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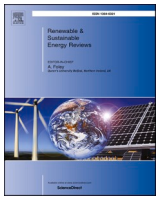

Introducing a typology of energy regions: A systematic literature review

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ABSTRACT

Low-carbon energy transitions are being increasingly developed at sub-national or regional levels, forming, thus, *energy regions*. More energy regions have been formed as energy systems become more decentralized, and national governments devolve decision-making power to local authorities. Energy regions have been studied in several countries, but no study has yet overviewed these regions' variety, transition process, and governance approach. It is important to draw lessons for other cases worldwide, like coal and carbon-intensive regions, to understand what type of regions and how they have stimulated their energy transition. Thus, this study investigated i) the concepts of energy regions that have been published and ii) the way energy regions have transitioned in terms of governance arrangements and innovation processes. A systematic literature review was conducted covering forty-seven academic publications and three grey literature reports of energy regions in ten countries. This review covered three academic (sub-)disciplines: i.e. sustainability transitions, regional studies, and innovation studies. Results show five concepts of energy regions: city-regions, peripheralized regions, coal and carbon-intensive regions, learning regions, and renewable energy regions. The formed typology shows the possible transition pathways that regions can follow. Interestingly, only those energy regions that adopted social innovations had the potential to empower their region, its organizations, and its citizens. Finally, recommendations for practitioners in similar regions worldwide are outlined to help overcome obstacles and advance their low-carbon transition.

1. Introduction

The devolution to regions is a phenomenon of transferring or reclaiming power from the central or national government to regional or local authorities [1–3]. This phenomenon has been fueled by social movements supporting regionalism and growing global economic competition [3,4]. Seeking more sub-national autonomy is a growing trend in regions with socio-cultural identity discrepancies, perceived low sovereignty, and high levels of income [5,6]. Additionally, globalization has led to the specialization of industries within cities and regions, contributing to certain regions' desire for autonomy [3,4]. In the EU, the regionalization process is based on the understanding that the management of natural "resources depends on the cooperation of appropriate international institutions on the one hand and national, regional, and local institutions on the other" [7] (pp.284). The European Union Congress of Local and Regional Authorities argues that regionalizing territories can make countries and intergovernmental cooperation work more effectively and efficiently. As a result, at least €200 billion was dedicated to helping EU regions become more efficient, competitive, inclusive, and sustainable between 2014 and 2020 [1,8]. Therefore, municipal, provincial, and national governance levels can consider leveraging regionalization processes by moving towards an intermediate regional governance level when working on their sustainable development agenda.

When the regionalization process permeates energy systems, the concept of regional energy transition can be applied. In this paper, *regional energy governance* refers to the formal and informal governance approach that steers an energy transition strategy at the sub-national, inter-municipality, and sometimes cross-national levels [9,10]. Additionally, the concept of *energy region* has been increasingly used when discussing sub-national territories whose energy systems undertake a regional energy transition strategy [9–11]. Although the term energy region has been used mainly by scholars in Western Europe and North America, energy regions can, in principle, be found worldwide. The Upper Nitra region in Slovakia, the South Kalimantan province of Indonesia, and the Coahuila region in Mexico are examples of coal regions undergoing energy transitions [12–15]. These regions can be considered energy regions because they are in the process of a low-carbon energy transition that involves the participation of regional

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List of acronyms and abbreviations

CCIRs	Coal and carbon-intensive regions
RIS	Regional Innovation Systems
TSI	Transformative Social Innovation
RES	Renewable energy strategies

(in)formal actor-networks [9].

The National government has created some examples of energy regions to implement a national Climate agenda. In the case of the Netherlands, thirty energy regions were formed to work towards the country's climate change mitigation goals by 2050 [16]. Each Dutch energy region has been tasked with drafting a regional energy transition strategy (RES) in negotiation and collaboration with formalized actor networks; however, RES has no formal constitution authority. Thus, energy regions are not legal entities in the country. Yet, by developing regional energy strategies (RES), Dutch energy regions have some degree of freedom to choose how to design their transition pathways and renewable energy projects that contribute to the national 35 TWh goal. In doing so, they are supported by a national program to share knowledge, build capacity, and use central government funding through subsidies and tax incentives. This includes examples such as the renewable energy support scheme 'SDE++'. However, each RES is critically assessed and calculated based on its contribution to the national objective and is approved by the central government [10]. A reason behind the establishment of RESs is that some renewable energy projects cut across municipal jurisdictions and, therefore, require inter-municipal coordination to prevent the uneven distribution of risks and benefits between municipalities, cities, and rural areas [17]. In this way, a national energy transition agenda is implemented with strong involvement of regional actors so that decentralized governments (i.e., municipalities, water boards, and provincial government) can have more agency and 'regional ownership' [17–19].

Other examples of energy regions have started as a bottom-up approach, with local governments and citizens having some degree of autonomy in managing local energy projects that have received support from the central government at later stages [11,20]. For example, in Austria and Germany, local governments, civil society organizations such as farmers' associations, and grassroots citizens' initiatives created energy regions to reclaim ownership of the energy sector. The creation of energy regions was fueled by demands for more social equity and sustainability, which resulted in more regional independency from fossil-fuel imports [2,11,21,22]. Yet, local energy initiatives require government incentives or regulations to form, mature, professionalize, and sustain [23]. For example, direct geothermal use regulations are needed for an energy community to develop a geothermal district heat system. This includes government subsidies, like the €2.98 billion German scheme approved in 2022, which helped finance renewable energy and waste-fueled district heating networks [24].

Regional energy governance could be leveraged by many territories worldwide [25]. For example, Baja California, a border state of Mexico, has an electric grid not connected to the national grid and heavily relies on imported fossil fuels. Additionally, the state has abundant underused renewable energy sources such as geothermal, solar, and wind [26]. However, local governments lack the decision-making power or influence to define a regional-focused sustainable energy agenda. This is mainly due to natural resources such as energy and water being inefficiently managed by the national government and a lack of institutions that could readily enable regional governance in the border region [27,28].

Nonetheless, a regional energy transition governance approach can positively impact environmental and climate co-benefits. A study showed that with a regional energy transition approach, Delhi, India, could reduce its primary energy demand by 40 % and energy costs by 25 % while reducing GHG emissions [25]. Other regions dependent on fossil fuels may benefit from an energy region approach. For example, regions economically-dependent on fossil-fuel extraction (e.g., coal mining) or carbon-intensive industries (e.g., steel and iron processing and manufacturing). These coal-and-carbon-intensive regions (CCIRs) could form energy regions to formulate transition strategies that address local problems like how to compensate for potential economic and job loss, for example, via the EU territorial just transition plans [10,29,30]. Other reasons for regions to adopt a regional transition approach are the benefits of cross-municipal management. For example, coordinating the development of energy projects that cover more than one municipal jurisdiction (e.g., wind parks and geothermal energy projects) or promoting the sharing of resources between municipalities with different capacities available [31]. Also, countries with extensive territories like Mexico that struggle with the geographical differences in demand, supply, and availability of energy resources might benefit from decentralizing decision-making for the transition [32].

The *energy region* term has been gaining popularity in Western Europe, with examples in the Netherlands, Germany, and Austria. Energy regions in these countries have not initiated their transition the same way, nor have they pursued the same goals. There seems to be no consensus on what an energy region may entail nor what territories could benefit from it. Yet, policymakers are increasingly interested in applying 'energy region' concepts in the Global North, for example, to govern the low-carbon transition of coal and carbon-intensive regions in Europe [29]. To date, studies on regional energy governance primarily focus on regions within the same country [10,33–35] or a few (two or three) similar countries [for example, see 20,21], impeding more general reflections around the energy region as a theoretical concept. Due to the lack of an overview of the variety of energy region concepts, a typology is needed. A typology that classifies the energy region concepts to a) describe their characteristics, b) inform decision-makers of the development of policies unique to the region's potential, and c) help benchmark and compare potential pathways developing across regions.

This study addresses the research gap in identifying energy region concepts applied in different contexts. Based on this research gap, research questions were formulated: i) What types of energy region concepts have been studied? And ii) how have regions transitioned regarding governance arrangements and innovation processes?

A novel systematic literature review of energy region studies through a sustainability transitions and institutional governance lens is conducted to answer the research questions. This conceptual review contributes to sustainability transitions and regional literature with a typology of regional energy transitions, accounting for different contexts in ten countries. The proposed typology distinguishes between a region's governance arrangement (formal/informal institutions) and transition stage [36–38]. Furthermore, the applied innovation (technological and social) policies of energy regions are discussed with empirical evidence. The typology provides an innovative and illustrative classification of energy regions that practitioners in other regions can use to learn from similar regional contexts.

Section 2 provides an overview of the theoretical frameworks used. Section 3 describes the systematic literature review process. Section 4 presents the results and introduces five concepts of energy regions. Section 5 discusses presents the typology of energy regions, by placing the energy region concepts in a 2D diagram. Contributions, limitations and policy recommendations are outlined in Section 5. Finally, Section 6 presents the conclusions of this study.

2. Theoretical frameworks to study energy regions

This section draws from regional sustainability transitions and innovation studies to review theoretical frameworks describing governance arrangements and major innovation processes that drive regional energy transitions.

Regional energy transitions have been studied from the perspective of sociotechnical systems and sustainability transitions [17,39–41]. Sociotechnical systems theory departs from complex systems understanding to explain how a technology system changes. It views the energy system as a sociotechnical system composed of the environment, society, technology, and economy. Sustainability transition frameworks help one understand why technological change happens and how economic, political, and societal agents influence it. Systemic change in sociotechnical systems is also called 'transition' because it implies a progressive shift from one regime to another (spread across economic and political structures, norms and values, institutions, and behavioral patterns) that determines the development of (new) technological sectors [39,42]. Transition Management is a theoretical framework that addresses sociotechnical transition and adopts a governance approach. This framework has been widely used as a reasonably prescriptive approach towards sustainability transition governance that sets sustainable development as a long-term goal [40,43,44]. The transition management framework studies energy transitions as a change process of institutions and regime changes in a given subsystem. In this context, the regime pertains to energy systems in regions. It is assumed that regime change will take about 25–30 years [40,43].

According to sustainability transitions, and more particularly transition management literature, there are four stages of an energy transition [40,45–48]. The first stage, predevelopment, indicates the continuation of unsustainable-energy-based economies and the introduction of sustainable-energy-based economies [40,45]. The second stage shows the take-off of sustainable-energy-based economies. The third stage describes the acceleration of sustainable-energy-based economies and the decline of non-sustainable-energy-based economies. The fourth stage covers the stabilization of sustainable-energy-based economies (Ibid.).

2.1. Innovation frameworks

Two innovation frameworks, regional innovation systems (RIS) and transformative social innovation (TSI), describe technological and social-driven innovation processes observed in regional energy transitions.

2.1.1. Regional innovation systems

The RIS framework is one of the most applied theoretical approaches of the articles surveyed in this research because it describes how a region goes through a process of socio-technological innovation. Additionally, it considers a region's resources and knowledge to spur innovation in the regional economic sector to become economically competitive [37,49,50]. RIS helps to understand how knowledge from various institutes, organizations, and the public influences industrial sectors in an (energy) region [9,49]. For example, the Ruhr Area in Germany was the country's major steel and coal producer. Still, the area experienced an industrial decline due to a lack of market competitiveness and declining policy support for the sector. The City of Bottrop decided to decarbonize this region's local energy-building sector. Together with over a hundred firms, the City administration set a 50 % CO2 reduction goal in 2020 compared to the 2010 levels [36]. Defining this goal also set in motion a focus on innovation projects to help decarbonize other areas, such as urban planning, housing, and transport (Ibid.). The RIS framework highlights the importance of coordinating economic sectors, sometimes referred to as knowledge elites, in driving innovation processes [36,37]. This framework also considers factors indirectly encouraging regional innovation, such as inter-agent coordination, focusing on trust [51]. Cooke (2001) argues that the likelihood of achieving RIS potential is higher when a region has centralized financial autonomy, can influence infrastructure development, has a culture of institutional cooperation (e.g., between the university and industry), supports the labor force, and aims to have inclusive organizations. Regional innovation experts argue that the RIS transformation process has not been thoroughly analyzed, and therefore, the framework has not evolved as a theory [52]. Furthermore, the approach of the RIS framework does not suffice in encompassing the richness and complexity of understanding energy regions, which can have a more bottom-up, informal, and socially-focused governance approach [50].

2.1.2. Transformative social innovation

The TSI framework departs from the sustainability transitions and social innovation literature to describe concept(s) and practices around social innovation, which also apply to energy regions. TSI describes a transformative innovation process that alters dominant institutions through social innovation practices [38]. Here, social innovation is understood as changes in social relations, the way society is organized, the way problems are framed or defined, and the knowledge created to contribute to low-carbon energy transitions, ultimately, citizens' empowerment and the wellbeing of communities [38,53,54]. Social innovation processes are characterized by having a social mission, the presence of (social entrepreneurs, networks, institutions, systems, and cross-sectoral partnerships [54,55]. Energy systems rely on collective action to achieve a sustainability-related social mission since these societal challenges require a system transformation [51]. An example of collective action is the Berlin-Brandenburg region in Germany, where municipalities successfully reclaimed critical energy infrastructure and formed regional energy utilities while joining the nation-wide energy transition strategy [11]. Collective action behind a social mission has been described as a model for institutional governance change based on the coercion of individuals in large groups like regional stakeholders pursuing a common goal [56]. According to social innovation studies, formal institutions (e.g., regulations and rules) and information and informal institutions are necessary for an energy transition. Informal institutions, often referring to values and norms, can be considered vital pieces to governance, enabling the emergence of new agents leading collective action [54].

2.2. Governance arrangements for regional energy transitions

Energy transitions can be viewed and analyzed from a governance perspective. Governance comprises decision-makers (e.g., social networks, government, and formal or informal organizations) who can rule through laws, norms, power, or language [57]. Governance is carried out by a formal government and is seen as an arrangement conceived and agreed upon by multiple decision-makers active at various administrative levels [58,59]. According to evolutionary governance theory, governance arrangements also found in regional energy transitions, can be distinguished in terms of centralization and formalization [17,59]. Governing the energy transition can be done in different ways, either via centralized or decentralized decision-making or a combination. However, any extreme may adversely affect society's sustainable development, for example, when decision-making is centralized by elites (i.e., monocentric governance) or when decisions are made individually without considering society's needs at large [59]. A mode of governance stressing the existence of multiple centers of decision-making is polycentric governance, which can consist of multi-level governance (between local, regional, national, and international levels), collaborative governance, network governance, including public and private sector actors, and citizen participation [17,60]. For example, the Netherlands' thirty energy regions (RES) are considered polycentric because of their decentralized decision-making centers. These centers include multiple municipalities, which, together with other decentralized government organizations (e.g., the provincial government and water boards), are involved in the structuring and formulation of regional strategies (RES) [10,17,61].

Moreover, the RES approach is ultimately aligned with the national Climate Agreement (i.e., energy transition agenda), following a lengthy negotiation process between central government, decentral governments, and other societal actors [17]. Another interesting aspect is

whether formal or informal institutions or incumbent or emerging agents constitute governance arrangements. Formal institutions are associated with written rules, laws, policies, and plans, whereas informal institutions pertain to social values, norms, and cultural guidelines [62]. Informal and formal institutions co-evolve and influence each other and regional energy transition processes (ibid).

2.3. Applying energy region concepts in different contexts

Different concepts of energy regions have proven helpful for sub-national territories seeking low-carbon pathways, as showcased with the Dutch energy regions [10,17]. More generally, it is crucial to understand how to govern energy regions directly or indirectly dependent on fossil fuels. For example, CCIRs in Europe find it particularly challenging to adopt strategies that comply with EU climate change goals toward decarbonization [63]. If only strict top-down national energy transition approaches are followed, CCIRs risk facing social energy injustices such as economic loss, loss of jobs, and population shrinkage if they do not consider necessary regional contextual conditions [64]. Additionally, strong ties between the fossil fuel industry and people's livelihoods and identities are common challenges for low-carbon transitions in CCIRs. These strong ties permeate the culture and impact readiness for sectoral transitions differently than in non-fossil-fuel-dependent regions [65]. For example, the Ruhr region reinvented its regional identity from a traditional coal and steel region to a postindustrial energy region [65]. Similar challenges are found in carbon-intensive regions, where the industrial sector's energy consumption heavily relies on fossil fuels [29]. Carbon-intensive sectors such as steel and cement production may negatively or positively influence people's livelihoods in certain regions because of employment, economic influx, health, or environmental impact. For these reasons, gaining a further understanding of regional governance arrangements for the energy transition, as a pillar of a multi-level governance approach, might be helpful for sub-national territories that struggle to meet Climate goals.

Differences between regions make it infeasible to have one single governance approach to bring transformative change to energy sectors. There is no one-fits-all blueprint of regional energy governance that decision-makers and planners could readily apply. Regions generally differ regarding geographical characteristics, the socio-economic and political setting, and development agendas. These contextual differences may determine the type of governance arrangement required for their transition. Therefore, there is a critical knowledge gap in understanding energy regions' concepts, practices, and examples and their adopted innovations, governance arrangements, and transition processes. A systematic literature review is conducted to address this gap. This review allows for further understanding, conceptualizing, and classifying energy region types regarding governance arrangement(s) and the transition processes they undergo.

3. Systematic literature review

A systematic literature review was conducted to identify concepts of the energy region of fifty crucial studies from ten countries over the last two decades. The studies were analyzed to answer the research questions on identifying the energy region concepts and understanding their governance arrangements, adopted innovation, and transition process. The systematic literature study approach by Van Wee and Banister was adopted because it provides an overview of the literature and adds value by analyzing and categorizing the studies reviewed [66]. In this study, the added value lies in formulating a typology of energy regions and their evolution along the energy transition stages. Also, the regions' governance arrangements and innovations that helped drive energy transitions are discussed.

3.1. Data collection

The keywords and their combinations (see Table 1) provide evidence of how studies on energy transitions apply the regional governance concept and come from three research fields: i.e. regional energy studies, sustainability transitions, and innovation studies. The keywords in Table 1 were chosen because they cover energy regions in these research fields. Emphasis was given to CCIRs for their potential to be studied from an energy region perspective.

The first two combinations of keywords from regional energy studies covered 1) "regional energy governance" and 2) "regional energy transition" since they represent the main topic of the study's literature review—the third combination, 3) "regional energy industry", covered papers on different industrial sectors. The second set of keywords reveals how regional governance is applied in low-carbon and coal-and-carbon-intensive territories that aim to achieve sustainability transition goals. The keywords covered regions seeking: 1) "low-carbon pathways" in general, or territories in 2) "coal-intensive regions", or 3) "carbon-intensive regions". The keyword "low-carbon pathways" refers mainly to territories with renewable energy source availability. The third set of literature explored regional energy governance in the policy innovation process, either as a technological innovation process with 1) regional innovation system studies or as a 2) social innovation process. The keyword 3) "regional innovation" was included to look for other frameworks describing the innovation process in regional energy governance.

The Scopus database was used instead of the Web of Science because Scopus contained more English-written peer-reviewed articles from the social sciences than the Web of Science, which has more articles from the natural sciences. The review covered articles on energy regions published in the last sixteen years, from 2007 to 2023, although the search started in 2000 (available time range on Scopus). There were two peaks of six publications in 2015 and 2022, as shown in Fig. 2. This histogram shows regional energy governance articles published in peer-reviewed journals and three reports. However, Germany started experimenting with learning region policies in the 1980s to reflect on the social innovation dynamics for spatial planning in regions in North Rhine-Westphalia and Saxony [67]. The German learning region policies, feed-in tariffs for renewable energy generation, and the EU power market liberalization influenced initiatives toward regional energy transition governance in Germany and other European countries. This was because these changes allowed local stakeholders such as farmers, municipalities, financial institutes, and regional governments to participate as energy generators or investors [20,21,68]. This indicates the socio-political relevance of the regional energy governance concepts and their mainstreaming [21,69]. These articles cover mainly energy regions in the European continent, as presented in Table 2.

The first survey included all keyword combinations and the Boolean operator OR (see the Identification step in Fig. 1), producing over one million papers. Papers were screened by selecting those mentioning "region" AND "energy transition" because many papers did not emphasize nor address regional energy transition. This screening process narrowed the list own to four hundred and forty-five articles. Then, the ten to twenty most cited papers for each keyword were selected. This step narrowed the pool to one hundred and twenty-six articles.

Table 1
List of keywords used and their relation to three disciplinary research domains.

Number	Regional energy studies	Sustainability transitions	Innovation studies
1	"Regional energy governance"	"Low-carbon pathways"	"Regional innovation systems"
2	"Regional energy transition"	"Coal-intensive region"	"Social innovation"
3	"Regional energy industry"	"Carbon-intensive region"	"Regional innovation"

Table 2
List of countries where energy regions have been studied.

Country	Reference
Germany	[2,20,21,67,68,70,71]
Austria	[9,20,21,33,70,72,73]
Netherlands	[10,17–19,34,35,74]
United Kingdom	[75,76]
Italy	[70]
Switzerland	[20]
Denmark	[21]
Sweden	[79]
United States	[80]
Indonesia	[15]

In the classification step, these papers were skimmed from the title to conclusions and categorized into seminal (n = 19), relevant (n = 41), and non-relevant (n = 66) papers. The seminal papers directly discussed the concept of energy regions and described the characteristics of energy regions. After adding the relevant and non-relevant papers and eliminating repeated papers, the selected list of publications added up to fifty-three papers. After a review of the references for the selected fifty-three papers, it was noticed that the keyword search or screening steps did not capture some relevant energy region papers. This was because these papers were only published recently. Therefore, a snowball approach was performed by looking at the references of the seminal papers that mentioned "energy region" or "regional energy governance." This snowballing step added twenty-seven papers to the final list, with eighty-two peer-reviewed articles in English and three reports in German and Dutch (some of these papers were not part of the Scopus database). In the second screening (see Fig. 1), these eighty-five articles were coded with a qualitative thematic analysis. With this analysis, the articles were selected based on their proximity to the regional energy governance topic; specifically, they discussed energy region types and their governance approach according to the research questions. After this first coding, thirty-five papers were excluded from the review because they lacked relevance to our research questions. Five additional publications were added during the manuscript revision process. This selection resulted in forty-seven academic publications and three grey literature reports. The list of the analyzed publications can be found in the Zenodo database [81].

3.2. Data analysis

A qualitative thematic analysis was conducted using the database of 50 articles and reports and the NVivo 12 Plus software, which is suitable for categorizing and analyzing text from multiple sources [83]. To build a typology of energy regions, the insights from these papers were categorized in a thematic analysis using five frameworks: RIS [52], the polycentric regions framework [17] as a framework rooted in RIS and STS [46], evolutionary governance theory [59], and TSI [38]. These frameworks were selected because they helped describe different cases of regional energy governance in terms of their transition agendas, governance arrangements, and transition processes.

The analysis began with defined themes highlighted by the polycentric regions framework because it was the most recent (2020) and comprehensive framework that described energy regions with various concepts from previous studies [17]. These initial themes covered 1) energy region definitions and characteristics such as 2) geography, 3) stakeholders, 4) industrial sectors, 5) energy technology, and 6) governance arrangements. After considering the governance and innovation frameworks, the final five themes were selected: 1) energy region types, 2) governance agenda, 3) governance arrangement, 4) region scope, and 5) transition process. The final fifty articles were coded with these themes three times, allowing the creation of new sub-codes under each of the five themes. The coding process for qualitative thematic analysis covered a selective coding step with pre-defined themes drawn from relevant frameworks, followed by the creation of new sub-codes [84].

4. Introducing the energy region concepts

Five energy region concepts were identified with the thematic analysis: Three geographical concepts and two transitioning concepts. The geographical concepts are city-regions, peripheralized regions, and CCIRs. City-regions and some CCIRs can be rich in economic resources, strong in formal institutions, and dependent on fossil-fuels. Peripheralized regions, including CCIRS and rural regions, are energy regions with limited financial resources, fossil-fuel dependency, and whose formal institutions cannot support an energy transition. These three geographical concepts are referred to as learning or renewable energy regions when transitioning. The articles corresponding to each energy region type are enlisted in Table 3 and described in Sections 4.1-4.5.

The five energy region concepts differ in their definition of governance arrangements and innovation processes. In terms of the governance arrangements, the energy regions' centralization and formalization levels were analyzed through the theoretical lenses of evolutionary governance theory, RIS, and TSI frameworks [17,37,54,62]. The centralization level goes from monocentric (centralized) to highly polycentric (decentralized) [17,85]. The formalization level refers to whether a governance arrangement is constituted by formal or informal institutions [59].

4.1. City energy regions

City-regionalization is a phenomenon that is commonly found, among others, in European countries and the United States. The city-region concept has been widely employed in regional studies since the 1980s, mainly in the Global North and megacities [25,89], with recent attention in the Global South [15]. Rodríguez-Pose has defined city-regions (2008) [3] as a city hub connected with 'spokes' (i.e., smaller populated areas) connected with functions and multiple 'hubs and spokes' with (bidirectional) interdependencies in the economy, environment, and society [3]. These regions host network configurations within or across states (e.g., the Øresund region across the Swedish-Danish border) and are driven by regional identity, policies, and macroeconomic dynamics such as globalization [3,4,80,89]. In sustainability transitions, city-regions represent energy-intensive urban and industrial areas (e.g., city districts, industrial parks) that seek to transition into fossil-free energy systems [106]. Some examples of transitioning city-regions are Rotterdam-Den Haag and Drechtsteden (Netherlands), Dublin (UK), Göteborg (Sweden), Catalonia (Spain), and Denver (US) [10,79,80,88,107,108].

Economically driven city regions can experience rapid urbanization, thus forming a 'metropolis' [4,80,89]. A major critique of city-regions' rapid urbanization is their limited capacity to meet their citizens' essential needs, such as water and food [4]. Only a few cases of economically-driven city-regions (e.g., Mexico City, Cairo, and Jakarta) have been reported as meeting the conditions for continuous development, that is, being able to compete in the global market while benefiting from trade [3]. Without these conditions and targeted policies that ensure regional empowerment, city-regions may risk greater inequality and stronger top-down influence [3].

The governance arrangements leading the energy transition in city-regions can be either monocentric or have some degree of polycentrism (e.g., hubs and spokes). However, urban cores are typically favored economically over rural areas. In city regions, decision-makers typically see rural areas as resource suppliers for urban institutions. The governance structure of city-regions is both horizontal (i.e., coordination between the civil society, public, and private sector actors within a region) and vertical (i.e., coordination between multiple –levels of government) [3,89]. The horizontal dimension is reflected in the partnership networks or actor constellations that form city-regions [68,89]. Regarding its institutions, city regions often have public, local, and

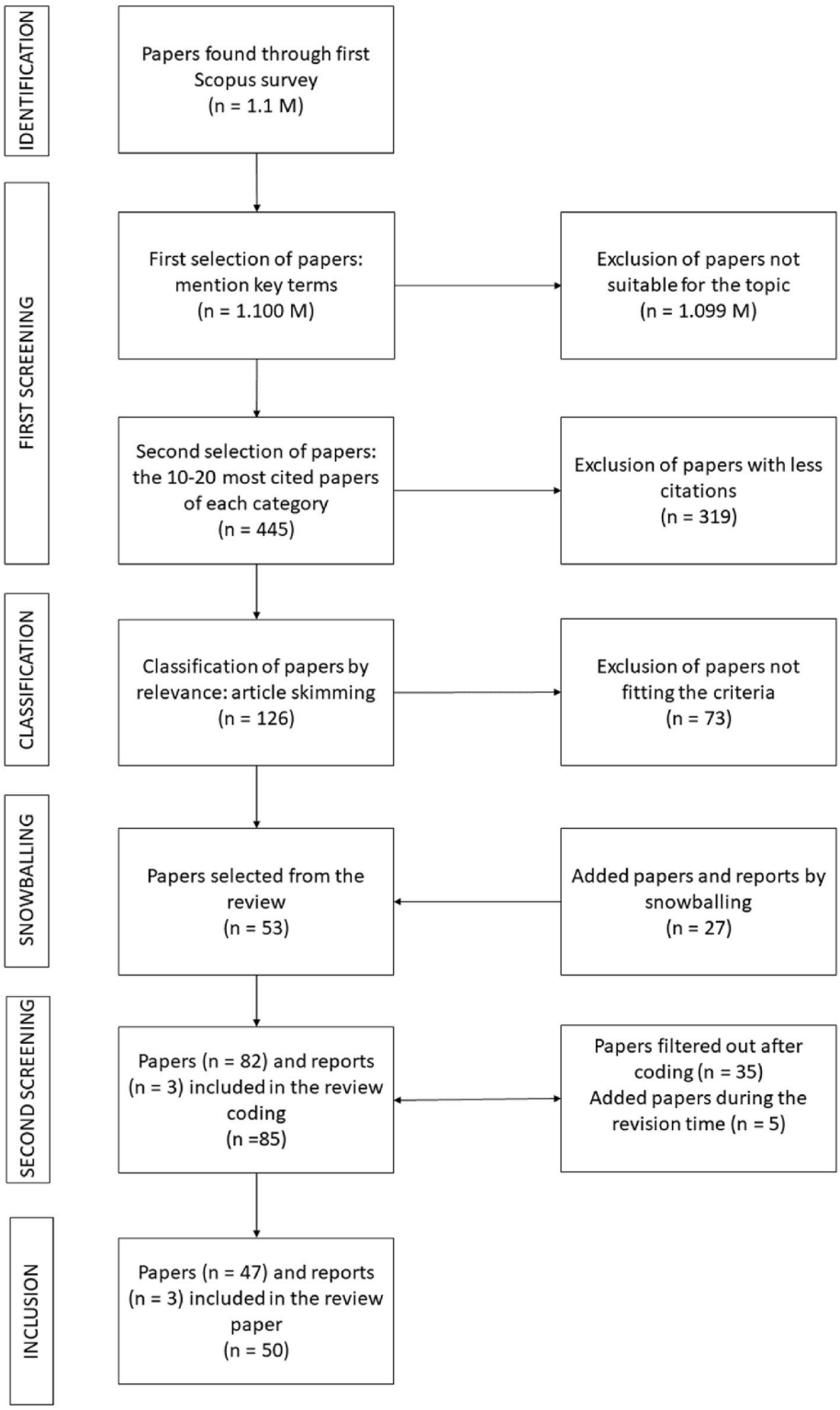


Fig. 1. Flow chart diagram showing how publications were selected. Adapted from [82].

formal institutions (e.g., regulatory and legal frameworks and rules) and strategies implemented by local government in collaboration with private sector actors and voluntary organizations [3]. Although sometimes unrecognized, grassroots initiatives can have an essential role in the transition vision framing of urban energy systems, also referred to as decentralized local governance, such as in Berlin (discussed in section 2.1.2) [109].

Depending on the city-region's energy transition agenda, the innovation process may follow a techno-economic or social innovation process [80]. City-regions following social innovation dynamics can benefit from the devolution process, returning decision-making power from the nation to city-regions [80]. This potential benefit may occur because when city-regions, their local organizations, and society are empowered with knowledge, skills, and opportunities, they can better navigate the competitive globalized economy [3]. However, with a pure techno-economic innovation process, city-regions may not achieve

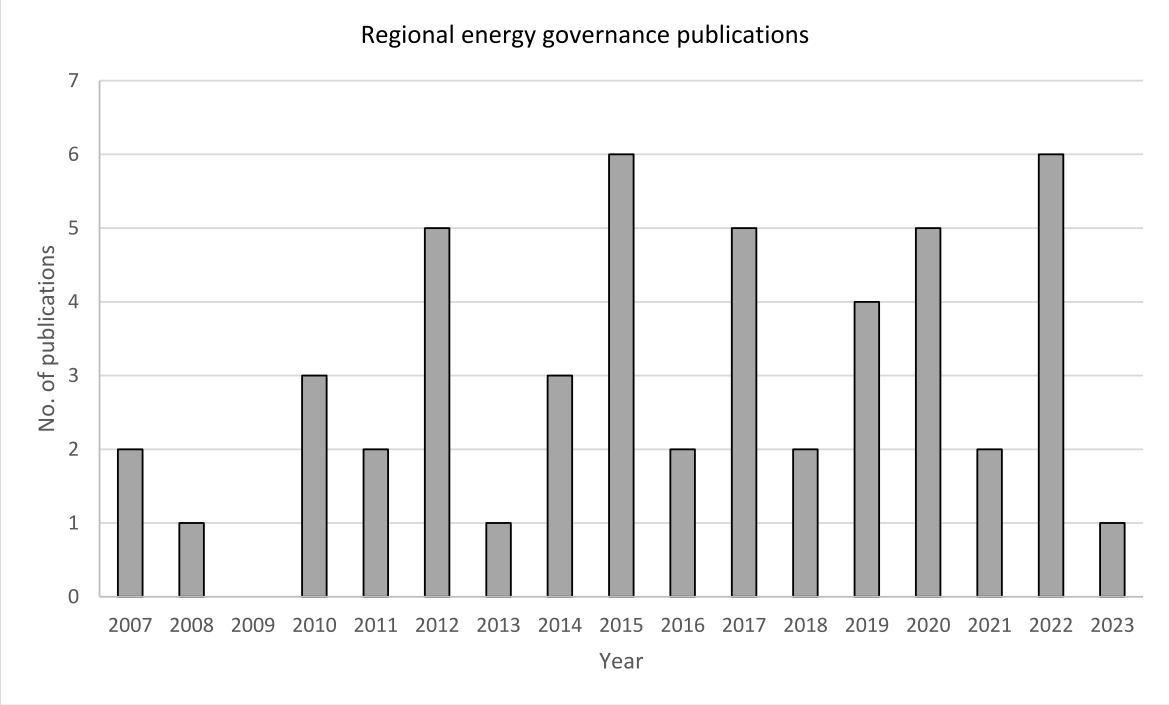


Fig. 2. Histogram of publications on regional energy governance from 2007 through 2023.

Table 3
Overview of the identified energy region concepts.

Energy region concept	Concept type	Concept description	Reference
City energy regions	Geographical concept	City energy regions are hubs connected with smaller population areas with formal institutions that can implement an energy transition strategy.	[3,4,71,77, 79,80,86–89]
Peripheralized energy regions	Geographical concept	Peripheralized energy regions have limited endogenous resources, informal institutions, and carbon lock-ins that impede their energy transition.	[20,36,65,67, 77,78]
Coal-and-carbon-intensive regions	Geographical concept	CCIRs are regions with socio-economic dependency on an upstream (extraction) or downstream (consumption) fossil fuel sector.	[12,29,36,67, 77,90–92]
Learning energy regions	Transitioning concept	Learning energy regions implement innovation policies and pilot demonstrations. This experimentation phase helps regions develop learning-based pathways to achieve sustainable energy transition goals.	[67,93]
Renewable energy regions	Transitioning concept	Renewable energy regions follow a strategy to develop renewable energy technologies at the regional or sub-national levels.	[2,9,10, 17–22,36,58, 67,70–72, 75–77, 94–105]

sustainable development goals [3]. For example, in the Amazonas state in Brazil, city-region initiatives have been rooted in the unsustainable extraction, exploitation, and manufacturing of natural resources, creating socio-economic inequalities [4]. Most available city-region examples tend to have poor sustainable conditions (e.g., Mexico City and Jakarta) [80], although some have sustainable development plans (e.g., Drechtsteden, Jakarta, and Montreal [4,110].

4.2. *Peripheralized and fossil-fuel-dependent energy regions*

The third energy region concept is referred to as a peripheralized, marginalized, or locked-in region due to having limited endogenous resources to pursue energy transitions [67,78]. These regions face lock-ins, which can be understood as a combination of social, economic, cultural, and political structures that block regional development and hinder sustainable transitions [67]. Some transition agendas in peripheralized regions focus on pursuing energy autarky [20,103]. In terms of governance arrangements, peripheralized regions tend to rely on informal institutions and informal actor networks because of issues with formal institutions. For example, a lack of trust between regional agents was present at the beginning of the Ruhr region's transition due to the contested discussion around coal mining and climate change [111]. Some Innovation Studies scholars hold that when formal institutions and actor networks fail to lead, new agents have to participate and co-create knowledge under existing (informal) institutions and later establish new "rules of the game", or new formal institutions [111,112]. Therefore, a peripheralized energy region may not be supported or led by formal institutions and incumbent actors at the start of the transition.

4.3. *Coal-and-carbon-intensive regions (CCIRs)*

CCIRs (introduced in Section 2.3) are a sub-group of peripheralized regions with carbon lock-ins and locked or limited formal institutions supporting the energy transition. CCIRs depend on fossil-fuel extraction industries such as coal, oil, and gas, as is witnessed in some regions of the United States, Slovakia, Australia, and other countries across the world [12,91,92]. CCIRs may depend on carbon-intensive industries such as

steel or cement production [113]. The European Commission has identified CCIRs in twelve EU countries, such as Germany, Poland, the Czech Republic, and Greece [29]. CCIRs typically face particular challenges, such as a shared cultural identity permeated by the CCI industries, carbon-locked formal institutions that do not promote sectoral transitions, path dependency on the fossil-fuel infrastructure networks, and a working force only specialized in the fossil-fuel industry, among others [36,65,77]. Because of these challenges, CCIRs are sometimes called locked-in or peripheral regions. One of the first studies on locked-in regions was in the Ruhr area in Germany, whose industrial development was in a structural crisis [67]. Coenen et al. (2018) explain that a major barrier in coal regions to sustainable energy transition in the Ruhr region was the coal-regime dependency [111]. This dependency permeated social structures, institutions, and politics, as often occurs in industrial fossil-fuel regimes. Other barriers include limited infrastructure and institutions to move away from coal-industry dependency [65, 111]. Although many CCIRs are referred to as peripheralized regions, there are also CCIRs with available financial resources but locked or insufficient formal institutions to carry out the transition, such as the iron and steel sector's transition in Upper Austria [113].

According to RIS studies, locked-in coal regions reflect a limited innovation capability in the industry's value chain, the enterprise's development of new ideas, and the public-private sector relationship [111]. This framework suggests that policy support for technological innovation is needed for coal regions to resolve their locked-in situation [111]. In the Ruhr region's low-carbon transition, the state government, coordinating with municipalities, universities, and the private sector, took on a leadership role in reshaping the regional development strategy. However, the energy transition process developed slowly because the region's system was not based on a skilled labor force, lacked a fair degree of knowledge exchange between regional agents, and did not sufficiently support local entrepreneurship [111].

4.4. Transitioning learning energy regions

Learning regions pertain to regions adopting innovations that enable learning in regional governance systems that support the creation of alternative development pathways [93]. Alternative pathways - such as pursuing a knowledge-based economy - result from the abilities of regional agents and developing learning policy programs [67,93]. A comprehensive overview of this concept beyond the sustainability transitions field is presented by Hassink (2005), who describes that most lock-ins are framed as political structures that keep old industries and hinder endogenous innovation [93]. In terms of the transition progress, learning regions represent the evolution from the first transition stage (predevelopment) to the third stage (acceleration) through the second stage (take-off) [30].

Particularly, learning regions are presented in selected studies as a development pathway alternative to regions having limited resources and institutions (i.e., for peripheralized regions) [78]. However, city-regions can also become learning regions once they start adopting innovations. Learning regions represent a subsequent energy region type where the governance arrangement changes despite the geographical unit remaining the same. The essential difference is that when a city-region or peripheralized region becomes a learning region, its governance structure can be transformed into a more polycentric structure, like with the formation of RES in the Netherlands [17], or rely more on informal institutions and actor networks and later reach formalization like the Ruhr region [111].

Several governance mechanisms have been reported to enable deconstructing lock-ins or path dependencies in regions. A commonly reported mechanism is shifting from a government to a governance approach. This shift suggests distributing the central government's power and responsibilities among the public and private sectors. Governments can promote such power decentralization by initiating cooperation and knowledge exchange between the public and private sectors and between individuals and organizations, for example, by pursuing cooperation between municipalities [67,93]. In some cases, learning regions are enabled by creating a new governance level that merges several administrative boundaries, such as municipalities, and by creating intermediaries that coordinate the work between public organizations, private enterprises, and civil society [67]. Mechanisms that can trigger the development of learning regions are innovation-oriented policies that create long-term visions, integrate sectors and disciplines, and open funding calls that incentivize sustainable projects [67].

The Austrian regions of Güssing, Hermagor, and Murau are examples where agents could find synergies to shape a regional transition despite limited resources and a lack of formal institutions supporting a transition [78]. In 1990, the municipality of Güssing saw the opportunity to address economic and population decline by shaping a new development pathway based on a regional low-carbon energy strategy. Municipality representatives formed a coalition of citizens and investors to reduce energy costs by promoting energy self-sufficiency. Regional agents created synergies by sharing local knowledge and financial and technological resources. After piloting energy-efficient housing, the municipal leaders gained regional support and launched a district heating system and a biomass power plant. The success of this project eventually led to a regional-scale energy transition in 2005. The key to this bottom-up success was the presence of a social network and trust between municipal leaders, which helped reach and convince citizens, organizations, and regional decision-makers [78]. This example highlights the importance of informal institutions and social innovation practices that trigger collective action because they are essential to the first steps in the transition stages of locked-in and peripheral regions [54,67]. However, one should notice that Güssing's regional energy transition in 2010 was also made possible by securing federal funding [30].

Other examples of policy promoting regional competition and eventual formalization, hence institutionalizing regional development strategies, are found in Germany. They are concerned with the 'Competition Impulse Regions program' in the 1990s and the 2016 'Regionale program' in 2016 [67]. These exemplary cases in Germany and Austria show that a social network can develop social innovation through exchanging knowledge, civil society mobilization, and cooperation between sectors. These regions could temporally substitute lacking institutions and resources with informal institutions and social innovation practices to open development pathways away from locked-in industrial structures and practices.

However, the learning region concept should be applied with care due to its ambiguous definition of breaking path dependencies with agents' abilities, which is present in different types of energy regions [93]. Therefore, this study distinguishes between learning regions that were peripheralized or city regions before adopting innovation policies. The first type of learning region is those that struggle due to a lack of resources or formal institutions to support energy transition. This definition is covered by the bricolage concept developed in Austrian energy regions, which refers to "an actor's behavior of problem-solving with available resources instead of acquiring specific resources for a certain problem". Some examples of these learning regions are mentioned above (e.g., Güssing, Hermagor, and Murau) [78]. The second type of learning region has a city-region structure. Drechtsteden, covering the southern path of the mega city-region Randstad in The Netherlands, is an example of a learning region with a city-region structure. This Dutch region participated in the RES pilots program, which guided seven pilot regions to formulate a transition strategy by 2016–2017 [114]. This RES pilot program promoted cooperation and cross-learning between public, private, and civil organizations, in seven pilot regions, later expanded to 30 regions, to formulate a short and long-terms strategy to become carbon neutral by 2050 [10,19]. Drechtsteden's RES seeks to reduce 20 % of energy consumption in buildings and achieve 0.60 TWh of local clean energy generation by 2030 [108,115]. Another general critique lies in the normative nature of the learning region concept because no

ideal principles can always underlie learning-based economies [93]. In this study, normative principles like just transitions, energy democracy, and equity are implied that underpin the direction of energy transitions [116–118].

4.5. Transitioning to renewable energy regions

Renewable energy regions were the largest energy region type identified in the systematic literature review. This type can be defined as regions with plans to develop renewable energy technologies at the regional level. Renewable energy regions usually have polycentric governance structures. They can have multiple levels of governance (e.g., local, provincial, and national) and are formed by a network of experts and stakeholders [10,85]. Cases of renewable energy regions are found in the Alpine regions in Austria [9,20,21,70,72,73] and Switzerland [20], Denmark, Italy [21], the Netherlands [10,17–19], and Germany [2,20,21,67,68,70,71]. We further distinguished two renewable energy subgroups: The ones that originated in the Netherlands, 'Regionale Energiestrategieën' (RES; renewable energy strategies in English; translation by the authors) driven by a combined top-down and bottom-up approach, and the renewable energy regions in Germany-Austria 'Erneuerbare-Energie-Regionen' (renewable energy regions in English; translation by the authors), with a distinctive bottom-up approach.

Since 2018, thirty renewable energy regions have defined the Dutch regions' energy transition strategies and implementation plans (RES). RES are conceived as either clusters of neighboring municipalities or, in some cases, entire provinces, among which the national funding for energy transitions is distributed [10,17]. Renewable energy regions in the Netherlands aim to contribute to the national climate agenda, which aims for a 50 % CO_2 emission reduction by 2030 through renewable-energy-based electricity and heating generation [10,16]. This top-down approach to agenda-setting may cause difficulties in the engagement of regional agents because they might not be familiar with the reasoning behind the agenda [18]. Hoppe (2021) explains that the country has inter-municipal regional governance bodies that manage environmental and mobility issues that require coordination between the municipalities but also concerning other levels of government like provinces, national, and supranational government. Since RESs are not considered a formal governance arrangement, they lack decision-making authority, making them vulnerable because regional transition strategies are not binding. A RES depends on decision-making and approval by formal decentralized government bodies (i.e., municipalities, provinces, and water boards) with the authority to decide. Also, the governance of RES is highly dependent on social and economic networks in the regions [18]. However, it is not only public bodies that participate in RESs. There is also the participation of citizens, NGOs, and renewable energy communities who contribute to formulating regional visions and the planning of RESs [10]. Since the RESs focus on networks of organizations developing clean energy technology, their innovation process can be studied from a RIS and STS perspective [17,36].

In Austria, renewable energy regions ('Energieregionen') have been studied and developed since the 1990s, and later in Germany, Switzerland, and other EU countries [9,72,73,90]. In Germany, the renewable energy region concept ("100 % Erneuerbare-Energie-Regionen"', 100 % renewable energy regions, translation by the authors) refers to the governance of inter-municipal or inter-communal energy transitions to define energy regional visions and strategies and implement them [90]. In Austria, energy regions have been framed as agent networks and regional initiatives supporting regional development using renewable energy [104]. The visions of these renewable energy regions focus on achieving 100 % supply from regional renewable energy, energy self-sufficiency, or becoming independent from fossil-fuel imports while pushing a regional economic development agenda [9,21,72,90]. These regional visions began as initiatives, as seen in Güssing, Austria, where the local government phased out fossil-fuel imports and developed a biomass-based district heating with EU funding [72]. This initiative has supported the energy sector's decarbonization plans (ibid). Another example is the Murau region in Austria, which defined energy autarky or energy self-sufficiency as its goal for the region's development pathway [73].

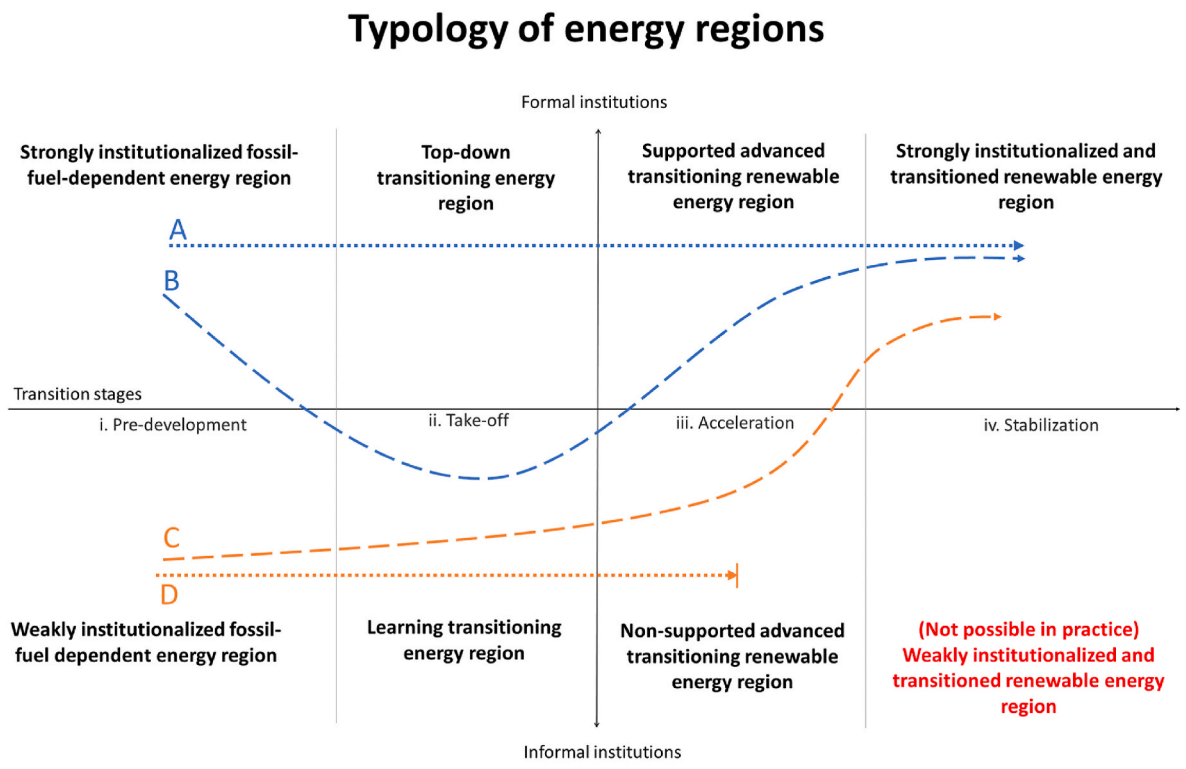
From 1983 until 2014, at least one hundred and forty energy regions were formed across Germany by adopting bottom-up approaches. These regional initiatives could receive funding from the local or national government [90]. The governance of these energy regions functioned as a bridge between the niche (i.e., initially informal and grassroots innovations) and regime levels (i.e., well-established, incumbent, and institutionalized technological sectors) [9,39]. Although these regions have been referred to as exemplary because of their quick response to global trends [109], the availability of renewable energy sources and access to competitive technologies have been insufficient to formalize energy region visions for a regime shift [9]. Studies of German and Austrian energy regions have used theoretical frameworks like multi-level governance, transition management, and institutional governance, which have revealed several important drivers. Necessary factors for regional energy transitions cover macro socio-political pressure for decarbonization, a cooperative regional social network, and having the ability to act as a constant learning region (i.e., social innovation factors) [9,22,70].

Regarding governance arrangements, strategies were created by formal (national) institutions, although they lacked formality in their regional organization. In the Netherlands, the six pilot RES followed a top-down and bottom-up governance approach, while the other twenty-four regions started with a top-down approach. In RESs, formal agent networks like incumbent stakeholders (system operators, municipalities, and the Ministry of Economic Affairs), although with limited autonomy and authority, have been designing transition strategies [17]. In contrast, 'Energieregionen' in Austria and Germany began as bottom-up initiatives where informal agent networks were vital for their emergence and formalization [9,36,90].

5. Discussion: towards a typology of energy regions

A typology of energy regions was developed to visualize the meaning of each energy region concept from a sustainability transition perspective. This typology answers the research question ii by describing the relationship between governance arrangements and innovation processes of energy transitions.

The diagram in Fig. 3 shows the energy region concepts according to their transition stages and whether the region's transition relies mainly on informal or formal institutions. The city-region concept describes highly urbanized territories driven by (non-sustainable) economic growth; thus, they were located at transition stage I (predevelopment). These city-regions are typically governed by formal institutions that seek development significantly based on economic growth. The next concept, the peripheralized region, is generally well governed by formal institutions that reinforce lock-in development pathways and may hinder regional energy transition processes. Peripheralized regions begin destabilizing current regimes by cooperating to work towards a social mission or sociotechnical vision, such as reinventing development pathways. When destabilization occurs, regions deviate from carbon lock-ins and become learning regions (stage ii. take-off). Learning regions can further transition to stage iii. (acceleration) through institutionalization or (inter)national support. Social innovation practices inside learning regions are enabled by informal institutions such as collaborative values and habits that can empower regions. The last concept is the transitioning renewable energy region, which either informal or formal institutions can govern, and it generally relates to the transition from stage ii (take-off) to stage iii (acceleration). At stage iv (stabilization), the region is considered fully transitioned and supported by formal institutions. Empirically, it has not been demonstrated that a region can be fully transitioned without the support of formal



Curve	Transition pathway	Geographical energy region concepts	Transitioning energy region concepts
A.	Top-down and stable	City regions	Top-down renewable energy region
B.	Learning and stable	Peripheralized, CCIRs and city regions	Learning region and renewable energy region
C.	Learning and stable	Peripheralized regions	Learning region and renewable energy region
D.	Learning and non-stable	Peripheralized regions	Learning region

Fig. 3. The pathways of the different region types are derived from the typology of energy regions according to the dimensions regarding the regions' level of institutional formality and transition stage. Four transition pathways are presented with the dotted and dashed curves for the geographical region concepts (city regions, peripheralized regions, and CCIRs). While pathways B, C, and D go through a learning region phase, pathway A does not and instead follows a top-down transition. The transition stages are adapted from Ref. [40].

institutions.

An interesting finding is the role of informal institutions and social innovation practices in transforming peripheralized or locked-in regions into learning regions [67]. Studies show that regions worldwide may have lock-ins due to the region's fossil-fuel-dependent history [93]. These locked-in or peripheralized regions face considerable challenges to transition. Yet, the bricolage concept developed in Austria showed how peripheralized regions could overcome their limited availability of resources to achieve a low-carbon regional transition [78]. This empirical-based framework shows that the transition from stage I (pre-development) to II (take-off) is possible when social networks and leaders support a transition, and there is a shared collective mission (ibid). For instance, social innovation practices and informal institutions enabled collective action and transformed the Austrian locked-in regions into learning regions [67]. Additionally, the Güssing region formed low-carbon pathways and a new regional innovation identity that changed the region's self-perception to become green energy pioneers [78].

For peripheralized regions to achieve acceleration (stage III) and for renewable energy regions to reach stabilization (stage IV), political support from formal institutions and actors networks is needed [67,78]. On the contrary, without informal institutions, there is a higher threshold for breaking path dependencies. Some city regions reported limited informal institutions, such as values and habits, and social innovation practices, such as a social mission, learning, and cooperation. These regions faced risks such as reduced agency and increased dependency on international market trades that did not improve the regional economy [3]. Curve A describes a region with support from formal institutions to initiate an energy transition, with a top-down transition strategy, and without a learning phase. Examples of this transition pathway are city regions like the Rotterdam-The Hague RES in the Netherlands, where policymakers designed a regional transition strategy without promoting learning dynamics in the region nor learning from existing practices elsewhere [119]. Although no clear example was identified, regional studies state that when peripheralized or transitioning renewable energy regions do not get support from formal

institutions or do not find a feasible transition strategy, their transition does not move forward [73,78], which is represented by curve D. Other possible pathways are not shown in the diagram. For example, CCIRs whose transition ends at earlier stages or does not start a transition at all, such as Jiu Valley, Romania, after the closure of coal mines in the 1990s [120].

Peripheralized and city regions may become learning regions through innovation policy programs. Two transition pathways are shown for city regions (curves A and B) and peripheralized regions (curves C and D) in Fig. 3. When innovation policy programs are combined with social innovation practices and informal institutions, they may trigger learning and experimentation practices [43]. This combination may ultimately enable renewable energy regions with more formalized institutions that bring them stability. The Drechtsteden region and the Ruhr area are examples of a city region and a CCIR, respectively, that were transformed into learning regions by innovation policy programs (curve B) [77,111,114,115]. Regional stakeholders established the transition strategy of Drechtsteden as a result of the RES pilot program that promoted cooperation and cross-learning. Similarly, the Güssing region exemplifies a peripheralized region that became learning region through innovation (curve C) [78]. In comparison, the innovative coalition of citizens and investors enabled the beginning of Güssing's energy transition to promote energy self-sufficiency. Although these regions have not yet completed their transition, they seem to follow the described transition pathways [78,115]. Other transition pathways for different regional contexts may not require informal institutions or learning policies. However, more studies are needed to define the region-type boundaries and their transition pathways clearly.

Concepts from evolutionary governance theory were applied to understand governance arrangements for energy regions, such as the level of governance centralization and institutional formality [59]. This theory suggests that the type of governance arrangement of the energy region changes along the innovation transition curve across four stages [39,40]. Results show that in stage I (predevelopment), energy regions are described as monocentric and formal due to the dominance of well-established institutions and incumbent stakeholders, such as city regions and CCIRs [67]. From stage I to stage II, the governance arrangement can become less formal and centralized with the emergence of new players, such as renewable energy cooperatives. Some examples are the peripheralized regions and the energy autarky regions in Germany and Austria, which were initiated mainly by informal institutions that enabled cooperation and collective action [11,20,103]. Contrary to what RIS argues, an informal and polycentric regional governance arrangement can lead to innovation in regional energy transitions like in the 'Energieregionen' and RESs [37].

The RIS framework could describe market competition and technological-innovation-driven regions, while the TIS framework could describe regional-empowerment-driven regions. A prosperous region (e.g., Silicon Valley in the United States), according to RIS, is formed when the private sector has an active role in technological innovation, ultimately leading the region to rapid economic growth [37,51]. If such development pathways do not enable the entrance of emergent agents, then the benefits of innovation will remain with incumbent stakeholders. In that sense, energy regions can experience regional technological innovation while not improving the distribution of benefits or justice beyond the incumbent stakeholders [121]. For this reason, the RIS framework must be complemented with social innovation that describes different power dynamics between emergent agents and incumbent stakeholders when studying just transitions.

5.1. Contribution to sustainability transitions research

This study makes three contributions to the field of sustainability transitions, in particular to the understanding of regional energy transitions. The first contribution is the identification of five concepts of energy regions, three geographical and two transitioning concepts. These concepts were identified following a systematic literature review of peer-reviewed academic publications, as well as grey literature publications. The geographical concepts cover 1) city regions as highly urbanized places, 2) peripheralized regions as territories with limited resources or carbon lock-ins that limit their transition, and 3) CCIRs with fossil-fuel sector dependency and locked or limited support from formal institutions to transition. The transitioning concepts are 4) learning regions, which can be regions 1, 2, or 3 that have implemented learning policies or innovation, and 5) transitioning renewable energy regions, as regions 1, 2, 3, or 4 that have an advanced renewable energy development.

The second contribution is the formation of a typology of energy regions, shown in Fig. 3. The five energy region concepts were distinguished by three aspects: Governance arrangement, innovations they pursue, and stage of the transition. In terms of governance, regional governance can create and pursue energy transition strategies with different degrees of institutionalization. This is relevant for peripheralized regions where informal institutions are crucial to initiating an energy transition. In contrast, formal institutions have been leading in city regions since the beginning of the transition. Another finding is that different types of innovation (e.g., social and technological) can help initiate low-carbon transitions in different energy regions. In the case of city-regions, technological and policy innovations are essential to advance low-carbon transitions. Whereas in peripheralized regions, social innovation is of even greater importance.

The third research contribution is a further understanding of transition pathways in energy regions, particularly those starting in city regions and peripheralized regions. Section 4.4 presented examples of city regions and peripheralized regions becoming learning regions, which assisted the transition into renewable energy regions. Yet, the learning region phase has been bypassed in some cases, indicating a different transition pathway (see curve A in Fig. 3). For example, twenty-four Dutch energy regions (some peripheralized and others city-regions) did not undergo an experimentation phase [114]. Instead, the central government applied the lessons learned from six regional pilots to serve as teaching examples to develop a regional energy transition program, which was then top-down implemented in the other energy regions, thus skipping the learning phase for these twenty-four regions.

5.2. Policy implications

Additionally, this study formulates policy implications for stakeholders in regions that can be identified as city-regions or peripheralized regions. Policymakers may refer to the examples described in regional energy transitions in similar contexts and learn from the innovations in the interactions between organizations, the particular governance arrangements, and policy mixes that can advance the transition. The typology can be illustrative for practitioners as a means to reflect on the followed or preferred transition pathways as well as to formulate more contextual and transition stage detailed policy advice. Yet, regional innovation platforms to share learnings, opportunities, and resources are needed to promote cross-regional learning [122,123]. Policy makers in CCIRs are recommended to learn from other peripheralized regions with carbon lock-ins that have become learning regions, like in Germany and Austria, by leveraging available informal institutions and social innovation practices [67,78]. Even when informal institutions and emerging agents are key for the energy transition, political support from formal and overarching institutions (e.g., national government) is eventually needed. Policy makers in city-regions like metropoles or highly-urbanized regions can rely on formal institutions to initiate a transition strategy because they tend to have more capacity and more specialists while having more protocols in place to implement policies, which allows them to tackle the different areas of an energy transition (electricity, transport, water). Yet, city-regions face challenges when implementing policies and reaching goals, given the complexity of the socioeconomic system in big cities. A potential limitation of this type of

energy region is that they resist introducing new agents because they are highly regulated. Policy and decision-makers should be aware that multiple transition agendas (e.g., from the national government and local communities) are usually present in a region. Since such agendas can sometimes be conflicting, an early interaction between different governance levels is needed to address various goals while meeting wider climate change objectives. The developed policy mixes should consider the distinctive characteristics of city-regions and peripheralized regions. For example, the presence of energy-intensive industrial activity (e.g., ports or large-scale industrial parks), and dense populations in city-regions, and natural resource-related economic activities in peripheralized regions.

5.3. Limitations and suggestions for future research

The studies on energy regions covered by this systematic literature study are mainly found in Western European countries. Studying energy regions in the Global South is recommended to move beyond a Global North or Eurocentric bias, which may provide new insights into how energy transitions can be started and advanced [124]. However, some of these regions might be well represented by the peripheralized region concept. Other areas may be described by a combination of the peripheralized and city-region concepts since big cities can also lack resources, capacities, and formal institutions to aid a transition. Therefore, it is suggested that the energy region typology be improved once more empirical cases are available.

Although CCIRs generally express characteristics similar to those of the reviewed energy regions, only a few studies were found that applied a regional energy governance approach in CCIRs. Thus, further research can provide more recent empirical evidence on how peripheralized CCIRs can transition into learning and renewable energy regions.

Another open question is to what extent energy regions can maneuver between local and national agendas and attain both. This requires strategic agency through collaborative governance and multilevel governance [125]. Additionally, only one case with cross-border regional energy governance (the Øresund region between Sweden and Denmark) was found [80]. Yet, other places worldwide with a history of cross-border governance of water resources could provide insights.

Lastly, since this study had a governance focus, a psychological approach may deepen the understanding of the role of human behavior in the progress of regional energy transitions. For example, social psychology can help explain to what extent social innovation and informal institutions such as values, norms, and collective habits influence the lifting of lock-ins in peripheralized regions. Environmental psychology surveys can reveal the drivers for decision-makers behavior, causal drivers, and ways to overcome barriers to citizens' engagement in the decision-making of regional energy transitions [126,127].

In the review process, some relevant papers may have been lost on the way because they were not among the most cited papers. Although this step was partially compensated with a snowballing search with references, it is recommended to complement or replace the most cited publications with the relevance filter option on Scopus for future reviews. Also, future reviews should consider covering non-English publications and other energy region-related terms such as district energy.

6. Conclusions

This study answered the first research question: i) What types of regional energy governance concepts have been studied? In doing so, a typology of energy regions was developed based on the concepts applied in ten countries and published over the last seventeen years. It includes four major energy region types: 1) city regions, the most applied concept in sustainability transitions; 2) renewable energy regions, including RES and 'Energieregionen', mainly developed in Germany, Austria, and the Netherlands; 3) peripheralized regions that have limited resources, with CCIRs as a subgroup with a carbon lock-in; and 4) learning regions (e.g., city-regions or peripheralized regions) that implement knowledge-based and learning innovation policies. Energy regions, starting as city or peripheralized regions, can transition into learning regions, especially to overcome challenges (like limited resources, institutions, and capacities), and then become renewable energy regions in a more advanced transition stage.

The RIS and TSI frameworks were used to answer the second research question: ii) How have regions transitioned in terms of governance arrangements and innovation processes? [54,111]. Two primary motivations underlying energy regions were discerned, being the effective operationalization of a national agenda (e.g., the Dutch RES program 'NP RES'), and reclaiming decision-making power for the region (e.g., the Austrian energy autarky regions) [10,103]. The energy region's agenda determines the type of innovation process the region follows: technological, social, or both. For instance, the RIS framework cannot describe the transition process of renewable energy regions in Austria and Germany that aim for a shared regional autarky. Instead, these regions are better described with the TSI framework because of citizens' active role in defining visions and owning energy projects [11,40,54]. The combination of social innovation practices and (in)formal institutions may enable the empowerment of collective actions like community energy initiatives (e.g., in Austrian and German 'Energieregionen') [9,53,54]. In the case of the Dutch RES approach, regions do not necessarily aim to empower citizens but rather pursue the goal of shifting towards low-carbon economies. Interestingly, emergent agents of energy regions had to rely on informal institutions to break path dependencies like in past coal regions. Eventually, support from formal institutions and incumbent stakeholders was necessary for energy regions to move towards stabilization and institutionalization [67,78].

The empirical gap from the findings on peripheralized regions revealed a subgroup of CCIRs. These regions (e.g., the Ruhr region) developed pathways that diverged from coal mining and steel by reinventing their regional identities [111]. This finding shows that the energy region framing goes beyond a particular (coal) sector and focuses on the regions' capacities and abilities to transition. This process could be triggered, like in some German regions, by the coordination between municipalities, universities, and the private sector. CCIRs that face path dependencies could benefit from learning regions that have overcome limited resources and unsupportive formal institutions. This study shows that city regions and peripheralized regions face different challenges to transition because of their unique characteristics. These barriers can be overcome depending on the innovations and governance approach adopted.

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Declaration of competing interest

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Data availability

Data will be made available on request.

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