



Delft University of Technology

## Enabling sustainable transitions in coal and carbon-intensive regions Interdisciplinary social science perspectives

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### DOI

[10.1016/j.gloenvcha.2025.103022](https://doi.org/10.1016/j.gloenvcha.2025.103022)

### Publication date

2025

### Document Version

Proof

### Published in

Global Environmental Change

### Citation (APA)

Mangalagiu, D., Lieu, J., Biddau, F., Martinez Reyes, A., & Witajewska-Baltvilka, B. (2025). Enabling sustainable transitions in coal and carbon-intensive regions: Interdisciplinary social science perspectives. *Global Environmental Change*, 93, Article 103022. <https://doi.org/10.1016/j.gloenvcha.2025.103022>

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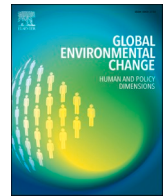
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## Global Environmental Change

journal homepage: [www.elsevier.com/locate/gloenvcha](http://www.elsevier.com/locate/gloenvcha)

## Editorial

## Enabling sustainable transitions in coal and carbon-intensive regions<sup>☆</sup>

### Interdisciplinary social science perspectives

## ARTICLE INFO

## Keywords:

Carbon-intensive regions  
sustainability transitions  
social-ecological tipping points  
justice  
cultural narratives  
energy system transformation  
governance  
transition trajectories

## ABSTRACT

Low-carbon transitions are particularly acute in coal and carbon-intensive regions (CCIRs), which face not only technological and economic barriers but also deep socio-political and cultural obstacles in moving away from carbon lock-in. Transforming these regions requires destabilizing and reconfiguring high-carbon regimes, often demanding structural changes across technological, socio-economic, political, and cultural domains. Despite increased attention to the decline of unsustainable energy systems, much research and policy remain short-sighted, often overlooking paradoxes, trade-offs, and spill-over effects during transitions. This Special Issue addresses the complexity of sustainability transitions in CCIRs from an interdisciplinary social science perspective, drawing on nine original contributions from the TIPPING+ project. The collection introduces advanced concepts, methods, and empirical evidence to better understand and navigate transitions in CCIRs, focusing on Social-Ecological Tipping Points. Through diverse case studies across Europe, Asia, and North America, the articles examine the interplay of forces shaping transition trajectories and highlight their non-linear, multi-scalar, and justice-sensitive nature. The Special Issue introduces frameworks for diagnosing transition states and identifying tipping dynamics, with attention to timing, territoriality, and equity. It further analyzes how political, economic, and governance conditions, as well as place-based narratives and cultural framings, influence the destabilization of carbon lock-ins and the legitimacy and direction of change. Collectively, the articles reframe transitions in CCIRs as embedded, justice-centred, and culturally contested processes, providing actionable insights for research, policy, and planning in sustainability transformations.

### 1. Exploring regional sustainability transitions and transformation through social-ecological tipping points

Accelerating global decarbonisation requires inter- and trans-disciplinary research to understand what political and socio-economic factors and actors' dynamics influence the adoption of just transformative changes towards sustainable and resilient pathways. *Sustainable transformation* is defined as 'the capacity to transform the stable high-carbon regime in order to become a different kind of system, to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable' (Roggema, 2012). We explore transformation through the lens of social-ecological tipping points (SETPs) that can be defined as smaller measurable changes in a system that can "trigger a non-linear change process" propelled by feedback loops in a system that leads to a new system, which is irreversible and self-reinforcing (Milkoreit et al., 2018, p.9). The concept of SETPs is largely rooted in the sustainability transition literature. Sustainability transitions are particularly acute in regions most intensive in the extraction and consumption of fossil fuels. Regional transitions have been studied through a social-technical lens where networks of actors

and institutions must navigate a destabilisation-reconfiguration pathway in which phase-out and innovations interact and mutually shape each other (Turnheim and Geels, 2012; Markard et al., 2018; Johnstone and Hielscher, 2017). The success and pace of coal phase-out and the establishment of low-carbon alternatives are closely linked to regime stability, which is shaped by various techno-economic and socio-political factors (Markard et al., 2023).

To assess the state, direction, and pace of sustainability transitions, it is crucial to consider both build-up and breakdown dynamics. This includes not only the destabilization and decline of entrenched systems and practices but also the adoption, scaling and stabilization of emerging and competing innovations. Ultimately, the trajectories and outcomes of transitions are shaped by the interplay between these processes (see also Hebinck et al., 2022; Biddau, Rizzoli and Sarrica, 2024; Mangalagiu et al., 2024). Transition has been argued to occur disconnected from the stable regime as 'a gradual, continuous process of societal change, altering the character of society (or a complex part) structurally' (Roggema, 2012). Transitions can occur from both incremental and radical systemic changes (Freeman, 1991) and can be initiated within or outside the regime (Lieu et al., 2020). The extent of

<sup>☆</sup> This article is part of a special issue entitled: 'Enabling Sustainable Transitions in Coal and Carbon-Intensive Regions: Interdisciplinary social science perspectives' published in Global Environmental Change.

<https://doi.org/10.1016/j.gloenvcha.2025.103022>

systemic change is often not well understood at the regional level; thus, underestimating how destabilisation efforts may ultimately reinforce lock-ins (Haas, 2021), perpetuate gender inequalities and social injustice (Lieu et al., 2020), exacerbate resistance towards sustainable innovations (Lockwood, 2018) or intensify economic and political struggles between key actors and increase polarisation between winners and losers (Markard, 2018). To understand these dynamics, it is key to consider local embeddedness in space and time, delimiting the analysis to socially and geographically based systems (Geels, 2019). At present, there is limited knowledge from empirical studies in different regional contexts combining socio-technical, economic and political conditions that either enable or constrain the emergence of deliberate structural changes at the regional level<sup>1</sup> (Martinez-Reyes et al., 2024).

Despite global ambition to phase out unsustainable systems as stated in the Paris Agreement, most research and national policy agendas suffer from a short-sighted gaze. For instance, narrowly focusing on the phase-out or adoption of a resource /technology /practice in isolation, instead of integrating them into broader analysis of pathways (Isoaho and Markard, 2020). This narrow focus often overlooks the need for systemic change or the interaction between complementary or competing elements, such as emerging and existing technologies competing for limited resources, inconsistent policy priorities, and actors' conflicting interests (Rinschheid et al., 2021; Köhler et al., 2019; Markard, Rinschheid, and Widdel, 2021). Failing to account for technology, sectorial, policy and actor interactions might lead to overlooking potential trade-offs, or spillover effects due to interventions aimed at advancing or accelerating sustainability transitions for transformations (Newell, Geels, and Sovacool, 2022). In fact, transformations are needed across multiple domains and scales of action, from individual behaviours, community arrangements, organisational practices as well as large-scale resource, policy, and governance systems (Kaufman et al., 2021; Hestad et al., 2020; Pahl-Wostl and Patterson, 2021; Hölscher and Frantzeskaki, 2020). Transformations required in CCIRs entail changes that go beyond a mere resource or technology shift. They require unmaking and re-making the set of relationships and feedback loops making up the system, calling for a fundamental shift in e.g., the distribution of authority and power, the socio-economic and livelihood foundation, as well as underlying norms, values and beliefs that underpin existing structures (Feola et al., 2021; Moore et al., 2022). However, the dynamic interactions between diverse sources of transformative agency and their amplifying or dampening feedback across spatial and temporal scales (Sovacool, 2016; Alkemade and de Coninck, 2021) have not yet been approached using an inter- and trans disciplinary social science approach within regions.

To better understand potential options for regional sustainable transitions pathways, there is a need to identify and understand how historical developments shaped various positive feedback and self-reinforcing mechanisms that lock-in socio-technical systems into a particular trajectory and how cultural frames and discursive dynamics are contributing to reproduce or undermine lock-ins regionally by justifying technologies, institutions and practices (Bouschman and Oels, 2019; Simoens et al., 2022). In fact, technological lock-ins are frequently reinforced by institutional (regulations, subsidies, policy incentives) and behavioural lock-in mechanisms embodied in user habits, routines, and cultural norms (Seto et al., 2016; Goldstein et al., 2023). Understanding these feedback loops is particularly important not only to understand how and why unsustainable systems are maintained, but also how deliberate interventions or exogenous conditions can potentially tip stable systems towards more sustainable socio-ecological

configurations. We refer to these processes as tipping events or interventions which can shift and stabilize “the system towards a different trajectory or systems' configuration, and the *structural effects* derived from such transformation” (Tàbara et al., 2021, p.565).

Advances in social and resilience theory, behavioural economics, ethics in transitions and transformations (Cronin et al., 2021; Chapman et al., 2022) – including the novel idea of transformative planetary justice (Gupta et al., 2021), as well as in social psychology, complex systems modelling regarding the potential role of public opinion trends in triggering systemic change (Centola et al., 2018; Galam and Cheon, 2020; Winkelmann et al., 2022; Moore et al., 2022) are fast contributing to sharpening our understanding of STPs in socio-environmental change research (Tàbara, Mangalagiu et al., 2021). The concept of tipping points, and their relative notions like leverage points, sensitive tipping interventions, social tipping points are receiving growing scholarly attention to conceptualise and explain multi-scalar complex processes of deliberate and rapid structural transformations (Tàbara et al., 2018; Farmer et al., 2019; Chan et al., 2020; Otto et al., 2020; Davelaar, 2021; Leventon et al., 2021; Stadelmann-Steffen et al., 2021; Lenton, 2020).

## 2. Contribution of the special issue

This Special Issue brings together nine articles based on research performed within the TIPPING + project that contribute conceptually, methodologically and empirically to the understanding of sustainable transitions in coal and carbon-intensive regions (CCIRs). The TIPPING + project<sup>2</sup> mobilized an international consortium of interdisciplinary social science researchers and practitioners to explore how CCIRs are navigating or resisting destabilization and reconfiguration dynamics and the conditions that can enable a system to tip – under the influence of events or interventions – to a different state. TIPPING + introduced and tested the concept of SETPs to study how transitions in CCIRs unfold through the interaction of political, socio-economic, socio-technical and cultural forces and tested it with the participation of stakeholders within 20 + case study regions in Europe, Asia, and North America.<sup>3</sup>

Altogether, the collection of articles advances current academic, industry and policy debates on socially relevant and just transitions in several ways. The studies address the multifaceted problem of transitions<sup>4</sup> by examining the destabilisation and decline of existing regimes and systems, as well as the diffusion of sustainable innovations (Rogge & Johnstone 2017, Loorbach et al. 2017). In this endeavour, the articles explore the underestimated policy, political, socio-economic, and cultural challenges, and consequences of decarbonization processes, as well as the enabling factors and capacities, in those regions where coal and carbon-intensive activities are deeply sedimented (Rinschheid et al., 2021). In doing so, they also inquire about the multiple forces and pressures for destabilisation and re-configuration, determining whether potential tipping dynamics in narratives of current and future visions, and if enabling capacities originating at multiple scales reflect sustainable transformations (Folke et al. 2010).

CCIRs refer to subnational territories with high economic dependency on either fossil-fuel extraction, such as coal mining or carbon-intensive industries such as steel (European Commission, 2018). In these regions, low-carbon transitions often face multiple challenges stemming from socio-economic concerns such as job losses, threats to energy security, and impacts on industrial competitiveness. These socio-economic concerns in turn shape the pace and orientation of political

<sup>1</sup> Revisiting and advancing the state of the art in this field is particularly urgent in the face of large re-structuring socio-energy systems and EU policies derived from the recent events, in which as in the words of the EC Vice-president Frans Timmermans when announcing the new RePowerEU policy asserted that: ‘In just two weeks, the course of our European history has changed, radically changed, and I believe for good’.

<sup>2</sup> TIPPING+ is a European Union Horizon 2020 project, see <https://tipping-plus.eu/about/objectives>.

<sup>3</sup> For case studies see: <https://tipping-plus.eu/case-studies>.

<sup>4</sup> I.e., the relation between change and stability reflected in the struggle between sustainable innovations and practices and deeply sedimented systems and locked-in patterns of production and consumption that create path dependent trajectories (Kohler et al., 2019).

and cultural change (Skoczkowski et al., 2020). We approach CCIR transitions from diverse disciplinary perspectives, and focus on understanding the narratives, conditions, and effects of tipping processes on multiple levels. This Special Issue builds on a unique social science component, drawing from human geography, anthropology, social psychology, sociology, energy economics, and political sciences.

As a starting point, we refer to positive tipping points within regions as those moments in which previous deliberate interventions (tipping interventions such as policies) or disruptive events (tipping events such as economic shocks, geopolitical instabilities, or natural hazards) trigger systemic changes towards a transformed sustainability state at a sectoral and/or regional level. A potential sectoral tipping *intervention* may transform a high-carbon socio-economic sector into a low-carbon trajectory. SETPs also entail changes in individual values and behaviours, in community lifestyles as well as in organisations, and power relationships and institutions. In the existing literature, the SETP remains mainly at the conceptual level and requires further development with empirical case studies (Milkoreit et al., 2018) in different social contexts and at various geographical scales. In this Special Issue we develop SETP concepts, methods and frameworks within empirical contexts that help understand sustainable transitions and transformations in CCIRs.

This Special Issue advances the state of the art in global environmental change in two ways: First, we advance concepts, methods, and frameworks to understand sustainable transitions in CCIRs and unpack the social processes that unravel pathways towards socially relevant and/or just, sustainable transformations in CCIR, exploring the timing, pace, territoriality and fairness of energy transitions. We build on socio-technical and resilience thinking, bridging socio-technical change dynamics with broader social-ecological considerations, and refine the understandings of sustainable transformation with the latest empirical knowledge on transitions in CCIRs. Thus, we deepen the understanding of interconnected social, technological systems with environmental goals that are crucial to prevent undesirable and unintended outcomes of interventions to move toward environmental, social, and economic sustainability.

Second, we contribute with new empirical evidence that advance the understanding of how material contingencies – including biophysical and infrastructural – and social dynamics – like socio-political interventions, socio-economic conditions, and cultural frames and discourses – interact and influence transition pathways enabling or disabling sectoral or systemic sustainable transformations in CCIRs. We studied regions in which decarbonisation actions are implemented but are especially difficult to scale up due to the challenge of aligning techno-economic feasibility with political and social legitimacy. The TIPPING+ case studies provide integrated insights across multiple spatial, temporal, and socio-political scales. We find that cultural frames and discourses from different perspectives and levels help understand how CCIRs can efficiently push forward their desired change. Transforming socio-energy systems in the CCIRs into clean and just systems has direct and far-reaching consequences across several socio-political levels, including the local, community, regional, and international ones. This Special Issue offers empirically grounded insights into how the strategic combinations of discourses, actions, solutions, and innovations at different points in time and space, can unleash knock-on effects to help the system flip into low-carbon energy trajectories. The special issue addresses the policy, political and socio-economic influences on CCIRs pathways and their consequences on transition dynamics and reveals how cultural frames, discourses, technologies, or practices have been delegitimized, gradually eroding the commitment of or redefining the role of incumbent actors, unlocking and legitimising new pathways.

While we distinguish between conceptual, methodological and empirical contributions, many articles in this Special Issue operate at multiple levels. They develop new frameworks, bridge concepts and apply analytical tools sensitive to feedback loops intrinsic to technology-society co-evolution and produce empirical insights that enlighten our

understanding of a range of dynamics, from tipping points and lock-ins to policy innovation, governance and regional narratives. The nine articles are described below, clarifying how they address overlapping knowledge gaps.

### 3. Collection of articles

The first three articles by Lieu et al. (2025), Mey, Mangalagiu and Lilliestam (2024) and Monasterolo et al. (2024), introduce theory of change frameworks that help diagnose system states and anticipate tipping dynamics by integrating justice considerations and alignment across subsystems. While these frameworks provide system-level insights with diagnostic and anticipatory value, understanding how transitions unfold on the ground requires attention to the region-specific interplay of structural, cultural and institutional forces.

#### 1. Just social-ecological tipping scales (JSETS)

Lieu et al. (2025) introduce an inductive conceptual framework to study systemic change at the regional level with an inclusion and equity lens and develop a mid-range theory (Just Social-Ecological Tipping Scales, JSETS) identifying five transition states in CCIRs, from high-carbon mainstream to transformed just regions. Drawing from a *meta-analysis* of 19 case studies, they find that transitions and progressions between these states are driven by cumulative enablers (policy support, market shifts, technological innovation and shifts in collective visions) and overcoming barriers (e.g., infrastructure lock-ins). Each transition state also considered the role of distributional, procedural, recognition, restorative and epistemic justice in reinforcing or changing its state. The JSETS framework offers a diagnostic and action framework for just transition planning, supporting researchers and decision-makers in planning tailored tipping interventions based on the regional state in their transition trajectory timeline.

#### 2. Anticipating socio-technical tipping points

Mey, Mangalagiu and Lilliestam (2024) raise the question of whether and how social and socio-technical tipping points can be anticipated and critically explore their predictive potential. The authors develop a heuristic framework to analyse socio-technical systems in terms of technological, material, and immaterial elements and how tipping in single sub-systems can produce cascading effects for tipping the whole system. Case studies of EV adoption in Norway and Germany and solar PV deployment in Germany reveal that system-wide tipping requires alignment across all elements. Norway's EV success stemmed from policy-legitimacy-infrastructure synergy, whereas Germany lagged due to fragmented incentives. Their findings suggest that while precisely predicting tipping points is difficult, their proximity can be anticipated. The authors define indicators for 'early warning' or tipping likelihood and proximity and assess the anticipatory potential permitting to understand the cumulative and cascading effect of tipping sub-elements of the three systems as attractors for the new desired state (e.g., attracting behaviours and institutions, or eroding the interest of incumbents towards the old) and unmaking those attractors of the old state (e.g., infrastructure and sunk costs). Assessing a region's anticipatory potential can help policy makers identify and address lagging elements with strategic interventions and resource allocation.

#### 3. Green financial sector initiatives (GFSIs)

Building on this systems-oriented approach, Monasterolo et al. (2024) propose a Theory of Change to operationalize how GFSIs – like green bonds and risk disclosures influence low-carbon transitions and use econometric methods – heterogeneous panel estimator and lasso classifier – to study the compatibility and simultaneity of cohesion policy's objectives and climate policy's objectives in the European



Union. Their findings show that while GFIs can adjust the sectoral economic composition and de-risk low-carbon investments, their effectiveness relies on complementary policies and credible national commitments. Rebound effects from liquidity increases highlight the need for complementary policies (e.g., carbon pricing) to avoid unintended emissions.

The next two articles by [Mey, Weik and Lilliestam \(2024\)](#), and [Biddau et al. \(2024\)](#) highlight how path dependencies, place-based narratives and cultural frames have a key role in shaping destabilisation-reconfiguration trajectories. These studies use tailored mixed method approaches and conceptual frameworks to capture feedback loops across time.

#### 4. Incremental transitions in the Ruhr region

[Mey, Weik and Lilliestam \(2024\)](#) combine policy analysis, quantitative socio-economic indicators, and stakeholder interviews to investigate the socio-economic transition pathways of Essen and Duisburg in the Ruhr region and the role of tipping interventions in the transition. Their findings show that cities have undergone incremental demographic and economic shifts but no systemic tipping. The incremental and path-dependent change has been shaped by policy sequencing – from coal subsidies to circular economy incentives – and narrative shifts (e.g., “Green Ruhr”) while infrastructural lock-ins, like legacy gas networks, slowed renewable integration. Qualitative differences in local narratives and visions emerge, setting the stage for differentiating the cities’ reconfiguration pathway. While Essen embraced a green identity and reframed its image and opportunities, Duisburg retained an industrial identity. The study contributes valuable empirical evidence and underscores the need for more nuanced, context-sensitive analyses of transformation in post-coal regions.

#### 5. Sense of place and lock-ins in Sulcis, Italy

[Biddau et al. \(2024\)](#) inquire how cultural identities, collective memories and sense of place can function as lock-in mechanisms contributing to path dependency and social-ecological traps using a mixed-methods approach combining longitudinal policy and media analysis with stakeholder interviews and workshops. The authors develop an integrative framework that combines social-ecological and socio-technical approaches to investigate feedback loops between structural factors (socio-political, economic, infrastructural) and psychosocial dimensions of place (i.e., place meanings, identities, and imaginaries) across transformation phases. Focusing on Italy’s Sulcis region (a prototype of CCIR blending extractive and metal processing industries) they show how industrial identity and place-based narratives have historically reinforced carbon lock-in by interacting with other structural lock-in mechanisms. These lock-in mechanisms includes economic and job dependency, interdependence of interests, sunk costs, technological competitiveness and interrelatedness. Additionally, shared myths – such as coal as a cultural heritage – legitimized incumbent industries and obstructed alternative visions. Only after the region’s coal’s destabilization, narratives and imaginaries of a renewable energy transition and sustainable transformation begin to emerge around circular and regenerative economies, grounded in restorative justice and place stewardship.

The next two studies by [Martínez-Reyes et al. \(2024\)](#) and [Maier et al. \(2024\)](#) highlight how market dynamics, industrial dependencies, and energy affordability either lock CCIRs and carbon-intensive sectors or create leverage for transformation.

#### 6. Energy affordability in CCIRs

[Martínez-Reyes et al. \(2024\)](#) use fuzzy-set Qualitative Comparative Analysis (fs-QCA) across 14 regions in Europe, Asia and North America to explore multi-level governance factors that influence energy

affordability as key drivers of energy poverty and just, sustainable, and prosperous regional energy transitions. Coal-dependent regions require market competition and diversification, while carbon-intensive regions need technical feasibility and policy coherence for energy affordability. Misaligned governance also exacerbates affordability gaps. For example, Silesia (Poland) achieved affordability through coal-to-renewables subsidies, while Alberta (Canada) struggled with affordability due to fossil fuel lobbying. Their study highlights the explanatory and analytical value of mixed-methods like fs-QCA with in-depth case study validation to unpack the complex, context-dependent conditions shaping energy affordability.

#### 7. Steel sector tipping points

[Maier et al. \(2024\)](#) focus on the steel sector, examining how large firms navigate low-carbon transitions under different national and economic conditions. Applying the Triple Embeddedness Framework ([Geels, 2014](#)), the authors operationalise tipping points to investigate when, why and with which consequences steel companies in Austria, South Korea, Australia, and the U.S. shaped company-level decisions and trajectories toward low-carbon technologies and net-zero emissions. National policies and customer demand drove frontrunners (voestalpine, POSCO), while laggards (BlueScope, U.S. Steel) faced weak regulatory pressure. South Korea’s POSCO transitioned faster due to state-backed R&D investments, whereas Australia’s BlueScope resisted change amid political inertia.

The final two contributions, [Todor et al. \(2025\)](#) and [Witajewska-Baltvilka et al. \(2024\)](#), focus on the politics and policy side of climate action, examining how policy design and politicization influence the emergence of SETPs and the uptake of ambitious climate policies.

#### 8. Policy strategies for SETPs in CCIRs

[Todor et al. \(2025\)](#) study the counter-effects of potential SETPs and their consequences on the justice dimension of the transition. Drawing on a cross-regional analysis of 13 CCIRs, the authors find that concentrated innovation policies outperform fragmented approaches, and that innovation-focused and narrative-driven approaches accelerate transitions. However, while justice-oriented narratives accelerate transitions more effectively than regional governance, the analysis reveals that few policies explicitly address justice in transitions. They conclude that transitions in CCIRs require region-specific policy mixes, with national governments playing a key role in leveraging financial and planning capacities while supporting regional governance institutions to design tailored policy mixes integrating the justice dimension to address socio-economic disparities and concerns.

#### 9. Politicization of the European green deal

[Witajewska-Baltvilka et al. \(2024\)](#) explore how political polarization and populism mediate national responses to EU climate policy in Central Europe. Through a comparative analysis, they show how party competition in Hungary, Poland, and Romania mediates climate ambition with European Green Deal (EGD) commitments linked to varying levels of climate politicisation. Romania’s low political polarization enabled technocratic and modest EGD adoption, while Poland’s fossil fuel dependence, conservative values and partisan conflict led to the weakest ambition. The study highlights how politicisation within party competition critically influences national EGD commitments, especially where populism and entrenched economic interests interplay.

Together, the nine articles in this Special Issue demonstrate that just and effective transitions demand more than technological innovation or policy relying on the alignment of systems across time. By integrating conceptual and empirical analysis, the collection advances the understanding of how tipping dynamics can be identified, leveraged, and navigated.

#### 4. Cross-cutting themes in the special issue

##### 4.1. Theoretical advances

The JSETS framework (Lieu et al., 2025), the Triple Embeddedness Framework operationalizing tipping points (Maier et al., 2024), the heuristic framework for anticipating tipping points (Mey, Mangalagiu and Lilliestam, 2024), as well as the integrative framework combining social-ecological and socio-technical systems' change (Biddau et al., 2024) provide diagnostic frameworks for assessing transition states, pace, and the feedback mechanisms. They provide insights on areas that need targeted tipping interventions – intended to the dissolution of attractors of the dominant state and the emergence or stabilization of new ones – for triggering cascading dynamics toward tipping sectors and larger regional systems. These frameworks move beyond binary or abrupt notions of tipping point, instead conceptualising transitions as gradual, multi-phase processes shaped by context-specific enablers. Justice, narrative framing and the alignment of socio-political and cultural systems are central to enabling the momentum. Together the contributions highlight the need for place-sensitive, timely and well-targeted approaches in complex systems.

##### 4.2. Methodological advances

The collection introduces a variety of mixed methods approaches that are tailored for sustainability transitions research. Lieu et al. (2025) and Mey, Mangalagiu and Lilliestam (2025) develop frameworks, which use standardized indicators – such as policy coherence scores and narrative polarization indices – to measure the strength of transition enablers and barriers over time and assess proximity to tipping points. Martinez-Reyes et al. (2024) combine fs-QCA with case study validation to identify how different local conditions shape pathways to energy affordability. Biddau et al. (2024) blend participatory workshops and narrative interviews with media and policy analysis to uncover underlying cultural lock-ins reinforcing path-dependent patterns. Long-term case studies are used in Biddau et al. (2024), Mey, Weik and Lilliestam (2024) and Todor et al. (2025) to track how policy sequencing and narrative shifts influence transition trajectories. Ruhr's 30-year timeline offers a clear example of how to analyse path dependencies and the effects of sequential policy change.

##### 4.3. Empirical advances

Empirically, the special issue delivers the most comprehensive inquiries of transitions in CCIRs to date, drawing on a variety of contexts in 20+ regions. The development and pace of transitions is constrained or favoured by uncontrolled contextual factors such as the local availability of energy resources, innovations, or global market changes, but also heavily shaped by informal and formal multi-level governance, including policies at the national and international levels. In CCIRs, fossil-fuel sectors generate socio-economic path dependencies – in the form of sunk costs, overreliance on limited power sources or economic sectors, and technology competitiveness – that can impede or slow-down a transition. Besides finding techno-economic alternatives to transition or replace a sector, CCIRs interestingly require addressing energy injustices to overcome socio-economic path-dependencies while promoting prosperity in the region. This compendium of comparative analyses and case studies offers multiple combinations of CCI sectors, contextual factors, governance approaches, and transition trajectories in Global South and North regions. This rich collection of real-world cases provides a more nuanced understanding of transitions and identifies hints of socio-technical tipping points in coal and carbon intensive regions across the world. Across cases, transitions are shown to unfold not through sudden ruptures – rather shocks and disruptive events are typically accommodated – but via incremental adjustments shaped by landscape pressures and the uneven alignment of diverse system

elements (Biddau et al., 2024; Mey, Mangalagiu and Lilliestam 2024; Mey, Weik and Lilliestam; Witajewska-Baltvilka et al., 2024). Job dependency, energy security concerns, limited readiness of alternative infrastructures, as well as institutional inertia, incumbent resistance and a lack of political action significantly contribute to the slow onset of destabilisation.

##### 4.4. Justice as a direction, catalyst, and constraint

CCI sectors have been embedded in, or directly contributed to, unjust systems. Therefore, their transition will remain unjust unless justice is explicitly addressed. In CCIRs, addressing justice is not only a normative requirement, but an essential part to ensure the transition is leading to the region's wellbeing. Following this line of thought, the JSETS framework introduced by Lieu et al. (2025) operationalize justice across transition states and thus conceptualises transformations not only in terms of industrial decarbonisation, but also in terms of justice progress. Particularly, four articles (Biddau et al., 2024; Martinez-Reyes et al., 2024; Todor et al., 2025; Lieu et al., 2025) demonstrate that procedural and distributive justice are prerequisites for legitimacy yet rarely prioritized in policy design and underscore justice as both a driver and barrier. Sulcis' case (Biddau et al., 2024) exemplifies how place-based identities and meanings can marginalize alternative visions beyond extractive economies, but also that just transition planning needs to account for restorative justice, remediating historical injustices and restoring the dignity of places turned into 'sacrifice zones'. Energy affordability (Martinez-Reyes et al., 2024) reveals that procedural justice – ensuring marginalized groups shape policy – is as critical as distributive outcomes.

##### 4.5. Multi-scale dynamics

Findings across the collection show that successful transitions require stronger coordination across different levels of governance. Mey, Mangalagiu and Lilliestam (2024), Mey, Weik and Lilliestam (2024) and Witajewska-Baltvilka et al. (2024) demonstrate that aligning local narratives with national and international policies is important for building support and ensuring policy effectiveness. This includes both vertical coordination – between local, national, and international levels – and horizontal coordination across sectors such as energy, finance, and social policy. Martinez-Reyes et al. (2024) and Monasterolo et al. (2024) highlight that efforts to improve energy affordability and implement green financial instruments (GFSIs) depend on integrated governance. When integration and coordination is lacking, transitions face delays and obstacles. For example, Germany's fragmented EV policies (Mey, Mangalagiu and Lilliestam, 2024) and Romania's limited enforcement of EU funding programs (Todor et al., 2025) illustrate how mismatches in governance scales can reinforce existing lock-ins.

##### 4.6. Nonlinear tipping processes

While abrupt SETPs remain elusive (Mey, Weik and Lilliestam, 2024; Lieu et al., 2025), the collection reveals that tipping often unfolds through cumulative, multidimensional enablers rather than sudden thresholds. Targeted interventions – such as Norway's coordinated EV policies – can align system elements and reinforce feedback loops, consolidating the new direction (Mey, Mangalagiu and Lilliestam, 2024). Other cases (Biddau et al., 2024; Maier et al., 2024) show that tipping momentum may build through narrative shifts, institutional sequencing, and the gradual erosion of lock-ins, underscoring the importance of timing, framing and cross-sector alignment.

##### 4.7. Narratives and imaginaries

Narratives play a crucial role in shaping responses to change, as seen through the influence of place-based meanings mobilized (Biddau et al.,

2024) and policy discourses (Todor et al., 2025; Witajewska-Baltvilka et al., 2024). Biddau et al. (2024), Mey, Weik and Lilliestam (2024), and Witajewska-Baltvilka et al. (2024) highlight how the tension between industrial nostalgia and green modernity shapes the legitimacy of transition efforts. Ruhr's gradual transformation (Mey, Weik and Lilliestam, 2024) and Hungary's Fidesz party instrumentalization of coal nationalism to resist decarbonization (Witajewska-Baltvilka et al., 2024) demonstrate the impact of future-oriented storytelling.

#### 4.8. Policy implications

The collection provides a range of cross-cutting policy insights to support more effective, just, and context-sensitive climate transitions in CCIRs. A recurring theme is the need for tailored interventions that account for regional diversity, transition stages, and socio-cultural dynamics. Several studies emphasize that justice – through inclusive decision-making, equitable distribution of burdens and benefits, and recognition of marginalized communities – must be embedded in all transition policies. Monasterolo et al. (2024) and Lieu et al. (2025) call for coordination across governance levels, highlighting the need for both top-down policy frameworks and bottom-up engagement strategies. Meanwhile, Martinez-Reyes et al. (2024) and Mey, Weik and Lilliestam (2024) argue for a broader focus beyond technology, incorporating material infrastructure, legitimacy, and political will to trigger or accelerate socio-technical tipping points. Biddau et al. (2024) stresses the importance of creating local narratives that align with community identities and histories, as an initial approach to address psychosocial lock-ins. Financial and institutional mechanisms also emerge as critical levers. Mey, Weik and Lilliestam (2024), Martinez-Reyes et al. (2024) and Monasterolo et al. (2024) explore the need to align green financial instruments with broader economic tools, such as carbon pricing and public procurement standards, while ensuring effective oversight to avoid greenwashing. Maier et al. (2024) and Todor et al. (2025) highlight the importance of empowering local actors, supporting off-stream innovation, and sequencing interventions thoughtfully to break path dependencies without creating undue hardship. Finally, Witajewska-Baltvilka et al. (2024) emphasizes the role of political dynamics in shaping climate policy outcomes, calling for strategies that build cross-party consensus and support civil society in polarized contexts.

Together, these findings advocate for integrated, participatory, and adaptive policy approaches that bridge technical, economic, cultural, and political domains to enable sustainable and equitable transitions.

#### 5. Conclusions

The Special Issue advances the understanding of sustainability transitions and SETPs in regions that depend or have depended on fossil-fuel sectors by following inductive case-based research processes. By bridging socio-technical and socio-ecological perspectives, this collection of studies equips policymakers and researchers with frameworks and regional lessons to navigate the complexities of CCIRs' transformations. We advanced concepts, methods, and frameworks to understand sustainable transitions in CCIRs. The studies contributed with empirical studies that describe how material elements (industry and infrastructure) and social dynamics (political, socio-economic, and cultural frames) and discourses interact and influence transition pathways for CCIRs. Key characteristics of SETPs in CCIRs identified are sustainability transition states, gradual changes, multiscale influence, non-linearity, and the strong socio-economic path dependencies rooted in coal and carbon intensive sectors. We reframe sustainability transitions as contextually embedded, justice-centred, and narrative-driven processes. Overall, the collection draws lessons and implications from past and recent experiences – not only of success but also of failure. These lessons help explain why visions, governance arrangements or community strategies did or did not bring the expected change.

Future research should further investigate the temporal dynamics of

sustainability transitions, particularly the role of delayed feedback loops in shaping tipping potential. As highlighted in Maier et al. (2024) and Mey, Weik and Lilliestam (2024), infrastructure investments – such as Ruhr's gas network – can create long-term lock-ins, with effects unfolding over decades. Understanding how such temporal lags interact with socio-technical enablers and barriers is critical for timing interventions effectively. Further exploration of the non-linear effects of justice measures on transitions is also needed. For instance, Biddau et al. (2024) show how participatory processes in Sulcis initially slowed progress but ultimately weakened dominant narratives and identities and fostered consensus and legitimacy, suggesting that justice-oriented policies may have shifting impacts over time.

Another promising direction for future research lies in the role of digital tools and new governance approaches. Agent-based models, Machine Learning and AI tools could help simulate how narratives spread within and across regions, how the sequencing of phase-out and phase-in policies interacts or shapes actor reorientation, or how different groups might react to policy changes – especially in polarized contexts like those described in Witajewska-Baltvilka et al. (2024). Such approaches can also be used to test how different strategies might accelerate or delay tipping dynamics, giving policymakers a better sense of where to focus their efforts. Beyond modelling, the design and implementation of Just Transition Plans and Roadmaps could benefit from experimental and participatory-action research testing the transformative potential of deliberative democratic innovations like climate assemblies in supporting transition in the making, and allowing to address procedural, epistemic, and restorative justice considerations complementing distributive ones. At the same time, there's a growing need to study post-growth-focused transition models. The JSETS framework (Lieu et al., 2025) hints at more post-consumerist or post-growth visions, but examples of a post-growth focus in the energy domain are still needed to understand how these ideas might play out in practice. Exploring how communities engage with these visions or respond to these alternative pathways could help broaden one's understanding on designing fairer and more sustainable transitions.

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