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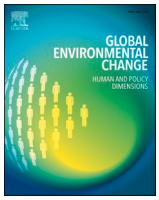

Policies to bring about social-ecological tipping points in coal and carbon intensive regions

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ABSTRACT

Achieving the worldwide greenhouse gases (GHGs) reduction targets set in the 2015 Paris Agreement and other international treaties requires reaching a fast tipping point towards sustainably decreasing emissions. Compared to sectoral energy transitions, where different parameters can be easily measured, transitions in Coal and Carbon Intensive Regions (CCIRs) are more complex and thus more challenging to plan, implement, and study. Despite CCIRs' heterogeneity in the population, level of development, economic structure, surface, and transition timing, achieving Social-Ecological Tipping Points (SETPs) poses some common dilemmas to the local, regional, and national authorities. Simultaneously, the transition process poses significant challenges to the economies and local populations.

To understand how policy choices can accelerate reaching positive SETPs, we systematically analyze policy responses since the start of the transition to a low-carbon economy for thirteen CCIRs. We evaluate whether, despite the heterogeneity, we can identify policy response patterns and whether these patterns correlate with other features of these regions. We extrapolate the characteristics of policy changes and local developments needed to generate SETPs and discuss the effects of different events on the regional transition's overall "justness" of this process. Finally, we advance some recommendations on designing policies to achieve positive SETPs.

1. Introduction

Along with the cross-sectoral and sectoral transition needed to operationalize environmental public policies necessary to avert irreversible environmental change and biodiversity degradation, the Coal and Carbon Intensive Regions (CCIRs) pose unique challenges. The concept of CCIRs describes regions that are currently or were in the past reliant on coal or industries with a high carbon emission output. In the European Union (EU), these regions have been recently treated institutionally by the European Commission (European Commission, 2018a). On the one hand, policies designed to phase out coal and other carbon-intensive industries are usually negotiated at the international level and implemented at the national level. Also, measures to alleviate the socio-economic transition must be focused regionally. On the other hand, policies promoting innovation in CCIRs can be adopted at the national, regional, or local level, and they can be mixed with phasing out policies or implemented separately. Similarly, the integration of CCIRs in the national economic and energy systems varies dramatically. Some of them benefit from autonomy, while others are fully integrated. Furthermore, variations in energy coal prices or economic recessions can significantly affect the effectiveness of well-planned policies.

CCIRs benefit from the growing attention of decision-makers because of the potential negative impact of transition on the local economy and society. CCIRs transformation needs to ensure the justness of transition, defined as "a fair and equitable process of moving towards a post-carbon society" (McCauley and Heffron, 2018, p. 2) that covers distributional, procedural, and restorative justice issues, integrates climate, energy, and environmental justice and aims that "no one is left behind" (European Commission, 2018b). In addition to the above, a particular emphasis will be placed on the degree of integration of the justice dimension in the public policies enacted to tackle the phase-out. Given the impact on inhabitants, a fair transition topic must accompany any discussion about the transition in CCIRs. From a policy result point of view, just transition can be understood as "greening the economy in a

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way that is as fair and inclusive as possible to everyone concerned, creating decent work opportunities and leaving no one behind" (International Labour Organization, 2015).

To this end, transformative actions and policies are required to diversify the inhabitants economic opportunities and well-being. In designing effective policies, the multiple dimensions of these social systems need to be considered. They are described by numerous "geographical, social, cultural, and political dimensions that are integral starting points of analysis." CCIRs are rarely exhaustively analyzed as complex systems (Mangalagiu et al., 2023b). Not considering the complexity and multi-social dimensions and perspectives of CCIRs may result in ineffective mitigation actions and climate policies (Geels et al., 2017; Tàbara et al., 2019). Take, for example, the decision to "leave fossil fuels in the ground". This can be interpreted as a positive tipping point, but judging from the climate policy perspective, it may also trigger alternative energy innovations. The consequences on employment, cultural identity, and social-ecological restructuring of such intervention at regional and local levels require careful examination (Dale et al., 2019; Dale and Kristoffersen, 2018).

Studying socio-ecological tipping points (SETPs), climate change-induced SETPs (van Ginkel et al., 2020, van Ginkel et al., 2022), and the role of global networks in triggering rapid response to these challenges (Galaz et al., 2016, Galaz et al., 2012) has gained importance in the context of decarbonization efforts and adapting the governance system to the current global challenges (Tàbara et al., 2022).

This article aims to identify the necessary conditions to transform social-ecological regional systems, heavily dependent on coal and carbon-intensive activities, into low-carbon, clean energy ones and avoid opposite trajectories. It contributes to the recent debate on Social-Ecological Tipping Points, which focuses on actions, policies, and conditions that may trigger positive tipping points to facilitate a system transformation. We focus on the public policies enacted to tackle the phase-out (Rogge and Johnstone, 2017) and the innovation aspects of reaching new SETPs and overall transition.

Innovation in public policies can be understood as introducing new solutions as a response to problems and challenges or in case of opportunities that arise in the social and economic environment (Edler and Fagerberg, 2017, p. 4). Innovation may be understood as product or process innovation. It might be seen as a "system of innovation," taking the form of a national, sectoral, or regional system of innovation (Edquist, 2006). Also, in a context when environmental challenges become more serious, public policies may be designed as "eco-innovation" or a way to encourage it (Ekins, 2010). Building on these approaches, innovation-focused policies in CCIRs are defined in this article as the systematic implementation of new types of strategies, methodologies, plans, and practices other than taxation and coal mines phase-out, which have been used for a long time for decarbonization efforts and instead are characterized by a top-down approach. Some examples are developing renewable energy facilities, strategies based on citizen education and large stakeholder participation, improving energy efficiency in industry and housing sectors, green transportation, and using hydrogen and biomass as energy sources.

The analytic effort started by mapping the timing and intensity of the transition of thirteen regions. This analysis starts from the endpoint of the "golden age" of carbon-intensive development, major policy initiatives, and local developments. A central assumption of this paper is that policy interventions containing innovation elements are implicitly or explicitly designed to push CCIRs toward positive SETPs and can be used to study policy pathways toward SETPs. Hence, the features of the public policy interventions in CCIRs will be investigated, hypothesizing that a higher density of innovation-focused policies leads to faster progress toward positive SETPs.

This systematic analysis of thirteen CCIRs shows significant heterogeneity in the social, economic, and energy transition roadblocks, environmental problems, and challenges to generate Social-Ecological Tipping Points (SETPs). These CCIRs also differ regarding surface, population, time since the transition started, dependence on specific industries, and integration with the national energy systems. Their surface ranges from a few hundred square kilometers, like Jiu Valley of Romania or Megalopolis of Greece, to enormous areas like Alberta province of Canada or Greenland of Denmark. Populations vary from tens of thousands to a few million.

In some CCIRs, their "golden age" culminated with the "year of glory," which refers to the period of time when carbon-intensive activities reached the highest intensity in the region, happened more than half of a century, and the transition started decades after, while in some, it just started. Yet, despite this tremendous complexity, the challenges to their transition bear some common issues, as they require simultaneous systemic transformation across multiple dimensions.

The paper is structured as follows: first, we provide a review of current debates on SETPs, followed by methods and data, including the main empirical limitations facing this study. In the Results section, we present the main empirical findings. The Discussion section extrapolates the link between public policies and SETPs and how the justness of transition can be incorporated into such public policies' goals. In the Conclusions, we analyze the main implications of our article.

2. Contemporary debates on social-ecological tipping points

Literature on climate mitigation policies and interventions reveal the limited ambition to meet the Paris Agreement goals (Rogelj et al., 2016), sometimes caused by the contradictions between short-term socio-economic goals and capacity for transformation (Amundsen et al., 2018), as well as the rising global carbon gap (Zheng et al., 2023) and policies to address this issue (Baptista et al., 2022). To ensure a fair transition for everyone affected, CCIRs may consider the effective implementation of climate policies designed to achieve the decarbonization goal and simultaneously their impact on the inhabitant's welfare. There is a growing literature on the justice dimension of policies aiming to decarbonize CCIRs (Abraham, 2017, 2017; Carley and Konisky, 2020; Beutel et al., 2022; Moesker and Pesch, 2022). Nevertheless, programs like the EU's Just Transition Mechanism are adopted without a clear understanding of CCIRs' systemic dynamics across multiple socio-economic dimensions and, thus, are susceptible to being ineffective (Tàbara et al., 2019).

Regarding literature on tipping points, van Ginkel et al. (2020) propose an interpretation of the literature broken into three branches: climate tipping points, concentrating on the impact of GHG gases on the climate system; ecological tipping points, where climate change is one of the drivers; transformation tipping points, showing human responses to climate change; and adaptation tipping points reflecting transformative adaptation to climate-induced policy thresholds. Milkoreit (2023) also divided the literature into three branches. First, tipping points are a "framing device or metaphor rather than an actual object of study." Second, it encompasses studies that appeared in the climate adaptation field, financial market, and resource management in social-ecological systems. The third assesses the link between social tipping and climate change solutions/decarbonization.

The scientific debate on Social-Ecological Tipping Points, the most recent one in the literature, addresses topics relevant to the energy transition and efforts to mitigate or adapt to climate change. While Eder and Stadelmann-Steffen (2023) analyze the role of politics in energy transition, Cai et al. (2016) argue that synergic interaction tipping points can lead to irreversible changes in the system state. Amundsen et al. (2018) assess the role of local governments in social transformation. Instead, Centola et al. (2018) support the "existence of a tipping point in the dynamics of changing social conventions."

In recent years, a growing interest in the study of tipping points (TP) has emerged in many disciplines, especially regarding solutions to address climate change and keeping global warming under 1.5° or 2 °C. The concept of tipping points originated from specialized chemical and mathematical papers and is currently often understood as qualitative

system change (Milkoreit et al., 2018). In the last decades, it has been imported into social sciences, where it is frequently used to explain the complex relationship between ecological systems and social or human systems. It appears to be generally accepted that tipping points are seen as a process where "a small change in the balance of the system causes large changes." In the field of social development, there is more than one tipping point that may trigger a change. Generally, "tipping points might be early (and not so visible and recognizable) signs of a major change" (Tàbara et al., 2023).

The distinction between positive and negative tipping points is one of the common elements of the existing interpretations in literature. Negative TPs refer to the impact of climate change on ecological and social systems. Positive TPs are more about solutions to address climate change. The last one can be understood "as emergent properties derived from complex systems dynamics that allow rapid transformations in individual and collective practices so as to reach evolutionary-like solutions to the present socio-climate quandary" (Stadelmann-Steffen et al., 2021).

Another distinction concerning the concept is related to natural and social TPs. Little is known if the same mechanisms characterize both natural tipping points and social tipping points. Stadelmann-Steffen et al. (2021) identified at least two directions in the literature starting from this distinction. Natural typing is seen in the context of global warming as an undesirable process. On the other hand, social tipping involves both negative and positive dynamics (Winkelmann et al., 2020). The second direction relates to the fact that Socio-Ecological Tipping Points depend on different social processes and dynamics, such as the behavior of different actors, transformation dynamics in time, and heterogeneities within and across societies (Trutnevyte et al., 2019).

SETPs can be defined as a change into a new, fundamentally different state induced abruptly by climate change in a socio-economic system (van Ginkel et al., 2020). SETPs could be considered effective *communicative metaphors* for the science-policy interface (Milkoreit et al., 2018). This helps policymakers to facilitate a "salient and credible dialogue between decision-makers and scientists about the amount of acceptable change, when unacceptable conditions could occur, how likely these conditions are, and what adaptation pathways to consider" (Werners et al., 2013). This paper takes into account that the multiple uses of the SETPs concept obscure the different causal logic in the natural vs. social systems and retain the four necessary conditions for SEPTs: multiple stable states, abruptness and non-linearity, feedback, and irreversibility (Milkoreit et al., 2018).

Events at different scales can trigger SETPs, and in "the case of social development, there are rather several tipping points than just one that triggers the change and becomes exponential." To sum up, tipping points might be early (and not so visible and recognizable) signs of a major change (Mangalagiu and Lieu, 2023). Our analysis is sensitive to the fact that local and regional developments can have unintended effects at different levels (Braswell and Heffernan, 2019).

When analyzing the public policy interventions adopted during the transition, the entire stream of social tipping elements (STEs) identified by Otto et al. (2020) is reviewed, such as removing subsidies for fossil fuel, stimulating carbon–neutral settlements, divesting from fossil fuel assets, underling the moral implications of fossil fuels, climate education, and advocacy, information disclosure. We have also reviewed papers that analyzed public policies that touched on specific aspects of the socio-economic and psychological transition of CCIRs and investment policies that would indirectly but relevantly affect the trajectory of CCIRs while minimizing organized opposition against this transition (Lockwood, 2018). Also, the recent analysis focuses explicitly on identifying tipping interventions that have the potential to accelerate positive transformation using lessons from hard sciences (Farmer et al., 2019).

Digging deeper into the topic of conditions, actions, and policies that may act as drivers of system transformation, this study reviewed the contribution of Tàbara et al. (2018). They consider it impossible to identify or develop the potential transformative solutions that must be implemented globally to contribute to the 2 or 1.5C policy target. However, identifying the capacities to implement these solutions can facilitate passing the needed positive tipping point and, hence, achieving the policy target. They based their approach on the fact that social-ecologic system transformation may be accelerated by "social action." In the case of policymaking, where the vision is the driver of transformation, Tàbara et al. (2018) consider that interlinked actions or systems of transformative solutions can induce positive tipping points as a consequence of "the cascading, feedback, and cumulative effects."

Lenton (2013) discusses the crucial role of SETPs, and Lenton et al. (2022) provide examples of actions that have the potential to create enabling conditions that may trigger positive tipping, including "targeting smaller populations, altering social network structure, providing relevant information, reducing price, improving performance, desirability, and accessibility, and coordinating complementary technologies."

Policymakers play a significant role in designing the conditions for transformation to happen. Fesenfeld et al. (2022) argue that policymakers can strategically create synergies between behavioral and technological changes that may spark "political feedback loops for enabling positive tipping." Policy interventions also have to take into consideration the importance of creating new adaptive capacities and multi-level learning processes for governance systems capable of allowing for a sustainable transition (Pahl-Wostl et al., 2007; Hölscher, 2020; Loorbach, 2020) and limiting the mobilization against energy transition in CCIRs (Sovacool et al., 2022).

While the interest in CCIRs' transition increased in the last decade, we identified no study that comparatively assessed the common features of public policy response to phasing out and adaptation in the CCIRs and no systematic effort to operationalize indicators describing these efforts. While the relevant literature implicitly analyses policy interventions, it does not explain their features or systematically compare these features. By proposing a comparative approach to the public policies required to generate SETPs in CCIRs, this article contributes to the branch in the literature that assesses actions, conditions, and interventions that trigger positive tipping points that may lead to climate change mitigation and adaptation.

3. Methods and data

We follow an interdisciplinary approach introduced by Gladwell (2001) and Mangalagiu and Lieu (2023) and consider the most relevant points of analysis advanced in the SETPs theories: human geography and demographics (Castree et al., 2013), social psychology and anthropology (Fisher Onar et al., 2014; Wiese et al., 2010) focusing on processes favoring adaptation and mitigation (Caillaud, 2016; Smith and Joffe, 2013). We employ the definition of transition as a "gradual, continuous process of societal change, changing the character of society (or a complex part) structurally" (Roggema et al., 2012).

This paper aims to explore if innovative policies adopted in the CCIR regions may lead to faster progress toward positive SETPs by mapping policy response patterns during the transition in thirteen CCIRs by searching for commonalities and correlations. Hence, policy responses will be operationalized in five indicators and complemented with additional indicators and data that reflect other relevant regional dimensions.

3.1. Challenges in studying SETPs in CCIRs

Approaching the causal link between public policies and positive SETPs in CCIRs would ideally require investigating what characteristics of policy changes and local developments are needed to effectively generate SETPs "at which the system shifts abruptly from one state to another" (Scheffer et al., 2009, p. 53). Nevertheless, there are no

methodological instruments to identify the occurrence of SETPs in time and space clearly. The CCIRs are highly heterogeneous, and methodologically, it is not easy to link public policies to SETPs causally. As the ideal dependent variable cannot be quantitatively operationalized and accurately pinpointed, we take an alternative route allowed by the data availability and map the patterns of policy response during the transition, identify commonalities and associations, and use qualitative data on the transition narrative to conclude commonalities. This mapping allows us to identify possible patterns in policy response and evaluate the efficiency of such approaches, inform future policy responses to challenges in reaching adequate SETPs, and avoid socio-ecological traps.

Furthermore, even attempting to identify commonalities of the public policy response poses significant methodological challenges, partially stemming from the heterogeneity of the CCIRs. The ideal dataset to compare CCIRs and the effect of public policies would include comparable economic data, comparable data about public policies and investment (general, phase-out vs. innovation), and their impact on decarbonization.

Furthermore, how statistical data are collected varies because regions are also heterogeneous in administrative organization. For example, the Jiu Valley of Romania comprises five cities in a much larger county. Thus, no statistical data for the regional level are collected. Considering these limitations, we use the best proxies in terms of policy describing the characteristics of the public policies affecting CCIRs' transition towards and post SETPs.

3.2. Methodological approach

The article proposes a comparative analysis methodology that employs bivariate correlations and case studies analysis that inform the interpretation of results. Additionally, the analysis uses innovative narratives to strengthen and contextualize the quantitative results. Narratives in CCIRs in transitions refer to different perspectives belonging to relevant stakeholders about how a specific region experienced or is currently experiencing the transition. To compare the thirteen case studies, we collected historical data about policies adopted since the transition started, pointing out the "golden age" of carbon-intensive activities, the year these activities reached their peak, and the starting year of the transition. Additionally, innovative policies have been located. Given the difficulty of collecting data, we propose a process analysis approach where policies are seen as potential causal points that may accelerate the transition efforts in CCIRs.

Five variables are used to operationalize the public policies adopted in the CCIRs under analysis, describe variations in public policy response, and identify commonalities across these responses.

The first variable is policy density in each CCIR (See Table 1 for details). Policy density is defined as the total number of policies impacting the regions' phase-out and transition elements, following the elements proposed by (Otto et al., 2020). We evaluated all case studies synthesis resulting from the analytical effort carried out in the Tipping + project (Mangalagiu et al., 2023a). Then, the history of public policies adopted in the thirteen CCIRs were independently reviewed using primary and secondary sources. Although some regions' "glory years" go back to as early as 1938 (Balearic Islands, Spain), and the transition started as early as 1968 (Essen and Duisburg, Germany), we focus on policy interventions undertaken after 1989, the year most communist regimes fell and triggered a massive wave of economic transformations, and thus, our time frame is 1989–2022 (Table1 and Table 2).

The second variable consists of public policies that contain partial or mostly elements focusing on innovations that would trigger a transition toward positive SETPs (Table 1). The focus here is on policies that promote a vision based on technological innovation, emission reductions, broader stakeholder integration, investment in carbon-free technologies, education, and public awareness.

Third, based on the period over which effects of policy decisions are considered in terms of timing, intensity, and distribution of these policies, especially on the phasing-out, we have grouped the thirteen CCIRs for which we had consistent data in four categories (Tuohy, 2015) in the"Time frames utilized" (Second column in Table 2): "Big-bang" refers to a large-scale, fast-paced change; "Blueprint" involves a large-scale change at a slow pace; "Mosaic" means several small-scale changes simultaneously; "Incremental" denotes small-scale, slow-paced changes. The placing of CCIRs in these four categories is independent of the policy density, as this one evaluates the existence of overarching planning and the pace of its implementation. The thirteen regions were distributed in these categories based on the information collected on each CCIR's policy reviewed and the literature related to them.

For the fourth and fifth operationalization of the feature of public policies adopted in the thirteen CCIRs, we used two indicators defined by Martínez-Reyes et al., 2024 based on the same systematic review of the case studies (see Table 2). The fourth variable measures if policy mixes at the national or international level have already promoted the energy transition in the region. CCIRs are placed into four categories from the existence of binding international or national policies promoting an energy transition that the region has already met, to binding international or national policies promoting an energy transition to be met, to the existence of international or national policies that are not binding for the region, and lack of international and national policies promoting an energy transition. This variable evaluates the regional transition of CCIRs from another angle, focusing on the planning of phasing out.

The fifth operationalization of policy response is the variable

Table 1
Policy interventions in the field of energy for the thirteen regions analyzed.

Indicator	Policy Intensity	Years of transition (after 1989)	Policies partially or totally focusing on innovation	% of innovation-focused policies from total adopted policies	Policies/ year	Innovation policies/year
Upper Austria, Austria	19	32	8	0.42	0.59	0.25
Moravian-Silesian, Czech Republic	25	32	12	0.48	0.78	0.38
Essen and Duisburg, Germany	9	32	4	0.44	0.28	0.13
Megalopolis, Greece	16	18	6	0.38	0.89	0.33
Balearic Islands, Spain	18	31	9	0.50	0.58	0.29
Teruel, Spain	18	31	9	0.50	0.58	0.29
Sulcis, Italy	14	28	11	0.79	0.50	0.39
Lofoten, Norway	14	30	5	0.36	0.47	0.17
Upper Silesia, Poland	35	30	14	0.40	1.17	0.47
Jiu Valley, Romania	21	32	4	0.19	0.66	0.13
Alberta, Canada	19	32	5	0.26	0.59	0.16
Bali, Indonesia	11	21	3	0.27	0.52	0.14
Greenland, Denmark	22	34	8	0.36	0.65	0.24
Average	**18.5**	**29.5**	**7.5**	**0.4**	**0.6**	**0.3**
Standard Deviation	**6.4**	**4.5**	**3.3**	**0.1**	**0.2**	**0.1**

Table 2
Policy mixes promoting energy transition in the analyzed case studies. Regional characteristics.

Indicator	Policy mixes at the national and international level () − Have policy mixes at the national or international level promoted the energy transition in the region?*	"Time frames utilized" (consisting in the period over which effects of policy decisions are considered).**	Energy region's polycentricity (decentralized governance structure) *** does the regional governance institutions (formal and informal) have on steering the energy transition?	Energy price fluctuation ****	Year of glory of the region	Year of start of transition	Population (close to start of transition)	Surface in square km
Upper Austria, Austria	0.7	2	0.8	0.6	1960	1995	523,000	19,186
Moravian-Silesian, Czech Republic	0.7	2	0.6	0.4	1989	1989	1,200,000	5430
Essen and Duisburg, Germany	1	1	0.8	0.6	1956	1968	5,300,000	4440
Megalopolis, Greece	0.7	4	0.6	0.6	1996	2011	8205	331
Balearic Islands, Spain	0.7	2	0.8	1	1938	1989	1,223,980	5961
Teruel, Spain	1	4	0.6	1	1986	2018	146,751	14,809
Sulcis, Italy	1	2	0.8	1	2013	1993	64,475	534
Lofoten, Norway	1	1	0.6	1	2010	2020	24,500	1227
Upper Silesia, Poland	0.7	2	0.8	0.4	1979	1990	4,500,000	12,333
Jiu Valley, Romania	0	4	0.6	0.4	1988	1990	100,000	260
Alberta, Canada	0	4	1	0	1989	2014	4,601,314	661,848
Bali, Indonesia	0.7	4	0.6	0	1997	2007	4,364,000	5700
Greenland, Denmark	0	2	1	1	1975	2021	59,900	2,166,000
Average	**0.6**	**2.6**	**0.7**	**0.6**	**1983**	**2000**	**1,701,240**	**222,928**
Standard Deviation	**0.4**	**1.1**	**0.1**	**0.4**	**20**	**15**	**2,041,556**	**587,328**

* Variable 4.2 from Martínez-Reyes et al., 2024) 1 − There are binding international or national policies promoting an energy transition that the region has already met. 0.7 − There are binding international or national policies promoting an energy transition that the region has to meet eventually. 0.4 There are international or national policies promoting an energy transition, but they are not binding for the region. 0 − There are no international or national policies promoting an energy transition. Methodology for assigning values: for each case study, an expert has used the two systemic reports of the TIPPING + Project, Mangalagiu et al., (2023b) and Mangalagiu et al., (2023a), as well as other relevant data sources, to assign a value for each case study, based on a short case-study report. Each assignment has been verified by other experts, and the database has been validated by the project experts. Databases available at:https://github.com/Amininor/fs-QCA-data-validation-and-sources.git.

** Methodology for assigning values: starting from the detailed description of the four categories proposed by (Tuohy, 2015), the case studies have been assigned to three of the authors of the article. 1"Big-bang" –refers to a large-scale, fast-paced change; 2"Blueprint" – involves a large-scale change at a slow pace; 3"Mosaic" – means several small-scale changes simultaneously; 4"Incremental" – small-scale, slow-paced changes. For each case study, an expert has used the two systemic reports of the TIPPING + Project, Mangalagiu et al., (2023b) and Mangalagiu et al., (2023a) as well as other relevant data sources. After the initial assignment, data has been cross-checked and verified by the other two authors for validation.

*** Variable 2.4 from Martínez-Reyes et al., 2024 – The case studies are assigned to four categories based on the expert evaluation given the following question: How much authority (or decision-making power) does the regional governance institutions (formal and informal) have on steering the energy transition? The four categories are assigned with the following values: 1 − Regional governance institutions are the main ones in charge of steering the regional transition 0.8 − Regional governance institutions can (legally) and have influenced the direction of the regional transition. 0.6 − Regional governance institutions could (legally) but have not influenced the direction of the regional transition. 0 − The decision-making power is not shared at the regional level but concentrated at the national level. Methodology for assigning values: for each case study, an expert has used the two systemic reports of the TIPPING + Project, Mangalagiu et al., (2023b) and Mangalagiu et al., (2023a) as well as other relevant data sources, to assign a value for each case study, based on a short case-study report. Other experts have verified each assignment, and the project experts have validated the database.

**** Variable 3.2 from Martínez-Reyes et al., 2024 The case studies are assigned to four categories based on the expert evaluation given the following question: Have energy price fluctuations affected the pace of the regional energy transition? The four categories are assigned with the following values: 1 Energy price fluctuations have speeded up the regional energy transition. 0.6 Energy price fluctuations are expected to but have not yet speeded up the regional energy transition. 0.4 Energy price fluctuations are expected to but have not yet slowed down the regional energy transition. 0 Energy price fluctuations have slowed down the regional energy transition. Methodology for assigning values: for each case study, an expert has used the two systemic reports of the TIPPING + Project, Mangalagiu et al., (2023b) and Mangalagiu et al., (2023a), as well as other relevant data sources to assign a value for each case study, based on a short case-study report. Other experts have verified each assignment, and the project experts have validated the database.

evaluating the degree of authority (or decision-making power) of the regional governance institutions (formal and informal) in steering the energy transition. This is an indicator of the region's polycentricity of the energy transition or the existence of a bottom-up approach (See Table 2 for details). It answers the question of what institutions held the decision and responsibility for transition in CCIRs, regional/local authorities, or the central government. Furthermore, the thirteen CCIRs are grouped into four categories, from those where regional governance institutions are the main in charge, to those where they can influence the transition, to those that could legally influence but have not, to those

without any such power, as it is concentrated at the national level.

3.3. Additional indicators

Besides the region's "year of glory" of coal or carbon-intensive activities, the year of the start of the transition, population (close to the start of change), and surface in square kilometers, we have also introduced the grouping in various clusters according to the mainstream narratives, type of regional cluster, alternative narratives, transformative capacities and case study's narrative and narrators (see Table 3 for details) and the rest of variables used by Martínez-Reyes et al., 2024. Given the limited number of cases and the synthetic nature of the data, we have only used averages, standard deviations, and correlations (Pierson for continuous variables and Spearman for correlations involving at least a nonparametric variable). Considering the very limited cases and the nature of scale coding for some variables, we have also analyzed correlations with a 0.1 (90 %) confidence level (for these, no * is reported, as well as the * for 0.05 level of confidence and ** for 0.01 level of confidence). We present and interpret only relevant correlations, but the entire set of correlations is present in Supplementary material 1.

Table 3
Types clusters in the case studies analyzed.

Indicator	Mainstream narratives (cluster)*	Region type (cluster)**	Transformation capacities (cluster)***	Industrial and energy transition – Case Studies' Narratives and Narrators (cluster)****
Fuzzy values				
Upper Austria, Austria	3	3	1	2
Moravian-Silesian, Czech Republic	2	3	1	
Essen and Duisburg, Germany	1	2	2	2
Megalopolis, Greece	1	1	2	3
Balearic Islands, Spain	3	3	3	1
Teruel, Spain	3		2	3
Sulcis, Italy	1	1	2	2
Lofoten, Norway			1	3
Upper Silesia, Poland	1	2	1	2
Jiu Valley, Romania	2	2	3	2
Alberta, Canada	4		1	
Bali, Indonesia	3	1	1	1
Greenland, Denmark	4	2	1	1

* Mainstream narrative (cluster): Cluster 1: Coal-centric regions transitioning; Cluster 2: Coal-centric and populist ideologies; Cluster 3: Emerging/innovating industries/sector.

** Region type (cluster): 1. Islands/islands/rural/isolated context region; 2. Urban region; 3. Large-scale regions.

*** Transformation capacities (cluster). 1. Economic diversity/energy mix; 2. Energy community/social innovation; 3. Tourism/migration; 4.Economic diversity/energy mix.

**** Industrial and energy transition Case Studies' Narratives and Narrators (cluster): 1. "No significant change"; 2. "Growing on-stream narrative"; 3. "Renewable' growth and diversification of economy".

We also use data from case study narratives, as systematized in Mangalagiu et al. (2023a), to strengthen the conclusions drawn from our quantitative analysis (See Table 3 for details). They define narratives as "the storyline describing how the CCIR pathway (i.e., pathway broadly is a course of direction) was historically developed until the present and how some promising CCIRs pathways can be potentially developed in the future" (Mangalagiu et al., 2023a, p.34). Accordingly, two additional elements are taken into consideration: the narrators, who are the "dominant stakeholders in power and who perpetuate the mainstream narratives,"and the energy policy environment that has facilitated "the development of high carbon energy technologies central to the energy mainstream system."

Narratives are operationalized as mainstream and alternative narrative(s). Mainstream refers to the pathway representing the dominant energy or high-carbon sectors, such as coal, oil, and green energy. An alternative narrative is a pathway that provides us with "indications of change or transition, which can potentially transform the energy profile in the CCIRs" (Mangalagiu et al., 2023a, p. 35). The alternative narrative is further operationalized as on-stream, a pathway that sustains new low-carbon technologies but kips the energy status quo in the region. Off-stream, which is the opposite, refers to an alternative perspective with the potential to change the mainstream pathway. The following data used from the same systematization of data: the mainstream narratives (see table "Mainstream narratives of case study regions," the social, economic, and political characterization (see the table "Characterizing the regions case study regions" (Mangalagiu et al., pp. 89–97); the alternative narratives in the areas we study (see the table entitled "Defining the alternative narrative" and the table entitled "Identifying Transformative narratives and synergies between case studies and work packages" (Mangalagiu et al., 2023a, pp.72–139).

In conclusion, our methodological approach allows us to identify possible patterns in policy response and evaluate the efficiency of such approaches, better understand future policy responses to challenges in reaching adequate SETPs, and avoid socio-ecological traps. We also question the extent to which the policy adoption patterns correlate with other regional structural features. Our quantitative analysis is strengthened by assessing public policy features and evaluating the structuring of CCIRs according to various narratives.

4. Results

The analysis of policy response patterns during the transition in thirteen CCIRs in a context characterized by heterogeneity revealed that a unique recipe for triggering positive tipping points in CCIRs could not be identified. Social and ecological dimensions have defined the transition experience in each case. It is essential to note that there are continuous efforts to decarbonize these regions. Policy actions, planning, and a small number of innovative policies appear to be drivers of transformation. This is the case of Germany's coal regions, where the government has spent 40 billion euros during the transition period (Mangalagiu and Lieu, 2023).

Judging by policy density implemented in the transition period, the analysis shows that the average amount of policies/year, since the transition started was 0.6, ranging from a minimum of 0.47 to a maximum of 1.17 and a Standard Deviation (SD) of 0.2. Instead, the number of innovation policies/ year was 0.3, ranging from 0.13 to 0.38, and an SD of only 0.1, indicating high homogeneity across the analyzed CCIRs. Nevertheless, if we compare this variable with the time frame used, we observe that the only two regions ranked as having large-scale, fast-paced changes (Lofoten in Norway and Essen and Duisburg in Germany) also have a lower-than-average number of policies and innovation policies/year. This means that adopting a higher number of sustainable policies during the transition period does not necessarily lead to the expected transition. Instead, the concentration of the effort on a few policies appears to be more indicated.

Conversely, some CCIRs whose transition is small-scale with slow-

paced changes usually have an above-average number of policies/years adopted but lower-than-average policies focused on innovation. Also, in the regions where the transition has been rather incremental, there is an association with a negative effect of energy price fluctuations on the regional energy transition. One of the most significant correlations is between the percentage of innovation-focused policies (see Table 1 in Annexes for details) and policy mixes at the national and international levels and being closer to having met the international and national binding energy transition that has been met or is in the course of being met (0.631*) (see Table 2).

Other relevant findings show that while the population of the CCIRs is larger, the role of energy price fluctuations in speeding transition is lower (−0.666*). CCIRs surface is associated with non-binding or absent international or national policies promoting an energy transition (−0.630*) and a higher role of regional governance institutions (See Table 2 for details). An example of this is the Alberta region of Canada or Greenland.

Also, expectedly, the longer the time since the start of the transition, the longer the time since a regional energy transition has been adopted (Essen and Duisburg in Germany, Upper Austria in Austria, Upper Silesia in Poland, or Jiu Valley in Romania). The rather coal-centric regions transitioning have a more recent year since the transition (0.619*), higher surface (0.585*), and are early in their regional economic independence from the carbon coal-intensive sector (see Table 2 for details).

Furthermore, when analyzing industrial and energy transition case studies narratives and narrators (Table 3), in those CCIRs where the regional governance institutions are the main ones in charge of steering the regional transition (−0.568) (Table 2), there are higher chances that no significant change appears in the industrial and energy transition narrative (−0.574) (see Table 3). This means that regional governance institutions are less efficient in conducting energy transition than national ones.

5. Discussions

5.1. The profile of CCIRs in transition

Our comparative analysis reveals a complex picture of CCIRs' sustainable transition. First of all, the transition of CCIRs is complex and difficult; no universal policy prescription exists, and the percentage of electricity consumed from renewable sources is still very low (under 10 % for the limited data we have). As a general trend, the transition starts with policies focused mainly on phasing out and, in some cases, taxation, while innovation-focused policies are developed later, representing an average of only 40 % of the total policies. One of the few relatively homogenous features identified is that the number of policies/year is highly correlated with innovation policies/ year across the 13 CCIRs (0.698**), the fact that might indicate a form of policy diffusion trend, although it is very difficult to identify the exact causes of this homogeneity (see Table 1 for details).

Adopting more policies or innovative policies does not lead to faster decarbonization, indicating that quantity does not mean quality. Those CCIRs with a more planned and rapid transition had fewer policies. Instead, the percentage of innovation-focused policies from total adopted policies (Table 1) is also positively correlated with a positive role of energy price fluctuations in speeding up the regional energy transition (0.594*) and a higher level of regional electricity consumption from renewable sources (0.600*).

Furthermore, larger CCIRs are more difficult to transition, as it appears that more regional authority on energy transition is negatively associated with a faster transition (see Table 2 for details). To a certain extent, decarbonization targets are assumed at the national level, and usually, the national government has access to the financial resources necessary to ensure a sustainable transition. Moreover, the most active actors in shaping the structural change in CCIRs are the national governments, which need to balance the national energetic system.

The analysis of the titles of policies adopted in the thirteen case studies reveals that most of them specifically mention achieving phasing out the mining sectors and energy transition, while justness of transition appears in only two cases (Jiu Valley – a Memorandum of Understanding among municipalities to access the Just Transition Fund, and a task force on just transition in Canada. In Jiu Valley, Romania, this policy analysis brings together mayors from cities across Jiu Valei to agree on common solutions. In this case, the just transition component is supported in the context of the EU Just Transition Fund (European Commission, 2022). In Canada, the policy reviewed involves consultation with stakeholders from coal-affected communities in Alberta, Saskatchewan, Nova Scotia, and New Brunswick. It aims to formulate policy recommendations based on the insights from local stakeholders (International Energy Agency, 2022, p. 17).

Also, Germany is the only country where one of the first transition policies aimed at the "socially responsible restructuring of the workforce." One of the implications of our analysis on the regional transition's overall "justness" of regional transition has to be interpreted considering multiple dimensions and comparative assessments on how similar policies adopted in other CCIRs have managed or not achieved the desired outcomes.

Analyzing the visualization of the evolution of the interaction of mainstream narratives with on-stream and off-stream narratives developed for each case study (Mangalagiu et al., 2023a, pp. 155–160) in relationship with the timing of policy adoption, we realize that for all the CCIRs that have a separate identity from the mainstream national identity, the moment when the off-stream narrative could become more important, and thus allow for reaching the positive SETP is in the future. In the CCIRs, where the off-stream narrative has overtaken the mainstream narrative, the process occurred only in the Ruhr region of Germany, while in the rest of the region, it took place in the last few years. The situation is similar for the CCIRs, where the diversification of the economy already started to play an important role. Overall, comparatively assessing the qualitative visualization of CCIRs' competing narratives and data on public policies and state of transition reveals that the innovation-focused (off-stream narratives) transition has accelerated in the last few years, while results should be more visible in the near future. Nevertheless, it's worth cautioning that this assessment might be caused by optimistically assessing the strength of the off-stream narratives in the present.

5.2. Are innovative policies coming from the local or national level?

One of the important themes we investigated was whether the innovation part is planned (locally or nationally) or emergent. The analysis of the policies adopted between 1989 and 2022 confirms that the phasing-out policies have been adopted and directed at the national level, while most policies that contain innovation elements, like the climate change adaptation strategies, also focus mostly on the national level and do not pay special attention to the needs of CCIRs.

Some exceptions of local policies containing innovation elements were identified, such as climate action plans in Denmark and Austria. In 2014, Denmark's municipalities finalized their climate action plans, "which include flood risk mapping and priority-setting for local climate adaptation measures" (International Energy Agency, 2017a). Based on the Climate Change Act approved in 2021, Austria has adopted a national mitigation program to meet the 2020 target under the EU Effort Sharing Decision. Most Austrian regional states have endorsed their regional climate change programs, considering specific regional circumstances and competence areas (Lachmayer and Müller, 2022). The regional states were also involved with the Austrian Federal government in adopting a joint strategy in 2010. The strategy aimed to operationalize the UN Millennium Development Goals and was intended to guide policy and administration. The work program assumes "global responsibility" and "sustainable production, consumption, and transport." Indicator-based monitoring is performed biennially (UNDRR, 2018).

In Italy, a program to modernize the energy system and make it more environmentally friendly has been identified for Sardinia. The program brings innovation across Sardinia Island's energy mix by supporting solutions that increase the share of renewable energy. The plan foresees a technological leap by entirely focusing the regional energy system on electricity to be produced with renewable energy plants (solar, wind) and with a system of energy storage power plants, thus skipping the already envisaged development of gas infrastructures (Collins, 2021).

At the national level, we found significantly more elements of innovation in a series of public policies. This is in line with the above observation that transition tends to be more center-governed and less at the regional level. An example was identified in the Czech Republic. In 2015, the RE: START Strategy was adopted. It offers solutions to support structurally disadvantaged coal regions. Reducing transport emissions is a way to achieve the strategy's purpose. The main objective is to keep purchasing low-emission road vehicles for transport services using CNG or LNG alternative fuel and complying with the EURO 6 standard. The strategy promotes the benefits of using emission-free road transport vehicles, which work with alternative fuel, electricity, or hydrogen. Public transportation is also considered a suitable solution. The strategy proposes solutions for emissions-free urban transport vehicles (trams or trolleybuses) (European Commission, 2019). The European Union appears to be the main driver of these policies in Czech CCIRs, but local communities shape them less (Mangalagiu et al., 2023a, p.132).

In Greece, an ambitious policy was adopted in 2012 to help the modernization of the country's energy system. National Energy Plan: Roadmap to 2050 for Greece was developed by the National Committee for Energy Planning, established by Law 3438/2006. It emphasizes the reduction of GHG emissions by 60 %-70 % by 2050 compared to the 2005 level. Among its goals, it supports 85 % to 100 % of electricity generation from renewable energy sources, utilizing all mature and commercially viable technologies. The plan also anticipates substantially incorporating renewables, constituting 60 % to 70 % of the total final energy consumption by 2050. Among the measures proposed are energy savings, stabilization of energy consumption, a substantial reduction in oil consumption, and reliance on biofuels in the transportation sector. Electrification of short-distance passenger transportation is another solution for a green and sustainable transport system. Furthermore, the plan endorses a commitment to enhancing the energy efficiency of buildings. The final cornerstone of this innovative pathway consists of fostering decentralized energy production units and the development of intelligent, adaptive grid systems (International Energy Agency, 2017b).

In Germany, in June 2018, the federal government launched a Commission on Growth, Structural Change and Employment to assess the impact of the federal climate protection plan on structural change in lignite regions and to propose measures to support economic development in these regions. In June 2018, the German federal government set up the Commission for Growth, Structural Change, and Employment, also known as the Coal Commission. The primary focus is providing concrete prospects for new, future-proof jobs in the affected regions (Federal Ministry for Economic Affairs and Energy (BMWi), 2019). In Germany, the transition appears to be successful. Community support for sustainable solutions exists, especially in the energy field (Mangalagiu et al., 2023a, p.133).

In 2019, in Poland, the Board of Directors of the Silesian Voivodeship adopted the Silesian Transformation Action Plan, which is the basis and starting point for further transition activities. A regional team for the EC Coalition in Transition (CRiT) initiative was set up, including regional self-government, cooperating with the national government, local authorities, non-governmental organizations, social and economic partners, and trade unions (European Commission, 2020). Regarding the impact of such policies across CCIRs, Upper Silesia, the region in Poland the article also focused on, is considered to be at the tipping point now, with the mainstream narrative declining since 2019 (Mangalagiu et al., 2023a, p.138).

In 2022, the "Jiu Valley Socio-Economic Development Strategy" was implemented. The Ministry of European Funds elaborated on this with the support of the European Commission through the Structural Reform Support Program (SRSP). Even if ambitious strategies or plans are adopted for Jiu Valley, the fact that it is a region consisting of places that are components of different administrative counties makes the implementation more challenging. At the same time, there is a need for better organization since the government cannot be the main actor in transition (Ibidem, p. 136).

Policies oriented toward raising awareness and educating citizens were also identified. These policies are oriented toward different groups. For example, Canada, the United States, and the European Commission launched the "Empowering People Initiative" under the Clean Energy Ministerial. This initiative focuses on workers and communities in the clean energy transition across energy technology initiatives (International Energy Agency, 2022).

6. Conclusions

This article contributes to the global debate on accelerating decarbonization, focusing on the unique challenges of designing public policy interventions for CCIRs. We selected an angle of analysis that has not been approached in recent literature on SETPs and CCIRs' transition strategies. We also defined innovation-focused policy interventions and operationalized policy interventions through different measures. Furthermore, these indicators were correlated with relevant features of CCIRs and qualitatively assessed the innovation-focused policies.

Our analysis reveals that the dual challenge to steer CCIRs through the simultaneous transition to phasing out carbon-intensive activities while fomenting innovation to reconfigure the socio-economic systems into positive SETPs proved very complex across the entire spectrum of CCIRs analyzed. Our angle of analysis allowed us to assess the importance of policy density comparatively, complementing the methodological approach of other articles in this issue that studied evolutions at the level of individual CCIRs or focused on sectoral developments, especially energy transition.

At the same time, we have argued that the longer the time since the start of the transition away from coal, the longer the time since a regional energy transition has been started. When it comes to the actors that shape a narrative favorable to transition, we observed that in places where regional governance institutions are responsible for regional transition, there is a higher chance that no significant change is offered in the industrial and energy transition narrative.

We also assessed the relationship between powerful regional governance and the transition probability. Despite differentiated success and pace seen by the European Union's members, each is moving forward in its energy transition. The policy pressure and funding availability at the European Union level can explain this exception. Both are stimulants for EU member states to accelerate their efforts to achieve their common environmental goals.

While we started from the hypothesis that innovation-focused policies' density should accelerate transition positive SETPs, current data do not offer enough support for this hypothesis. Nevertheless, the government interventions impact narratives, capacities, and the development of local solutions and strategies to promote/trigger a low carbon trajectory in the region. The efficiency of this intervention in moving SETPs towards positive SETPs depends on the direction in which innovation is promoted and the consistency of its policy implementation. Data on innovation-focused policies reflect that while there is worldwide pressure to promote innovation-focused policies, their effect differs dramatically.

The most important recommendation for designing policies to ensure a sustainable and just transition for CCIRs is identifying the right policy mix that can be established only on a case-by-case basis, depending on the intricacies of each CCIR. Among these, choosing appropriate narratives to focus the efforts of the local communities and government can

have a great positive effect in mobilizing synergies towards positive SETPs.

This study has promoted an alternative approach to understanding CCIRs' transition to low carbon. At the same time, there are several limitations to our approach. First, given the scarcity of data about the CCIRs, the accuracy of our conclusions may be impacted. It is difficult to collect the necessary fine-grain data to conduct a comparative study about regions where population and area vary widely and where there are alternative ways of administration, regulation, and policymaking traditions with various energy profiles. In some cases, the region studied is not an administrative unit *per se* but part of a much more comprehensive one, as in the case of Jiu Valley. Additionally, the number of CCIRs is limited, which may affect the representativeness at the population level. Second, as complexity makes accurately measuring CCIRs transition un-parametrizable, and unintended policies, economic evolutions, or other events (e.g., wars, pandemics), assessing causality between public policies, especially towards SETPs is difficult, and requires a process approach, an approach that is nevertheless difficult to make comparable, due to the heterogeneity of the CCIRs.

This article brings significant evidence that more than three decades of creating policies in CCIRs led, to some extent, to the development of means and capacities that may trigger SETPs. It is almost impossible to forecast transformative solutions or the time when the tipping point can be activated (Otto et al., 2020). Identifying concrete and specific capacities (Tàbara et al., 2018, Tàbara et al., 2021), reinforcing feedback, interventions (Lenton et al., 2022), the actors, their networks, and the agencies (Stadelmann-Steffen et al., 2021), policies (Fesenfeld et al., 2022) are more plausible. Even if the literature pointed out the role of innovative policies in system transformation (Ekins, 2010), we find a weak impact in the CCIRs analyzed.

Analyzing policy responses in CCIRs was facilitated by the region's characteristics. In this sense, we agree with van Ginkel et al. (2020) observation that SETPs can be identified more clearly in small systems. Few policies related to the justice dimension were found. This is in line with other authors who revealed that many justice issues are present in public policies designed for transition, even in the most ambitious decarbonization agenda, such as in the EU (Tàbara et al., 2019; Moesker and Pesch, 2022; Johansson, 2023).

Further initiatives to create databases dedicated to CCIRs could help acquire a clearer view of the transition of these regions and overcome the limitations exposed above. Moreover, special attention could be oriented to innovative energy and environmental policies in these regions. As we mentioned, these policies are correlated to an accelerated green transition. Grassroots data could supplement and verify our conclusions. Thus, qualitative studies focused on a limited number of cases, depending on the research team's capacity, can bring a better understanding and move the debate on the CCIRs transition forward.

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CRediT authorship contribution statement

Arpad Todor: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Andrei Țăranu:** Writing – review & editing, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Robert Udrea:** Writing – review & editing, Writing – original draft, Validation, Investigation, Data curation, Conceptualization. **Mihai Dănilă:** Writing – review & editing, Writing – original draft, Validation, Investigation, Data curation, Conceptualization. **Florența-Elena Helepciuc:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2024.102952.

Data availability

Data will be made available on request.

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