds is that participants can learn from it. This learning aspect may be actively stimulated and promoted while recognizing and removing bottlenecks. Tying E&Ds to real customers, prices, and even competition can provide an important channel for learning, even if those markets are small, nascent, and protected [72,87]. However, regarding learning effects, it is often mainly the participants in E&Ds who gather knowledge and learn [94]. As a practical example, Neste, as a pioneer company, developed its next-generation biofuel technology in-house, prototyped it with its own voluntary employees, and verified it with third-party evaluators. These measures were necessary for accumulating sufficient proof of safety and efficiency for regulators as a precondition for commercializing Neste's first next-generation fuel products [95,149]. The Neste case illustrates that the transfer of knowledge and learning experiences can be limited to the participants included and is influenced by their interaction and applicable rules and regulations. New ways of collaboration, for example, reconsidering the various stakeholders involved, collaborative forms used, and regulations applied, can be developed to actively overcome knowledge transfer hurdles and create new and open learning contexts.

Self-interest of E&D participants can have an inhibiting affect on the exchange of knowledge and experience, and mergers of interest are often far away [150,151]. For example, Evers and Chappin [60] found that knowledge sharing mainly occurs at the E&D-project level and not so much between E&D projects. Moreover, the same actors tend to populate consecutive E&Ds, and they are repeatedly involved in follow-up projects [60], which makes it difficult for knowledge and experience to flow to organizations outside E&Ds. Furthermore, when knowledge transfer and learning experiences occur, there are often many failure moments and delays. This is one of the causes of the substantial time for new sustainable energy technology to develop via E&Ds to become established and upscaled on the market, which can be 25 years or longer [17,81–84,99]. Another key reason behind such long timeframes is technology transfer challenges among partners in scaling sustainable technology. In practice, industrial projects to scale new sustainable energy technology often require collaboration between high-tech firms - such as providers of specialized process equipment - and low-tech firms - such as firms needing novel technological applications, e.g., hydrogen, biofuels, or electricity to decarbonize. These two types of firms have vastly different knowledge bases and learning approaches, making collaboration and technology transfer challenging [108,112].

4.2.3. Putting market formation central

It is relevant to open the black box of market formation further and explore the elements and dynamics of markets that relate to the processes and outcomes of E&Ds [152–155]. Salient elements of market formation include user preferences and practices, regulations, governance and business models, and exchange infrastructures. Market dynamics are created by various stakeholders [156], ranging from companies and governmental and academic organizations to communities, citizens, and user groups.

Market formation has both a supply and a demand side. Mechanisms through which E&Ds contribute to market formation for the use and upscaling of sustainable energy technology by reducing supply and demand uncertainties are, on the supply side, that E&Ds help build credibility for the technology, enable learning, and facilitate the orchestration of the business ecosystem around sustainable energy technology [11]. These mechanisms allow sustainable energy technology actors to mitigate the perceived unpredictability of their endeavors and develop capabilities to position novel technologies in new market segments. On the demand side, E&Ds contribute to sustainable energy technology standardization, constructing the narrative and creating legitimacy for the new technology, thereby mitigating the unpredictability of customer preferences and the cognitive recognition of a novel technology or its by-product's value in a new market segment [11].

E&Ds can benefit from investments that establish and maintain a basic infrastructure. The importance of continuity and deep pockets is essential in market formation. E&Ds are preferably set up and continued in coherent programs so that basic investments in experimenting and demonstrating do not have to be made repeatedly [11]. Combining public and private funding can be of great value, especially if a publicly available and open research infrastructure that covers its operating costs can be created. Low fixed costs associated with experimentation allow for continuous experimentation with, for example, different fuels and accessing different "slipstreams" to conduct further experimentation without additional costs for creating the basic E&D infrastructure. In previous research, examples of such set-ups originated in Austria, with TU-Vienna experimenting with new and emerging biofuels based on a commercially operating gasification plant [157]; in Sweden by the company Chemrec setting up an infrastructure for black liquor gasification [115] and by Chalmers University of Technology experimenting with gasification for various applications based on a combined heat and power plant [114].

Following or alongside the basic infrastructure and the technical E&Ds building on it, organizational and market E&Ds can be set up to advance these technologies [16], for example, in next-generation biofuels. Because of their high applicability in the existing business and consumer fuel markets and infrastructure, a rise in E&Ds for next-generation biofuels is happening that utilize novel technologies to convert vegetable oils, animal fats, and waste and residue into energy. These biofuel E&Ds evolve in long-term processes to build market E&Ds and eventually profitable businesses [95,149]. Here, technical E&Ds are dynamically advanced in interaction with the organizational and market E&Ds to bring next-generation biofuels to the market: the novel technology allows fuel providers to innovate novel business models for, e.g., transportation and aviation markets and renew their business strategies and supply networks in alignment with the expectations of the market and society [95,158].

In these market formation processes, entrepreneurs and entrepreneurship are central. Entrepreneurs can use their freedom from existing markets and patterns to develop groundbreaking innovations for societal challenges [159,160]. For example, Palmié et al. [161] found that entrepreneurs' startup firms develop more radical business models in the energy sector than their incumbent counterparts. Furthermore, creating and growing a start-up can be seen as an iterative series of experiments from which entrepreneurs continuously learn and adapt their business model [162,163]. At relatively low costs, they can demonstrate to society which technologies and associated business models might work and which might not [162]. The experimental character of the start-ups and the radical nature of their innovation increases the number of technological alternatives in the sector, which can help prevent society from becoming too dependent on a single solution [164,165]. Moreover, start-ups can and are incentivized to explore solutions for niche markets or specific user groups [166] that are too specific for incumbent firms with a vested interest [167].

4.3. Concentrating transformative upscaling on new cross-sectoral systems and institutions

E&Ds can lead to the creation of collaboration forms that transcend organizations and sectors and introduce new institutions that normalize sustainable energy technology.

4.3.1. Building cross-sectoral systems

Key challenges for E&Ds can lie in developing sustainable energy technologies that work in a broader system, considering integration and interaction across industrial sectors. Policy support for E&Ds can focus on creating a rich and heterogeneous structure from which new "system builders" and strong industrial alliances can emerge [114,115]. New sustainable energy innovations in E&Ds can also be aligned with user environments. Stakeholders choosing and combining smart energy technologies may consider the local context and the residents' requirements. This involves identifying the science, technology, business, and market infrastructure created by E&Ds and who can continue to learn from it [109,168].

An example of such system building is the power-to-X concept, where green electrons are converted via electrolysis into hydrogen and derivates such as ammonia, methanol, or electrofuels [169]. Further conversion involves combining hydrogen with nitrogen from the air to produce ammonia or carbon dioxide from the air, biogas, or captured from different stationary sources. This concept enables cross-sectoral integration by offering options for the green transition of the transport sector. It provides links with the heat sector by integrating waste heat streams [79] or utilizing other byproducts such as oxygen. An integrated part of the fuel production is the water supply for hydrogen production, which can be challenging to access in areas where renewable solar energy is relatively cheap, but water is scarce, such as Australia, the

Sahara, or Patagonia [170]. Water can also be sourced from wastewater streams via desalination or regular water supply. As the water needs to be pure, it requires treatment that allows its utilization in the electrolysis units. Waste heat streams from power-to-X processes can be utilized in district heating networks [171]. Oxygen is a valuable by-product used for various purposes, such as in water treatment plants [172] or oxyfuel combustion and carbon capture [173].

Vehicle-to-grid is another example of cross-sectoral sustainable energy technology in the experimental phase. Storing electricity in batteries of electric cars can play an important role in a future electricity grid based on intermittent renewables such as solar and wind [174]. However, experiments that cross sectors can be complicated because transitions in different sectors are often out-of-sync. For example, the transition towards renewables has progressed considerably further in electricity production compared to mobility. A deep understanding of sectoral developments outside of energy is required for experimentation. For example, Meelen et al. [175] report how vehicle-to-grid experiments in the United Kingdom are fostered by developments in the fleet sector, such as increased use of telematics to track vehicles and a growing interest in EVs among fleet managers. On the other hand, the rise of small and medium-sized enterprises that only have a small number of vehicles complicates the upscaling of vehicle-to-grid experiments.

In the policy domain, coordination of cross-sectoral system building may need more attention [176]. The goal from a policy perspective differs from an entrepreneur's perspective, who is often in charge of developing E&Ds and focused on succeeding with their company and business model. The policy goal may create a supportive ecosystem for sustainable energy technology innovation in which several actors can utilize the created infrastructure, even if front-running projects and companies fail. At the same time, entrepreneurs will be focused on business viability, growth, and continuity [177].

E&Ds can also be used to align sectors and realize cross-sectoral sustainable energy innovations because they allow experimentation with technical and socially sustainable energy developments on a limited scale. A striking example of this is research conducted by Aalborg University, which observed energy innovation in the annual 'Into the Great Wide Open' festival on Vlieland Island, the Netherlands [178]. Several technologies first tested here approximately a decade ago have become significantly present in several markets. For instance, a smart hybrid system for the autonomous powering of music stages using sustainable energy – instead of diesel generators – is now a repeatedly applied technology [179]. Various companies, including those that originated as startups from 'Lab Vlieland', are now significant players in the Dutch market, providing additional deployable, sustainable energy as a temporary solution to the current shortages in electricity network capacity [178].

4.3.2. *Focusing on institutional change*

Social acceptance can be an essential factor in the further deployment of sustainable energy technology. Traditionally, many E&Ds are based on technocentric assumptions, sometimes even viewing people as obstacles to technological solutions. Technically oriented E&D participants may overlook the situational and psychological factors influencing social acceptance and institutionalization of sustainable energy innovations [117]. However, this perspective can be challenged, as numerous social aspects, outcomes, relationships, and prerequisites of transformational experimentation and transformative upscaling are part of the sustainable energy innovation mission developing in industry, politics, and society [129]. Scaling up is thus not just technologies being upscaled but also crystallizing in the form of changing social institutions more conducive to sustainable than non-sustainable energy. E&Ds can aid in establishing broader visions and expectations among various actors around technologies and how these are embedded in institutional societal structures and markets [37]. E&Ds can, for example, aid in establishing advocacy coalitions, legitimizing new technology, and, in doing so, change public opinion [113]. This can be direct and essential outcomes and effects of E&Ds and the efforts and strategies used by its partners. Indirectly, E&Ds can also be mobilized by external actors and networks when framing certain narratives and lobbying for technologies that E&Ds promote or demonstrate [160]. These processes can lead to institutional change [64] by creating shared expectations and affecting norms, values, regulations, and worldviews that create, uphold, or strengthen emerging technological and market niches [180] or align with existing institutions [12,181].

A development in this area is the emergence of energy communities, i.e., associations of citizens cooperating with other private and public actors aiming at energy system transformation through participatory and engaging processes while seeking collective outcomes [182]. Energy communities encourage social acceptance of sustainable energy technology and promote behavioral change towards using energy in more sustainable ways while keeping established cognitive and normative institutions among the population by which the technology is to be adopted in mind [183]. As such, these communities can serve as venues for sustainable energy niche market development. Energy communities are also increasingly recognized as having a distinct capacity to develop demand-side solutions by combining renewable energy installations, sensors, and information technology [183]. Related is the transformation of lead users and consumers into so-called producer-consumers or prosumers. These prosumers consume energy products and services and actively use them privately. For example, in the early 2000s, there was a low uptake of residential PV in Australia. However, this rapidly changed once financial support was introduced, including point-of-sale rebates and generous feed-in-tariffs [116,184,185]. This appeared to be critical for establishing a new operating framework for residential energy and creating energy prosumers who started to find and implement application possibilities for PV cells.

5. Discussion: Avenues for future research

Various research avenues for the future can be distinguished within the themes and subthemes of research into E&Ds for sustainable energy innovation. These are listed in Table 6, using the three central themes from the previous section, including the number of experts who mentioned them, and further elaborated in the sections below. In addition, a fourth row has been added to the table with a corresponding fourth sub-section to the text, addressing biases in current E&D research and opportunities to remove these biases in future research.

5.1. *Sustainable energy technology portfolios and missions*

Future research can focus on how E&Ds can contribute to creating resilient sustainable energy technology portfolios, with a balanced attention to social interests that can enable the adoption and diffusion of these technologies. Research can also pay attention to multi-missions in which the development of sustainable energy technology is integrated with one or more sustainability aspects.

5.1.1. *Socio-technical composition of sustainable energy portfolios*

Various implementation challenges exist in E&D programs, which need further research. These challenges to be studied predominantly concern the socio-technical composition of sustainable energy portfolio creation. Relevant questions to be answered are which E&D projects to select and how to deal with tradeoffs between public and private investing in a diverse portfolio of sustainable energy technologies [87]. The latter is challenging when governmental bureaucracies appear to be risk averse [186], despite the literature on innovation and E&Ds often clarifying that the public sector needs to take more risk and invest more resources to move technologies past the technology valley of death [187]. Similarly, researching when and under which conditions E&Ds should be planned to accommodate tests for multiple rival sustainable energy technologies or when it is more appropriate or feasible to construct E&Ds whose scope and purpose are narrower holds a

Table 6
Avenues for future E&D research.

Theme	Avenue for future E&D research	# Experts
Sustainable energy technology portfolios and missions	Socio-technical composition of sustainable energy technology portfolios	8
	Electrification-circularity missions	8
	Multi-missions whereby the 'Affordable Clean Energy' goal is complemented by other societal goals	7
Experiments and demonstrations as inherent instruments for learning and market formation	Local governments' new roles and responsibilities	7
	E&Ds as one-off examples and as subjects of upscaling	27
	How to measure learning within and across E&Ds	15
	Friction between learning goals and the participants' individual interests in E&Ds	10
	How to establish external validity for specific case study knowledge	9
	Actor roles that contribute to knowledge exchange and learning	9
Concentrating transformative upscaling on new cross-sectoral systems and institutions	Long-term impacts of E&Ds on market formation	21
	Transforming fossil energy technology companies	6
	Change dynamics in innovation ecosystems around E&Ds	11
	Integration of renewable energy sources across different energy sectors	8
	Economic aspects of cross-sectoral collaboration	6
	E&Ds function as instigators of drastic institutional change	10
	The effectiveness of energy communities	5
	Integrating a socio-institutional dimension into E&Ds	15
	A broader conceptualization of scaling	27
	The role of E&Ds in moving away from existing unsustainable energy institutions	10
Biases in E&Ds for sustainable energy innovation research	The most vulnerable in communities	9
	Geographical bias of E&Ds for sustainable energy innovation	6

promising avenue for future scientific inquiry.

Technological interrelatedness, which involves adopting complementary technologies to decrease uncertainty, is another important aspect of business ecosystem orchestration in the context of E&Ds [11,188]. Future studies can examine the factors influencing the selection and integration of complementary technologies in E&Ds and the challenges and opportunities associated with increasing technological interrelatedness. Research can also investigate how collaborations between core sustainable energy technology suppliers and complementary technology providers are formed and managed to reduce risks and enhance the overall performance of E&Ds. The role of complementary formation mechanisms in technology value chains can be further explored [108,189,190].

Integrating societal aspects and considering societal interests in E&Ds is vital for creating resilient, sustainable energy technology portfolios. For example, in smart community projects in Norway, the interests of citizens are at the center of the experiments and shape the structure of the smart energy technology applied, emphasizing the role of social impact in smart energy innovation [109,168]. Another example is a comparison of the case of Demo Lyse – located in Stavanger, Norway – and that of the HIKARI building – located in Lyon, France. The logic of designing a smart energy grid structure in both cases is the same: to provide a comfortable life for local citizens. However, the results of smart energy innovation are different, and their impact also differs given the situation that there are differences in stakeholders involved. Therefore, an integrative approach in E&D research and practice comes with challenges, as research and practical paradigms and languages differ among scientists, practitioners, and populations from different backgrounds [191]. To tackle these challenges, truly interdisciplinary E&D research and practice teams, combining and integrating technical, social, and societal aspects are needed, developing unequivocal paradigms and languages that are understood and mastered by researchers and practitioners from different backgrounds and disciplines [191] complemented by considerations of societal interests in projects of such transformative scale.

5.1.2. Electrification-circularity missions

The legitimacy and recognition of circularity's importance as a key mission in the energy transition is either lacking or insufficient to merit prioritization. Policies that merely address circularity may be perceived as barriers towards electrification, potentially facing significant resistance. However, policy approaches that address electrification and circularity can be more effective in mobilizing industrial sectors. In the long run, the absence of circularity as a mission that complements the electrification mission might severely hamper energy technologies due to their high dependency on critical resources. Future research can investigate electrification-circularity missions and explore how the suggested synergies between missions for electrification and circularity can be facilitated. In doing so, policymakers and policy-oriented researchers can investigate methods to improve the perceived importance of circularity for the energy system over time. For example, the rapid upscaling of solar PV, offshore wind, and EVs has led to a substantial increase in material waste, particularly electronic waste, impeding the goal of a circular economy [192–194]. The increasing demand for critical materials, such as lithium, cobalt, nickel, and platinum, compromises the protection of indigenous populations and the local environments from which these materials are extracted [195]. Countries that endorse the United Nations Declaration on the Rights of Indigenous Peoples and other commitments to human rights may find themselves at odds with their climate obligations; for example, cost shifts and 'Green Sacrifice Zones' contradicting a just transition [196,197]. E&D research can target efforts to make products more circular, require fewer resources, or use alternative materials. Exploring circular economy principles in designing, producing, and disposing of renewable energy infrastructures becomes increasingly important, reducing resource consumption, waste generation, and environmental impacts. For now, research has mainly addressed developing recycling methods for materials for solar panels, wind turbines, and batteries [198]. It is essential to have E&Ds that further explore design principles that prioritize durability, repairability, maintainability, refurbishment, upcycling, repurposing, and reusability in the development of renewable energy technologies [198,199] and are based on the green and blue cycles of biological and technical resources [200].

5.1.3. Multi-missions whereby the Affordable Clean Energy goal is complemented by other societal goals

While including circularity as a key mission, a considerable gap in understanding sustainable energy innovations' indirect and lifecycle impacts exists and needs to be covered. In addition, also the social, industrial, and societal changes that sustainable energy innovations ignite need more attention and call for an integrated appraisal of the economic, social, and environmental aspects of sustainability in energy transition strategies [201–203]. Ultimately, the sustainable development goal 'Affordable Sustainable Energy' is only one of the 17 sustainable development goals (SDGs) of the United Nations, and an integrated sustainable approach to sustainable energy also requires additional attention to other SDGs. Considering various missions and integrating them, this comprehensive perspective in future research results in multi-missions whereby the 'Affordable Clean Energy' SDG, for example, is complemented by two or more of the other 16 SDGs. This is crucial for crafting policies, strategies, business models, and practices that balance the triple bottom line of economic viability, social equity, and environmental stewardship in the transition to sustainable energy systems.

5.2. Experiments and demonstrations as inherent instruments for learning and market formation

Fruitful research avenues for the near future can include research into the permanent and more substantial embedding of E&Ds in government policy, the structured coordination and improvement of joint learning experiences and knowledge sharing in and around E&Ds, and the formation of markets for the supply and demand of sustainable energy.

5.2.1. Local governments' new roles and responsibilities

E&Ds provide an important local approach to organize for impactful, sustainable energy transformation and potential avenues for transformative upscaling. Future E&D research can investigate local governments' new roles and responsibilities in E&D processes since local governments are positioned to set, monitor, and act on the necessary institutional frameworks [204,205]. As sustainable energy innovations increasingly focus on neighborhoods and districts, local governments become key actors due to their authoritative position within the local context and scale and their connection to the city. Local governments can also prioritize cities' needs through urban visions within a broader democratic framework [206]. This focus on local governments and policy enables the study of the dynamic and complex interplay between sustainable energy production and consumption, economic growth, and environmental sustainability [207]. Pursuing this research trajectory can elucidate pathways to bridge the gap between relatively manageable small-scale E&Ds and complex and wicked systemic, sustainable energy solutions, potentially offering blueprints for policymakers to navigate the complexities of scaling up energy innovations in a dynamic and changing environment.

5.2.2. E&Ds as one-off examples and as subjects of upscaling

Although transformative scaling is a core goal of E&Ds, one-off E&Ds still deserve a prominent and continuous place in research and practice. E&Ds can, for example, go wrong, challenging the idea of scaling up as a virtue and its inherent narrative of success, calling, instead, for greater acknowledgment to learn from failures [208,209]. A diverse literature on, for example, climate urbanism, sustainability transitions, and living labs have collectively embraced an experimentalist turn [210]. These feed on the popular grand societal challenges or mission discourse and insight that adequate policy responses will require drastic transformations of technology and society [211]. Experiments denote small-scale technological and social interventions and initiatives to develop, test, and demonstrate alternative, more environmentally sustainable, socially just, low-carbon, and inclusive societies [111]. To better understand how the necessary big changes can be developed, organized, and implemented, future E&D research will benefit not just from research into transformational scaling up but also from the innovative developments that are being developed on a small scale in one-off E&Ds. E&Ds as one-off examples and as subjects of upscaling is a research avenue that pays attention to both the intrinsic value and direct effects of E&Ds and the possibility of using them as examples that can be scaled up.

5.2.3. How to measure learning within and across E&Ds

Various E&Ds must be continuously organized and be the subject of scientific research to explore how lessons learned from E&Ds in one sector or technology can be applied to others [11]. It helps to understand the transferability of insights across different contexts and the potential for cross-pollination of ideas and practices. While there is a strong consensus that the overall objective of E&Ds is to generate new knowledge and spur learning [12,48], the question of how to measure learning within and across E&Ds remains elusive [72,87]. Relevant questions are: What metrics should be prioritized, how should learning measurement occur, and how and at what stage public and private funders should determine that sufficient learning has occurred? Furthermore, citizens in energy communities may acquire new technical skills and knowledge related to controlling the functioning of renewable energy installations and managing internet portals and specific energy-related apps. How to consider these prosumers' perspectives when assessing learning from E&Ds?

5.2.4. Friction between learning goals and the participants' individual interests in E&Ds

Another knowledge and learning-related question revolves around the challenge of making new knowledge that E&Ds may generate widely available. Often, public funding is directed towards private sector projects, which take advantage of the distinct capabilities of participating firms. However, those project partners often see high value in the knowledge created and can make claims that the knowledge generated is proprietary [72,87]. The high social value of shared knowledge, designs, and datasets about performance creates a need for openness and shared knowledge that contrasts with claims that data are proprietary. Future research is needed to deeply investigate the friction between learning goals and the participants' interests in E&Ds [72,87].

5.2.5. How to establish external validity for specific case study knowledge

Given the array of E&Ds constructed and investigated to date, the question remains to what extent scholars and practitioners can use past E&D case study research examples to inform future E&D practice. E&D case studies are informative [212,213]. However, the challenge remains to establish external validity for specific case study knowledge [214,215]. A possibility is to develop and apply a methodology in future research that uses the technical, economic, business, social, and societal characteristics of past E&D case studies [216] to match the characteristics of E&Ds in future research [217], creating a growing picture of the do's and don'ts of specific categories of E&Ds. Regarding this, it is relevant and timely to also study the interplay between different characteristics in these cases and adopt a configurational approach. Also, qualitative comparative analysis (QCA) can be a way forward here [218]. Using QCA in the context of E&D projects has potential as it can deal with the complex reality and diversity of how E&Ds are structured and governed [219]. It can be used to identify multiple pathways to the success or failure of such projects in terms of knowledge development and knowledge sharing.

5.2.6. Actor roles that contribute to knowledge exchange and learning

In addition to the analytical level of the E&D itself, considering the broader network in which E&Ds are embedded is important to address in future research. As already stated, the potential of knowledge sharing between E&Ds is often not realized [60], and knowledge accumulation in energy technology demonstration networks is oftentimes hampered [17]. A key research direction is to explore further the role different actors play, such as brokers in and between E&Ds or as central leaders in the stable core of a sectoral, regional, or national E&D network [220,221]. More research is needed to identify what actor roles that contribute to knowledge exchange and learning exactly entail, what kind of organizations can fulfill such roles, and understand the conditions under which these actors can successfully take up these roles.

5.2.7. Long-term impacts of E&Ds on market formation

Future research can concentrate on investigating the long-term impacts of E&Ds on market formation [11,16]. This can involve longitudinal studies that trace the evolution of specific sustainable energy technologies from experimental phases through to widespread adoption and integration into existing systems. It can focus on retrospective studies of the period in which current technologies such as PV, wind turbines, and heat pumps developed from laboratory-based inventions to the large upscaling that is now underway. In these studies, market mechanisms, strategies, stakeholder interests, business models, forms of cooperation, and political interventions can be studied integrally. The aim is to deepen the understanding of the interactions between these aspects and gain insight into how that results in delaying, supporting, improving, and accelerating these technologies' development, use, and upscaling. This insight can be used for the future upscaling of sustainable energy technologies that still need further technical, organizational, and market boosts, for example for carbon capture, utilization, and storage (CCUS) technology. Being largely technically oriented, the literature neglected the business opportunities that underlie E&Ds for CCUS technologies [222,223]. Future research can explore how CCUS technologies shape the way for companies to simultaneously make a profit and create value for key stakeholders, particularly in highly carbon-intense industries that may not even be able to avoid fossil fuels [224], such as cement and plastics industries. Thus, an important future research avenue relates to uncovering what kind of changes decarbonization through CCUS implies to market formation, including companies' business models, value chains, and relevant user groups [224,225] and how these changes can be aligned with the constantly growing institutional and regulative developments in the field [226].

5.2.8. Transforming fossil energy technology companies

Research is essential not only for market formation for newly founded organizations and companies. Market-forming aspects of adjustments of existing and dominant incumbent companies, such as the traditional oil and gas companies, towards clean and sustainable energy sources also require research [131,227]. A critical research path is to conduct studies that aim to understand how E&Ds can accelerate the transformation of oil and gas companies into clean and sustainable energy companies [95,149]. A question related to this is how different fossil and sustainable energy technologies mutually compete. Presently, research has been centered on comparing sustainable and conventional energy technologies to assess the feasibility of the former replacing the latter [228,229]. However, as conventional energy technologies are progressively phased out, the question shifts to which sustainable energy technologies should be prioritized for larger-scale deployment. Future research needs to examine the competitive landscape between sustainable and conventional energy technologies and among various sustainable options [131,227]. For example, while PV technology may be economically competitive with traditional energy in certain regions, how it fares against other renewables like wind or biomass is not always clear. Upcoming studies can develop models to evaluate the relative feasibility of different sustainable energy technologies, considering both techno-economic factors and social and environmental impacts.

5.3. Concentrating transformative upscaling on new cross-sectoral systems and institutions

Relevant avenues for further research can include research into the origins and development of cross-sectoral systems of collaborating organizations in existing and new structures, with an eye on economic aspects such as growth, prosperity, and well-being. In addition to a technical approach, more attention is needed to the social aspects of E&Ds in research, as E&Ds play an important role in institutional change and related new ways of thinking, narrating, and acting on sustainable energy.

5.3.1. Change dynamics in innovation ecosystems around E&Ds

Demonstrations of cross-sectoral energy systems are a critical element of the collection of E&Ds for sustainable energy innovation. Future research can focus on the specific role of E&Ds in enabling and promoting the integration of renewable energy sources across different industrial sectors and their markets, as well as the technical, economic, and regulatory challenges associated with cross-sectoral energy system integration [230]. For example, a transition from gas-powered vehicles to EVs is achievable but leads to coordination issues between elements of the innovation system [231,232]. When more gas-powered vehicles are disposed of, there will be a heavier burden on waste management systems, which will also require waste management systems to innovate [233]. Sustainable energy innovation is often a dynamic cross-sectoral and cross-organizational process of change. Changes lead to new changes, setting in motion a continuing innovation process. Future E&D research can investigate these change dynamics in innovation ecosystems around E&Ds. This can involve mapping the actors, relationships, and resources that contribute to the functioning and outcomes of E&Ds related to their surrounding ecosystems. Additionally, this connects to the previously described need to become multi-mission oriented, as striving to achieve various missions inherently entails innovation in multiple sectors, thus calling for cross-sectoral multi-mission-oriented innovation.

5.3.2. Integration of renewable energy sources across different energy sectors

The concept of integrated energy systems and their relationship with E&Ds can also be further investigated, particularly in terms of how E&Ds facilitate the development and deployment of integrated energy systems. In line with this, energy sector coupling, which refers to integrating different energy sectors, e.g., electricity, heat, and hydrogen, to increase flexibility and efficiency in energy systems, is a closely related concept [230]. While Ramsebner et al. [230] provide a comprehensive overview of the energy sector coupling concept, future research can focus on the specific role of E&Ds in enabling and promoting this coupling of sectors. This can include investigating how E&Ds can be designed and operated to facilitate the integration of renewable energy sources across different energy sectors and the technical, economic, and regulatory challenges associated with energy sector coupling in and through E&Ds.

5.3.3. Economic aspects of cross-sectoral collaboration

Regarding the economic aspects of cross-sectoral collaboration, a relevant research question is how innovative financing and investment models can support the cross-sector scaling of E&Ds. This includes identifying mechanisms for attracting private investment, leveraging public funds, and creating sustainable business models [234]. Another economically oriented research area is how entrepreneurship further boosts E&Ds and influences cross-sectoral sustainable energy innovation [160,165]. More research is needed on how entrepreneurs and their start-ups inspire further sustainable energy technology development in E&Ds. Further highly relevant economics-oriented research topics that deserve attention in E&D research are how collaborative business models develop [190,234,235], how users and customers can be included in the E&D process at an early phase [236], and how mini-ecosystems, for example, festivals can serve as E&D-settings in which all technical, economic and social factors can be influenced and studied in a manageable way and on a small scale [178].

5.3.4. E&Ds function as instigators of drastic institutional change

In addition to technological, organizational, industrial, and market changes initiated and propelled by E&Ds, institutional change - that is, changes in informal institutions such as social norms, values, narratives, agreements, habits, and patterns of behavior as well as formal institutions such as laws and regulations - are also required to facilitate innovation [97]. An important step in researching E&Ds function as instigators of drastic institutional change is the articulation of novel visions that diverge from the dominant institutional status quo [237]. There is an urgent need for new, exciting 'earth-shifting' images, initiatives, and examples that fundamentally innovate social and societal patterns of thought and action. Here, too, E&Ds are highly suitable for bringing about institutional change. The United States Department of Energy has established several 'earth shots' (akin to moonshots) to illustrate this new type of thinking and acting. One of these earth shots, the Carbon Negative Shot, aims to bring the costs of CO_2 removal to below $100/t$CO_2$ within a decade [238]. There is also a Hydrogen Shot that aims to bring the cost of clean hydrogen down by 80 % to $1 per 1 kg in 1 decade (coined as '1 1 1') **[239]** . Relatedly, there have also been efforts to award prizes using private funds to incentivize energy and climate technology innovation. The first significant initiative was the $25 m Virgin Earth Challenge announced in 2007 by Richard Branson and designed to encourage inventions related to capturing CO_2 from the atmosphere. The prizes are often led by prominent figures, such as the Earth Shot Prize launched by UK's Prince William in 2020 or the X-Prize, including one for carbon removal funded by Elon Musk in 2022 [240]. Little research has been done on the efficacy of such grand E&D initiatives that showcase divergent visions for the future, resulting in an interesting research opportunity. Suppose the world has to develop new ideas and visions about a sustainable energy earth. In that case, innovators must also dare to develop these ideas in E&Ds, even if they later become too utopian. Therefore, ample attention can be paid to E&Ds and research into E&Ds in which highly innovative ideas are developed, such as the energy internet, new public-private-community energy infrastructure ownership structures, the energy internet of things, smart energy cities, blockchain-driven energy systems, AI-supported energy decision-making, 100 % electric driving, peer-to-peer energy trading, shipping and aviation, virtual powerplants, energy hubs, and desert-situated energy production.

5.3.5. The effectiveness of energy communities

Another new type of thinking and acting demonstrated by collectives of institutional change agents is being put into practice by energy communities. New avenues for research on the effectiveness of energy communities can focus on new collaboration structures between energy communities and profit and not-for-profit organizations and the potential roles of these organizations in developing energy communities and, more specifically, under what conditions they can cooperate [241]. Related to this, new insights are expected to be gained by exploring how intermediaries can contribute to the further development of energy communities. Collaboration and networking with others are often listed as among the top facilitating factors by energy communities [242,243]. Umbrella organizations can also be seen as important actors in this regard. Another interesting avenue can be to focus on making energy communities more inclusive. For example, more knowledge about actively engaging young people in energy communities may be needed to accelerate the sustainable energy transition. Furthermore, the energy community movement is often criticized for being non-inclusive [244]. This calls for research into energy communities' interventions and strategies to encourage inclusiveness, preferably in a (quasi) experimental setting. The same is roughly advised regarding energy democracy, energy justice perceptions, and alleviating energy poverty. Research into what energy communities do vis-à-vis public values can also be suggested based on the institutional innovation aspect of energy communities.

5.3.6. Integrating a socio-institutional dimension into E&Ds

Informal institutional change occurs in human consciousness and is highly social. Formal institutional changes are also the result of social construction. Therefore, increased attention to the social side of the sustainable energy issue is relevant and integrating a socio-institutional dimension into E&Ds for sustainable energy emerges as another essential research trajectory. The limitations of purely technological solutions in addressing the layered challenges of sustainability underscore the imperative to weave social considerations—such as public acceptance, behavioral shifts, and equity issues—into the fabric of E&D research. This perspective is reinforced by Corsini and Moultrie [245] and Rocha et al. [246], who advocate for embedding social sustainability within research agendas to foster holistic approaches to sustainable energy development. Engaging in this line of inquiry can reveal comprehensive strategies that effectively incorporate socio-institutional dynamics into sustainable energy initiatives, thereby enhancing the likelihood of their acceptance and success. This approach promises to enrich the design and implementation of E&Ds, making them more socially inclusive and ensuring that technological advancements in energy are aligned with societal needs and values.

5.3.7. A broader conceptualization of scaling

How scaling up is viewed also needs to be expanded. While scaling up is often seen as production and consumption growth, many more forms of scaling up can be distinguished and, therefore, institutionalized. For example, Palmié et al. [247] divide scaling into financial, organizational, market, and volume scaling, whereas Jansen et al. [248] outline different scaling strategies by delineating the scope, mode, value logic, dynamics, and scaling unit. E&D research can embrace a broader conceptualization of scaling, where organizational and managerial approaches can complement the prevailing focus on scaling technology. In addition, new institutions that are at odds with scaling, economic growth, and unlimited consumption principles can also be developed and tried in E&Ds.

5.3.8. The role of E&Ds in moving away from existing unsustainable energy institutions

Further on, research in the field of sustainability transitions has predominantly concentrated on the adoption of new technologies or practices. However, there has been a lack of equal attention towards technologies that should be discontinued or that address unsustainable practices such as car-based mobility. These practices, often deeply entrenched in current socio-technical systems and people's socio-institutional sensemaking around transport or energy use, are challenging to destabilize and disengage from. This highlights the need for a balanced approach in E&D research that promotes sustainable technologies and addresses the reduction of unsustainable practices [227,249]. It also underscores the importance of understanding the role of E&Ds in moving away from existing unsustainable energy institutions [131].

5.4. Biases in E&Ds for sustainable energy innovation research

Past research shows that the inclusiveness of E&Ds for sustainable energy innovation is limited and deficient. E&Ds and E&D programs are mainly present in developed economies. Furthermore, within these developed economies, E&Ds and E&D programs focus strongly on innovating the energy use of affluent citizens. Citizens who are less economically and socially situated usually do not participate. In addition, and strikingly, E&D programs and E&D research hardly occur in economies in the Global South. At the same time, a significant part of the renewable energy potential lies in developing countries in this part of the world [227,250].

5.4.1. The most vulnerable in communities

Research can further include the most vulnerable in communities. For example, it is insufficient to assume that low-income households can afford to transition to sustainable energy. Concerns exist that those who can afford to engage with sustainable energy create a more significant financial gap with those who cannot financially engage [227,251,252]. E&Ds and associated policies tend to exacerbate existing socioeconomic disparities because these technologies are primarily bought and used by the already well-off. Economic support schemes tend to boost these dynamics, meaning these groups gain access to capital and new technology. On the other hand, low-income groups often live low-tech and low-emission lifestyles without being rewarded. Researchers can better recognize the broader social justice impacts of access to sufficient and sustainable energy.

5.4.2. Geographical bias of E&Ds for sustainable energy innovation

There has been little attention to how E&Ds for sustainable energy and technology adoption take place within pre-existing power structures and, therefore, happen unevenly across the world and contribute to an 'unevenness of laboratorizatioń [227,251,252]. Franco et al. [253], for example, note that many building facilities in the Global South have limited access to electricity and emphasize the significance of energy availability as a vital aspect of life quality. In addition, Olatomiwa et al. [254] claim that 17 % of the world's population lacks access to electricity, with 85 % of these people living in rural Sub-Saharan Africa and South Asia, causing a high level of poverty, high death rates, and economic and social challenges in these areas. The geographical bias of E&Ds for sustainable energy innovation deserves further attention in scholarly research.

5.5. Contribution to the literature, research and practice, and limitation

E&Ds are a phenomenon in the innovation management literature, with a primary function of being the protected places where innovations can be developed. However, the innovation management literature pays relatively little attention to the precise nature, size, function, and impact of these E&Ds. This present study fills this knowledge gap in the literature by presenting a coherent overview of research themes and insights regarding the transformative impact of innovative sustainable energy E&Ds on the sustainable energy system from the past, present, and near future.

The overview of research themes and insights relates to and contributes to the innovation management literature streams. Regarding sustainable energy experiments literature [7,13,16], it provides insight into the technical, organizational, market, regulatory, stakeholder and society-related functions of E&Ds in developing and scaling sustainable energy technologies. With regard to the adoption and diffusion of innovation theory [20–22], it provides insights into how E&Ds contribute to the different forms of market and social acceptance of new sustainable energy and the way in which this does or does not come about. Additional insights this research provides to technology readiness level (TRL) methodology [23–25] is that even after the last TRL phase, E&Ds are often still needed to improve lower-generational sustainable energy innovations' technical, organizational, and market quality. Additional insights that this study provides regarding E&Ds in dynamic capabilities theory [26–28] is that collaboration in a network of competitors and suppliers in E&Ds is not just risky in terms of intellectual property and knowledge leakage but can also provide competitive advantages by becoming a frontrunning multi-stakeholder-linked player in the sustainable energy innovation race. Furthermore, taking into account the stage-gating model [29–31], this study provides the insight that E&Ds not only reduce the chance of market failure of sustainable energy innovation but can actively contribute to the success of these innovations on the market and in society by developing powerful examples. Furthermore, this study provides insights into the theoretical field of the multi-level perspective [32–34], strategic niche management [35–37], and transition management [44–46] by providing an overview of ways in which niches for sustainable energy innovation can develop, grow into regime positions and contribute to an overall transition towards more sustainable energy generation, distribution and use. Finally, system-oriented theory, such as national systems of innovation [38–40] and technical systems of innovation [41–43], can also benefit from the findings of this study, which describes various multi-stakeholder network situations in and around E&Ds that can be deployed in practice and investigated in follow-up research.

E&Ds are an empirical phenomenon that, in addition to being a part of innovation management literature, also occupy a central place in sustainable energy innovation practice. This is a complex practice where many sustainable energy technologies are in different phases of development [7,13,16], within different empirical domains [13–15], and in which a large number of stakeholders are involved [7,13,16]. Within this complex of application combinations, this study provides a comprehensive overview of current and future research directions that can serve practice and the growth of different sustainable energy technologies in different application domains and by different collaborating stakeholders. Policymakers and practitioners can leverage this to inform their sustainable energy policies and business strategies. Since the answers to the two parts of the research questions are broad, given the experts' freedom of choice in focusing on various sustainable energy technologies, application domains, and stakeholders, the overviews of their answers in sections 4 and 5 should be seen as indicative and guiding, not as prescriptive and directive.

6. Conclusion

This study reviews and reflects on a large body of research on E&Ds. It draws several key conclusions about their organization, structure, governance (see Table 5), and presents an outlook on the near future (see Table 6). Previous research has held on to the idea of E&Ds as technical developments with economically relevant outputs for a single sustainable energy technology within a single niche market. E&D projects often operated in an almost hermeneutically sealed vacuum, orchestrating their activities by a diversity of public and private partners whose roles and dependence trajectories adjust as the E&Ds approach upscaling to market and society. While previous research has provided many insights about E&D project structure, phases of its growth and upscaling, and particularly the process by which its socio-techno-economic enabling takes place, as is captured in the process model presented in this study, further scientific inquiry is necessary to understand the full implementation, acceleration and upscaling potential of E&Ds with a more considerate integration of their relation to environmentally focused missions, societal dynamics and needs, and the effects on and changes in institutions and multi-stakeholder practices E&Ds can provoke.

Based on the insights of 47 international scholars active in E&D research, researchers in the field need to move away from isolated silos towards integrated sustainable technology portfolio building to avoid innovation residues and build resilience and longevity of sustainable energy technology innovations for its community of users, both in developed as well as developing countries. This shift from technocratic to community and societal interest-driven inclusion in E&D focalization is paramount to building cross-sectoral systems driving institutional change across the markets and societies within which the E&Ds are upscaled. This approach calls explicitly for policy and business governance change with multi-mission and multi-stakeholder orientation and appropriate recognition of citizen agency while preserving the inherent role of E&Ds and their place and space in knowledge transfer and learning for a sustainable future together.

CRediT authorship contribution statement

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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 article.

Data availability

No data was used for the research described in the article.

References

[1] W.B. Arthur, The Nature of Technology: What it Is and how it Evolves, The Free Press, New York, 2009.
[2] S.S. Erzurumlu, Y.O. Erzurumlu, Development and deployment drivers of clean technology innovations, Journal of High Technology Management Research 24 (2013) 100–108, https://doi.org/10.1016/j.hitech.2013.09.001.
[3] J. Mossberg, J. Frishammar, P. Söderholm, H. Hellsmark, Managerial and organizational challenges encountered in the development of sustainable technology: analysis of Swedish biorefinery pilot and demonstration plants, J. Clean. Prod. 276 (2020) 124150, https://doi.org/10.1016/j.jclepro.2020.124150.
[4] K. Sjöö, J. Frishammar, Demonstration projects in sustainable technology: the road to fulfillment of project goals, J. Clean. Prod. 228 (2019) 331–340, https://doi.org/10.1016/j.jclepro.2019.04.302.
[5] T. Von Wirth, L. Fuenfschilling, N. Frantzeskaki, L. Coenen, Impacts of urban living labs on sustainability transitions: mechanisms and strategies for systemic change through experimentation, Eur. Plan. Stud. 27 (2) (2019) 229–257, https://doi.org/10.1080/09654313.2018.1504895.
[6] Femenías, P., Hagbert, P. (2013) The habitation lab: using a design approach to foster innovation for sustainable living. Technol. Innov. Manag. Rev., 3(11) https://creativemedpt.wordpress.com/wp-content/uploads/2013/12/timreview_november2013.pdf (accessed on 6 January 2025).
[7] J. Frishammar, P. Söderholm, K. Bäckström, H. Hellsmark, H. Ylinenpää, The role of pilot and demonstration plants in technological development: synthesis and directions for future research, Tech. Anal. Strat. Manag. 27 (1) (2015) 1–18, https://doi.org/10.1080/09537325.2014.943715.
[8] A.I. Gaziulusoy, H. Brezet, Design for system innovations and transitions: A conceptual framework integrating insights from sustainablity science and theories of system innovations and transitions, J. Clean. Prod. 108 (2015) 558–568, https://doi.org/10.1016/j.jclepro.2015.06.066.
[9] P. Harborne, C. Hendry, J. Brown, The development and diffusion of radical technological innovation: the role of bus demonstration projects in commercializing fuel cell technology, Tech. Anal. Strat. Manag. 19 (2) (2007) 167–188, https://doi.org/10.1080/09537320601168060.
[10] P. Kivimaa, P. Mickwitz, The challenge of greening technologies: environmental policy integration in Finnish technology policies, Res. Policy 35 (5) (2006) 729–744, https://doi.org/10.1016/j.respol.2006.03.006.
[11] S. Mousavi, H. Hellsmark, P. Söderholm, How can pilot and demonstration plants drive market formation? Lessons from advanced biofuel development in Europe, Technol. Forecast. Soc. Chang. 194 (2023) 122703, https://doi.org/10.1016/j.techfore.2023.122703.
[12] H. Hellsmark, J. Mossberg, P. Söderholm, J. Frishammar, Innovation system strengths and weaknesses in progressing sustainable technology: the case of Swedish biorefinery development, J. Clean. Prod. 131 (2016) 702–715, https://doi.org/10.1016/j.jclepro.2016.04.109.
[13] B.A.G. Bossink, Demonstration projects for diffusion of clean technological innovation: a review, Clean Techn. Environ. Policy 17 (2015) 1409–1427, https://doi.org/10.1007/s10098-014-0879-4.
[14] C. Hendry, P. Harborne, P. Brown, So what do innovating companies really get from publicly funded demonstration projects and trials? Innovation lessons from solar photovoltaics and wind, *Energy Policy* 38 (8) (2010) 4507–4519, https://doi.org/10.1016/j.enpol.2010.04.005.
[15] Koch, C., Bertelsen, N.H. (2014) Learning from demonstration project? Developing construction for sustainability. Open Construction and Building Technology Journal, 8:9–17. https://www.researchgate.net/profile/Christian-Koch-14/publication/270101060_Learning_from_Demonstration_Developing_Construction_for_Sustainability/links/568d21c708aeecf87b21ac4f/Learning-from-Demonstration-Developing-Construction-for-Sustainability.pdf (accessed on 6 January 2025).
[16] B.A.G. Bossink, Demonstrating sustainable energy: a review-based model of sustainable energy demonstration projects, Renew. Sust. Energ. Rev. 77 (2017) 1349–1362, https://doi.org/10.1016/j.rser.2017.02.002.
[17] B. Bossink, Learning strategies in sustainable energy demonstration projects: what organizations learn from sustainable energy demonstrations, Renew. Sust. Energ. Rev. 131 (2020) 110025, https://doi.org/10.1016/j.rser.2020.110025.
[18] B. Bossink, M. Blankesteijn, S. Hasanefendic, Upscaling sustainable energy: from demonstration to transformation, *energy research and social*, Science 103-(1) (2023) 1–14, https://doi.org/10.1016/j.erss.2023.103208.
[19] S. Reddy, J.P. Painuly, Diffusion of renewable energy technologies—barriers and stakeholders' perspectives, Renew. Energy 29 (9) (2004) 1431–1447, https://doi.org/10.1016/j.renene.2003.12.003.
[20] E.M. Rogers, Diffusion of Innovations, The Free Press, New York, 1962.
[21] E.M. Rogers, A prospective and retrospective look at the diffusion model, J. Health Commun. 9 (S1) (2004) 13–19, https://doi.org/10.1080/10810730490271449.
[22] J.A. Van Oorschot, E. Hofman, J.I. Halman, A bibliometric review of the innovation adoption literature, Technol. Forecast. Soc. Chang. 134 (2018) 1–21, https://doi.org/10.1016/j.techfore.2018.04.032.
[23] Mankins, J.C. (1995) *Technology readiness levels*. White paper, April, 6. http://www.artemisinnovation.com/images/TRL_White_Paper_2004-Edited.pdf (accessed 0n 6 January 2025).
[24] J.C. Mankins, Technology readiness assessments: A retrospective, Acta Astronaut. 65 (9–10) (2009) 1216–1223, https://doi.org/10.1016/j.actaastro.2009.03.058.
[25] A. Olechowski, S.D. Eppinger, N. Joglekar, Technology readiness levels at 40: A study of state-of-the-art use, challenges, and opportunities, in: In *2015 Portland International Conference on Management of Engineering and Technology (PICMET)*, IEEE, 2015, pp. 2084–2094, https://doi.org/10.1109/PICMET.2015.7273196.
[26] K.M. Eisenhardt, J.A. Martin, Dynamic capabilities: what are they? Strateg. Manag. J. 21 (10−11) (2000) 1105–1121.
[27] D.J. Teece, G. Pisano, A. Shuen, Dynamic capabilities and strategic management, Strateg. Manag. J. 18 (7) (1997) 509–533, https://doi.org/10.1002/(SICI)1097-0266(199708)18:7%3C509::AID-SMJ882%3E3.0.CO;2-Z.
[28] C.L. Wang, P.K. Ahmed, Dynamic capabilities: A review and research agenda, Int. J. Manag. Rev. 9 (1) (2007) 31–51, https://doi.org/10.1111/j.1468-2370.2007.00201.x.
[29] R.G. Cooper, Stage-gate systems: a new tool for managing new products, Bus. Horiz. 33 (3) (1990) 44–54, https://doi.org/10.1016/0007-6813(90)90040-I.
[30] R.G. Cooper, What's next?: after stage-gate, Res. Technol. Manag. 57 (1) (2014) 20–31, https://doi.org/10.5437/08956308X5606963.
[31] J. Grönlund, D.R. Sjödin, J. Frishammar, Open innovation and the stage-gate process: A revised model for new product development, Calif. Manag. Rev. 52 (3) (2010) 106–131, https://doi.org/10.1525/cmr.2010.52.3.106.
[32] F.W. Geels, Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study, Res. Policy 31 (8–9) (2002) 1257–1274, https://doi.org/10.1016/S0048-7333(02)00062-8.

[33] F.W. Geels, Processes and patterns in transitions and system innovations: refining the co-evolutionary multi-level perspective, Technol. Forecast. Soc. Chang. 72 (6) (2005) 681–696, https://doi.org/10.1016/j.techfore.2004.08.014.

[34] F.W. Geels, Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective, Res. Policy 39 (4) (2010) 495–510, https://doi.org/10.1016/j.respol.2010.01.022.

[35] R. Kemp, J. Schot, R. Hoogma, Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management, Tech. Anal. Strat. Manag. 10 (2) (1998) 175–198, https://doi.org/10.1080/09537329808524310.

[36] R. Raven, S. Van den Bosch, R. Weterings, Transitions and strategic niche management: towards a competence kit for practitioners, Int. J. Technol. Manag. 51 (1) (2010) 57–74, https://doi.org/10.1504/IJTM.2010.033128.

[37] J. Schot, F.W. Geels, Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy, Tech. Anal. Strat. Manag. 20 (5) (2008) 537–554, https://doi.org/10.1080/09537320802292651.

[38] Freeman, C. (1995) 'The national innovation system in historical perspective', Camb. J. Econ., Vol. 19, pp.5–24. https://EconPapers.repec.org/RePEc:oup:cambje:v:19:y:1995:i:1:p:5-24 (accessed 7 January 2025).

[39] B.Å. Lundvall, National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning, Pinter Publishers, London, 1992.

[40] B.Å. Lundvall, National innovation systems—analytical concept and development tool, Ind. Innov. 14 (1) (2007) 95–119, https://doi.org/10.1080/13662710601130863.

[41] A. Bergek, S. Jacobsson, B. Carlsson, S. Lindmark, A. Rickne, Analyzing the functional dynamics of technological innovation systems: A scheme of analysis, Res. Policy 37 (3) (2008) 407–429, https://doi.org/10.1016/j.respol.2007.12.003.

[42] M.P. Hekkert, R.A. Suurs, S.O. Negro, S. Kuhlmann, R.E. Smits, Functions of innovation systems: A new approach for analysing technological change, Technol. Forecast. Soc. Chang. 74 (4) (2007) 413–432, https://doi.org/10.1016/j.techfore.2006.03.002.

[43] J. Markard, B. Truffer, Technological innovation systems and the multi-level perspective: towards an integrated framework, Res. Policy 37 (4) (2008) 596–615, https://doi.org/10.1016/j.respol.2008.01.004.

[44] R. Kemp, D. Loorbach, J. Rotmans, Transition management as a model for managing processes of co-evolution towards sustainable development, The International Journal of Sustainable Development & World Ecology 14 (1) (2007) 78–91, https://doi.org/10.1080/13504500709469709.

[45] D. Loorbach, Transition management for sustainable development: a prescriptive, complexity-based governance framework, Governance 23 (1) (2010) 161–183, https://doi.org/10.1111/j.1468-0491.2009.01471.x.

[46] J. Rotmans, R. Kemp, M. Van Asselt, More evolution than revolution: transition management in public policy, Foresight 3 (1) (2001) 15–31, https://doi.org/10.1108/14636680110803003.

[47] P.E. Auerswald, L.M. Branscomb, Valleys of death and Darwinian seas: financing the invention to innovation transition in the United States, J. Technol. Transf. 28 (3–4) (2003) 227–239, https://doi.org/10.1023/A:1024980525678.

[48] D.M. Reiner, Learning through a portfolio of carbon capture and storage demonstration projects, Nat. Energy 1 (1) (2016) 1–7, https://doi.org/10.1038/NENERGY.2015.11.

[49] S.M. Macey, M.A. Brown, Demonstrations as a policy instrument with energy technology examples, Sci. Commun. 11 (3) (1990) 219–236, https://doi.org/10.1177/107554709001100301.

[50] S.C. Wheelwright, K.B. Clark, Creating project plans to focus product development, Harv. Bus. Rev. 70 (2) (1992) 70–82.

[51] J. Brown, C. Hendry, Public demonstration projects and field trials: accelerating commercialisation of sustainable technology in solar photovoltaics, Energy Policy 37 (9) (2009) 2560–2573, https://doi.org/10.1016/j.enpol.2009.01.040.

[52] M.B. Lindberg, L. Kammermann, Advocacy coalitions in the acceleration phase of the European energy transition, Environ. Innov. Soc. Trans. 40 (2021) 262–282, https://doi.org/10.1016/j.eist.2021.07.006.

[53] K. Palage, R. Lundmark, P. Söderholm, The impact of pilot and demonstration plants on innovation: the case of advanced biofuel patenting in the European Union, Int. J. Prod. Econ. 210 (2019) 42–55, https://doi.org/10.1016/j.ijpe.2019.01.002.

[54] H. Breetz, M. Mildenberger, L. Stokes, The political logics of clean energy transitions, Business and Politics 20 (4) (2018) 492–522, https://doi.org/10.1017/bap.2018.14.

[55] M. Downing, T.A. Volk, D.A. Schmidt, Development of a new generation cooperatives in agriculture for renewable energy research, development, and demonstration projects, Biomass Bioenergy 28 (5) (2005) 425–434, https://doi.org/10.1016/j.biombioe.2004.09.004.

[56] J. Hoppmann, Hand in hand to Nowhereland? How the resource dependence of research institutes influences their co-evolution with industry, *Research Policy* 50 (2) (2021) 104145 https://doi.org/10.1016/j.respol.2020.104145.

[57] S. Jolly, R. Raven, H. Romijn, Upscaling of business model experiments in off-grid PV solar energy in India, Sustain. Sci. 7 (2012) 199–212, https://doi.org/10.1007/s11625-012-0163-7.

[58] S. Scarpellini, A. Aranda, J. Aranda, E. Llera, M. Marco, R&D and eco-innovation: opportunities for closer collaboration between universities and companies through technology centers, Clean Techn. Environ. Policy 14 (2012) 1047–1058, https://doi.org/10.1007/s10098-012-0514-1.

[59] V. Albino, U. Berardi, Green buildings and organizational changes in Italian case studies, Bus. Strateg. Environ. 21 (6) (2012) 387–400, https://doi.org/10.1002/bse.1728.

[60] G. Evers, M. Chappin, Knowledge sharing in smart grid pilot projects, Energy Policy 143 (2020) 111577, https://doi.org/10.1016/j.enpol.2020.111577.

[61] T. Hoppe, G. De Vries, Social innovation and the energy transition, Sustainability 11 (1) (2018) 141, https://doi.org/10.3390/su11010141.

[62] E. Mlecnik, H. Visscher, A. Van Hal, Barriers and opportunities for labels for highly energy-efficient houses, Energy Policy 38 (8) (2010) 4592–4603, https://doi.org/10.1016/j.enpol.2010.04.015.

[63] A. Schreuer, M. Ornetzeder, H. Rohracher, Negotiating the local embedding of socio-technical experiments: a case study in fuel cell technology, Tech. Anal. Strat. Manag. 22 (6) (2010) 729–743, https://doi.org/10.1080/09537325.2010.496286.

[64] Ryghaug, M., Skjølsvold, M. (2021) Pilot society and the energy transition: the co-shaping of innovation, Participation and Politics, Springer Nature, 2021, p. 130. https://library.oapen.org/bitstream/id/e1527248-f67d-4886-b5db-2d807c7007d4/2021_Book_PilotSocietyAndTheEnergyTransi.pdf (accessed on 6 January 2025).

[65] N. Van der Grijp, F. Van der Woerd, B. Gaiddon, R. Hummelshøj, M. Larsson, O. Osunmuyiwa, R. Rooth, Demonstration projects of nearly zero energy buildings: lessons from end-user experiences in Amsterdam, Helsingborg, and Lyon, Energy Res. Soc. Sci. 49 (2019) 10–15, https://doi.org/10.1016/j.erss.2018.10.006.

[66] M.J. Van der Kam, A.A.H. Meelen, W.G.J.H.M. Van Sark, F. Alkemade, Diffusion of solar photovoltaic systems and electric vehicles among Dutch consumers: implications for the energy transition, Energy Res. Soc. Sci. 46 (2018) 68–85, https://doi.org/10.1016/j.erss.2018.06.003.

[67] F.J. Van Rijnsoever, A. Van Mossel, K.P. Broecks, Public acceptance of energy technologies: the effects of labeling, time, and heterogeneity in a discrete choice experiment, Renew. Sust. Energ. Rev. 45 (2015) 817–829, https://doi.org/10.1016/j.rser.2015.02.040.

[68] E. Heiskanen, K. Hyvönen, S. Laakso, P. Laitila, K. Matschoss, I. Mikkonen, Adoption and use of low-carbon technologies: lessons from 100 Finnish pilot studies, field experiments and demonstrations, Sustainability 9 (5) (2017) 1–20, https://doi.org/10.3390/su9050847.

[69] M. Nigra, B. Bossink, Cooperative learning in green building demonstration projects: insights from 30 innovative and environmentally sustainable demonstrations around the world, J. Constr. Eng. Manag. 149 (4) (2023) 05023002, https://doi.org/10.1061/JCEMD4.COENG-12881.

[70] J. Gosens, A. Gilmanova, J. Lilliestam, Windows of opportunity for catching up in formative clean-tech sectors and the rise of China in concentrated solar power, Environ. Innov. Soc. Trans. 39 (2021) 86–106, https://doi.org/10.1016/j.eist.2021.03.005.

[71] D. Hain, R. Jurowetzki, P. Konda, L. Oehler, From catching up to industrial leadership: towards an integrated market-technology perspective, An application of semantic patent-to-patent similarity in the wind and EV sector, *Industrial and Corporate Change* 29 (5) (2020) 1233–1255, https://doi.org/10.1093/icc/dtaa021.

[72] G.F. Nemet, V. Zipperer, M. Kraus, The valley of death, the technology pork barrel, and public support for large demonstration projects, Energy Policy 119 (2018) 154–167, https://doi.org/10.1016/j.enpol.2018.04.008.

[73] Y. Dai, S. Hasanefendic, B. Bossink, A systematic literature review of the smart city transformation process: the role and interaction of stakeholders and technology, Sustain. Cities Soc. 105112 (2023), https://doi.org/10.1016/j.scs.2023.105112.

[74] Envall, F. (2021) *Experimenting for Change?: The Politics of Accomplishing Environmental Governance Through Smart Energy Pilot Projects*, Linköping University Electronic Press, 2021 (Doctoral dissertation). https://scholar.google.com/scholar?hl=nl&as_sdt=0%2C5&q=Envall%2C+F.+%282021%29+Experimenting+for+Change%3F%3A+The+Politics+of+Accomplishing+Environmental+Governance+Through+Smart+Energy+Pilot+Projects%2C+Link%C3%B6ping+University+Electronic+Press%2C+2021+%28Doctoral+dissertation%29.&btnG= (accessed on 6 January 2025).

[75] W.P. Boon, S. Bakker, Learning to shield–policy learning in socio-technical transitions, Environ. Innov. Soc. Trans. 18 (2016) 181–200, https://doi.org/10.1016/j.eist.2015.06.003.

[76] T. Moore, D. Higgins, Influencing urban development through government demonstration projects, Cities 56 (2016) 9–15, https://doi.org/10.1016/j.cities.2016.02.010.

[77] Z. Ma, K.D. Augustijn, I.J.P. De Esch, B.A.G. Bossink, Micro-foundations of dynamic capabilities to facilitate university technology transfer, PLoS One 18 (3) (2023) e0283777, https://doi.org/10.1371/journal.pone.0283777.

[78] M.A. Mosgaard, S. Kerndrup, Danish demonstration projects as drivers of maritime energy efficient technologies, J. Clean. Prod. 112 (2016) 2706–2716, https://doi.org/10.1016/j.jclepro.2015.10.047.

[79] I.R. Skov, N. Schneider, Incentive structures for power-to-X and e-fuel pathways for transport in EU and member states, Energy Policy 168 (2022) 113121, https://doi.org/10.1016/j.enpol.2022.113121.

[80] M. Van der Koogh, E. Chappin, R. Heller, Z. Lukszo, Are we satisfying the right conditions for the mobility transition? A review and evaluation of the dutch urban mobility policies, Sustainability 13 (22) (2021) 12736, https://doi.org/10.3390/su132212736.

[81] H.A. Van der Loos, S.O. Negro, M.P. Hekkert, Low-carbon lock-in? Exploring transformative innovation policy and offshore wind energy pathways in the Netherlands, Energy Res. Soc. Sci. 69 (2020) 101640, https://doi.org/10.1016/j.erss.2020.101640.

[82] A. Van der Loos, S.O. Negro, M.P. Hekkert, International markets and technological innovation systems: the case of offshore wind, Environ. Innov. Soc. Trans. 34 (2020) 121–138, https://doi.org/10.1016/j.eist.2019.12.006.
[83] J. Gibbins, H. Chalmers, Preparing for global rollout: a 'developed country first' demonstration programme for rapid CCS deployment, Energy Policy 36 (2) (2008) 501–507, https://doi.org/10.1016/j.enpol.2007.10.021.
[84] R.S. Haszeldine, Carbon capture and storage: how green can black be? Science 325 (2009) 1647–1652, https://doi.org/10.1126/science.1172246.
[85] P.H. Kobos, J.D. Erickson, T.E. Drennen, Technological learning and renewable energy costs: implications for US renewable energy policy, Energy Policy 34 (13) (2006) 1645–1658, https://doi.org/10.1016/j.enpol.2004.12.008.
[86] A. Mangipinto, F. Lombardi, F.D. Sanvito, M. Pavičević, S. Quoilin, E. Colombo, Impact of mass-scale deployment of electric vehicles and benefits of smart charging across all European countries, Appl. Energy 312 (2022) 118676, https://doi.org/10.1016/j.apenergy.2022.118676.
[87] G.F. Nemet, M.W. Callaghan, F. Creutzig, S. Fuss, J. Hartmann, J. Hilaire, W. F. Lamb, J.C. Minx, S. Rogers, P. Smith, Negative emissions - part 3: innovation and upscaling, Environ. Res. Lett. 13 (2018), https://doi.org/10.1088/1748-9326/aabff4.
[88] M.V. Sarakinioti, M. Turrin, T. Konstantinou, M. Tenpierik, U. Knaack, Developing an integrated 3D-printed façade with complex geometries for active temperature control, Materials Today Communications 15 (2018) 275–279, https://doi.org/10.1016/j.mtcomm.2018.02.027.
[89] F. Sengers, A.J. Wieczorek, R. Raven, Experimenting for sustainability transitions: a systematic literature review, Technol. Forecast. Soc. Chang. 145 (8) (2016) 153–164, https://doi.org/10.1016/j.techfore.2016.08.031.
[90] R. Naber, R. Raven, M. Kouw, T. Dassen, Scaling up sustainable energy innovations, Energy Policy 110 (2017) 342–354, https://doi.org/10.1016/j.enpol.2017.07.056.
[91] S. Ruggiero, M. Martiskainen, T. Onkila, Understanding the scaling-up of community energy niches through strategic niche management theory: insights from Finland, J. Clean. Prod. 170 (2018) 581–590, https://doi.org/10.1016/j.jclepro.2017.09.144.
[92] F. Sengers, B. Turnheim, F. Berkhout, Beyond experiments: embedding outcomes in climate governance, Environmental Planning C Politics and Space 39 (6) (2021) 1148–1171, https://doi.org/10.1177/2399654420953861.
[93] S.G. Sjøtun, A ferry making waves: A demonstration project 'doing'institutional work in a greening maritime industry, Norsk Geografisk Tidsskrift-Norwegian Journal of Geography 73 (1) (2019) 16–28, https://doi.org/10.1080/00291951.2018.1526208.
[94] B. Bossink, The influence of knowledge flow on sustainable innovation in a project-based industry: from demonstration to limited adoption of eco-innovations, J. Clean. Prod. 193 (2018) 249–262, https://doi.org/10.1016/j.jclepro.2018.05.063.
[95] J. Kaipainen, L. Aarikka-Stenroos, How to renew business strategy to achieve sustainability and circularity? A process model of strategic development in incumbent technology companies, Bus. Strateg. Environ. 31 (5) (2022) 1947–1963, https://doi.org/10.1002/bse.2992.
[96] S. Laakso, E. Heiskanen, K. Matschoss, E.L. Apajalahti, F. Fahy, The role of practice-based interventions in energy transitions: a framework for identifying types of work to scale up alternative practices, Energy Res. Soc. Sci. 72 (2021) 101861, https://doi.org/10.1016/j.erss.2020.101861.
[97] M.J. Hoogstraaten, K. Frenken, W.P. Boon, The study of institutional entrepreneurship and its implications for transition studies, Environ. Innov. Soc. Trans. 36 (2020) 114–136, https://doi.org/10.1016/j.eist.2020.05.004.
[98] N. Bento, C. Wilson, Measuring the duration of formative phases for energy technologies, Environ. Innov. Soc. Trans. 21 (2016) 95–112, https://doi.org/10.1016/j.eist.2016.04.004.
[99] M. Junginger, E. de Visser, K. Hjort-Gregersen, J. Koornneef, R. Raven, A. Faaij, W. Turkenburg, (2006) technological learning in bioenergy systems, Energy Policy 34 (18) (2006) 4024–4041, https://doi.org/10.1016/j.enpol.2005.09.012.
[100] C. Wilson, Up-scaling, formative phases, and learning in the historical diffusion of energy technologies, Energy Policy 50 (2012) 81–94, https://doi.org/10.1016/j.enpol.2012.04.077.
[101] D. Lincot, The new paradigm of photovoltaics: from powering satellites to powering humanity, C. R. Phys. 18 (7–8) (2017) 381–390, https://doi.org/10.1016/j.crhy.2017.09.003.
[102] J.C. Ortiz Lizcano, Z. Haghighi, S. Wapperom, C. Infante Ferreira, O. Isabella, vd Dobbelsteen, A., & Zeman, M., Photovoltaic chimney: thermal modeling and concept demonstration for integration in buildings, Prog. Photovolt. Res. Appl. 28 (6) (2020) 465–482, https://doi.org/10.1002/pip.3194.
[103] R. Wang, S. Hasanefendic, E. Von Hauff, B. Bossink, The cost of photovoltaics: re-evaluating grid parity for PV systems in China, Renew. Energy 194 (2022) 469–481, https://doi.org/10.1016/j.renene.2022.05.101.
[104] R. Wang, S. Hasanefendic, E. Von Hauff, B. Bossink, A system dynamics approach to technological learning impact for the cost estimation of solar photovoltaics, Energies 16 (24) (2023) 8005, https://doi.org/10.3390/en16248005.
[105] R. Wang, S. Hasanefendic, E. Von Hauff, B. Bossink, Towards carbon neutrality: A multi-objective optimization model for photovoltaics systems installation planning, Sustain Energy Technol Assess 62 (2024) 103625, https://doi.org/10.1016/j.seta.2024.103625.
[106] H.A. Linstone, M. Turoff (Eds.), The Delphi Method, Addison-Wesley, Reading, MA, 1975, pp. 3–12.
[107] W.J. Sutherland, H.J. Woodroof, The need for environmental horizon scanning, Trends Ecol. Evol. 24 (10) (2009) 523–527, https://doi.org/10.1016/j.tree.2009.04.008.
[108] E. Mlecnik, Opportunities for supplier-led systemic innovation in highly energy-efficient housing, J. Clean. Prod. 56 (2013) 103–111, https://doi.org/10.1016/j.jclepro.2012.03.009.
[109] T.M. Skjølsvold, M. Ryghaug, Embedding smart energy technology in built environments: A comparative study of four smart grid demonstration projects, Indoor and Built Environment 24 (7) (2015) 878–890, https://doi.org/10.1177/1420326X15596210.
[110] A. Van der Loos, K. Frenken, M. Hekkert, S. Negro, On the resilience of innovation systems, Ind. Innov. 31 (1) (2024), https://doi.org/10.1080/13662716.2023.2269110.
[111] K. Davidson, I. Håkansson, L. Coenen, T.M.P. Nguyen, Municipal experimentation in times of crises:(re-) defining Melbourne's innovation district, Cities 132 (2023) 104042, https://doi.org/10.1016/j.cities.2022.104042.
[112] C. Simms, J. Frishammar, Technology transfer challenges in asymmetric alliances between high-technology and low-technology firms, Res. Policy 53 (3) (2024) 104937, https://doi.org/10.1016/j.respol.2023.104937.
[113] A. Fevolden, L. Coenen, T. Hansen, A. Klitkou, The role of trials and demonstration projects in the development of a sustainable bioeconomy, Sustainability 9 (3) (2017) 419, https://doi.org/10.3390/su9030419.
[114] H. Hellsmark, Unfolding of the formative phase of gasified biomass in the European Union: The role of system builders in realising the potential of second-generation transportation fuels from biomass, in: Department of Energy and Environment vol. Doctoral, Chalmers University of Technology, 2010. https://www.proquest.com/openview/a9a051b0293fdb931697c1bf01fb45de/1?pq-origsite=gscholar&cbl=18750&diss=y (accessed on 6 January 2025).
[115] H. Hellsmark, J. Frishammar, P. Söderholm, H. Ylinenpää, The role of pilot and demonstration plants in technology development and innovation policy, Res. Policy 45 (2016) 1743–1761, https://doi.org/10.1016/j.respol.2016.05.005.
[116] T. Moore, Strategic niche management and the challenge of successful outcomes, in: T. Moore, F. de Haan, R. Horne, B. Gleeson (Eds.), Urban Sustainability Transitions. Australian Cases - International Perspectives, Springer, Singapore, 2018, https://doi.org/10.1007/978-981-10-4792-3_7.
[117] M. Ryghaug, M. Ornetzeder, T.M. Skjølsvold, W. Throndsen, The role of experiments and demonstration projects in efforts of upscaling: an analysis of two projects attempting to reconfigure production and consumption in energy and mobility, Sustainability 11 (20) (2019) 5771, https://doi.org/10.3390/su11205771.
[118] G.C. Unruh, Escaping carbon lock-in, Energy Policy 30 (4) (2002) 317–325, https://doi.org/10.1016/S0301-4215(01)00098-2.
[119] K. Yoshikawa, H. Kawasaki, W. Yoshida, T. Irie, K. Konishi, T. Uto, D. Adachi, M. Kanematsu, H. Uzu, K. Yamamoto, Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%, Nat. Energy 2 (5) (2017) 1–8, https://doi.org/10.1038/nenergy.2017.32.
[120] A. Richter, M. Hermle, S.W. Glunz, Reassessment of the limiting efficiency for crystalline silicon solar cells, IEEE Journal of Photovoltaics 3 (2013) 1184–1191, https://doi.org/10.1109/JPHOTOV.2013.2270351.
[121] S. De Wolf, E. Aydin, Tandems have the power, Science 381 (2023) 30–31, https://doi.org/10.1126/science.adi6278.
[122] I. Hannula, D.M. Reiner, Near-term potential of biofuels, electrofuels and battery electric vehicles in decarbonising road transport, Joule 13 (10) (2019) 2390–2402, https://doi.org/10.1016/j.joule.2019.08.013.
[123] Fraunhofer FEP. (2023, 20 March) Retrofittable electrochromic films for windows and glass facades control light incidence [press release]. https://www.coatema.de/en/presse/pressemeldungen/351-retrofittable-electrochromic-films-for-windows-and-glass-facades-control-light-incidence (accessed on 6 January 2025).
[124] Vardon, P.J., Abels, H., Barnhoorn, A., Daniilidis, A., Bruhn, D., Drijkoningen, G., Elliott, K., van Esser, B., Laumann, S., van Paassen, P., Vargas Meleza, L., Vondrak, A., Voskov, D. (2024) A research and energy production geothermal project on the TU Delft campus: Project implementation and initial data collection. *Proceedings of the 49th Workshop on Geothermal Reservoir Engineering.* https://research.tudelft.nl/en/publications/a-research-and-energy-production-geothermal-project-on-the-tu-del (accessed on 6 January 2025).
[125] Bloemendal, M., Vardon, P.J., Medema, A., Snelleman, A., Marif, K., Beernink, S. T.W., van Veldhuizen, F., Pijnenborg, M., Sudintas, G. (2020) HT-ATES at the TU Delft Campus. TU Delft / ENGIE, Delft. https://www.warmingup.info/documenten/window-fase-1—a1—verkenning-hto-tud—feasibilityht_ates_tudelft.pdf (accessed on 6 January 2025).
[126] L. Di Natale, Y. Lian, E.T. Maddalena, J. Shi, C.N. Jones, Lessons learned from data-driven building control experiments: Contrasting gaussian process-based MPC, bilevel DeePC, and deep reinforcement learning, in *2022 IEEE*, in: *61st Conference on Decision and Control (CDC),* Pp, 2022, pp. 1111–1117, https://doi.org/10.1109/CDC51059.2022.9992445.
[127] Y. Lian, J. Shi, M. Koch, C.N. Jones, Adaptive robust data-driven building control via bilevel reformulation: an experimental result, IEEE Trans. Control Syst. Technol. 31 (6) (2023) 2420–2436, https://doi.org/10.1109/TCST.2023.3259641.
[128] E.T. Maddalena, Y. Lian, C.N. Jones, Data-driven methods for building control — a review and promising future directions, Control. Eng. Pract. 95 (2020) 104211, https://doi.org/10.1016/j.conengprac.2019.104211.
[129] C. Foulds, G. Valkenburg, M. Ryghaug, I. Suboticki, T.M. Skjølsvold, M. Korsnes, S. Heidenreich, Implementing Mission-oriented experiments: recommendations on epistemic inclusion for City stakeholders working in climate change initiatives, Journal of City Climate Policy and Economy 2 (1) (2023) 55–76, https://doi.org/10.3138/jccpe-2022-0014.

[130] L. Ingeborgrud, I. Suboticki, M. Ryghaug, T.M. Skjølsvold, Planners as middle actors in facilitating for city cycling, Mobilities 19 (1) (2024) 103–115, https://doi.org/10.1080/17450101.2023.2186799.
[131] M. Ryghaug, T.M. Skjølsvold, How policies and actor strategies affect electric vehicle diffusion and wider sustainability transitions, Proc. Natl. Acad. Sci. 120 (47) (2023) e2207888119, https://doi.org/10.1073/pnas.2207888119.
[132] M. Mazzucato, Mission-oriented research & innovation in the European Union: A problem-solving approach to fuel innovation-led growth, Publications Office. (2018), https://doi.org/10.2777/360325.
[133] M.P. Hekkert, M.J. Janssen, J.H. Wesseling, S.O. Negro, Mission-oriented innovation systems, Environ. Innov. Soc. Trans. 34 (2020) 76–79, https://doi.org/10.1016/j.eist.2019.11.011.
[134] R. Elzinga, M.J. Janssen, J. Wesseling, S.O. Negro, M.P. Hekkert, Assessing mission-specific innovation systems: towards an analytical framework, Environ. Innov. Soc. Trans. 48 (2023) 100745, https://doi.org/10.1016/j.eist.2023.100745.
[135] J. Wesseling, N. Meijerhof, Towards a Mission-oriented innovation systems (MIS) approach, application for Dutch sustainable maritime shipping, PLOS Sustainability and Transformation 2 (8) (2023) e0000075, https://doi.org/10.1371/journal.pstr.0000075.
[136] B. Zhang, J. Kroeger, N. Planavsky, Y. Yao, Techno-economic and life cycle assessment of enhanced rock weathering: a case study from the Midwestern United States, Environ. Sci. Technol. 57 (37) (2023) 13828–13837, https://doi.org/10.1021/acs.est.3c01658?goto=supporting-info&articleRef=control.
[137] D.M. Reiner, I. Hannula, T. Koljonen, M. Allen, W. Lucht, G. Guillén-Gosálbez, N. Mac Dowell, Europe's 'green deal' and carbon dioxide removal, Nature 589 (2021) 19, https://doi.org/10.1038/d41586-020-03643-0.
[138] M. Boettcher, F. Schenuit, O. Geden, The formative phase of German carbon dioxide removal policy: positioning between precaution, pragmatism and innovation, Energy Res. Soc. Sci. 98 (2023) 103018, https://doi.org/10.1016/j.erss.2023.103018.
[139] G. Nemet, J. Greene, F. Müller-Hansen, J.C. Minx, Dataset on the adoption of historical technologies informs the scale-up of emerging carbon dioxide removal measures, Commun Earth Environ 4 (2023) 1–10, https://doi.org/10.1038/s43247-023-01056-1.
[140] E. Eneqvist, A. Karvonen, Experimental governance and urban planning futures: five strategic functions for municipalities in local innovation, Urban Plan. 6 (1) (2021) 183–194, https://doi.org/10.17645/up.v6i1.3396.
[141] A. Karvonen, The City of permanent experiments?, in: Innovating Climate Governance: Moving beyond Experiments Cambridge University Press.doi: 10.1017/9781108277679.014, 2018, pp. 201–205.
[142] A. Kronsell, D. Mukhtar-Landgren, Experimental governance: the role of municipalities in urban living labs, Eur. Plan. Stud. 26 (5) (2018) 988–1007, https://doi.org/10.1080/09654313.2018.1435631.
[143] H. Bulkeley, The condition of urban climate experimentation, Sustainability: Science, Practice, and Policy 19 (1) (2023), https://doi.org/10.1080/15487733.2023.2188726.
[144] Femenías, P., & Thuvander, L. (2018) Transdisciplinary research in the built environment: A question of time. Technol. Innov. Manag. Rev., 8(8) https://www.proquest.com/openview/37f32ca6d306beb465e1bd6f6c5d8d23/1?pq-origsite=gscholar&cbl=2034500 (accessed on 6 January 2025).
[145] F. Leone, F. Reda, A. Hasan, Hu Rehman, F.C. Nigrelli, F. Nocera, V. Costanzo, Lessons learned from positive Energy District (PED) projects: cataloguing and Analysing technology solutions in different geographical areas in Europe, Energies 16 (1) (2023) 356, https://doi.org/10.3390/en16010356.
[146] S.G. Krangsås, K. Steemers, T. Konstantinou, S. Soutullo, M. Liu, E. Giancola, B. Prebreza, T. Ashrafian, L. Murauskaitė, N. Maas, Positive energy districts: identifying challenges and interdependencies, Sustainability 13 (19) (2021), https://doi.org/10.3390/su131910551.
[147] M. Van Wees, B. Pineda Revilla, H. Fitzgerald, D. Ahlers, N. Romero, B. Alpagut, J. Kort, C. Tjahja, G. Kaiser, V. Blessing, L. Patricio, S. Smit, Energy citizenship in new energy concepts, Environmental Sciences Proceedings 11, Article 27 (2021), https://doi.org/10.3390/environsciproc2021011027.
[148] P. Civiero, G. Turci, B. Alpagut, M. Kuzmic, S. Soutullo, M.N. Sánchez, O. Seco, S. Bossi, M. Haase, G. Massa, et al., Operational insights and future potential of the database for positive energy districts, Energies 17 (4) (2024) 899, https://doi.org/10.3390/en17040899.
[149] J. Kaipainen, L. Aarikka-Stenroos, From vision to commercialization of a circular economy innovation – A longitudinal study of overcoming challenges throughout the full innovation process, in: S. Jakobsen, T.A. Lauvås, M.T. Steinmo, E. A. Rasmussen, F. Quatraro (Eds.), Handbook of Innovation for Circular Economy, Edgar Elgar Publishing, Cheltenham, UK, 2021, pp. 59–71, https://doi.org/10.4337/9781800373099.00013.
[150] Van Hal, A. (2016) The third success factor of renovations with energy ambitions. *Conference SBE16* Toronto*, Regenerative and Resilient Urban Environments*, 19/20 September 2016, Toronto. https://trcaca.s3.ca-central-1.amazonaws.com/app/uploads/2020/03/30121355/Paper-A.van-Hal-SBE16-Toronto-pdf.pdf (accessed on 6 January 2025).
[151] Van Hal, A., Tom, N. & Coen, M. (2023) The third success factor of energy transition in disadvantaged neighbourhoods, findings of a Dutch environmental programme. *7th European conference on behaviour change and energy efficiency*, 28-29 November 2023, Maastricht.
[152] W.P. Boon, J. Edler, D.K. Robinson, Market formation in the context of transitions: A comment on the transitions agenda, Environ. Innov. Soc. Trans. 34 (2020) 346–347, https://doi.org/10.1016/j.eist.2019.11.006.
[153] W.P. Boon, J. Edler, D.K. Robinson, Conceptualizing market formation for transformative policy, Environ. Innov. Soc. Trans. 42 (2022) 152–169, https://doi.org/10.1016/j.eist.2021.12.010.
[154] M. Ottosson, T. Magnusson, H. Andersson, Shaping sustainable markets—A conceptual framework illustrated by the case of biogas in Sweden, Environ. Innov. Soc. Trans. 36 (2020) 303–320, https://doi.org/10.1016/j.eist.2019.10.008.
[155] H. Schanz, J. Federer, M. Wilczynski, Markets as leverage points for transformations of economic systems: the example of the German bioeconomy, Environ. Innov. Soc. Trans. 33 (2019) 140–161, https://doi.org/10.1016/j.eist.2019.04.003.
[156] S. Hyysalo, E. Heiskanen, J. Lukkarinen, K. Matschoss, M. Jalas, P. Kivimaa, E. Primmer, Market intermediation and its embeddedness–lessons from the Finnish energy transition, Environ. Innov. Soc. Trans. 42 (2022) 184–200, https://doi.org/10.1016/j.eist.2021.12.004.
[157] H. Hellsmark, S. Jacobsson, Opportunities for and limits to academics as system builders—the case of realizing the potential of gasified biomass in Austria, Energy Policy 37 (12) (2009) 5597–5611, https://doi.org/10.1016/j.enpol.2009.08.023.
[158] L. Aarikka-Stenroos, D. Chiaroni, J. Kaipainen, A. Urbinati, Companies' circular business models enabled by supply chain collaborations: an empirical-based framework, synthesis, and research agenda, Ind. Mark. Manag. 105 (2022) 322–339, https://doi.org/10.1016/j.indmarman.2022.06.015.
[159] T.J. Dean, J.S. McMullen, Toward a theory of sustainable entrepreneurship: reducing environmental degradation through entrepreneurial action, J. Bus. Ventur. 22 (1) (2007) 50–76, https://doi.org/10.1016/j.jbusvent.2005.09.003.
[160] R. Klein Woolthuis, F. Hooimeijer, B. Bossink, G. Mulder, J. Brouwer, Institutional entrepreneurship in sustainable urban development: Dutch successes as inspiration for transformation, J. Clean. Prod. 50 (2013) 91–100, https://doi.org/10.1016/j.jclepro.2012.11.031.
[161] M. Palmié, J. Boehm, J. Friedrich, V. Parida, J. Wincent, J. Kahlert, O. Gassmann, D. Sjödin, Startups versus incumbents in 'green' industry transformations: A comparative study of business model archetypes in the electrical power sector, Ind. Mark. Manag. 96 (2021) 35–49, https://doi.org/10.1016/j.indmarman.2021.04.003.
[162] N. Bocken, Y. Snihur, Lean startup and the business model: experimenting for novelty and impact, Long Range Plan. 53 (4) (2020) 101953, https://doi.org/10.1016/j.lrp.2019.101953.
[163] E. Ries, The Lean Startup: How today's Entrepreneurs Use Continuous Innovation to Create Radically Successful Businesses, Random House LLC, New York, 2011.
[164] J.C.J.M. Van den Bergh, Optimal diversity: increasing returns versus recombinant innovation, J. Econ. Behav. Organ. 68 (3–4) (2008) 565–580, https://doi.org/10.1016/j.jebo.2008.09.003.
[165] F.J. Van Rijnsoever, J. Van Den Berg, J. Koch, M.P.M.P. Hekkert, J. Van der Berg, Smart innovation policy: how network position and project composition affect the diversity of an emerging technology, Res. Policy 44 (5) (2015) 1094–1107, https://doi.org/10.1016/j.respol.2014.12.004.
[166] Callon, M. (1987) Society in the making: the study of technology as a tool for sociological analysis. The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology, 83–103. https://books.google.nl/books?hl=nl&lr=&id=SUCtOwns7TEC&oi=fnd&pg=PA83&dq=%5D+Callon,+M.+(1987).+Society+in+the+making:+The+study+of+technology+as+a+tool+for+sociological+analysis.+The+Social+Construction+of+Technological+Systems:+New+Directions+in+the+Sociology+and+History+of+Technology,+83%E2%80%93103.&ots=RyxGUPafYs&sig=QiLbtSyXDuA9Vosl1j_6zRGnooA&redir_esc=y#v=onepage&q&f=false (accessed 6 January 2025).
[167] C.M. Christensen, The innovator's Dilemma: When New Technologies Cause Great Firms to Fail, Harvard Business School Press Boston MA USA, 1997.
[168] D. Porcu, S. Castro, B. Otura, P. Encinar, I. Chochliouros, I. Ciornei, A. Bachoumis, Demonstration of 5G solutions for smart energy grids of the future: a perspective of the Smart5Grid project, Energies 15 (3) (2022) 839, https://doi.org/10.3390/en15030839.
[169] I. Ridjan, B.V. Mathiesen, D. Connolly, Terminology used for renewable liquid and gaseous fuels based on the conversion of electricity: a review, J. Clean. Prod. 112 (2016) 3709–3720, https://doi.org/10.1016/j.jclepro.2015.05.117.
[170] M. Grahn, E. Malmgren, A.D. Korberg, M. Taljegård, J.E. Anderson, S. Brynolf, J. Hansson, I.R. Skov, T.J. Wallington, Review of electrofuel feasibility—cost and environmental impact, Progress in Energy 4 (3) (2022) 032010, https://doi.org/10.1088/2516-1083/ac7937.
[171] E. Van der Roest, R. Bol, T. Fens, A. Van Wijk, Utilisation of waste heat from PEM electrolysers – unlocking local optimisation, Int. J. Hydrog. Energy 48 (72) (2023) 27872–27891, https://doi.org/10.1016/j.ijhydene.2023.03.374.
[172] G. Skouteris, G. Rodriguez-García, S.F. Reinecke, U. Hampel, The use of pure oxygen for aeration in aerobic wastewater treatment: A review of its potential and limitations, Bioresour. Technol. 312 (2020) 123595, https://doi.org/10.1016/j.biortech.2020.123595.
[173] H. Hekmatmehr, A. Esmaeili, M. Pourmahdi, S. Atashrouz, A. Abedi, M. A. Abuswer, D. Nedeljković, M. Latifi, S. Farag, A. Mohaddespour, Carbon capture technologies: A review on technology readiness level, Fuel 363 (2024) 130898, https://doi.org/10.1016/j.fuel.2024.130898.
[174] B.K. Sovacool, J. Axsen, W. Kempton, The future promise of vehicle-to-grid (V2G) integration: a sociotechnical review and research agenda, Annu. Rev. Environ. Resour. 42 (2017) 377–406, https://doi.org/10.1146/annurev-environ-030117-020220.
[175] T. Meelen, B. Doody, T. Schwanen, Vehicle-to-grid in the UK fleet market: an analysis of upscaling potential in a changing environment, J. Clean. Prod. 290 (2021) 125203, https://doi.org/10.1016/j.jclepro.2020.125203.

[176] T. Meelen, T. Schwanen, Organizations as users in sustainability transitions: embedding vehicle-to-grid technology in the United Kingdom, Energy Res. Soc. Sci. 106 (2023) 103303, https://doi.org/10.1016/j.erss.2023.103303.
[177] E. Autio, M. Kenney, P. Mustar, D. Siegel, M. Wright, Entrepreneurial innovation: the importance of context, Res. Policy 43 (7) (2014) 1097–1108, https://doi.org/10.1016/j.respol.2014.01.015.
[178] Brezet, J. C., Belmane, N., & Tijsma, S. (2019) TIPPING GUIDE: The Innovation Program's Perspective for the New Governance of Islands. https://vbn.aau.dk/en/publications/tipping-guide-the-innovation-programs-perspective-for-the-new-gov (accessed on 6 January 2025).
[179] K. Dimitropoulos, Design, Test and Evaluation of Hybrid Systems for Powering Stages with Limited Access to Main Electricity, MSc Thesis,, Faculty of Industrial Design Engineering, Delft University of Technology, Netherlands, 2013.
[180] R. Hoogma, R. Kemp, J. Schot, B. Truffer, Experimenting for sustainable transport, Taylor & Francis. (2002), https://doi.org/10.4324/9780203994061.
[181] A. Smith, R. Raven, What is protective space? Reconsidering niches in transitions to sustainability, Res. Policy 41 (6) (2012) 1025–1036, https://doi.org/10.1016/j.respol.2011.12.012.
[182] J. Blasch, N.M. van der Grijp, D. Petrovics, J. Palm, N. Bocken, S.J. Darby, J. Barnes, P. Hansen, T. Kamin, U. Golob, S.J. Andor, S. Sommer, A. Nicita, M. Musolino, M. Mlinarič, New clean energy communities in polycentric settings: four avenues for future research, Energy Res. Soc. Sci. 82 (2021) 102276, https://doi.org/10.1016/j.erss.2021.102276.
[183] A.L. Berka, E. Creamer, Taking stock of the local impacts of community owned renewable energy: A review and research agenda, Renew. Sust. Energ. Rev. 82 (2018) 3400–3419, https://doi.org/10.1016/j.rser.2017.10.050.
[184] A. Macintosh, D. Wilkinson, Searching for public benefits in solar subsidies: A case study on the Australian government's residential photovoltaic rebate program, Energy Policy 39 (6) (2011) 3199–3209, https://doi.org/10.1016/j.enpol.2011.03.007.
[185] D. Sivaraman, R. Horne, Regulatory potential for increasing small scale grid connected photovoltaic (PV) deployment in Australia, Energy Policy 39 (2) (2011) 586–595, https://doi.org/10.1016/j.enpol.2010.10.030.
[186] Webster, M., Fisher-Vanden, K., Popp, D., Santen, N., 2015. Should We Give Up After Solyndra? Optimal Technology R\&D Portfolios under Uncertainty. National Bureau of Economic Research Working Paper Series No. 21396. https://web.archive.org/web/20190501224904id_/https://www.nber.org/papers/w21396.pdf (accessed on 6 January 2025).
[187] D.M. Hart, Beyond the technology pork barrel? An assessment of the Obama administration's energy demonstration projects, Energy Policy 119 (2018) 367–376, https://doi.org/10.1016/j.enpol.2018.04.047.
[188] A. Van der Loos, H.E. Normann, J. Hanson, M.P. Hekkert, The co-evolution of innovation systems and context: offshore wind in Norway and the Netherlands, Renew. Sust. Energ. Rev. 138 (2021), https://doi.org/10.1016/j.rser.2020.110513.
[189] T. Mäkitie, J. Hanson, M. Steen, T. Hansen, A.D. Andersen, Complementarity formation mechanisms in technology value chains, Res. Policy 51 (7) (2022) 104559, https://doi.org/10.1016/j.respol.2022.104559.
[190] I. Oskam, B. Bossink, A.P. de Man, Valuing value in innovation ecosystems: how cross-sector actors overcome tensions in collaborative sustainable business model development, Bus. Soc. 60 (5) (2021) 1059–1091, https://doi.org/10.1177/0007650320907145.
[191] G. De Vries, K. Biely, E. Chappin, Psychology: the missing link in transitions research, Environ. Innov. Soc. Trans. 41 (2021) 42–44, https://doi.org/10.1016/j.eist.2021.09.015.
[192] J.R. Goddin, The role of a circular economy for energy transition, in: The Material Basis of Energy Transitions, Academic Press, 2020, pp. 187–197, https://doi.org/10.1016/B978-0-12-819534-5.00012-X.
[193] U.E. Hansen, I. Nygaard, M. Dal Maso, The dark side of the sun: solar e-waste and environmental upgrading in the off-grid solar PV value chain, Ind. Innov. 28 (1) (2021) 58–78, https://doi.org/10.4324/9781003259084.
[194] D. Sica, O. Malandrino, S. Supino, M. Testa, M.C. Lucchetti, Management of end-of-life photovoltaic panels as a step towards a circular economy, In Renewable and Sustainable Energy Reviews. 82 (2018) 2934–2945, https://doi.org/10.1016/j.rser.2017.10.039.
[195] D. Vela Almeida, V. Kolinjivadi, T. Ferrando, B. Roy, H. Herrera, M. Vecchione Gonçalves, G. Van Hecken, The "greening" of empire: the European green Deal as the EU first agenda, Polit. Geogr. 105 (2023), https://doi.org/10.1016/j.polgeo.2023.102925.
[196] D. Andreucci, G. García López, I.M. Radhuber, M. Conde, D.M. Voskoboynik, J. D. Farrugia, C. Zografos, The coloniality of green extractivism: unearthing decarbonisation by dispossession through the case of nickel, Polit. Geogr. 107 (2023), https://doi.org/10.1016/j.polgeo.2023.102997.
[197] Zografos, C., & Robbins, P. (2020) Green sacrifice zones, or why a green new Deal cannot ignore the cost shifts of just transitions. In *one earth* (Vol. 3, issue 5, pp. 543–546) https://www.cell.com/one-earth/fulltext/S2590-3322(20)30542-X (accessed on 6 January 2025).
[198] J. Gallagher, B. Basu, M. Browne, A. Kenna, S. McCormack, F. Pilla, D. Styles, Adapting stand-alone renewable energy technologies for the circular economy through eco-design and recycling, J. Ind. Ecol. 23 (1) (2019) 133–140, https://doi.org/10.1111/jiec.12703.
[199] H.S. Kristensen, M.A. Mosgaard, A review of micro level indicators for a circular economy–moving away from the three dimensions of sustainability? J. Clean. Prod. 243 (2020) 118531 https://doi.org/10.1016/j.jclepro.2019.118531.
[200] E. MacArthur, Towards the circular economy, Ellen MacArthur Foundation. (2012). https://www.werktrends.nl/app/uploads/2015/06/Rapport_McKinsey-Towards_A_Circular_Economy.pdf (accessed on 6 January 2025).
[201] G.D. Sharma, M. Verma, B. Taheri, R. Chopra, J.S. Parihar, Socio-economic aspects of hydrogen energy: an integrative review, Technol. Forecast. Soc. Chang. 192 (2023) 122574, https://doi.org/10.1016/j.techfore.2023.122574.
[202] Y. Sun, A. Anwar, A. Razzaq, X. Liang, M. Siddique, Asymmetric role of renewable energy, green innovation, and globalization in deriving environmental sustainability: evidence from top-10 polluted countries, Renew. Energy 185 (2022) 280–290, https://doi.org/10.1016/j.renene.2021.12.038.
[203] D. Zhang, M. Zheng, G.F. Feng, C.P. Chang, Does an environmental policy bring to green innovation in renewable energy? Renew. Energy 195 (2022) 1113–1124, https://doi.org/10.1016/j.renene.2022.06.074.
[204] K. Sperling, F. Arler, Local government innovation in the energy sector: A study of key actors' strategies and arguments, Renew. Sust. Energ. Rev. 126 (March) (2020) 109837, https://doi.org/10.1016/j.rser.2020.109837.
[205] J. Van der Leer, A. Calvén, W. Glad, P. Femenías, K. Sernhed, Energy systems in sustainability-profiled districts in Sweden: A literature review and a socio-technical ecology approach for future research, Energy Res. Soc. Sci. 101 (2023) 103118, https://doi.org/10.1016/j.erss.2023.103118.
[206] D. Mukhtar-Landgren, A. Kronsell, Y. Voytenko Palgan, T. von Wirth, Municipalities as enablers in urban experimentation, J. Environ. Policy Plan. 21 (6) (2019) 718–733, https://doi.org/10.1080/1523908X.2019.1672525.
[207] C. Xue, M. Shahbaz, Z. Ahmed, M. Ahmad, A. Sinha, Clean energy consumption, economic growth, and environmental sustainability: what is the role of economic policy uncertainty? Renew. Energy 184 (2022) 899–907, https://doi.org/10.1016/j.renene.2021.12.006.
[208] B. Collins, "It's not talked about": the risk of failure in practice in sustainability experiments, Environ. Innov. Soc. Trans. 35 (2020) 77–87, https://doi.org/10.1016/j.eist.2020.02.008.
[209] K.C. Von Schönfeld, On the'impertinence of impermanence'and three other critiques: reflections on the relationship between experimentation and lasting–or significant?–change, Journal of Urban Mobility 5 (2024) 100070, https://doi.org/10.1016/j.urbmob.2023.100070.
[210] C.K. Ansell, M. Bartenberger, Varieties of experimentalism, Ecol. Econ. 130 (2016) 64–73, https://doi.org/10.1016/j.ecolecon.2016.05.016.
[211] F. Engels, A. Wentland, S.M. Pfotenhauer, Testing future societies? Developing a framework for test beds and living labs as instruments of innovation governance, Res. Policy 48 (9) (2019) 103826, https://doi.org/10.1016/j.respol.2019.103826.
[212] L.R. Cohen, R.G. Noll, The Technology Pork Barrel, Brookings, Washington, 1991.
[213] A. Grubler, C. Wilson, Energy Technology Innovation: Learning from Historical Successes and Failures, Cambridge University Press, Cambridge, 2014.
[214] Flyvberg, B. (2011) Case study. In: Denzin, N.K., Lincoln, Y.S. The Sage Handbook of Qualitative Research, 4th ed., Thousand Oaks, CA, 301–316.
[215] Yin, R. K. (2009) Case Study Research: Design and Methods (Vol. vol. 5) Sage, CA.
[216] L. Steg, J. Veldstra, K. de Kleijne, Ş. Kılkış, A.F.P. Lucena, L.J. Nilsson, M. Sugiyama, P. Smith, M. Tavoni, H. de Coninck, R. van Diemen, P. Renforth, S. Mirasgedis, G. Nemet, R. Görsch, H. Muri, P. Bertoldi, L.F. Cabeza, É. Mata, A. Novikova, L.R. Caldas, M. Chàfer, R. Khosla, D. Vérez, A method to identify barriers to and enablers of implementing climate change mitigation options, One Earth 5 (2022) 1216–1227, https://doi.org/10.1016/j.oneear.2022.10.007.
[217] C. Roberts, G. Nemet, Systematic historical analogue research for decision-making (SHARD): introducing a new methodology for using historical case studies to inform low-carbon transitions, Energy Res. Soc. Sci. 93 (2022) 102768, https://doi.org/10.1016/j.erss.2022.102768.
[218] D. Berg-Schlosser, G. de Meur, B. Rihoux, C.C. Ragin, Qualitative comparative analysis (QCA) as an approach, in: B. Rihoux, C.C. Ragin (Eds.), Configurational Comparative Methods: Qualitative Comparative Analysis (QCA) vol. 51, SAGE Publications, Thousand Oaks, CA, 2009, pp. 1–18, and related techniques (Applied Social Research Methods Series,.
[219] D.C. Invernizzi, G. Locatelli, N. Brookes, A.R. Davis, Qualitative comparative analysis as a method for project studies: the case of energy infrastructure, Renew. Sust. Energ. Rev. 133 (2020) 110314, https://doi.org/10.1016/j.rser.2020.110314.
[220] M.M.H. Chappin, P. Schipper, In kaart brengen versterking collectieve kennisbasis na acht jaar Topsector Energiebeleid Eindrapportage, Universiteit Utrecht, 2021.
[221] M.M.H. Chappin, P. Schipper, Vervolgonderzoek collectieve kennisbasis naar aanleiding van Topsector Energiebeleid en missiegedreven beleid, Universiteit Utrecht, 2023.
[222] T. Pieri, A. Nikitas, A. Castillo-Castillo, A. Angelis-Dimakis, Holistic assessment of carbon capture and utilization value chains, Environments 5 (10) (2018) 108, https://doi.org/10.3390/environments5100108.
[223] C.J. Quarton, S. Samsatli, The value of hydrogen and carbon capture, storage and utilisation in decarbonising energy: insights from integrated value chain optimisation, Appl. Energy 257 (2020) 113936, https://doi.org/10.1016/j.apenergy.2019.113936.
[224] M. Sairanen, L. Aarikka-Stenroos, Low-carbon business models: review and typology, Ind. Mark. Manag. 123 (2024) 222–250. https://www.sciencedirect.com/science/article/pii/S0019850124001627.
[225] J. Kaipainen, O. Dziubaniuk, M. Sairanen, L. Aarikka-Stenroos, What determines value creation in innovating carbon-neutral supply chains? ISPIM innovation management conference, Tallinn, Estonia, 10–12 (June 2024) (2024).
[226] O. Dziubaniuk, M. Sairanen, L. Aarikka-Stenroos, E.-L. Pohls, Understanding value mining of the carbon capturing innovations, IPDMC Conference, Lecco, Italy, 6–7 (June 2023) (2023).

[227] M. Ryghaug, B.T. Haugland, R.A. Søraa, T.M. Skjølsvold, Testing emergent technologies in the Arctic: how attention to place contributes to visions of autonomous vehicles, Sci. Technol. Stud. 35 (4) (2022) 4–21, https://doi.org/10.23987/sts.101778.
[228] Y. Yang, P.E. Campana, J. Yan, Potential of unsubsidized distributed solar PV to replace coal-fired power plants, and profits classification in Chinese cities, Renew. Sust. Energ. Rev. 131 (June) (2020) 109967, https://doi.org/10.1016/j.rser.2020.109967.
[229] M.M. Zhang, C. Zhang, L.Y. Liu, D.Q. Zhou, Is it time to launch grid parity in the Chinese solar photovoltaic industry? Evidence from 335 cities, Energy Policy 147 (September) (2020) 111733, https://doi.org/10.1016/j.enpol.2020.111733.
[230] J. Ramsebner, R. Haas, A. Ajanovic, M. Wietschel, The sector coupling concept: A critical review, Wiley Interdisciplinary Reviews: Energy and Environment 10 (4) (2021) 1–27, https://doi.org/10.1002/wene.396.
[231] A. Aggarwal, V.K. Chawla, A sustainable process for conversion of petrol engine vehicle to battery electric vehicle: A case study, Materials Today: Proceedings 38 (2021) 432–437, https://doi.org/10.1016/j.matpr.2020.07.617.
[232] Patlins, A., Hnatov, A., Arhun, S., Hnatova, H., & Saraiev, O. (2022) Features of converting a car with an internal combustion engine into an electric car. In *2022 IEEE 7th international energy conference (ENERGYCON)* (pp. 1-6) doi:https://doi.org/10.1109/ENERGYCON53164.2022.9830183.
[233] S. Cassells, J. Holland, A. Meister, End-of-life vehicle disposal: policy proposals to resolve an environmental issue in New Zealand, J. Environ. Policy Plan. 7 (2) (2005) 107–124, https://doi.org/10.1080/15239080500338499.
[234] I. Oskam, B. Bossink, A.P. de Man, The interaction between network ties and business modeling: case studies of sustainability-oriented innovations, J. Clean. Prod. 177 (2018) 555–566, https://doi.org/10.1016/j.jclepro.2017.12.202.
[235] E. Mlecnik, A. Straub, T. Haavik, Collaborative business model development for home energy renovations, Energ. Effic. 12 (2018) 123–138, https://doi.org/10.1007/s12053-018-9663-3.
[236] E. Von Hippel, Open user innovation, in: Handbook of the Economics of Innovation vol. 1, North-Holland, 2010, pp. 411–427, https://doi.org/10.1016/S0169-7218(10)01009-9.
[237] J. Battilana, B. Leca, E. Boxenbaum, How actors change institutions: towards a theory of institutional entrepreneurship, Acad. Manag. Ann. 3 (1) (2009) 65–107, https://doi.org/10.1080/19416520903053598.
[238] US Department of Energy (USDOE) (2021) Carbon Negative Shot. https://www.energy.gov/fecm/carbon-negative-shot (accessed on 6 January 2025).
[239] US Department of Energy (USDOE) (2021) Hydrogen Shot: An Introduction. https://www.energy.gov/eere/fuelcells/articles/hydrogen-shot-introduction (accessed on 6 January 2025).
[240] D. Merino, N. El Hadi, Do Glitzy Awards like the Earthshot Prize Actually Help Solve Problems of Climate Change? – Podcast, *the Conversation*, 6 April, https://theconversation.com/do-glitzy-awards-like-the-earthshot-prize-actually-help-solve-problems-of-climate-change-podcast-203384, 2023. (Accessed 6 January 2025).
[241] J. Barnes, P. Hansen, T. Kamin, U. Golob, S. Darby, N.M. van der Grijp, D. Petrovics, Creating valuable outcomes: an exploration of value creation pathways in the business models of energy communities, Energy Res. Soc. Sci. 108 (2024) 103398, https://doi.org/10.1016/j.erss.2023.103398.
[242] E. Boyle, C. Watson, G. Mullally, Ó' Gallachóir, B., Regime-based transition intermediaries at the grassroots for community energy initiatives, Energy Res. Soc. Sci. 74 (January) (2021), https://doi.org/10.1016/j.erss.2021.101950.
[243] B. Warbroek, T. Hoppe, F. Coenen, H. Bressers, The role of intermediaries in supporting local low-carbon energy initiatives, Sustainability 10 (7) (2018), https://doi.org/10.3390/su10072450.
[244] F. Hanke, R. Guyet, M. Feenstra, Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases, Energy Res. Soc. Sci. 80 (2021) 102244, https://doi.org/10.1016/j.erss.2021.102244.
[245] L. Corsini, J. Moultrie, What is design for social sustainability? A systematic literature review for designers of product-service systems, Sustainability 13 (11) (2021) 5963, https://doi.org/10.3390/su13115963.
[246] C.S. Rocha, P. Antunes, P. Partidário, Design for sustainability models: A multiperspective review, J. Clean. Prod. 234 (2019) 1428–1445, https://doi.org/10.1016/j.jclepro.2019.06.108.
[247] M. Palmié, V. Parida, A. Mader, J. Wincent, Clarifying the scaling concept: A review, definition, and measure of scaling performance and an elaborate agenda for future research, J. Bus. Res. 158 (2023) 113630, https://doi.org/10.1016/j.jbusres.2022.113630.
[248] J.J. Jansen, C. Heavey, T.J. Mom, Z. Simsek, S.A. Zahra, Scaling-up: building, leading and sustaining rapid growth over time, J. Manag. Stud. 60 (3) (2023) 581–604, https://doi.org/10.1111/joms.12910.
[249] T. Hansen, L. Coenen, Unpacking resource mobilisation by incumbents for biorefineries: the role of micro-level factors for technological innovation system weaknesses, Tech. Anal. Strat. Manag. 29 (5) (2017) 500–513, https://doi.org/10.1080/09537325.2016.1249838.
[250] M.M.V. Cantarero, Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries, Energy Res. Soc. Sci. 70 (2020) 101716, https://doi.org/10.1016/j.erss.2020.101716.
[251] M. Hodson, S. Marvin, Cities mediating technological transitions: understanding visions, intermediation and consequences, Tech. Anal. Strat. Manag. 21 (4) (2009) 515–534, https://doi.org/10.1080/09537320902819213.
[252] T. Santarius, L. Dencik, T. Diez, H. Ferreboeuf, P. Jankowski, S. Hankey, P. Staab, Digitalization and sustainability: a call for a digital green deal, Environ. Sci. Pol. 147 (2023) 11–14, https://doi.org/10.1016/j.envsci.2023.04.020.
[253] A. Franco, M. Shaker, D. Kalubi, S. Hostettler, A review of sustainable energy access and technologies for healthcare facilities in the global south, Sustain Energy Technol Assess 22 (2017) 92–105, https://doi.org/10.1016/j.seta.2017.02.022.
[254] L. Olatomiwa, R. Blanchard, S. Mekhilef, D. Akinyele, Hybrid renewable energy supply for rural facilities: an approach to quality healthcare delivery, Sustain Energy Technol Assess n.30 (2018) 121–138, https://doi.org/10.1016/j.seta.2018.09.007.