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2025

Original citation:
Hoicka, C. E., Graziano, M., Willard-Stepan, M., & Zhao, Y. (2024). Insights to accelerate place-based at scale renewable energy landscapes: An analytical framework to typify the emergence of renewable energy clusters along the energy value chain. *Applied Energy*, *377*, 124559.
https://doi.org/10.1016/j.apenergy.2024.124559

Applied Energy 377 (2025) 124559

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Insights to accelerate place-based at scale renewable energy landscapes: An analytical framework to typify the emergence of renewable energy clusters along the energy value chain

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HIGHLIGHTS

- Renewable energy clusters potentially drive a reliable low-carbon energy transition.
- Renewable energy clusters are place-based and heterogenous.
- Industrial and material renewable energy cluster types are identified.
- Seven dimensions are proposed to predict renewable energy cluster emergence.
- The typification of renewable energy clusters will support policy development.

ARTICLE INFO

Keywords:
Renewable energy clusters
Energy geography
Regional science
Typification
Technology innovation system
Diffusion of innovations
Industrial clusters
Place-based

ABSTRACT

Renewable energy transitions depend on activities at both ends of the value-chain or lifecycle, from the development of new innovations and technologies to their widespread diffusion. Place-based at scale approaches to renewable energy landscapes create local value, incorporate multifunctionality and decentralisation, mitigate harm for ecosystems, address justice and local resilience. That the potential, demand, and production of renewable energies are place-based phenomena is not accounted for in dominant energy-economy models, requiring new methods of analysis for an energy transition. The emergence of renewable energy across landscapes is increasingly linked in practice to the concept of "renewable energy clusters" that acknowledge the emergence of renewable energy as spatially distributed, heterogeneous and place-based phenomena. Renewable energy clusters describe a range of place-based energy activities along the energy value chain, from production of technologies and innovations to their use. Despite their promise, there lacks a clear definition and typology of renewable energy clusters, and research has not yet synthesised the place-based factors that influence or inhibit their emergence, that could be used to inform place-based strategies that address local assets, actors, space, labour, knowledge issues, or localised justice issues. This work offers a first step by serving as a preliminary investigation of renewable energy clusters and the factors that may predict their emergence. First, a qualitative approach is used to identify three initial types of renewable energy clusters along the energy value chain. The fields of regional sciences, technology innovation systems, and energy geography are drawn upon to identify factors that may influence or inhibit the emergence and form of renewable energy clusters. The seven synthesised dimensions that can be tested to typify and predict renewable energy cluster emergence: actors, institutions, networks, knowledge and tools, proximity, location characteristics, and path dependency. These initial types can guide the development of a sample of empirical cases of renewable energy clusters that can be analysed through machine learning typification to identify a more nuanced articulation of vertically integrated cluster types along the energy value chain. Typification can reveal characteristics these renewable energy clusters have in common with others, and what outcomes emerge from these characteristics within the specific context of place-based energy transitions.

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https://doi.org/10.1016/j.apenergy.2024.124559
Received 29 May 2024; Received in revised form 22 August 2024; Accepted 18 September 2024

List of acronyms

IPCC	Intergovernmental Panel on Climate Change
VRES	Variable Renewable Energy Sources
SMEs	Small and Medium-Sized Enterprises
IRECs	Industrial Renewable Energy Clusters
SHRECs	Shared Renewable Energy Clusters for the production, distribution and consumption of renewable energy
RECPECIs	Renewable Energy Clusters That Power Existing Communities and Industries
ICESs	Integrated Community Energy Systems
RED II	The revised Renewable Energy Directive
cVPP	A community-based Virtual Power Plant
DisGenMi	Distributed Generation Microgrid
RECs	Renewable Energy Clusters
R&D	Research and Development

1. Introduction

Energy use is responsible for over two thirds of global greenhouse gas emissions [1]. There are a range of low-carbon technology options available that could be employed in an energy transition to mitigate climate change [2]. The declining costs of renewable energy technologies have made them the lowest cost option, including compared to coal [3]. Renewable energy is emerging across a range of contexts due to activities along the energy value-chain, from the development of new innovations and technologies, to their manufacture, to their widespread diffusion, to the production, distribution and consumption of energy [4]. Currently, 3870 GW of renewable energy is installed, globally [5]. A transition to predominantly renewable energy could see a global system of 8700 GW [6] to 30,000 GW of renewable energy through the addition of predominantly wind and solar power, with a much smaller share of geothermal and hydroelectricity, while global annual investment could reach $4.5 trillion USD in 2030 and $4.7 trillion USD in 2050 [7]. The speed and scale of an energy transition that relies on renewable energy has many societal implications and opportunities to incorporate citizen participation, equity and justice in workforce transitions, and reconciliation with Indigenous people [8].

To so dramatically increase the share of renewable energy in global energy systems requires overcoming a wide range of challenges oftentimes related to path dependencies that are infrastructural, institutional and cultural [9,10]. For example, one important challenge to increasing the share of renewable energy in energy systems is based on their socio-technological and spatial limitations in comparison to incumbent hydroelectricity, thermal power electricity and fossil fuel based energy systems that can more easily meet demand both temporally and spatially [11,12]. Many forms of renewable power are temporally variable renewable energy sources (VRES), whether hourly, daily or seasonally [13], and their potential is spatially dependent and dispersed, often outside centres of demand (cities and communities) [14]. VRES can be difficult to dispatch and to integrate into electricity grids to meet demand reliably [9]. Many hypothetical engineering optimization models indicate technological solutions, showing that one way to address VRES and reliability is through the grouping, or clustering, of multiple types of VRES (complementarity) and integrating flexibility, such as demand response or storage. A systematic literature review to address complementarity and actors simultaneously demonstrated that these methods of providing load balancing among VRES are well established in hypothetical engineering optimization models [15]. Institutional challenges to the diffusion of renewable energy are often from incumbents, vested interests [16,17], and institutional inertia [18]. Social acceptance can also be challenged through backlash to renewable energy procurement policies [19]. The social acceptance and implementation of renewable energy is often linked to the transparency of decision making processes and the distribution of impacts and benefits[1] among local actors [20], often requiring the removal of structural barriers to participation [21–23].

These combined social, spatial, and temporal challenges can be addressed through the lens of “renewable energy landscapes” and “place-based at scale” approaches that aim to adapt technology and infrastructure collectively and coherently towards community goals and create value locally [24]. Place-based at scale approaches to renewable energy landscapes create local value, incorporate multifunctionality and decentralisation, mitigate harm for ecosystems, address justice and local resilience [24]. O’Neil et al. [24] argue that new cooperation between disciplines to design renewable energy landscapes at scale could support scaled approaches, provide insights for replicability that would accelerate a low-carbon energy transition, as well as reconcile the acknowledged challenges and tensions between top-down and bottom-up approaches [24].

The emergence of renewable energy across landscapes is increasingly linked in practice to the concept of “renewable energy clusters” that acknowledge the emergence of renewable energy as spatially distributed, heterogeneous and place-based phenomena. Renewable energy clusters are described by a range of terminology and synonyms across literature, exist in different forms along the energy value chain, and are hypothesised as important to a transition towards predominantly renewable energy systems and could help drive sustainability transitions [15,25–28]. For example, the “renewable energy clusters” defined by Jaegersberg and Ure [29] describe the research, development and manufacture of renewable energy technology, as similar to the place-based concept of industrial clusters, built upon regional agglomeration economies. Whereas, “renewable energy clusters” defined by Hoicka et al. [26] are characterised by the production, distribution and consumption of energy, as the combination of multiple renewable technologies (e.g., wind and solar complementarity) with flexibility for balancing, such as storage, demand response, virtual power plants, and peer to peer sharing, and relate these to governance and procedural justice aspects of renewable energy transitions.

Renewable energy clusters in their various forms currently exist on several continents [27,29], but the factors that influence their emergence in the real-world are much less understood [30]. That is, there exists a gap in understanding between models, scenarios and forecasts that hypothetically predict the uptake of renewable energy on the ground, and what occurs in practice [15]. This study seeks to move beyond hypothetical engineering and economic modelling to contribute empirical and place-based knowledge about the factors that influence the emergence of renewable energy by analysing how renewable energy clusters emerge in different forms across the energy value chain, in different places. Despite the perceived importance of renewable energy clusters in energy transitions research, there exists little empirical evidence about what influences their emergence. Furthermore, between the two ends of the energy value chain there could exist a range of renewable energy clusters that exist in practice. If the factors that influence the emergence of renewable energy clusters could be identified empirically, the analysis would contribute to a better understanding of how to replicate, accelerate and operationalize energy transitions that employ large shares of renewable energy. As renewable energy clusters are place-based phenomena, these empirical analyses could be more easily linked to procedural (who participates in making decisions) and distributive (who benefits through the distribution of revenue and employment) energy justice concerns, as well as to their alignment with ecosystem services and provision of local value creation.

This work offers a first step in addressing these research objectives by

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[1] These include socioeconomic benefits, such as the creation and distribution of jobs and revenues.

providing a preliminary investigation of the concept of renewable energy clusters and the factors that may predict their emergence. At a later stage, beyond this study, the outcomes from this first step of research can guide the development of a sample of existing cases of renewable energy clusters to provide empirical analysis. Gathering a wide range of empirical examples of renewable energy clusters offers the opportunity to incorporate a wide range of empirical data and offer a nuanced articulation of cluster types along the energy value chain, and to test the factors that predict their emergence. Machine learning typification is one modelling tool that can achieve these outcomes, by identifying the characteristics these agglomerations have in common with others, and what consequences emerge from these characteristics within the specific context of place-based energy transitions. That is, the typification of an empirical dataset of different types of renewable clusters could enhance our understanding of place-based at scale renewable energy landscapes by identifying how they may emerge differently in different locations with different cultural, social, political and economic contexts.

To this end, in the first step in this study, several types of renewable energy clusters are identified qualitatively. In the second step, the technology innovation system approach in the field of sustainability transitions, energy geography, and spatial and regional approaches are assessed against the range of qualitative clusters, upon which an initial analytical framework of the factors that could influence the emergence of a range of renewable energy clusters is developed and presented.

2. Context in current literature

2.1. Challenges of renewable energy systems

Although renewable energy transitions are possible, their characteristics, pathways and timeframes are strongly debated [e.g., 12,31,32].

Renewable energy suffers from a range of disadvantages when compared to traditional thermal generation that make it difficult to replace fossil-fuel based systems with renewable energy systems. For example, the low spatial density (often measured in Watts produced or consumed per m^2) of energy production of renewable energy is orders of magnitude lower than that of traditional thermal, fossil fuel and nuclear energy [12]. Unlike fossil fuels and nuclear power that can be sited closer to locations of demand, renewable energy potential is often site specific, making it a spatially dispersed resource, interacting with landscapes and communities differently than historically developed systems [33].

One long standing critique for the production, distribution and consumption of renewable energy is that many renewable energy sources are time-variable and typically do not match with demand either spatially or temporally [13]. Reliable renewable energy systems exist hypothetically in engineering models of multi-energy systems that cluster multiple sources, uses and flexibility mechanisms to better match supply and demand [15,34]. In theory, the reliability of renewable energy improves as innovations and technologies are clustered, taking advantage of complementarity of renewable energy, demand response, load balancing, storage, prosumership and other forms of flexibility, and bi-directionality of energy supply in order to match supply and demand temporally [27,35,36]. However, in practice, how these clusters of technologies and innovations converge to be implemented and governed to provide more reliable renewable energy in space and time, and which types of actors are involved, remains largely unclear [15,30].

2.2. Production of renewable energy technologies and innovations

Over the past decade, the role of industrial clusters have been proposed as loci where to foster sustainable transitions and/or forms of sustainability within new synergistic processes [37,38]. The place-based concept of “industrial clusters” can support the production of renewable energy along different stages of the value chain and have been proposed as important to understanding how to accelerate this transition [28,29].

Industrial clusters have long been studied in regional sciences and economic geography [28]. As policy tools and analytical concepts, industrial clusters are part of the broader stream of literature in economic geography that looks at regional industrial path development [39].

Industrial clusters refer to geographic concentrations of interconnected companies, specialised suppliers, service providers, and associated institutions, such as universities, research centres or government agencies, in a particular field present in a nation or region [38,40]. The concept of “clusters” was popularised by Porter [41] although there are several definitions of “industrial clusters”. For example, “clusters are geographic concentrations of interconnected companies and institutions in a particular field” clusters as “geographic concentrations of industries related by knowledge, skills, inputs, demand and/or other linkages” [42]. Clusters can also be “firms in a region producing similar or related products, using similar processes, or engaging in similar functions (headquarters; research and development).” [43]. These clusters are defined as “a population of firms, mostly small and medium-sized enterprises (SMEs), carrying out different activities in the same industry and located in a geographically bounded area” [44].

2.3. Modelling energy through typification

To inform an energy transition, models are often used for their predictive and decision-making capacity to support policy decisions [45]. Many of the dominant energy-economy models are Integrated Assessment Models and techno-economic models [46]. While these are useful to estimate the impacts of policies on outcomes like greenhouse gas emissions and energy use, they do not incorporate operational [47], spatial [11] or actor dimensions [15] or provide insight into socio-technical transitions [48]. Sustainability transition models that incorporate actors, but not space, are less dominant. Engineering models take into account technology and behaviour but are not necessarily place-based and context driven [15].

The creation of a good typology can support the identification, prediction and explanation of emergence and evolution of renewable energy clusters. Renewable energy clusters are representative of real-world, place-based phenomena that have strong potential to transform our current energy systems. Typification models hold promise as the factors of analysis are able to incorporate place-based phenomena more accurately than other types of dominant models.

2.3.1. Typification as a method of analysis

Typification is a commonly used method or model of analysis in social sciences, especially for informing policymaking.

Typologies are “ex-ante classifications” that result in types or clusters with a predictive and explanatory capacity [49]. The term “typology” is also often used interchangeably with terms such as “classification” [50–52], “categorization” [53] or “grouping” [54]. Typologies can be formed by a diverse number of types or multiple categories, sometimes called clusters. For example, several authors employ concept clustering identifying one to five types to create a typology [54–56]. However, typologies also allow the use of a larger number of types. For instance, Fiaschetti et al. [57] applied a statistical data-clustering algorithm to identify 20 different regional clusters in Europe.

Typologies are measured or predicted through four major approaches:

1. User defined clustering: the user defines the main thresholds for each cluster. For example, Copus et al. [58] identifies 6 types of demographic changes using a set of thresholds based on positive or negative total population change combined with positive or negative natural increase, and in- and out-migration.
2. Threshold clustering: the user defines pre-specified thresholds, identifying specific characteristics that each cluster should have.

Hedlund [53] applies this method to create a typology of rural areas. The author defines a populational threshold before creating an agglomerative hierarchical cluster analysis using Ward's method measured with squared Euclidean distance [53].

3. Data driven clustering: unsupervised clustering which groups the data according to similar properties or features. For example, Graskemper et al. [59] used Partitioning Around Medoids, an unsupervised clustering method, to identify clusters of German farmers. This method allows the analysis of multiple variables and reduces issues caused by researcher bias [59].
4. Concept/Qualitative-based Clustering: comprises methodologies that rely on literature reviews, surveys, and methods based upon non quantitative inference of primary or secondary research. For example, Ermolaeva and Agapeeva [54] identified typologies of Russian corporate social responsibility practices from surveys and interviews. These approaches often are useful for identifying relevant differences from primary data, and to synthetize [54] and identify commonalities among existing studies [55].

2.3.2. *Typification using data driven approaches*

Unsupervised machine learning models are considered data driven approaches. An advantage of these approaches is that they are able to analyse multiple variables to see which characteristics are most common (or diverse) within the same typology [57,60]. These models allow for the use of numeric inputs from a variety of sources which results in clusters based almost entirely on the data: through these inputs, the models can identify which observations are most similar to each other.

The main advantage of this method is that it can reduce large datasets with many variables to portable and manageable comparative metrics and allow researchers to create multidimensional inputs for better describing their unit of analysis through the use of numeric inputs from different fields, and further, reduces the level of arbitrarity affecting threshold-based measures [59,61].

The typification of renewable energy clusters by relevant characteristics as well as by the synthesis of factors that typify their emergence would be useful to understand how a renewable energy transition might occur (or conversely, be disrupted) in various locations. The potential factors that may influence the emergence of various types of clusters can be input into a machine learning model to identify typologies of renewable energy clusters as they relate to the production of technology or of energy. This would allow the identification of commonalities and differences among types of renewable energy clusters. The outcome would be increased insight to support decision-makers in selecting, prioritising, and financing clean innovation strategies, taking into account sector-specific pathways and the distributional impacts of proposed low-carbon and/or resilient recovery policies and programs.

The first steps, however, are to identify existing clusters to use as inputs into a future model, and further, identify the potential factors that can be tested for their influence on the emergence, characteristics, and position of the value chain of a renewable energy cluster.

3. Material and methods

The first two steps of analysis were 1) a literature review to identify initial concept/ qualitative types of renewable energy clusters; 2) a review of the literature to identify the potential explanatory factors of emergence of renewable energy clusters.

Concept/ qualitative-based clusters are useful for identifying relevant differences from primary data. The starting point to identify initial concept/qualitative-based cluster types was to consider empirically derived evidence about the manufacture, production and distribution of more reliable renewable energy. To address the challenge of a lack of common terminology around similar concepts, starting concepts used to define the clusters were derived from literature around:

- renewable or sustainable energy clusters from regional sciences approaches [e.g., 28,29,62];
- renewable energy clusters from socio-technical and governance literature [27,28,35];
- community Virtual Power Plants from socio-technical literature [63];
- technical aspects of decentralisation [64];
- and integrated community energy systems [36].

To expand the range of literature consulted, the reference lists of these studies were checked, and a forward search of citations was conducted. To address potential gaps in this list and identify additional literature about renewable energy clusters, additional academic literature was identified through searching the Google Scholar database. A search string combined the search terms (both with and without quotes) related to (1) renewable energy clusters; (2) renewable energy industrial clusters; (3) green energy clusters/sustainable energy clusters/cleantech clusters/green tech clusters (4) renewable energy communities. The reference lists of the identified literature were checked, and forward search of citations were conducted to find more relevant literature. 52 additional sources were identified through this process. The initial concept/qualitative-based cluster types were typified by consolidating clusters using broad conceptual similarities depending on the goal of the cluster and its position on the value chain.

In the second stage of analysis, the potential explanatory factors for the emergence of renewable energy clusters were identified. Three literatures that define factors that could predict the emergence of renewable energy technologies and innovations are:

1. The technology innovation system approach in the field of sustainability transitions. This approach recognizes that innovations diffuse through both technological and social systems [65]. Diffusion of innovations theory, which originated from Rogers [66], was selected as it explains the diffusion portion of the technology innovation system, and it has recently been expanded to include a range of explanatory factors [67–69]. The technology innovation system literature was employed as it addresses the emergence and supply of socio-technical innovations depends on institutions, networks and actors across the research, development, deployment, diffusion stages [70], that provide the know-how that support them [71], and require supports to challenge the established socio-technical fossil fuel regime [35,72].
2. Energy geography was selected as it frames low-carbon energy transitions as spatially-constituted and a major driver in land cover change, by redistributing energy and economy related activities across space [73]. This approach accounts for the characteristics of spatial heterogeneity and unevenness of actors, communities and renewable energy potential due to geographic and spatial determinants of resources, and the emergence of a range of new actors involved in the development and governance of renewable energy projects in energy transitions [e.g., 73].
3. Spatial and regional approaches were selected as they have recently been applied to energy transitions to examine the spatial agglomerations, clustering of innovations, urban and rural differences, and actors in liberalised energy markets [74,75].

These literatures were assessed against the range of qualitative clusters for factors that could be tested to predict their emergence.

4. Findings

4.1. *Renewable energy cluster types*

The results of the literature review to identify initial concept/ qualitative types of renewable energy clusters identified three types:

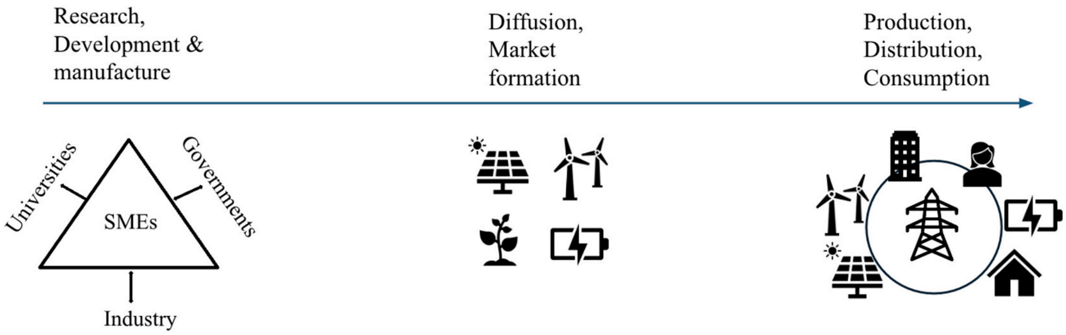

Fig. 1. Three Qualitative Cluster Types.

1. Industrial renewable energy clusters (IRECs) that relate to research, development and manufacturing of renewable energy technologies and innovations.
2. Shared renewable energy clusters for the production, distribution and consumption of renewable energy (SHRECs) that relate to the production, distribution and consumption of renewable energy.
3. Renewable energy clusters that power existing communities and industries (RECPECIs) relate to the diffusion and market formation of renewable energy technologies.

These three qualitative cluster types are presented along the energy value chain in Fig. 1, and more detail of each type of renewable energy cluster is provided in the results that follow.

4.1.1. Industrial renewable energy clusters (IRECs)

The first qualitative/ concept type of renewable energy cluster type found from the analysis was Industrial renewable energy clusters (IREC). The findings indicate that conceptually, industrial clusters that produce renewable energy technologies and innovations emerge from and exploit the advantages of agglomeration economies, with a clear reference to the vast body of literature and experience devoted to regional economic clusters. IRECs are characterised by the spatial and/or network agglomerations of the firms, governments, universities, services and suppliers, as industry and small and medium enterprises, that produce renewable energy technologies and complementary low-carbon innovations [29], described visually in Fig. 2 through interconnected relationships. These groups of clusters are also the closest to the Porterian definition of clusters [76] in that they build upon existing competitive advantages and the relationships between firms and other main actors for creating additional value compared to other forms of territorial and industrial organisation. For example, IRECs can function as intermediary actors accelerating sustainability transitions and facilitate the diffusion of sustainable practices at the regional level [28], support low carbon emissions goals and can create local jobs and raise employment levels [25]. The range of illustrative definitions of IRECS that were found are outlined in Table 1.

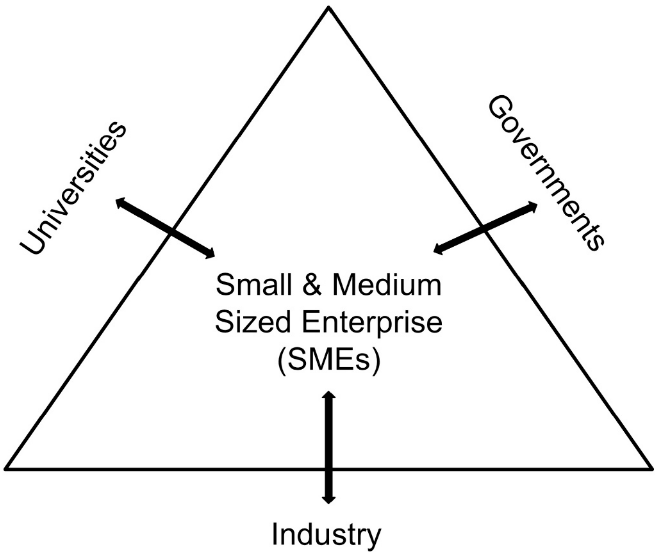

Fig. 2. Industrial Renewable Energy Clusters [adapted from Jaegersberg and Ure 29].

IRECs are characterised by the spatial and/or social concentration of all or some of the elements of the value chain. Cleantech clusters and green energy clusters are more strictly focused on the production of or research and development related to green energy technologies [77,78]. In both cases, the agglomeration concerns the firms and institutions engaging in the production of often export-oriented technologies and services, leading to broad sectors and supporting institutions [78], but with a lower emphasis on the role of residents and society at large. IRECs may display characteristics from the SHRECs and RECPECIs, especially if social ties across the actors are strong. Some IRECs were found to be vertically integrated-structured to include several steps along the energy value chain, from research and development to energy distribution and consumption. For example, in Butturi et al., [79], McCauley and Stephens [28], and Soukissian et al. [80] renewable energy clusters are conceptualised as industrial clusters that include firms supported by both the general public and public institutions, where the production of renewable energy locally is one of the drivers of the cluster. The firms within the IREC described by Soukissian et al., [80] operate primarily in sectors that are ancillary to technologies, such as in the permitting processes for marine renewable energy, designed for procuring offshore renewable energy. This is reflected in Germany and Denmark, where energy policies were built to address both domestic energy production and to build an export industry [81].

4.1.2. Shared renewable energy clusters for production, distribution and consumption (SHRECs)

The second qualitative/ concept type of renewable energy cluster type found from the analysis was shared renewable energy clusters for the production, distribution and consumption of renewable energy (SHRECs) the focus on the production, distribution and consumption of energy within a local area or region. SHRECs are closer to local energy systems modelled in engineering studies [34,87]. The objective of SHRECs is often to provide reliable and resilient electricity resulting from combining technologies, innovations and actors. Technologically, SHRECs are considered the building blocks of a reliable, renewable energy system [88]. SHRECs are described as having the following general features [27]:

- An interconnected energy system among a range of actors [27,30,36]
- Bidirectionality of electricity flows, for example, via prosumership or micro-grid connection and isolation from the main grid [27,36,88]

Table 1
Types of industrial renewable energy clusters.

Terminology	Description	Definitions	Key characteristics	Context
Renewable energy clusters	Agglomeration of related businesses, organisations, in geographic proximity and benefit from co- localisation and collaboration [29]. Spatial proximity among actors is not necessary as other forms of reduced distance may occur [80]. Promise similar to other industrial clusters to accelerate transformations and value creations. Policy, research- related barriers hinder cluster emergence often due to conflicting objectives among cluster actors (e.g. universities vs SMEs) [29].	Jaegersberg and Ure [29] use a broad definition of clusters based on: Marshall's industrial districts [82], to Beccatini [83], to Camagni [84], Krugman [85], and Porter [76]. Strongly related to that of industrial clusters, with renewable energy being the object of production.	Top-down approaches work if sociocultural, intellectual, and organisational capital of clusters is fostered by continuous interaction among cluster actors.	Global
Renewable energy production clusters	Different sectors within the renewable energy industry collaborate as a unified hub to enhance effectiveness and productivity to produce sustainable technology [25].	Clusters formed by various renewable energy technology production industries, that could be solar power or wind turbine clusters [25].	Renewable energy production	China
Sustainable energy clusters/ Green energy clusters/ Green tech clusters	Create conditions in the region to support a range of niche-level technologies, firms, social practices, endeavours to advance sustainable energy. This strategy aims to build networks and capacity among the niche-level activities, providing networks to core decision makers, established power elite, in a broad, multifaceted socio-technical energy transition. [28].	Sustainable energy clusters, green energy clusters, green tech clusters identified as the same [28]. Green clusters encompass a group of industries (e.g., electricity, transportation, building industries, software, consulting), refer to production, R&D activities that involve multiple application pathways, where industrial boundaries are more difficult to define than traditional sectors [78].	Complex socio-technical place-based phenomena	Central Massachusetts, USA
Cleantech clusters	Clusters as both natural phenomena and policy-driven outcomes, include academic institutions, industry, and governmental institutions [77]. Cleantech refers to a diverse range of innovative products and services that optimise the use of both finite and renewable natural resources for long-term environmental and commercial sustainability [77]. Cleantech comprises knowledge-based products, technologies, and services based on improved operational performance, energy efficiency, reduction in waste and environmental externalities.	Agglomeration of interconnected economic, creative endeavours within specific regions, characterised by collective collaboration, competition among companies, institutions [77]. Interconnected businesses in close geographical proximity to each other [86]. Davies [77] defined cleantech and clusters individually, but no clear definition on cleantech clusters.	Agglomerations and clustering of cleantech remain marked by contingency, nonlinearity, and uncertainty [77].	N/A

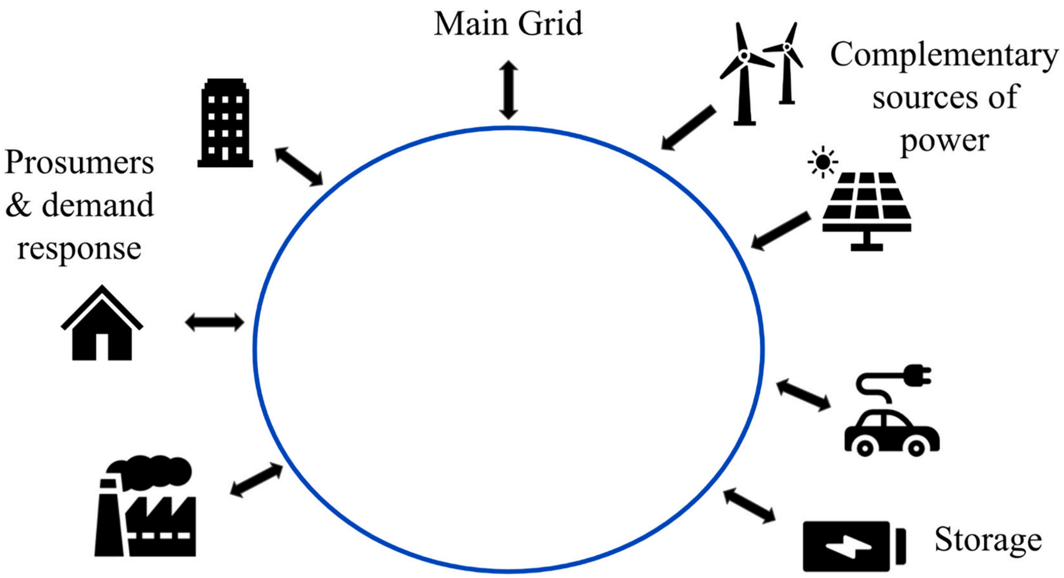

Fig. 3. Shared renewable energy clusters for the production, distribution and consumption (SHRECs).

- A range of combined renewable energy sources, owned and operated by different types of actors [27,30,36,88]. Ideally, this portfolio of energy sources exhibits complementarity–i.e., intermittent sources that balance each other to reduce variability and flexibility costs [27,88,89]
- Flexibility, such as demand response, load balancing, and storage [27,88,89].
- These features are included in an example of what a SHREC could be, as identified from the literature, in Fig. 3.

The range of SHRECs identified in the analysis is provided in Table 2. In the socio-technical literature, that considers both social and technological factors, Table 2 outlines a range of terminology is used to describe these clusters, such as DisGenMiGrid systems based in local actors managing common pool resources [30], renewable energy clusters [27], Integrated Community Energy Systems (ICESs) [36], Community Virtual Power Plants [63] and, based on new EU legislation, renewable energy communities [26,27]. The few empirical studies found identify the importance of governance, the inclusion of a range of actors, as well as supply chains [15]. Because sometimes these actors are citizens, municipalities, and local small and medium enterprises that are often identified as 'community' [e.g., 36], much literature has focused on the participatory, governance, decentralisation, and justice aspects [15,26,27,30]. Due to the predominantly spatially determined nature of VRES potentials, of flexibility and demand, it is less clear how this clustering could occur spatially [26,27].

4.1.3. Renewable energy clusters that power existing communities and industries (RECPECIs)

The third qualitative/ concept type of renewable energy cluster type found from the analysis was RECPECIs that relate to the general diffusion and market formation of renewable energy technologies. RECPECIs are focused on increasing the share of renewable energy in a reference community or industrial cluster, often materialising as an added layer on top of existing industrial policies and regional industrial networks. According to Hidayatno et al. [25] few studies exist about RECPECI's. Drivers of RECPECI's can include reduced lifecycle emissions [90], reduced direct emissions [25,90], more efficient and sustainable use of

Table 2
Types of shared material renewable energy clusters (SHRECs).

Termino- logy	Description	Definitions	Key characteristics	Context
Integrated Community Energy Systems (ICESs)	Locally and collectively organised energy systems. Fulfils energy requirements of local communities through synergies among different energy carriers. ICESs aim at the self-provision for the local communities and provide system services such as balancing and ancillary services to neighbouring systems. Includes community micro-grids, goals to optimise, provide resilience, autarky [36].	Cross-sector integration at the local level capable of effectively integrating energy systems through a variety of local generation of heat and electricity, flexible demand as well as energy storage. Integrating smart-grid technologies and demand side management facilitate an increase in reliability and efficiency. [36].	Complementarity of technology: integrated energy systems can be realised at local scale combining rooftop photovoltaics, small wind turbines, district heating, and community energy storage or biogas and hydrogen production systems. Local energy exchange one of the most important attributes of ICES. [36]. Smart grid advances provide the basis for ICESs [36].	Conceptual
Renewable energy clusters	Interconnected renewable energy sources that are operated by a range of interconnected actors. Energy sources are Complementary temporally. Flexibility, and interconnectivity of actors, and bidirectionality of energy flows [27].	Lowitzsch et al. [27] defined renewable energy clusters as comprising complementarity of energy sources, flexibility, interconnectivity, and bidirectionality of energy flows.	Complementarity, flexibility, interconnectivity, bidirectionality. Typically include flexibility of demand, energy efficiency, storage, and peer-to-peer trading within cluster and between cluster and broader market [27].	European Union, India, Chile [27]
Renewable energy communities	The revised Renewable Energy Directive (RED II) establishes a supportive framework for the establishment of "Renewable Energy Communities" (RECs), which is being implemented as legislation across the 27 European Union Member States [27,88].	Renewable energy communities are defined by their ownership [88], and/or their existence as formal entities and proximity to renewable energy projects. [27]; Renewable energy communities can generate renewable energy for their own consumption, store surplus production, and sell it to the grid e.g., via peer-to-peer trading, power purchase agreements, engaging with energy suppliers [27,88].	Owned by local members or shareholders, authorised to share energy within the community [27,88]. RECs and renewable energy clusters are socio- technical mirrors. [27] RECs have the potential to facilitate private investment and financing for renewable energy sources while delivering social benefits [88].	European Union
Community Virtual Power Plants	Software-based solution that aggregates distributed energy resources into one coordinated and controlled portfolio that operates as one single entity similar to a conventional power plant, allows for managing and trading of electricity [63] community based due to community involvement and community-logic under which it operates [63].	A community-based Virtual Power Plant (cVPP) is a portfolio of distributed energy resources aggregated and coordinated by an internet and communications technology based control architecture, adopted by a (place- and/or interest-based) network of people who collectively perform a certain role in the energy system [63].	Building blocks that form a cVPP: the community involved, the community-logic under which a project operates, the portfolio of distributed energy resources aggregated and controlled, and the roles communities can collectively play in the energy system [63].	Ireland, Belgium, Netherlands [63]
DisGenMi Grid	The social construction of smart metering is a key factor in determining the character of the smart grid. [30] The social foundations of smart grids consist of decentralised socio-technical networks that underpin the electricity consumption of groups of consumers/end-users which form a community. [30]	"DisGenMi" refers to microgrids with a substantial amount of distributed energy generation. [30]	DisGenMi model is positioned to "make generation of electricity from resources based close to end users competitive with central generation". [30] Community of place or interest investments and ownership of the energy project is a determinant of acceptance. [30]	Conceptual

Table 3
Types of Renewable energy clusters that power existing communities and industries (RECPECIs).

Terminology	Description	Definitions	Key characteristics	Context
Renewable energy-powered industrial clusters	Industrial clusters that use renewable energy. [25]	Renewable energy is used as a method to empower industries in a cluster. [25]	Potential to improve sustainable industrial development with reduced carbon emissions. [25]	Indonesia [25]
Net zero energy communities	Conceptualised in multiple ways that rely on different terminologies, emission sources, timescales, and energy sources [90].	No clear definitions for assessing renewable energy-based strategies in net-zero communities [90]. University campus, commercial office and high-rise residential buildings are groups that are powered by hybrid renewable energy and hydrogen storage supply through peer energy trading [93]. Communities fully powered by renewable energy [92].	Characterised by zero carbon, energy efficiency, renewable energy, electrification community, economic, regulatory, political, social and technological features [93].	US, UK, Germany
Energy Sustainable communities	Communities that use renewable energy and energy efficiency measures. [91]	Communities that use renewable energy and energy efficiency measures. [91]	Electricity and heat production, consumption, transport sector. [91]	Germany [91]

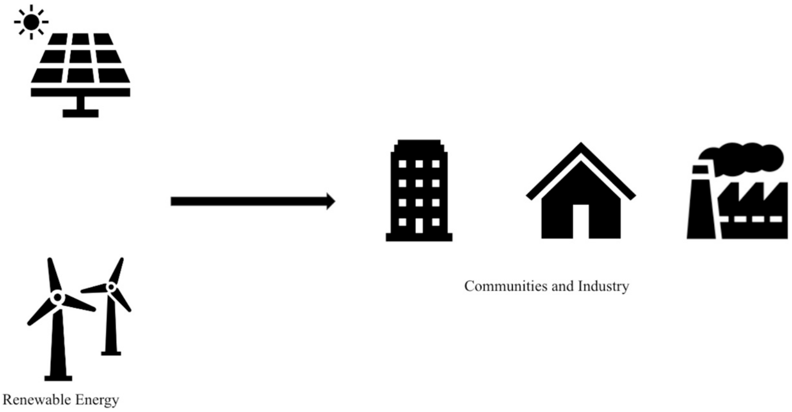

Fig. 4. Renewable energy clusters that power existing communities and industries (RECPECIs).

energy [91], competitiveness [25] and changing energy system path dependencies in industrialising contexts [25]. Identified terminology includes: energy sustainable communities [91], net zero energy communities [25,90–93], and renewable energy-powered industrial clusters [25]. Examples of these clusters are defined in Table 3 and Fig. 4.

4.2. *Explanatory factors for the emergence of renewable energy clusters*

The findings of the analysis of three literatures assessed against the potential to explain the identified qualitative/concept type clusters indicate a complex and wide-ranging set of potential factors.

4.2.1. *Energy geography*

Although the origins of energy geography and the relationships between space and energy emerged as early as the 1980s with works by Nijkamp [75] and Owens [94,95] energy geography as a field has emerged more prominently over the past two decades. Spatial energy density is the ratio of energy produced or consumed compared to its spatial footprint of production or consumption (W/m^2). One important distinction between low-carbon sources of energy, such as renewable energies like wind and solar power, and historical, traditional, centralised sources, such as fossil fuels and nuclear power, is their "energy density", which has potentially disruptive implications on land-uses in an energy transition [12]. Furthermore, whereas value chains for energy technology and innovations are designed for transmission across locations to selected sites, renewable energy generation depends more on location than fossil fuels and nuclear, since renewable energy potential is context specific. For example, solar and wind potential vary spatially, and favourable locations for hydroelectricity depend on characteristics of specific sites. On the other hand, fossil fuels and nuclear fuels can be transported to a specific location for generation.

For these reasons, spatial reorganisation and the transition of path dependent infrastructures is inherent to renewable energy transitions. Energy geography focuses on how renewable and low-carbon energy transitions affect spatial and economic reorganisation, characterised by the changing energy landscapes that result from the spatial unevenness between energy potential and sources, sites of energy demand, land-uses, value chains, liberalisation of markets to allow for new actors, and investment [33,73, e.g., 74,96]. Energy geography highlights how land-use planning impacts energy use, and energy supply affects land-use changes and leads to spatial pressures across landscapes and communities [11,97]. This spatial reorganisation opens up opportunities to actors new to the energy sector, and the new interactions between these new actors across scales (i.e., local and regional actors) may become societally and technologically disruptive [e.g., 73,88]. How actors interact and engage in these clusters and transitions may reinforce injustices of the present energy system, or offer new pathways towards increased justice and inclusion of historically marginalised communities [26].

There are many implications for the overlap of renewable energy potential across communities; whether and how this potential is harnessed will depend in part on interactions with local communities, industries and spatial patterns. Urban areas are densely populated with high energy density of demand (W/m^2), which will increase with the decarbonization of transportation through the widespread adoption of electric vehicles, requiring new sources of supply [12,97]. This opens up risks of constrained transmission networks and bottlenecks to providing supply [74].

Table 4
The identified range of potential energy geography factors determining the emergence of renewable energy clusters.

Factors	Rationale/ Examples
Location	The location and landscape of renewable energy resource potential (supply) [33]; Location of network constraints [74]; Location of clustering of innovations [74]; Location of demand [74,88]; Relative location: the proximity of supply and demand actors/ infrastructures [26,74]; Spatial planning tools for renewable energy siting and analysis [11]; Land-use planning [96,99].
Characteristics	Urban density/density of demand/urbanisation and urban and rural differences [26,74,100]; Path dependencies, initial conditions and starting points [73];
Actors	The decentralisation or liberalisation of actors and infrastructures [73,74,88]; Social acceptance of renewable energy projects is influenced by socioeconomic impacts, fairness, participation, and trust during the development process [20]; Interscalar relationships between demand (cities) and supply (rural areas), across civic, public, and private actors that are in cities, in regions, and at higher/more centralised scales [88].

An energy geography perspective offers that different types of renewable energy clusters will emerge in different locations, due to the differences in locational characteristics. For example, clusters in cities may have limited potential for renewable energy generation, and with transmission constraints, may focus more on conservation and demand to overcome network constraints, and the integration of electric vehicles [26,74]. With the impacts of climate change being felt by communities now [98], renewable energy clusters may focus on resilience to environmental hazards, such as heat waves, fires, and storms. In rural areas, where the potential for renewable energy resides, renewable energy clusters may focus on exporting renewable electricity out of the region or into the city as an income source for local economic development [88].

SHRECs imply proximity between actors, renewable energy generation, and grid connections [26] as well as governance across a range of relevant actors, such as how ownership, management and control are structured [27,30,36,63,88].

The range of factors considered by energy geography in renewable energy transitions are outlined in Table 4.

4.2.2. *Technology innovation system and diffusion of innovations approaches*

Socio-technical innovations are the recognition that innovations, such as products, services, and new processes diffuse not only into technological systems, but also into social and institutional systems that are characterised by path dependency and lock-in [10,18]. Sustainability transitions theory defines socio-technical systems as complex, multi-scalar systems made up of regimes that are resistant to change, and that transitions come about through dynamic processes within and between innovations and the socio-technical regime [10,18]. Within this context, disruptive innovations provide new features (attributes) to products or services that alter the existing technological paradigm, create major societal change, can introduce new social values and political beliefs, and lead to broader socio-technical regime change [101].

The technology innovation system explains the role of actors, networks, and institutions in influencing the emergence of innovations from the stages of research and development, to deployment, to widespread diffusion stages, and the potential for feedback loops within the system [102,103]. As such, the technology innovation system conceptual framework offers credible explanations for the emergence of innovations in social and technological systems and the range of innovation system actors that influence the emergence of niche innovations [35,67,70,103–111]. One of the most prevalent methods of analysis emerging from the technology innovation system is the use of policy mix analysis of the institutions that influence an innovation's emergence and diffusion [70,106,112].

Olbrich and Bauknecht [113] argue that system building is required in addition to niche scale up and regime destabilisation in order to effect a sustainability transition. System building incorporates a broad range of complementary system elements such as innovations, or elements from the regime (e.g., rules and regulations) to bring about a new system architecture. Olbrich and Bauknecht [113] define system building as the "restructuring dynamics in the existing regime [that] involves the institutionalisation of innovations, the alignment of old and new system elements as well as an interaction between old and new regime actors" (p. 1), that leads to "new socio-technical systems …that fulfil societal functions in a more sustainable way, thereby gradually replacing current systems that are considered to be unsustainable" (p. 2). From this perspective, SHRECs could represent disruptive reconfiguration of innovations that emerge when the current energy system regime is destabilised.

The portfolio structure of SHRECs suggest a range of technologies that are complementary and require support to diffuse from the technology innovation system into specific locations, and potentially, as part of electricity grids. Specific considerations to these types of clusters include:

- Complementary policy instruments or the encouragement of complementarity [15,88,114];
- The encouragement of specific innovations, and combinations of innovations [114,115];
- Technology specific policy instruments for all types of clusters, whether material (supply) or industrial (demand) as opposed to general policy instruments that do not target specific technologies [88];
- These instruments and supports often vary by jurisdiction and location, requiring analysis using multi-level policy mixes [e.g., 116];

Table 5
Potential technology innovation system factors influencing renewable energy cluster emergence.

Factors	Catalyst	Sources
Path dependencies and initial conditions of actors, networks and institutions	Interactions with existing multi-scalar and locked-in institutional, infrastructural and cultural systems.	[10,18]
Agency and actions from agents within the regime	Niche and innovation support from entrepreneurs, suppliers, financial resources. Actors acting as spanners linking across networks, regimes, niches, and actors, for example, the role of intermediaries. Actors providing legitimacy of innovations through support or pushback from public, regime, incumbents, users, communities.	[67,70,103–105,107–111]
Institutions	Multi-level policy mixes across regimes (policy instruments can be economic, regulatory, knowledge creation and diffusion, general or technology specific); Regime structure influences the emergence of innovations.	[26,27,35,70,106,112,125]
Innovation Characteristics	Whether innovation reinforces incremental or disruptive regime change.	[35,106]
Knowledge and Creation sharing	International collaborations on offshore wind energy across countries.	[102–104,126–128]

- Cooperation and coordination of networks and actors across complementary innovations and value chains [15,26,109,117].

Literature that describes the diffusion and adoption of renewable energy innovations includes Dóci and Vasileiadou [118], Mignon and Bergek [119], Bergek and Mignon [120], Clausen et al. [121], Clausen and Fichter [67], Fichter and Clausen [68,69], Hoicka et al. [26,106], REN 21 [122–124]. The specific factors that are known to impact the diffusion of socio-technical innovations, such as renewable energy and complementary technologies and innovations, are summarised in Table 5. These factors are both regime's actors (e.g. institutions) and regime's outcomes emerging from the mediated interactions among these actors.

4.2.3. *Regional science*

Regional approaches developed within regional science since the late 1940s provide rigorous tools for identifying sub-to-supra-national trends and their underlying microphenomena, while relying on varied natural experiments (i.e. between different regions) [129,130]. At the root of regional science and its approaches, there is the definition of region, which is both a powerful tool but can also be constraining in the setting of spatial boundaries when it interacts with multi-scalar relationships [130]. For example, by defining a region, one places boundaries and defines operational extents and foci that may not clearly align with multi-scalar relationships. Regional approaches, organised within regional science, cover a wide range of topics and methodologies: from regional economic modelling [131], to diffusion of innovations [132–134], and urban growth [135]. Borrowing from socioecological fields such as ecosystem based-management, recent advancements have developed frameworks for identifying and managing the scalar mismatches between, for example, boundaries and ecological systems or global supply chain networks [e.g., 136]. Through the 'power of the region', regional approaches can provide a locational grounding for sustainability transitions [130] and energy transitions [137,138].

Some regional approaches are related to energy geography as presented here, however, the specific concern with regional economies is still distinct. The importance of regional approaches and economies to energy transitions has been outlined by several scholars [e.g., 74,75,88,138]. The most important consideration of regional approaches in the case of renewable energy clusters is that of industrial clusters that create synergies among firms and other actors to achieve higher efficiencies via economies of aggregation and (spatial and relational) proximity. These clusterization processes can spur accelerated growth within a region [37,139], and create spillovers of knowledge and practices in further ones, especially if connected via relational networks [140].

Clusters emerge from a combination of pre-existing conditions and triggering factors [141,142]. The main factors revealed by the literature that would affect the emergence of IRECs are drawn from literature about industrial clusters and IRECs. These factors are presented in Table 6. Proximity, whether geographical or not, government support, and institutional coordination at different scales and across actors are three factors emerging routinely from this literature. Path dependency processes, whether rooted in pre-existing conditions or recent successes, or through cultural factors enabling the operationalization of the other three factors. These factors are not mutually exclusive, and, rather, are interlinked, operating dynamically through time. Government programs can create a supportive culture towards clusterization processes, leading to co-location effects. For example, government policies may determine the location of universities, thus endowing certain locales with an important institution for supporting clusterization processes. In this latter example, coordination plays a fundamental role for successfully enabling interactions among actors, thus ensuring the emergence of a renewable energy cluster.

5. Discussion and synthesis of the literature

5.1. *Synthesis to distinguish renewable energy cluster types*

These initial findings demonstrate that empirically, renewable energy clusters take various forms across the energy value chain. The concept of vertically integrated clusters emerged in the findings. Vertical integration means that a cluster is structured to include several steps along the energy value chain, from research and development to energy distribution and consumption. The potential vertical integration of clusters are outlined in Fig. 5, organised by whether singular or multiple technologies are involved in the clusters. These potential cluster types could all exist in practice, and several have been identified in literature

Table 6
Potential regional sciences factors that affect the emergence of renewable energy clusters.

Pre-existing conditions/ triggering factors	Rationale/Examples	Sources
Historical paths of clusterization	This translates into pre-existing conditions and triggering factors.	[85,141,142]
Social and spatial proximities of main actors	Collective learning processes.	[141,143]
Interactions among main actors	Collaboration with the research sector (including universities) characterised by non-conflicting objectives; Governance (e.g. long-term policies and early-stage funding), the availability of venture capital, education (e.g. higher education cleantech programs), global competitive advantages (e.g. proximity of natural resources) and performance tracking.	[29,142–144]
Co-location among actors and factors along the value chain and Multilevel coordination	Localizations of smart specialisation and agglomeration of firms in support of renewables.	[29,74,76,145,146]
Government support with implementation of innovative initiatives and supportive policies	Martin and Coenen [147] found biogas clusters only gained momentum in Sweden after the implementation of the governmental Climate Investment Programme which provided legitimacy to the local biogas industry.	[142,143,147]
Qualified labour and other forms of local knowledge	The presence of entrepreneurs with relevant scientific knowledge [142,143], as cluster emergence "depends on building institutions that enable coordinated learning among firms to improve capabilities, processes and products" [143].	[142,143,148,149]
Past successes	Collaborations with (biotech) clusters and collaborations between different actors, such as communities, local governments and universities.	[28]
Level of regional coordination and cooperation between centres within the urban system	The ability for urban centres to rely on borrowed size of rural areas, rural areas gain productivity and ability to rely on borrowed function [150,151] greater accessibility of services, labour, and physical spatial spillovers of functions from larger cities [132].	[132,150,151]
Presence of universities and public research as prerequisites to create new clusters of universities and firms	The emergence of a wind power cluster in the Northern Finland region is not only related to the existing wind power-related companies in the region, but also connected to the availability of educational and research institutions in the area [152].	[141,142,149,152]
Culture	Influences attitudes towards self-employment, cooperation or innovation that are relevant for local cluster.	[141]

already. For example, renewable energy clusters analysed by Butturi et al., [79], McCauley and Stephens [28], and Soukissian et al. [80] all describe IRECs that have a goal of producing energy technologies to be embedded locally in communities and industries (RECPECIs), indicating vertical integration across IRECs and RECPECI's, as outlined in Fig. 5.

In Fig. 5: Visualisation of the intersection between value chain stage and technology portfolio observed in different renewable energy clusters, as well as their potential vertical integration. The three types considered are IRECs (Industrial renewable energy clusters), SHRECs (Shared renewable energy clusters for the production, distribution and consumption of renewable energy), and RECPECIs (Renewable energy clusters that power existing communities and industries).

Fig. 5 offers a method to support the collection of empirical cases of clusters, and initial characteristics to look for through the range of possibilities of vertical integration. From the perspective of vertical integration between IRECs, RECPECIs, and SHRECs, Fig. 5 outlines that there are many distinct ways in which distinct renewable energy cluster types could exist, beyond the initially identified qualitative/ concept types. Typification of empirical examples will allow the identification of a more nuanced articulation of cluster types along the energy value chain. The framework presented in Fig. 5 can support the development of an empirical sample of renewable energy clusters, and the emergence of a range of vertically integrated clusters may be identified based on existing real-world cases.

5.2. *Synthesis of dimensions and factors to predict the emergence of renewable energy cluster types*

In the final step of analysis, based on the results of the literature review, an analytical framework is proposed, with which to test existing renewable energy clusters with the purpose of identifying relevant influences or inhibitors of types of clusters. Learning which influences or inhibitors are dominant across a range of cluster types can inform place-based regional development and energy policies.

The potential explanatory factors of the emergence of a more nuanced range of renewable energy cluster typologies was synthesised from the literature across sections 4.2.1, 4.2.2 and 4.2.3 identified seven dimensions of factors found in the literature: 1) actors, 2) institutions, 3) networks, 4) knowledge and tools, 5) proximity, 6) location characteristics, 7) path dependency. Within each dimension, the specific factors that may characterise a renewable energy cluster are identified across all three literatures. These dimensions and factors are colour-coded among the three literatures to demonstrate the overlapping factors found in the literature (Fig. 6) and each specific factor is defined in Table 7. These factors suggest that the emergence of renewable energy clusters will vary by the resource availability of a particular location, the low-carbon technologies developed by the cluster, land-use, demographics of investment, intra- and inter-sectoral connections, multi-level institutions, proximity of various sources of supply and supply to demand, and the location of energy infrastructures. Empirical testing of these factors will allow the development of more nuanced insights into these issues, including, for example, how they are governed, what their spatial concentrations are, what types of locations they are embedded in, and who the beneficiaries are.

One benefit of this research is the scalability of the results. With the development of a wide-ranging, ideally global, empirical dataset of renewable energy cluster cases, heterogeneity across clusters and their associated characteristics can provide deep insights and inform the scalability of a wide range of options, and ideally, improved distribution of outcomes.

The next step will be to use (Fig. 1) these characteristics for testing whether typologies of renewable energy clusters exist - i.e. whether differences among groups of renewable energy clusters are significant - and for understanding which determine these typologies.

To achieve this, global occurring observed data will be gathered around the seven dimensions of potential influencing factors illustrated above. The dataset will be then fed into a clustering algorithm, Affinity Propagation [see the seminal work of 153,154]. This unsupervised machine learning algorithm will identify the clusters as well as the relevant characteristics determining each cluster. By grouping together renewable energy clusters based on their similarities, clusters of renewable energy clusters will represent typologies of renewable energy clusters. Additionally, within each cluster, Affinity Propagation will identify exemplars, i.e. the most representative renewable energy cluster within each typology. This use of typification has long been used in policymaking: from informing development policies [58] to transfer know-how among 'peers' based on data-driven approaches [155]. The typification process will provide the opportunity to understand how drivers and barriers affect the rise and performance of renewable energy clusters, and, consequently, how to replicate the success stories and/or counter those elements that negatively affect their performance.

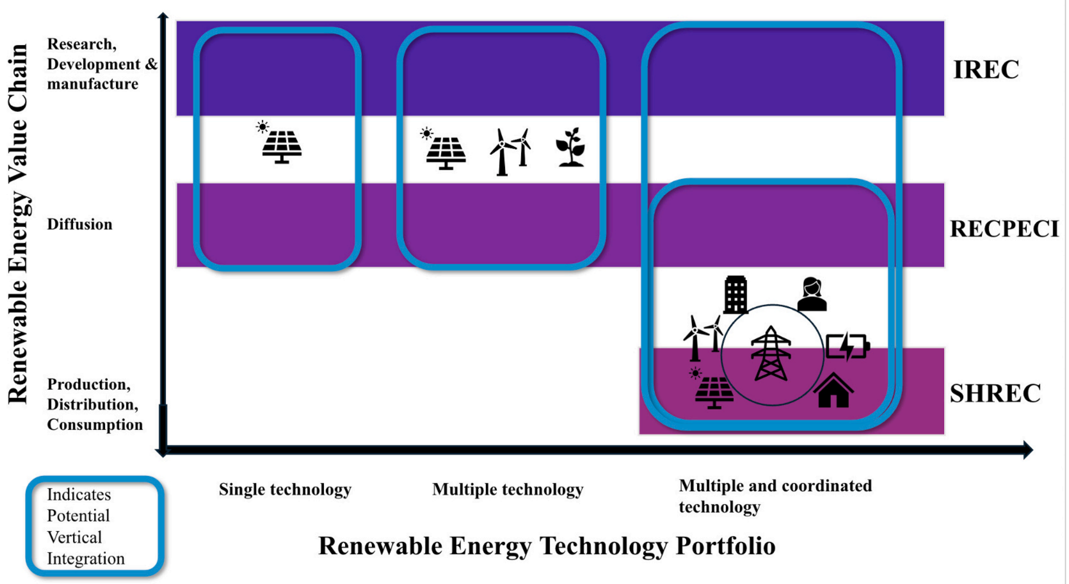

Fig. 5. The range of possible renewable energy cluster types achieved through vertical integration.

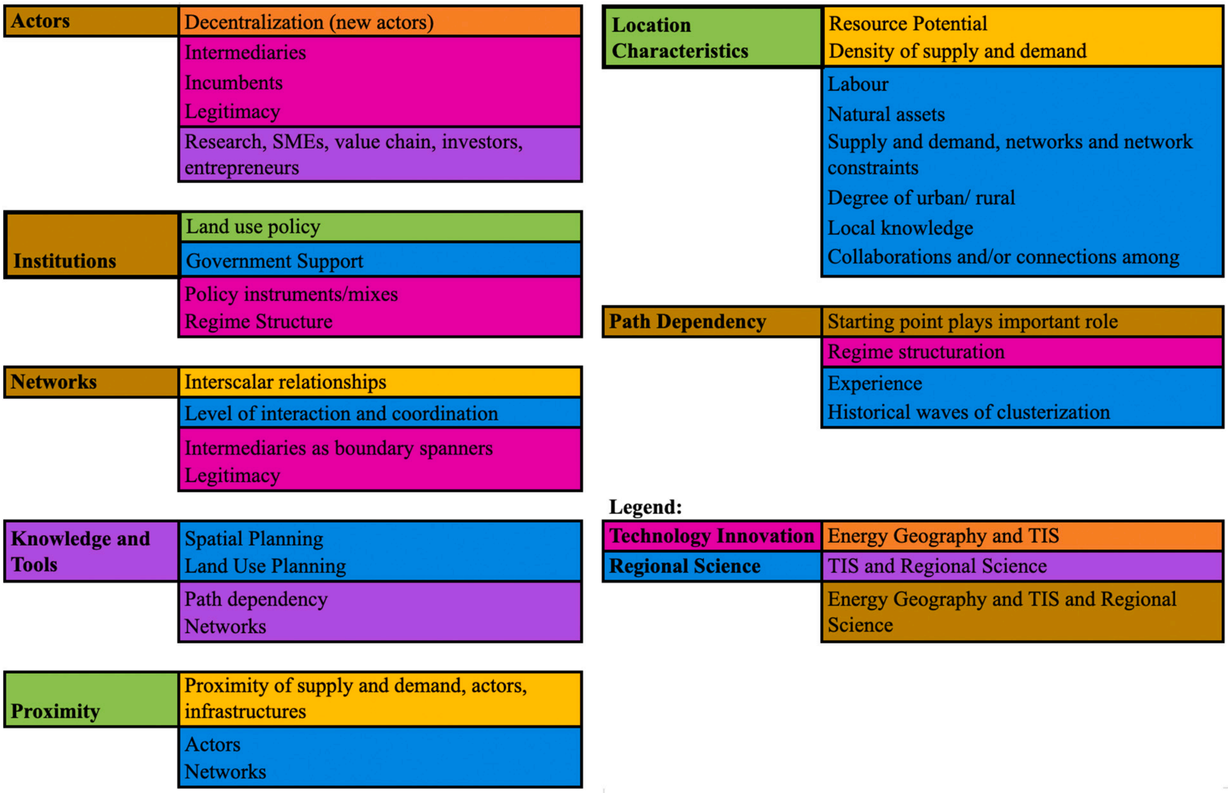

Fig. 6. Identified Factors That May Affect Renewable Energy Cluster Emergence.

Table 7
Synthesis of Dimensions and Factors to Predict the Emergence of Renewable Energy Cluster Types.

Dimension	Factor	Definition
Actors	Decentralisation (new actors)	Devolution of decision-making from centralised to local levels, or localised ownership, information and financial flows with localised financial gains [16].
	Intermediaries	Defined by their roles of providing and distributing information, services, mediation, connection of niche activities with regime institutions, to support the diffusion of innovations [105].
	Incumbents	Some of the largest and most powerful industries with historical market share [18].
	Legitimacy	The degree to which actors support the scale up of an innovation [72].
	Research, SMEs, position on the value chain, investors, entrepreneurs	Research: R&D activities in firms or in universities and R&D institutes [142]. "Firms, mostly small and medium-sized enterprises (SMEs), carry out different activities in the same industry and located in a geographically bounded area" [44]. The relative size depends on each country's definition, often based on the number of employees and turnover [156]. Investors: providers of capital and institutional structures that help investors manage risk and drive the pace of transactions and value creation [157]. Position on the value chain: cluster's position on the multi-scalar, non-unidirectional flow of materials, finance or intellectual exchanges of renewable energy [158]. Entrepreneurs: single actors who build on local knowledge, create or obtain and mobilise new knowledge [142].
Institutions	Land use policy	Set of policies used for implementing Land Use Planning. A wide range of activities that designate and control land use to ensure optimal use of land [159].
	Government Support	Totality of direct and indirect support policies implemented by local, regional, and national governments, as well as government-owned institutions. This support can materialise either as factors that condition the policy design of regional and national government [142,143,147] and/or as direct investments in necessary R&D for the emergence of the cluster [141–143].
	Policy instruments/ mixes	Implementation of policies that support or inhibit the diffusion of innovations [72].
	Regime Structure	Configuration in a societal system that is stable and dominant in a societal system [65].
Networks	Interscalar relationships	Network of regime-level actors and intermediaries operating across policy domains facilitating niches [72].
	Level of interaction and coordination	Coordination among and between actors is an act of "lowering of uncertainty, though aligning agents' incentives and/or expectations" [160], aimed, for example, at developing new knowledge [161]. Coordination can be achieved through interactions which can either be within the cluster (network bonding), the cluster and outside actors (bridging) [11].
	Intermediaries as boundary spanners	Actors who use strategies that connect across regimes [162].
	Legitimacy	The degree to which networks support the scale up of an innovation [72].
Knowledge and Tools	Spatial Planning	The allocation of space for the development of renewable energy technologies [11].
	Land Use Planning	A wide range of activities that designate and control land use to ensure optimal use of land [159], where 'optimality' is defined by government objectives [163].
	Path dependency	Lock-in of specific innovations in existing socio-technical systems, common in complex systems [10,65].
	Networks	Structure of linkages/ties/relationships between individuals or organisations, that enable the flow of innovations, knowledge, technologies and so on beyond the places where they were initially conceived [18,164].
Proximity	Proximity of supply and demand, actors, infrastructures	The relational and geographical closeness of actors [27,29] as well as the geographical closeness of beneficiaries to the cluster [15,26,109,117].
	Actors	The ensemble of both market and nonmarket entities [15,30] including enterprises, utilities, authorities, agencies, different publics, civil society organisations [15,25,27,28,35].
	Networks	Intermediate form of organisation between hierarchies (internal organisation within entities such as firms) and markets. Their essential function is the exchange of information [70,165].
Location Characteristics	Resource Endowment/ Potential	The achievable energy generation of a particular technology given system performance, topographic limitations, environmental, and land-use constraints [166].
	Density of (energy) supply and demand	Density of energy supply refers to the Watts/m2 ratio of the relevant energy technologies produced or used within the cluster. Density of energy demand refers to distribution and intensity of demand of energy driven by changes in population, levels of income, or sectoral transformations (e.g. adoption of EVs) [12,167].
	Labour	The labour force availability within the labour market of the cluster [141–143].
	Supply and demand, networks and network constraints	Supply and demand of energy and/or renewable energy technologies in the market of interest of the cluster's actors. Network constraints represent the level of economic concentration at which the marginal costs of energy production outweigh the marginal benefits of agglomeration [74].
	Degree of urbanity/ rurality	The regional characteristics determining the degree and type of rurality and urbanity of the cluster and its region [see e.g.,57].
	Local knowledge	The availability of technological gatekeepers or international entrepreneurs and local knowledge networks within the cluster and its region of reference [142].
	Collaborations and/or connections among actors	Degree of within-cluster (network bonding), or among-clusters/external actors (bridging) collaborations [11].
Path Dependency	Starting point plays important role	The degree of spatial embeddedness of current energy and socioeconomic systems within the cluster and its region of reference [e.g., 73].
	Regime structuration	process of institutionalisation of a regime whose strength can be assessed by identifying the degrees of institutionalisation of its core elements [168].
	Experience	Generation, accumulation, and memory of know-how accumulated through time by cluster's actors and institutions [9,169].
	Historical waves of clusterization	Historical events and preconditions that have contributed to the emergence and end of other clusters within the renewable energy cluster's region [85,141,142].

5.3. Limitations

There are limitations to this research. Although this study provides first indications of the types of renewable energy clusters that can emerge along the energy value chain and the range of factors that may predict their emergence, until an empirical dataset is built and tested, the outcomes remain unclear. Developing an empirical dataset with which to analyse existing renewable energy clusters will be a significant undertaking, whether coded manually, or by using training of machine learning techniques [35,170]. Furthermore, the outcome of learning from empirical data is nuanced. Typification can provide a tool to support the appropriate design and implementation, and replication of policies [50,171,172], but inefficient typologies (or reference models) can lead to the creation of inappropriate policy tools or targeting inexistent objectives [49].

6. Conclusion

Identifying a range of renewable energy cluster types is important to support understanding place-based renewable energy transitions and their links to social, economic, institutional and cultural considerations as a means to replicate and accelerate a low-carbon energy transition.

During a climate emergency, the risks of disruptions to social ecological systems are increasing with greenhouse gas emissions. Shifting our understanding of how a renewable energy transition occurs as landscape change, quite literally on the ground in practice, as it interacts with communities, justice, governance and ecosystems, can support the replication of renewable energy infrastructures and acceleration of renewable energy uptake [24]. The emergence of renewable energy uses requires activities along the energy value chain from the development and manufacture of technologies and innovations to their diffusion into markets can offer important insights, although understanding how these occur in practice and how they can be replicated requires new place-based methods of analysis outside of dominant engineering and energy economy models [11,15].

The contribution of this study is to provide a preliminary investigation of the concept of renewable energy clusters and the factors that may predict their emergence. A qualitative/concept typology approach was used to identify three initial types of renewable energy clusters along the energy value chain: shared renewable energy clusters (SHRECs), industrial renewable energy clusters (IRECs) and renewable energy clusters that power existing communities and industries (RECPECIs). Further, it was described (in Fig. 5) how the potential types of vertical integration between IRECs, RECPECIs, and SHRECs that may occur in distinct permutations could also be identified empirically based on existing real-world cases.

This preliminary analysis has confirmed that renewable energy clusters describe a range of place-based energy activities along the energy value chain, from production of technologies and innovations to their use, and involve a range of types of actors, from energy producers to consumers, to industry, and innovation system actors. The place-based factors that may influence or inhibit the emergence of renewable energy clusters, that could be used to inform place-based strategies that address local assets, actors, space, labour, knowledge issues, or localised justice issues are also important to understand. For this reason, the fields of regional sciences, technology innovation systems, and energy geography were drawn upon to identify factors that may influence or inhibit the emergence and form of renewable energy clusters. The seven synthesised dimensions that can be tested to typify and predict renewable energy cluster emergence: actors, institutions, networks, knowledge and tools, proximity, location characteristics, and path dependency.

How these clusters of technology and innovation converge to be implemented in space and time, and with a range of potentially decentralised actors, remains largely unclear [15,30]. This study offers a path forward to applying typification to renewable energy clusters, which can address gaps in current energy modelling practices, and also address place-based considerations and factors.

The concepts from this first step of research can guide the development of a sample of empirical cases of renewable energy clusters that can be analysed through machine learning typification. This would allow the identification of a more nuanced articulation of cluster types along the energy value chain, and to test the factors that predict their emergence in locations with different social, geographic, institutional, and economic characteristics.

The findings can provide the opportunity to actors of the innovation system, advocates, citizens, communities, planners, and policy makers to understand how drivers and barriers affect the emergence and performance of renewable energy clusters, and how to replicate the success stories and/or counter those elements that negatively affect their performance and benefits. As such, this study could offer useful guidance for decision-makers in selecting, prioritising, and financing clean innovation strategies, taking into account sector-specific pathways and the distributional impacts of proposed low-carbon and/or resilient recovery policies and programs and implementing place-based regional development policies.

CRediT authorship contribution statement

Christina E. Hoicka: Writing – original draft, Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marcello Graziano:** Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Maya Willard-Stepan:** Writing – original draft, Writing – review & editing, Visualization, Conceptualization. **Yuxu Zhao:** Writing – original draft, Writing – review & editing, Validation, Investigation, Formal analysis, Data curation.

Declaration of competing interest

There are no known conflicts of interest associated with this publication.

Data availability

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

Acknowledgements

Funding for this research is provided by Smart Prosperity Institute Social Science and Humanities Council Research Grant #895-2017-1018, Social Science and Humanities Research Council Insight Grant 435-2021-0386 and the Canada Research Chair Secretariat. The researchers thank research assistant Chris Holmes, Renata Leonhardt of the University of Saskatchewan, and appreciate the feedback from colleagues at the 6th Geography of Innovation Conference and at the Global Conference on Economic Geography, and from the anonymous reviewers.

References

[1] International energy agency. Greenhouse gas emissions from energy data Explorer. 2021.
[2] IPCC. Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 2022.
[3] Luderer G, Madeddu S, Merfort L, Ueckerdt F, Pehl M, Pietzcker R, et al. Impact of declining renewable energy costs on electrification in low-emission scenarios. Nat Energy 2022;7:32–42. https://doi.org/10.1038/s41560-021-00937-z.
[4] International energy agency. World energy outlook 2023. International Energy Agency; 2024.
[5] REN21. Renewables 2024 global status report collection, global overview. Paris: REN21 Secretariat; 2024.
[6] Jacobson MZ. 100% clean, renewable energy and storage for everything. Cambridge: Cambridge University Press; 2020. https://doi.org/10.1017/9781108786713.
[7] International Energy Agency. Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach - 2023 Update. Paris: International Energy Agency; 2023.
[8] MacArthur JL, Hoicka CE, Castleden H, Das R, Lieu J. Canada's green new Deal: forging the socio-political foundations of climate resilient infrastructure? Energy Res Soc Sci 2020;65:101442. https://doi.org/10.1016/j.erss.2020.101442.
[9] Martinot E. Grid integration of renewable energy: flexibility, innovation, and experience. Annu Rev Env Resour 2016;41:223–51. https://doi.org/10.1146/annurev-environ-110615-085725.

[10] Seto KC, Davis SJ, Mitchell RB, Stokes EC, Unruh G, Ürge-Vorsatz D. Carbon lock-in: types, causes, and policy implications. Annu Rev Env Resour 2016;41:425–52. https://doi.org/10.1146/annurev-environ-110615-085934.

[11] Ramirez Camargo L, Stoeglehner G. Spatiotemporal modelling for integrated spatial and energy planning. Energy, Sustainability Soc 2018;8:32. https://doi.org/10.1186/s13705-018-0174-z.

[12] Smil V. Making sense of power densities. Power density: A key to understanding energy sources and uses. MIT Press; 2016. p. 190–220.

[13] Hoicka CE, Rowlands IH. Solar and wind resource complementarity: advancing options for renewable electricity integration in Ontario. Canada Renewable Energy 2011;36:97–107. https://doi.org/10.1016/j.renene.2010.06.004.

[14] Barrington-Leigh C, Ouliaris M. The renewable energy landscape in Canada: a spatial analysis. Renew Sustain Energy Rev 2017;75:809–19. https://doi.org/10.1016/j.rser.2016.11.061.

[15] Bekirsky N, Hoicka CE, Brisbois MC, Ramirez Camargo L. Many actors amongst multiple renewables: a systematic review of actor involvement in complementarity of renewable energy sources. Renew Sustain Energy Rev 2022;161:112368. https://doi.org/10.1016/j.rser.2022.112368.

[16] Berka A, Dreyfus M. Decentralisation and inclusivity in the energy sector: preconditions, impacts and avenues for further research. Renew Sustain Energy Rev 2021;138:110663. https://doi.org/10.1016/j.rser.2020.110663.

[17] Brisbois MC. Powershifts: a framework for assessing the growing impact of decentralized ownership of energy transitions on political decision-making. Energy Res Soc Sci 2019;50:151–61. https://doi.org/10.1016/j.erss.2018.12.003.

[18] Köhler J, Geels FW, Kern F, Markard J, Onsongo E, Wieczorek A, et al. An agenda for sustainability transitions research : state of the art and future directions ☆. Environ Innov Soc Trans 2019;31:1–32. https://doi.org/10.1016/j.eist.2019.01.004.

[19] Stokes LC. The politics of renewable energy policies: the case of feed-in tariffs in Ontario. Canada Energy Policy 2013;56:490–500. https://doi.org/10.1016/j.enpol.2013.01.009.

[20] Rand J, Hoen B. Thirty years of north American wind energy acceptance research: what have we learned? Energy Res Soc Sci 2017;29:135–48. https://doi.org/10.1016/j.erss.2017.05.019.

[21] Boucher M, Pigeon M-A. Scaling renewable energy cooperatives for a net-zero Canada: challenges and opportunities for accelerating the energy transition. Energy Res Soc Sci 2024;115:103618. https://doi.org/10.1016/j.erss.2024.103618.

[22] Hoicka CE, Savic K, Campney A. Reconciliation through renewable energy? A survey of indigenous communities, involvement, and peoples in Canada. Energy Res Soc Sci 2021;74:101897. https://doi.org/10.1016/j.erss.2020.101897.

[23] Tarhan MD. Renewable energy co-operatives and the struggle for energy democracy: The case of Ontario. 2020.

[24] O'Neil R, Preziuso D, Arkema K, Ko Y, Pevzner N, Diamond K, et al. Renewable Energy Landscapes: Designing Place-Based Infrastructure for Scale. 2022. https://doi.org/10.2172/1961993.

[25] Hidayatno A, Destyanto AR, Handoyo BA. A conceptualization of renewable energy-powered industrial cluster development in Indonesia. Energy Procedia 2019;156:7–12. https://doi.org/10.1016/j.egypro.2018.11.074.

[26] Hoicka CE, Lowitzsch J, Brisbois MC, Kumar A, Ramirez Camargo L. Implementing a just renewable energy transition: policy advice for transposing the new European rules for renewable energy communities. Energy Policy 2021;156:112435. https://doi.org/10.1016/j.enpol.2021.112435.

[27] Lowitzsch J, Hoicka CE, van Tulder FJ. Renewable energy communities under the 2019 European clean energy package – governance model for the energy clusters of the future? Renew Sustain Energy Rev 2020:109489. https://doi.org/10.1016/j.rser.2019.109489.

[28] McCauley SM, Stephens JC. Green energy clusters and socio-technical transitions: analysis of a sustainable energy cluster for regional economic development in Central Massachusetts, USA. Sustain Sci 2012;7:213–25. https://doi.org/10.1007/s11625-012-0164-6.

[29] Jaegersberg G, Ure J. Renewable energy clusters. Recurring barriers to cluster development in eleven countries. Springer; 2017. https://doi.org/10.1007/978-3-319-50365-3.

[30] Wolsink M. The research agenda on social acceptance of distributed generation in smart grids: renewable as common pool resources. Renew Sustain Energy Rev 2012;16:822–35. https://doi.org/10.1016/j.rser.2011.09.006.

[31] Sovacool BK. How long will it take? Conceptualizing the temporal dynamics of energy transitions. Energy Res Soc Sci 2016;13:202–15. https://doi.org/10.1016/j.erss.2015.12.020.

[32] York R, Bell SE. Energy transitions or additions?: why a transition from fossil fuels requires more than the growth of renewable energy. Energy Res Soc Sci 2019;51:40–3. https://doi.org/10.1016/j.erss.2019.01.008.

[33] Pasqualetti MJ. Reading the changing energy landscape. In: Stremke S, van den Dobbelsteen A, editors. Sustainable energy landscapes: Designing, planning, and development. Boca Raton, vol. 7. CRC Press: Florida; 2012. p. 11–45.

[34] Mancarella P. MES (multi-energy systems): an overview of concepts and evaluation models. Energy 2014;65:1–17. https://doi.org/10.1016/j.energy.2013.10.041.

[35] Hoicka CE, Das RR, Zhao Y, Mcmaster M, Lieu J, Wyse S. Methodology to identify demand-side low-carbon innovations and their potential impact on socio-technical energy systems. MethodsX 2021;8:101295. https://doi.org/10.1016/j.mex.2021.101295.

[36] Koirala BP, Koliou E, Friege J, Hakvoort RA, Herder PM. Energetic communities for community energy: a review of key issues and trends shaping integrated community energy systems. Renew Sustain Energy Rev 2016;56:722–44. https://doi.org/10.1016/j.rser.2015.11.080.

[37] Baldassarre Brian, Schepers Micky, Bocken Nancy, Cuppen Eefje, Korevaar Gijsbert, Calabrretta Giulia. Industrial Symbiosis: towards a design process for eco-industrial clusters by integrating circular economy and industrial ecology perspectives. J Clean Prod 2019;216:446–60. https://doi.org/10.1016/j.jclepro.2019.01.091.

[38] Götz M. Clusters and industry 4.0 – do they fit together? Eur Planning Studies 2017;25:1633–52. https://doi.org/10.1080/09654313.2017.1327037.

[39] Hasink R, Isaksen A, Trippl M. Towards a comprehensive understanding of new regional industrial path development. Regional Studies 2019;53:1636–45. https://doi.org/10.1080/00343404.2019.1566704.

[40] Porter ME. Location, competition, and economic development: local clusters in a global economy. Econ Dev Quarterly 2000;14:15–34. https://doi.org/10.1177/089124240001400105.

[41] Porter M. Competitive advantage: Creating and sustaining superior performance. New York, NY: Free Press; 1998.

[42] Delgado M, Porter ME, Stern S. Defining clusters of related industries. J Econ Geograp 2015;16:1–38. https://doi.org/10.1093/jeg/lbv017.

[43] Wolman H, (Hal), Hincapie D.. Clusters and cluster-based development policy. Econ Dev Quarterly 2015;29:135–49. https://doi.org/10.1177/0891242413517136.

[44] De Marchi V, Di Maria E, Gereffi G. Industrial districts, clusters and global value chains. Local clusters in global value chains. Taylor & Francis Group; 2017. p. 13.

[45] Rhodes E, Hoyle A, McPherson M, Craig K. Understanding climate policy projections: a scoping review of energy-economy models in Canada. Renew Sustain Energy Rev 2022;153:111739. https://doi.org/10.1016/j.rser.2021.111739.

[46] Pathak M, Slade R, Shukla PR, Skea J, Pichs-Madruga R, Ürge-Vorsatz D. Technical summary. In: Climate change 2022: Mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press; 2022. https://doi.org/10.1017/9781009157926.002.

[47] McPherson M, Rhodes E, Stanislaw L, Arjmand R, Saffari M, Xu R, et al. Modeling the transition to a zero emission energy system: a cross-sectoral review of building, transportation, and electricity system models in Canada. Energy Rep 2023;9:4380–400. https://doi.org/10.1016/j.egyr.2023.02.090.

[48] Li FGN, Trutnevyte E, Strachan N. A review of socio-technical energy transition (STET) models. Technol Forecasting Soc Change 2015;100:290–305. https://doi.org/10.1016/j.techfore.2015.07.017.

[49] Paniccia I. Cutting through the chaos - towards a new typology of industrial districts and clusters. In: Asheim B, Cooke P, Martin R, editors. Clusters and regional development. New York, NY: Routledge; 2006. p. 90–114.

[50] Copus A. The new rural economy and macro-scale patterns. 2014. p. 11–34.

[51] Dická JN, Gessert A, Sninčák I. Rural and non-rural municipalities in the Slovak Republic. Null 2019;15:84–93. https://doi.org/10.1080/17445647.2019.1615010.

[52] Dijkstra L, Poelman H. Regional Working Paper 2014. A harmonised definition of cities and rural areas: the new degree of urbanisation. Directorate-General for Regional and Urban Policy, European Commission 2014;WP:24.

[53] Hedlund M. Mapping the socioeconomic landscape of rural Sweden : Towards a typology of rural areas mapping the socioeconomic landscape of rural. Sweden: Towards a Typology of Rural Areas; 2016. p. 3404. https://doi.org/10.1080/00343404.2014.924618.

[54] Ermolaeva P, Agapeeva K. Sustainability practices among Russian business communities: drivers and barriers towards change (the cases of Moscow and Kazan). Innovations Traditions Sustainable Dev 2021:467–83.

[55] Kivimaa P, Boon W, Hyysalo S, Klerkx L. Towards a typology of intermediaries in sustainability transitions: a systematic review and a research agenda. Res Policy 2019;48:1062–75. https://doi.org/10.1016/j.respol.2018.10.006.

[56] Rodrigo P, Mu P, Wright A. Transitions dynamics in context : key factors and alternative paths in the sustainable development of nations94; 2015. https://doi.org/10.1016/j.jclepro.2015.01.057.

[57] Fiaschetti M, Graziano M, Heumann BW. A data-based approach to identifying regional typologies and exemplars across the urban–rural gradient in Europe using affinity propagation. Regional Studies 2021;55:1939–54. https://doi.org/10.1080/00343404.2021.1871598.

[58] Copus AK, Johansson M, Mcquaid RW. One size fits all? regional differentiation and rural development Policy6; 2007. p. 13–21.

[59] Graskemper V, Yu X, Feil J. Farmer typology and implications for policy design – an unsupervised machine learning approach. Land Use Policy 2021;103:105328. https://doi.org/10.1016/j.landusepol.2021.105328.

[60] Heumann BW, Graziano M, Fiaschetti M. A Data-Driven Algorithm to Redefine the U.S. Rural Landscape: Affinity Propagation as a Mixed-Data/Mixed-Method Tool. Economic Development Quarterly. 2022. In Press. 10.1177%2F08912424221103556.

[61] Khalaf C, Michaud G, Jolley GJ. Toward a new rural typology: mapping resources, opportunities, and challenges. Econ Dev Quarterly 2021. https://doi.org/10.1177/08912424211069122. 089124242110691.

[62] Martins F. PV sector in the European Union countries – clusters and efficiency. Renew Sustain Energy Rev 2017;74:173–7. https://doi.org/10.1016/j.rser.2017.02.026.

[63] van Summeren LFM, Wieczorek AJ, Bombaerts GJT, Verbong GPJ. Community energy meets smart grids: reviewing goals, structure, and roles in virtual power plants in Ireland, Belgium and the Netherlands. Energy Res Soc Sci 2020;63:101415. https://doi.org/10.1016/j.erss.2019.101415.

[64] Bauknecht D, Andersen AD, Dunne KT. Challenges for electricity network governance in whole system change: insights from energy transition in Norway. Environ Innov Soc Trans 2020;37:318–31. https://doi.org/10.1016/j.eist.2020.09.004.

[65] Loorbach D, Frantzeskaki N, Avelino F. Sustainability transitions research: transforming science and practice for societal change. Annu Rev Env Resour 2017;42:599–626. https://doi.org/10.1146/annurev-environ-102014-021340.

[66] Rogers E. Diffusion of innovations. New York: Free Press; 2003.

[67] Clausen J, Fichter K. The diffusion of environmental product and service innovations: driving and inhibiting factors. Environ Innov Soc Trans 2019;31: 64–95. https://doi.org/10.1016/j.eist.2019.01.003.

[68] Fichter K, Clausen J. Diffusion of environmental innovations: sector differences and explanation range of factors. Environ Innov Soc Trans 2021;38:34–51. https://doi.org/10.1016/j.eist.2020.10.005.

[69] Fichter K, Clausen J. Diffusion dynamics of sustainable innovation - insights on diffusion patterns based on the analysis of 100 sustainable product and service innovations. J Innovation Manage 2016;4:30–67. https://doi.org/10.24840/2183-0606_004.002_0004.

[70] Bergek A, Jacobsson S, Carlsson B, Lindmark S. Rickne a. Analyzing the Functional Dynamics of Technological Innovation Systems: A scheme of analysis; 2008. p. 407–29.

[71] Jordaan SM, Romo-Rabago E, McLeary R, Reidy L, Nazari J, Herremans IM. The role of energy technology innovation in reducing greenhouse gas emissions: a case study of Canada. Renew Sustain Energy Rev 2017;78:1397–409. https://doi.org/10.1016/j.rser.2017.05.162.

[72] Hoicka CE, Coutinho A, Zhao Yuxu. Conroy J. Philanthropic organisations advancing equity, diversity and inclusion in the net-zero carbon economy in Canada. 2022. https://doi.org/10.13140/RG.2.2.28861.74721.

[73] Bridge G, Bouzarovski S, Bradshaw M, Eyre N. Geographies of energy transition: space, place and the low-carbon economy. Energy Policy 2013;53:331–40. https://doi.org/10.1016/j.enpol.2012.10.066.

[74] Balta-Ozkan N, Watson T, Mocca E. Spatially uneven development and low carbon transitions: insights from urban and regional planning. Energy Policy 2015;85:500–10. https://doi.org/10.1016/j.enpol.2015.05.013.

[75] Nijkamp P. Energy problems and regional development. Regional Sci Urban Econ 1980;10:299–301.

[76] Porter ME. On competition. Updated and expanded ed. Boston, MA: Harvard Business School Pub; 1998.

[77] Davies AR. Cleantech clusters: transformational assemblages for a just, green economy or just business as usual? Glob Environ Chang 2013;23:1285–95. https://doi.org/10.1016/j.gloenvcha.2013.07.010.

[78] Marra A, Antonelli P, Pozzi C. Emerging green-tech specializations and clusters – a network analysis on technological innovation at the metropolitan level. Renew Sustain Energy Rev 2017;67:1037–46. https://doi.org/10.1016/j.rser.2016.09.086.

[79] Butturi MA, Lolli F, Sellitto MA, Balugani E, Gamberini R, Rimini B. Renewable energy in eco-industrial parks and urban-industrial symbiosis: a literature review and a conceptual synthesis. Appl Energy 2019;255:113825. https://doi.org/10.1016/j.apenergy.2019.113825.

[80] Soukissian TH, Adamopoulos C, Prospathopoulos A, Karathanasi F, Stergiopoulou L. Marine renewable energy clustering in the Mediterranean Sea: the case of PELAGOS project. Frontiers Energy Res 2019:7.

[81] Graziano M, Lecca P, Musso M. Historic paths and future expectations: the macroeconomic impacts of the offshore wind technologies in the UK. Energy Policy 2017;108:715–30. https://doi.org/10.1016/j.enpol.2017.06.042.

[82] Marshall A. Industry and trade. London, UK: Macmillan; 1919.

[83] Beccatini G. Dal 'settore' industriale al 'distretto' industriale. Alcune considerazioni sull'unità di indagine dell'economia industriale. Rivista Di Economia e Politica Industriale 1989;5:7–21.

[84] Camagni R. Innovation networks: Spatial perspectives. London, UK: Belhaven Press; 1991.

[85] Krugman P. Geography and trade. Cambridge (MA), USA: The MIT Press; 1991.

[86] Gray M, Caprotti F. Cleantech clusters and the promotion of the low carbon transition: criteria for success and evidence from Copenhagen. Masdar Online platforms Carbon Manage 2011;2:529–38. https://doi.org/10.4155/cmt.11.56.

[87] Kyriakarakos G, Piromalis DD, Dounis AI, Arvanitis KG, Papadakis G. Intelligent demand side energy management system for autonomous polygeneration microgrids. Appl Energy 2013;103:39–51. https://doi.org/10.1016/j.apenergy.2012.10.011.

[88] Hoicka CE, Conroy J, Berka AL. Reconfiguring actors and infrastructure in city renewable energy transitions: a regional perspective. Energy Policy 2021;158: 112544. https://doi.org/10.1016/j.enpol.2021.112544.

[89] Ramirez Camargo L, Nitsch F, Gruber K, Valdes J, Wuth J, Dorner W. Potential analysis of hybrid renewable energy Systems for Self-Sufficient Residential use in Germany and the Czech Republic. Energies 2019;12:4185. https://doi.org/10.3390/en12214185.

[90] Bakhtavar E, Prabatha T, Karunathilake H, Sadiq R, Hewage K. Assessment of renewable energy-based strategies for net-zero energy communities: a planning model using multi-objective goal programming. J Clean Prod 2020;272:122886. https://doi.org/10.1016/j.jclepro.2020.122886.

[91] Schweizer-Ries P. Energy sustainable communities: environmental psychological investigations. Energy Policy 2008;36:4126–35. https://doi.org/10.1016/j.enpol.2008.06.021.

[92] Karunathilake H, Hewage K, Mérida W, Sadiq R. Renewable energy selection for net-zero energy communities: life cycle based decision making under uncertainty. Renew Energy 2019;130:558–73. https://doi.org/10.1016/j.renene.2018.06.086.

[93] Liu J, Yang H, Zhou Y. Peer-to-peer energy trading of net-zero energy communities with renewable energy systems integrating hydrogen vehicle storage. Appl Energy 2021;298:117206. https://doi.org/10.1016/j.apenergy.2021.117206.

[94] Owens SE. Land-use planning for energy efficiency. Appl Energy 1992;43:81–114. https://doi.org/10.1016/0306-2619(92)90075-M.

[95] Owens SE. Energy, planning and urban form. London: Pion; 1986.

[96] Calvert K, Smit E, Wassmansdorf D, Smithers J. Energy transition, rural transformation and local land-use planning: insights from Ontario, Canada. Environ Planning E: Nat Space 2021. https://doi.org/10.1177/25148486211024909. 251484862110249.

[97] Hoicka CE, MacArthur J. The infrastructure for electricity: A technical overview. In: Hancock KJ, Allison JE, editors. The Oxford handbook of energy politics. Oxford University Press; 2021. p. 67–98. https://doi.org/10.1093/oxfordhb/9780190861360.013.33.

[98] Masson-Delmotte V, Zhai P, Pirani A. Climate change 2021: The physical science basis : Summary for policymakers : Working group I contribution to the sixth assessment report of the intergovernmental panel on climate change. Geneva, Switzerland: IPCC; 2021.

[99] Poggi F, Firmino A, Amado M. Planning renewable energy in rural areas : impacts on occupation and land use. Energy 2018;155:630–40. https://doi.org/10.1016/j.energy.2018.05.009.

[100] Naumann M, Rudolph D. Conceptualizing rural energy transitions: energizing rural studies, ruralizing energy research. J Rural Studies 2020;73:97–104. https://doi.org/10.1016/j.jrurstud.2019.12.011.

[101] Dixon T, Lannon S, Eames M. Reflections on disruptive energy innovation in urban retrofitting: methodology, practice and policy. Energy Res Soc Sci 2018;37: 255–9. https://doi.org/10.1016/j.erss.2017.10.009.

[102] Grubler A, Aguayo F, Gallagher K, Hekkert M, Jiang K, Mytelka L, et al. Policies for the energy technology innovation system (ETIS). In: Johansson TB, Nakicenovic N, Patwardhan A, Gomez-Echeverri L, editors. Global energy assessment (GEA). Cambridge: Cambridge University Press; 2012. p. 1665–744. https://doi.org/10.1017/CBO9780511793677.030.

[103] Sims Gallagher K, Gr A, Kuhl L, Nemet G, Wilson C, Grubler A, et al. The energy technology innovation system. Annu Rev Env Resour 2012;37:137–62. https://doi.org/10.1146/annurev-environ-060311-133915.

[104] Edsand H. Technology in Society Technological innovation system and the wider context : a framework for developing countries. Technol Soc 2019;58:101150. https://doi.org/10.1016/j.techsoc.2019.101150.

[105] Gliedt T, Hoicka CE, Jackson N. Innovation intermediaries accelerating environmental sustainability transitions. J Clean Prod 2018;174:1247–61. https://doi.org/10.1016/j.jclepro.2017.11.054.

[106] Hoicka CE, Zhao Y, McMaster M-L, Das RR. Diffusion of demand-side low-carbon innovations and socio-technical energy system change. Renewable Sustainable Energy Trans 2022;2:100034. https://doi.org/10.1016/j.rset.2022.100034.

[107] Johnstone P, Rogge KS, Kivimaa P, Fratini CF, Primmer E, Stirling A. Waves of disruption in clean energy transitions: sociotechnical dimensions of system disruption in Germany and the United Kingdom. Energy Res Soc Sci 2020;59: 101287. https://doi.org/10.1016/j.erss.2019.101287.

[108] Karakaya E, Sriwannawit P. Barriers to the adoption of photovoltaic systems: the state of the art. Renew Sustain Energy Rev 2015;49:60–6. https://doi.org/10.1016/j.rser.2015.04.058.

[109] Li A, Xu Y, Shiroyama H. Solar lobby and energy transition in Japan. Energy Policy 2019;134:110950. https://doi.org/10.1016/j.enpol.2019.110950.

[110] Meelen T, Doody B, Schwanen T. Vehicle-to-grid in the UK fleet market: an analysis of upscaling potential in a changing environment. J Clean Prod 2021; 290:125203. https://doi.org/10.1016/j.jclepro.2020.125203.

[111] Ornetzeder M, Rohracher H. Of solar collectors, wind power, and car sharing: comparing and understanding successful cases of grassroots innovations. Glob Environ Chang 2013;23:856–67. https://doi.org/10.1016/j.gloenvcha.2012.12.007.

[112] Kivimaa P, Kern F. Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. Res Policy 2016;45:205–17. https://doi.org/10.1016/j.respol.2015.09.008.

[113] Olbrich S, Bauknecht D. System building: towards a conceptualisation of the third phase of transitions. SSRN J 2022. https://doi.org/10.2139/ssrn.4170503.

[114] Haley B. Promoting low-carbon transitions from a two-world regime: hydro and wind in Québec. Canada Energy Policy 2014;73:777–88. https://doi.org/10.1016/j.enpol.2014.05.015.

[115] Axon S, Bertana A, Graziano M, Cross E, Smith A, Axon K, et al. The US blue new Deal: What does it mean for just transitions, sustainability, and resilience of the blue economy?. 2022. https://doi.org/10.1111/geoj.12434.

[116] Matti C, Consoli D, Uyarra E. Multi level policy mixes and industry emergence: the case of wind energy in Spain. Environ Planning C: Politics Space 2017;35: 661–83. https://doi.org/10.1177/0263774X16663933.

[117] Mäkitie T, Hanson J, Steen M, Hansen T, Andersen AD. Complementarity formation mechanisms in technology value chains. Res Policy 2022;51:104559. https://doi.org/10.1016/j.respol.2022.104559.

[118] Dóci G, Vasileiadou E. "Let's do it ourselves" individual motivations for investing in renewables at community level. Renew Sustain Energy Rev 2015;49:41–50. https://doi.org/10.1016/j.rser.2015.04.051.

[119] Mignon I, Bergek A. System- and actor-level challenges for diffusion of renewable electricity technologies: an international comparison. J Clean Prod 2016;128: 105–15. https://doi.org/10.1016/j.jclepro.2015.09.048.

[120] Bergek A, Mignon I. Motives to adopt renewable electricity technologies: evidence from Sweden. Energy Policy 2017;106:547–59. https://doi.org/10.1016/j.enpol.2017.04.016.

[121] Clausen J, Fichter K, Winter W, Clausen J, Fichter K, Winter W, et al. Theoretische Grundlagen für die Erklärung von Diffusionsverläufen von Nachhaltigkeitsinnovationen. Borderstep Inst Für Innovation Und Nachhaltigkeit GmbH; 2011.

[122] REN21. Renewables in Cities 2021 Global Status Report. 2021.

[123] REN21. Renewables 2020 Global Status Report. 2020.

[124] REN21. Community Renewable Energy. 2016.

[125] Dóci G, Vasileiadou E, Petersen AC. Exploring the transition potential of renewable energy communities. Futures 2015;66:85–95. https://doi.org/10.1016/j.futures.2015.01.002.

[126] Hekkert MP, Suurs RAA, Negro SO, Kuhlmann S, Smits REHM. Functions of innovation systems: a new approach for analysing technological change. Technol Forecasting Soc Change 2007;74:413–32. https://doi.org/10.1016/j.techfore.2006.03.002.

[127] Jacobson MZ, Delucchi MA, Bauer ZAF, Goodman SC, Chapman WE, Cameron MA, et al. 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world. Joule 2017;1:108–21. https://doi.org/10.1016/j.joule.2017.07.005.

[128] Wieczorek AJ, Negro SO, Harmsen R, Heimeriks GJ, Luo L, Hekkert MP. A review of the European offshore wind innovation system. Renew Sustain Energy Rev 2013;26:294–306. https://doi.org/10.1016/j.rser.2013.05.045.

[129] Isard Walter. Regional science, the concept of region, and regional structure. Papers Regional Sci 1956;2:13–26. https://doi.org/10.1111/j.1435-5597.1956.tb01542.x.

[130] Ruth M. Regional science in a resource-constrained world. Annals Regional Sci 2018;61:229–36. https://doi.org/10.1007/s00168-018-0879-0.

[131] Boyce D. A short history of the filed of regional science. Papers Regional Sci 2003;83:31–57. https://doi.org/10.1007/s10110-003-0176-9.

[132] Camagni R. Spatial diffusion of pervasive process innovation. Seminal studies in regional and urban economics. Springer Nature; 2017. p. 49–64.

[133] Caragliu A. Energy efficiency-enhancing policies and firm performance: evidence from the paper and glass industries in Italy. Energy Policy 2021;156:112415. https://doi.org/10.1016/j.enpol.2021.112415.

[134] Hagerstrand T. Innovaiton diffusion as a spatial process. First: University of Chicago Press; 1967.

[135] Duranton G, Henerson JV, Strange WC. Handbook of regional and urban economicsvol. 5A. Amsterdam: Elsevier; 2015.

[136] O'Higgins Tim, Alexander Karen A, Graziano Marcello. Mismatches in spatial scale of supply and demand and their consequences for local welfare in Scottish aquaculture. Anthropocene Coasts 2019;1:261–78. https://doi.org/10.1139/anc-2018-0025.

[137] Caragliu A, Graziano M. The spatial dimension of energy transition policies, practices and technologies. Energy Policy 2022;168:113154. https://doi.org/10.1016/j.enpol.2022.113154.

[138] Coenen L, Hansen T, Glasmeier A, Hassink R. Regional foundations of energy transitions. Camb J Reg Econ Soc 2021:rsab010. https://doi.org/10.1093/cjres/rsab010.

[139] Turkina E, van Assche A. Global connectedness and local innovation in industrial clusters. J Int Bus Stud 2018:49. https://doi.org/10.1057/s41267-018-0153-9.

[140] Corrocher Nicoletta, Mancusi Marial Luisa. International collaborations in green energy technologies: what is the role of distance in environmental policy stringency? Energy Policy 2021;156:112470. https://doi.org/10.1016/j.enpol.2021.112470.

[141] Brenner T, Mühlig A, Marburg D. Email G. Factors and mechanisms causing the emergence of local industrial clusters : a summary of 159 cases factors and mechanisms causing the emergence of local industrial clusters : a summary of 159 cases. Regional Studies 2013;47:480–507. https://doi.org/10.1080/00343404.2012.701730.

[142] Isaksen A. Cluster emergence: combining pre-existing conditions and triggering factors. Entrep Reg Dev 2016;5626:1–20. https://doi.org/10.1080/08985626.2016.1239762.

[143] Perez-Aleman P. CLUSTER formation, institutions and learning : the emergence of clusters and development in Chile. Ind Corporate Change 2005;14:651–77. https://doi.org/10.1093/icc/dth063.

[144] Bittencourt BA, Zen AC, Schmidt V, Wegner D. The orchestration process for emergence of clusters of innovation. J Sci Technol Policy Manage 2018. https://doi.org/10.1108/JSTPM-02-2018-0016.

[145] Andersson M, Tamanini J, Asplund C, Fransson M, Sporre M, Parliden J. NORDIC INNOVATION REPORT 2012:04: Strategic global marketing of Nordic cleantech clusters and competencies. Lighthouse project: Communicating Nordic green solutions and competencies. Nordic Council of Ministers; 2012.

[146] Porter ME, Ketels Christian. Clusters and industrial districts: Common roots, different perspectives. A handbook of industrial districts. Edward Elgar Publishing; 2009. https://doi.org/10.4337/9781781007808.

[147] Martin H, Coenen L. Institutional context and cluster emergence: the biogas industry in southern Sweden. Eur Planning Studies 2015;4313:2009–27. https://doi.org/10.1080/09654313.2014.960181.

[148] Casper S. How do technology clusters emerge and become sustainable?: social network formation and inter-firm mobility within the San Diego biotechnology cluster. Res Policy 2007;36:438–55. https://doi.org/10.1016/j.respol.2007.02.018.

[149] Robinson DKR, Rip A, Mangematin V. Technological agglomeration and the emergence of clusters and networks in nanotechnology36; 2007. p. 871–9. https://doi.org/10.1016/j.respol.2007.02.003.

[150] Burger MJ, Meijers EJ, van Oort FG. Editorial: the development and functioning of regional Urban Systems. Regional Studies 2014;48:1921–5. https://doi.org/10.1080/00343404.2014.979782.

[151] Parr JB. The regional economy, spatial structure and regional Urban Systems. Regional Studies 2014;48:1926–38. https://doi.org/10.1080/00343404.2013.799759.

[152] Sarja JM. The Actors of a Wind Power Cluster: A Case of Wind Power Capital7; 2013. p. 143–50. https://doi.org/10.4090/juee.2013.v7n1.143150.

[153] Frey BJ, Dueck D. Clustering by passing messages between data points. Science 2007;315:972–6. https://doi.org/10.1126/science.1136800.

[154] Givoni IE, Chung C, Frey BJ. Hierarchical Affinity Propagation9; 2011.

[155] Federal Reserve Bank of Chicago. Peer City Identification Tool; 2022. https://www.chicagofed.org/region/community-development/data/pcit.

[156] Directorate-General for Internal Market. Industry, entrepreneurship and SMEs (European Commission). User guide to the SME definition. Publications Office of the European Union; 2020.

[157] Engels JS. Global clusters of innovation: Cafornia Management Review57; 2015. p. 36–65. https://doi.org/10.1525/cmr.2015.57.2.36.

[158] Sturgeon T, van Biesebroeck J, Gereffi G. Value chains, networks and clusters: reframing the global automotive industry. J Econ Geograp 2008:8. https://doi.org/10.1093/jeg/lbn007.

[159] Lee J, Jung S. Industrial land use planning and the growth of knowledge industry: location pattern of knowledge-intensive services and their determinants in the Seoul metropolitan area. Land Use Policy 2020;95:104632. https://doi.org/10.1016/j.landusepol.2020.104632.

[160] Lorenzen M. Ties, trust, and trade. Int Stud Manag Organ 2001;31:14–34. https://doi.org/10.1080/00208825.2001.11656825.

[161] Cagnin C, Amanatidou E, Keenan M. Orienting European innovation systems towards grand challenges and the roles that FTA can play. Sci Public Policy 2012;39:140–52. https://doi.org/10.1093/scipol/scs014.

[162] Smink M, Negro SO, Niesten E, Hekkert MP. How mismatching institutional logics hinder niche–regime interaction and how boundary spanners intervene. Technol Forecasting Soc Change 2015;100:225–37. https://doi.org/10.1016/j.techfore.2015.07.004.

[163] Gomes E, Banos A, Abrantes P, Rocha J. Future land use/cover changes and participatory planning. Mapping and forecasting land use: The present anf future of planning. 1st ed. Amsterda, the Netherlands: Elsevier; 2022. p. 29–53.

[164] Axsen J, Kurani KS. Social influence, consumer behavior, and low-carbon energy transitions. Annu Rev Env Resour 2012;37:311–40. https://doi.org/10.1146/annurev-environ-062111-145049.

[165] Carlosson B, Stankiewicz R. On the nature, function and composition of technological systems. J Evolutionary Econ 1991;1:93–118. https://doi.org/10.1007/BF01224915.

[166] Lopez A, Roberts B, Heimiller D, Blair N, Porro G. U.S. Renewable energy technical potentials: A GIS-based analysis. Boulder, CO, USA: National Renewabl Energy Laboratory; 2012.

[167] Hoicka CE, MacArthur JL. From tip to toes: mapping community energy models in Canada and New Zealand. Energy Policy 2018;121:162–74. https://doi.org/10.1016/j.enpol.2018.06.002.

[168] Fuenfschilling L, Truffer B. The structuration of socio-technical regimes—conceptual foundations from institutional theory. Res Policy 2014;43:772–91. https://doi.org/10.1016/j.respol.2013.10.010.

[169] Palensky P, Kupzog F. Smart Grids. Annu Rev Env Resour 2013;38:201–26. https://doi.org/10.1146/annurev-environ-031312-102947.

[170] Lamb WF, Antal M, Bohnenberger K, Brand-Correa LI, Müller-Hansen F, Jakob M, et al. What are the social outcomes of climate policies? A systematic map and review of the ex-post literature. Environ Res Lett 2020;15:113006. https://doi.org/10.1088/1748-9326/abc11f.

[171] Eupen MV, Metzger MJ, Pérez-soba M, Verburg PH, Doorn AV, Bunce RGH. A rural typology for strategic European policies. Land Use Policy 2012;29:473–82. https://doi.org/10.1016/j.landusepol.2011.07.007.

[172] Mignon I, Kanda W. A typology of intermediary organizations and their impact on sustainability transition policies. Environ Innov Soc Trans 2018;29:100–13. https://doi.org/10.1016/j.eist.2018.07.001.