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Cascading Lock-Ins in the Energy Transition of Post-Mining Regions: Towards an Integrated Governance Framework

Olga Janikowska [1,*], Agnieszka Generowicz [2,*] and Joanna Kulczycka [3]

[1] Mineral and Energy Economy Research Institute of the Polish Academy of Sciences, Wybickiego 7A Str., 31-261 Cracow, Poland
[2] Department of Environmental Technologies, Cracow University of Technology, ul. Warszawska 24, 31-155 Cracow, Poland
[3] Faculty of Management, AGH University of Science and Technology, Mickiewicza 30, 30-059 Cracow, Poland; kulczycka@agh.edu.pl
* Correspondence: olgajan@min-pan.krakow.pl (O.J.); agnieszka.generowicz@pk.edu.pl (A.G.)

Abstract

The energy transition of post-mining regions requires not only the replacement of fossil fuel-based technologies but also the restructuring of infrastructures, institutions, labour markets, local economies and social relations shaped by mining and conventional energy production. This article develops a conceptual framework of cascading lock-ins through a critical literature review and conceptual synthesis of research on path dependence, carbon lock-in, socio-technical transitions, just transition and regional governance. The framework distinguishes infrastructural, technological, institutional and social lock-ins and examines the mechanisms through which constraints are transmitted and reinforced across these domains. Cascading is defined as a context-dependent process in which a mechanism operating in one domain changes the incentives, capabilities, decisions or expectations in another, potentially generating cumulative effects and feedback. The main contribution of this study lies in shifting attention from the classification of individual barriers to the cross-domain transmission mechanisms through which they reproduce regional transition inertia. The conceptual synthesis suggests that addressing cascading lock-ins requires coordinated interventions linking infrastructural modernisation, technological and economic diversification, institutional reform, skills development and meaningful community participation.

Keywords: post-mining regions; energy transition; cascading lock-ins; path dependence; transition governance

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Academic Editor: Jay Zarnikau

Received: 8 July 2026
Revised: 5 August 2026
Accepted: 17 August 2026
Published: 18 August 2026

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1. Introduction

1.1. Context and Motivation

The energy transition of post-mining regions requires a fundamental restructuring of regional development systems rather than merely replacing fossil fuel-based technologies with renewable energy sources. Decades of mining and conventional energy production have shaped technical infrastructure, economic specialisation, labour markets, institutional arrangements, spatial development and regional identities. Mine closures, land reclamation and the deployment of low-carbon technologies therefore constitute only selected components of a broader territorial transformation [1,2]. This transformation requires the coordinated reconfiguration of infrastructures, economic activities, institutions and social relations historically organised around the mining-energy system [2,3].

Post-mining regions represent a distinct type of transition territory because their present development conditions reflect long-term reliance on mining and conventional energy [1,4]. Mining performed not only a productive function but also a structure-forming role by shaping settlement patterns, transport and energy networks, vocational education, public institutions, labour markets and regional identities [2,4,5]. The phase-out of fossil fuels therefore disrupts an established territorial configuration rather than affecting the energy sector alone [2,4,6].

However, the mining-energy legacy should not automatically be equated with path dependence or lock-in. It becomes a source of path-dependent persistence only when it is reproduced through self-reinforcing mechanisms such as sunk costs, increasing returns, long asset lifetimes, technological compatibility, specialised competences, institutional routines, vested interests and adaptive expectations [5,7–10].

1.2. Review of Previous Work

Previous research has identified numerous barriers to the transition of post-mining regions, including infrastructure modernisation costs, the persistence of carbon-intensive technologies, limited economic diversification, skills mismatches, institutional fragmentation, employment dependence and social conflict [2,4–6,9,10].

Path dependence research explains how earlier decisions constrain later alternatives through self-reinforcing processes [7,8], while the carbon lock-in literature emphasises the persistence of interconnected fossil fuel-based technologies, infrastructures and institutions [9,10]. Socio-technical transition studies examine the stability and transformation of regimes composed of technologies, rules, actors and practices [11–14]. Just transition research focuses on employment, distribution, recognition, participation and social legitimacy [3–6,15,16], whereas regional governance studies highlight the need for coordination across sectors, actors and levels of government [17–19].

Taken together, these approaches provide essential explanations of transition persistence, but they do not always specify how a constraint originating in one domain is transmitted to another part of a post-mining regional system [10,14]. Existing studies often identify infrastructural, technological, institutional and social constraints as parallel or mutually reinforcing conditions without clearly distinguishing coexistence, directional transmission and feedback. As a result, it remains difficult to explain how individual constraints accumulate, why interventions in one domain may be weakened by dependencies operating in another, and which governance responses should address the mechanisms connecting them.

Against this background, the aim of this article is to develop a conceptual framework of cascading lock-ins in the energy transition of post-mining regions. The main question of research is as follows:

Through which mechanisms are lock-ins transmitted and reinforced across different domains of post-mining regional systems?

In this study, cascading refers to a context-dependent process in which a self-reinforcing mechanism operating in one domain changes the incentives, capabilities, decisions or expectations in another domain, thereby producing an additional constraint or strengthening an existing lock-in. Cascading is therefore distinguished from coexistence, which denotes the simultaneous presence of several constraints, and from interaction, which refers to mutual influence without a clearly identifiable direction. Feedback occurs when an outcome generated in one domain subsequently reinforces the originating mechanism or another earlier component of the regional system.

The framework does not assume a universal sequence beginning with infrastructural lock-in. Infrastructure may influence technological choices through sunk costs, asset life-

times and compatibility requirements, but alternative starting points are also possible. Institutional arrangements, financing systems, technological standards, employment dependence or social opposition may initiate or intensify cross-domain transmission. The direction and strength of these relationships depend on regional conditions and must therefore be established analytically or empirically rather than assumed in advance.

The contribution of the framework lies not in identifying new categories of lock-in, but in providing a relational structure for analysing how familiar forms of dependence are transmitted and accumulated across domains. It distinguishes a source mechanism, a transmission pathway, a reinforcing outcome and, where applicable, a feedback effect. This approach helps explain why apparently separate barriers may generate cumulative regional inertia and why isolated technological, infrastructural or social interventions may produce limited results.

The framework also provides a more explicit basis for deriving governance implications. Coordinated intervention is required where a source mechanism, transmission pathway and reinforcing outcome extend across different policy sectors or levels of government. Integrated, polycentric and deliberative governance are therefore treated not as universally effective solutions, but as conditional arrangements whose usefulness depends on clear responsibilities, coordination mechanisms, accountability and procedures for managing conflicts among infrastructure modernisation, economic diversification, institutional reform, employment protection and community participation [17–20].

The remainder of this article is organised as follows. Section 2 presents the literature review procedure and conceptual model-development process. Section 3 discusses path dependence in post-mining regional systems. Section 4 distinguishes transition barriers, lock-ins, cross-domain transmission and feedback. Section 5 examines the infrastructural, technological, institutional and social domains. Section 6 synthesises the cascading framework and links specific lock-in mechanisms with governance interventions and trade-offs. Section 7 presents the conclusions, limitations and directions for future research.

2. Materials and Methods

2.1. Research Design

This study is conceptual and analytical in character. Its purpose is not to present original empirical field research, but to develop a theoretical framework for analysing how different forms of lock-in are transmitted and reinforced across post-mining regional systems. The study combines a critical literature review with conceptual synthesis and theory-building.

A critical review approach was selected because the research problem extends across several partially overlapping fields, including path dependence, carbon lock-in, socio-technical transitions, just transition, regional development and transition governance. The objective was not to produce an exhaustive or statistically representative inventory of publications, but to identify, compare and critically interpret the concepts and self-reinforcing mechanisms used to explain the persistence of fossil fuel-based regional trajectories.

The analytical procedure consisted of five stages:

1. Identification and reassessment of the literature corpus;
2. Extraction of self-reinforcing mechanisms;
3. Classification of mechanisms into analytical domains;
4. Identification of cross-domain transmission pathways and feedback effects;
5. Conceptual synthesis and development of the cascading lock-in framework.

The methodological procedure applied in the study is presented in Figure 1.

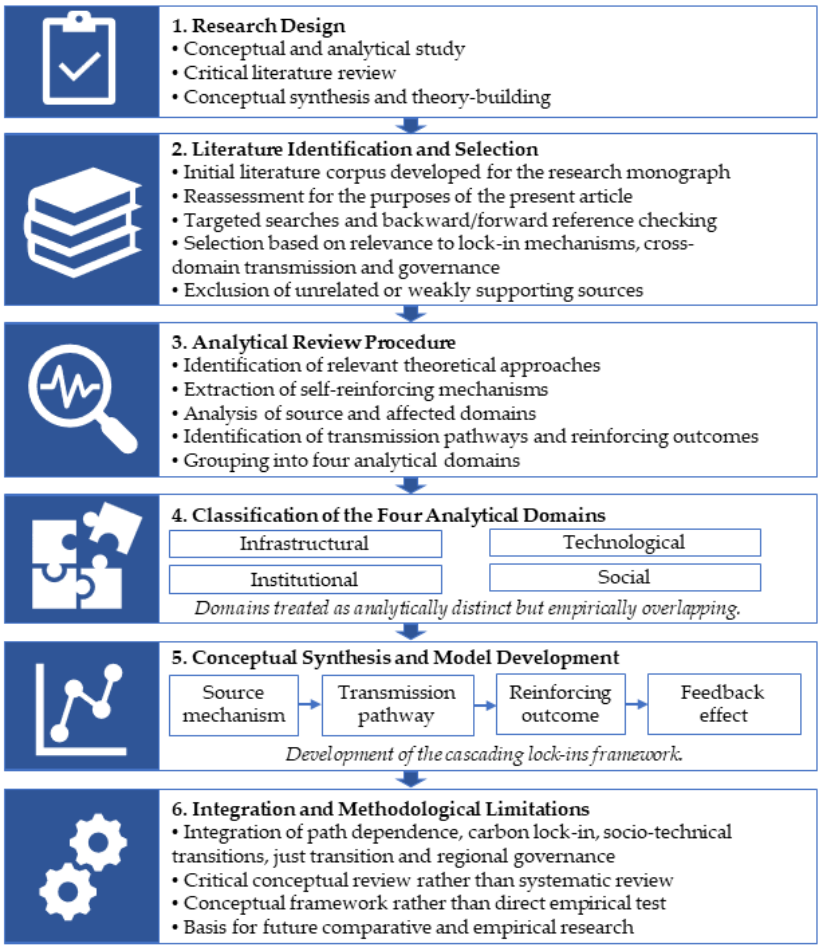

Figure 1. Methodological procedure applied in the development of the cascading lock-in framework.

2.2. Literature Identification and Selection

The literature corpus was developed iteratively over approximately six months during the preparation of a broader research monograph on the energy transition of post-mining regions. Literature identification formed part of an extended conceptual research process rather than a single systematic search conducted specifically for the present article. The corpus included foundational theoretical contributions, review articles, empirical studies, comparative analyses, regional case studies and selected policy-oriented reports concerning path dependence, carbon lock-in, socio-technical transitions, just transition, post-mining and coal-dependent regions, regional development and transition governance.

Relevant publications were identified through repeated searches in Scopus, Web of Science and Google Scholar, as well as through backward reference checking of bibliographies and forward citation searching for the most relevant and foundational studies. The searches used combinations of terms such as “post-mining regions”, “coal-dependent regions”, “energy transition”, “just transition”, “path dependence”, “carbon lock-in”, “socio-technical transitions”, “regional governance”, “polycentric governance” and “deliberative governance”. The search process was iterative: additional concepts and publications were included as relationships among infrastructural, technological, institutional and social forms of dependence emerged during the preparation of the monograph.

For the purposes of the present article, the accumulated literature corpus was reassessed and narrowed according to its relevance to the research question. Particular attention was paid to publications that identified self-reinforcing mechanisms, relationships between analytical domains, cross-domain transmission pathways or feedback effects. The aim was not to reconstruct the complete literature-search history of the monograph or

to produce an exhaustive and statistically representative database of publications, but to select and critically synthesise the sources that directly supported the development of the cascading lock-in framework.

Sources were retained where they contributed directly to at least one of the following analytical areas:

1. Path dependence and self-reinforcing lock-in mechanisms;
2. Carbon lock-in and the persistence of socio-technical regimes;
3. The transformation of post-mining and coal-dependent regions;
4. Employment dependence, identity, justice, trust and social legitimacy;
5. Regional, multi-level, polycentric or deliberative governance;
6. The reuse and reconfiguration of post-mining infrastructure and territorial assets.

Publications were excluded for the following reasons:

1. Focused exclusively on individual technologies, materials or engineering processes without examining regional transition persistence;
2. Addressed environmental impacts of mining without analysing transition mechanisms;
3. Did not provide sufficient conceptual or empirical detail to identify self-reinforcing mechanisms;
4. Did not contribute directly to the analysis of cross-domain relationships, feedback effects or governance implications;
5. Duplicated other publications or did not directly support the claims developed in the manuscript.

The final analytical corpus comprised 43 publications, including foundational theoretical studies, review articles, empirical regional case studies, comparative analyses and selected policy-oriented reports. Because the literature had been accumulated iteratively during the broader monograph research process, the review did not use a fixed initial number of database records or a PRISMA-type selection procedure. Its purpose was instead to identify, compare and synthesise the mechanisms most relevant to explaining the transmission and reinforcement of lock-ins across post-mining regional systems.

2.3. Analytical Review Procedure

Within the broader five-stage research design, the publications retained in the analytical corpus were examined through a four-stage analytical procedure. In the first stage, the main theoretical approaches relevant to the persistence and transformation of fossil fuel-based regional systems were identified. These included path dependence, carbon lock-in, the multi-level perspective on socio-technical transitions, just transition and regional transition governance.

In the second stage, the publications were examined for specific self-reinforcing mechanisms through which established regional trajectories are reproduced. These mechanisms included sunk costs, increasing returns, long asset lifetimes, technological compatibility, network effects, learning effects, specialised competences, institutional routines, vested interests, policy fragmentation, employment dependence, adaptive expectations, identity reinforcement and distrust towards transition institutions.

In the third stage, each mechanism was analysed according to the following:

1. Its source domain;
2. The incentives, capabilities, decisions or expectations it affected;
3. The domain in which these effects occurred;
4. The transmission pathway linking the source and affected domains;
5. The reinforcing outcome through which the established regional trajectory was reproduced.

The analysis therefore focused not only on the presence of barriers but also on whether the literature provided a theoretically plausible explanation for how a mechanism operating in one part of the regional system affected another.

In the fourth stage, conceptually related mechanisms were grouped into four analytical domains: infrastructural, technological, institutional and social. The grouping was used to organise overlapping relationships rather than to establish mutually exclusive categories or a predetermined sequence.

2.4. Classification of the Four Analytical Domains

The infrastructural domain included mechanisms related to material assets, energy and transport networks, spatial configurations, land constraints, sunk costs, technical interdependence and long asset lifetimes.

The technological domain included technical standards, compatibility requirements, specialised competences, operational routines, learning effects, supply chains and established technological expectations.

The institutional domain included regulations, financing arrangements, organisational routines, vested interests, divisions of responsibility, policy fragmentation and administrative procedures.

The social domain included employment dependence, economic insecurity, occupational and regional identity, distributive concerns, expectations, recognition, trust and social acceptance.

The four domains were not treated as fully separate. Where a mechanism could operate across more than one domain, it was classified according to its principal function in the relationship described by the analysed publication. Skills, for example, may function as technological capabilities, institutional outcomes or social resources depending on the context.

Economic and political mechanisms were not excluded from the framework but were treated as cross-cutting. Sunk costs, investment risks and financing arrangements were analysed within the infrastructural, technological or institutional domains, whereas employment dependence was considered within the social domain. Political mechanisms were examined through institutional arrangements, vested interests, authority structures and feedback generated by social pressure.

2.5. Conceptual Synthesis and Model Development

The cascading lock-in framework was developed iteratively from the relationships identified in the literature rather than by imposing a predetermined sequence on the reviewed studies.

The analysis distinguished four elements:

1. A source mechanism operating within a particular domain;
2. A transmission pathway through which this mechanism affects another domain;
3. A reinforcing outcome that increases the persistence of the established regional trajectory;
4. A feedback effect through which the outcome may subsequently reinforce the originating mechanism or another earlier dependency.

For example, sunk costs and long infrastructure lifetimes may favour technologies compatible with existing systems. These technologies may subsequently become embedded in regulations, financing arrangements, professional competences and administrative procedures. Institutional arrangements may then influence employment structures, education systems and social expectations. Social concerns, political pressure or distrust may subsequently affect institutional and investment decisions, thereby reinforcing earlier technological or infrastructural dependencies.

The coexistence of several constraints was not treated as sufficient evidence of a cascade. A cascading relationship was retained in the framework only where the reviewed literature provided a theoretically plausible explanation for how a mechanism in one domain changed incentives, capabilities, decisions or expectations in another.

The framework therefore does not assume a universal sequence beginning with infrastructural lock-in and ending with social lock-in. The starting point, direction, intensity and duration of a cascade may vary depending on the historical development trajectory, economic structure, infrastructure adaptability, institutional capacity, political context, labour market conditions and the availability of credible alternative development pathways.

2.6. Integration of Theoretical Perspectives

The framework integrates insights from several research traditions while preserving their distinct explanatory contributions.

Path dependence research explains how earlier choices constrain later alternatives through self-reinforcing mechanisms. Carbon lock-in and socio-technical transition studies clarify the persistence of interconnected technologies, infrastructures, institutions, actors and user practices. Just transition literature contributes an understanding of employment, distribution, recognition, participation and social legitimacy. Regional governance approaches explain the need for coordination across actors, policy sectors and levels of government.

The purpose of the synthesis was not to replace these approaches or to propose new categories of lock-in. Its added analytical value lies in tracing how mechanisms identified in these areas of the literature are transmitted across domains within post-mining territorial systems and how they generate cumulative constraints and feedback effects.

2.7. Methodological Limitations

The adopted method has several limitations. First, the study is based on a critical conceptual review rather than a systematic review or meta-analysis. It therefore does not claim to provide an exhaustive or statistically representative account of all research on post-mining transitions.

Second, the literature corpus was initially developed during broader research on the energy transition of post-mining regions and was subsequently reassessed for the specific purpose of this article. The selection and interpretation of publications were therefore guided by the conceptual objective of identifying self-reinforcing mechanisms and cross-domain relationships. This introduces an interpretive element into the review and limits full reproducibility.

Third, the proposed framework is conceptual and does not constitute a direct empirical test of causal relationships among the four lock-in domains. The reviewed studies differ in geographical scope, terminology, research design and level of analysis, which limits the possibility of establishing one configuration applicable to all post-mining regions.

Fourth, some mechanisms operate across more than one analytical domain. The four domains should therefore be treated as relational and overlapping categories rather than as fully separate components.

Future research should empirically test the framework through comparative case studies, process tracing, expert interviews, document analysis and longitudinal regional assessments. Such studies could examine which mechanisms dominate in particular regions, under what conditions cross-domain transmission and feedback emerge, and how cascading lock-ins can be interrupted, redirected or reversed.

3. Post-Mining Regions as Territories of Path Dependence

Post-mining regions can be understood as path-dependent territories whose current development opportunities are shaped by earlier economic, infrastructural, technological and institutional choices. Their present structures are not simply the consequences of mine closure, but the outcome of decades during which urbanisation, industrial development, labour markets, education systems and spatial planning were organised around mining and conventional energy production [1,2,4,5]. Mining therefore performed not only a productive function but also a structure-forming role by concentrating investment, employment, infrastructure, competences, public institutions and regional identities around a resource-based development model [3–6].

These regions should not be treated solely as areas where extraction has ended or as sites requiring environmental reclamation. They are territorial systems in which the mining-energy legacy continues to influence land use, infrastructure, economic activity, institutional arrangements and social relations [1–5]. Mines, power plants, district-heating systems, transport connections and energy networks formed interconnected configurations whose components were adapted to one another over time [9,10,18]. Although this configuration supported the stability of the fossil fuel-based development model, it also reduced the flexibility of regions seeking alternative economic and energy pathways [4,9,10].

Path dependence should be distinguished from historical legacy, sectoral dependence and lock-in. Historical legacy refers to the material and immaterial structures inherited from the past, including infrastructure, competences, institutional routines, spatial arrangements and social identities. Sectoral dependence refers to the current reliance of employment, income, public revenues or regional production on a particular industry. Path dependence, by contrast, is a dynamic process in which earlier decisions continue to shape later alternatives through self-reinforcing mechanisms. Lock-in denotes a condition in which these mechanisms substantially reduce the feasibility, attractiveness or legitimacy of alternative development pathways [7–10].

In post-mining regions, path dependence may be reproduced through sunk costs, increasing returns, long asset lifetimes, technological compatibility, network effects, specialised competences, institutional routines, vested interests and adaptive expectations [5,7–10]. These mechanisms make established solutions easier to reproduce while increasing the cost, uncertainty or coordination requirements associated with alternative trajectories.

Material infrastructure is one of the principal carriers of path dependence. Energy and industrial assets are capital-intensive, interconnected and characterised by long service lives. Once established, they influence subsequent investment decisions because new projects must either remain compatible with existing systems or bear the costs of modification, conversion or replacement [9,10,18]. This may favour incremental adaptation, particularly where grid limitations, remediation costs, technical risks or restricted access to capital reduce the feasibility of alternative solutions [2,4,18].

Economic specialisation constitutes another self-reinforcing mechanism. The long-term concentration of employment, suppliers, capital and public revenues around mining and conventional energy may support regional stability during periods of sectoral growth, but it creates vulnerability during phase-out. Limited diversification reduces the availability of alternative employment and weakens the capacity of the regional economy to absorb workers, competences and assets released by declining industries [3–5]. This may generate political and institutional pressure to prolong the operation of existing facilities or preserve elements of the established development model [3–6].

Path dependence also has institutional and socio-cultural dimensions. Public policies, financing systems, vocational education, administrative procedures and regional governance arrangements were often developed in close connection with mining and con-

ventional energy. These arrangements may continue to favour established actors, familiar technologies and sector-specific solutions even when formal policy objectives support decarbonisation [4,5,9,10]. At the same time, mining employment may be associated with the occupational status, collective memory, community institutions and regional identity [3,5,6]. Where transition strategies fail to provide credible alternatives or recognise these social meanings, concerns about employment, recognition and distributive justice may reduce trust and strengthen resistance to change [3,5,6,15,16].

Path dependence does not imply determinism. The mining-energy legacy may constrain transformation, but inherited sites, infrastructure and technical competences may also provide resources for alternative development pathways. Their capacity to support new economic and energy functions depends on their technical adaptability, institutional support, financing conditions and integration into broader regional development strategies [1,2,4,18].

Whether inherited structures reinforce dependence or enable transformation depends on the mechanisms through which they are governed and reconfigured. Policies that address individual assets without considering their technological, institutional, economic and social relationships may reproduce the established trajectory. Coordinated interventions may instead alter the incentives, capabilities and expectations that sustain path dependence [2,4,17–19]. This provides the conceptual basis for distinguishing ordinary transition barriers from specific lock-ins and for analysing how constraints are transmitted across domains.

4. From Transition Barriers to Cascading Lock-Ins

Research on the energy transition of post-mining regions has identified numerous barriers, including infrastructure constraints, high investment costs, technological rigidity, limited economic diversification, skills mismatches, institutional fragmentation, social resistance and concerns about employment security [2–6,9,10]. Although this perspective is useful for identifying the principal difficulties of transition, it provides only a limited explanation for why these difficulties persist, accumulate and re-emerge despite the introduction of new technologies, funding programmes and policy instruments.

A barrier may delay change, increase its cost or reduce the feasibility of a particular intervention. A lock-in is more persistent because it is reproduced through self-reinforcing mechanisms that stabilise an established development trajectory. Such mechanisms may include sunk costs, increasing returns, long asset lifetimes, technological compatibility, network effects, specialised competences, institutional routines, vested interests, adaptive expectations and social dependence on the existing system [5,7–10]. Not every barrier therefore constitutes a lock-in. A lock-in exists where the conditions constraining alternatives are actively reproduced over time.

The concept of cascading lock-ins extends this distinction by focusing on how self-reinforcing constraints are transmitted across different parts of a regional system. In this study, cascading refers to a directional process in which a mechanism operating in one domain changes the incentives, capabilities, decisions or expectations in another domain, thereby creating an additional constraint or reinforcing an existing lock-in. A cascading relationship therefore consists of three elements: a source mechanism, a transmission pathway and a reinforcing outcome.

Cascading should be distinguished from coexistence and interaction. The simultaneous presence of infrastructure constraints, institutional fragmentation and low social acceptance does not in itself demonstrate a cascade. Interaction indicates that two domains influence one another, but it does not necessarily establish the direction or mechanism of that influence. A cascade can be identified only where a plausible transmission pathway explains how a mechanism in one domain affects another. The conceptual distinction

between an ordinary transition barrier, a self-reinforcing lock-in and cascading lock-ins is illustrated in Figure 2. Brief regional examples illustrate how the framework can be applied. In the Rhineland lignite district, long-term economic and employment dependence on lignite can be interpreted as a source mechanism that strengthens the position of incumbent actors and established development priorities. This dependence is transmitted into the institutional domain through contested decision-making, competing stakeholder interests and difficulties in coordinating regional transition measures. The resulting uncertainty and limited trust may weaken social acceptance of the transition, thereby reinforcing political pressure to preserve existing structures. This creates a possible feedback effect in which social resistance and institutional fragmentation further delay economic diversification and prolong dependence on the lignite-based regional pathway [4].

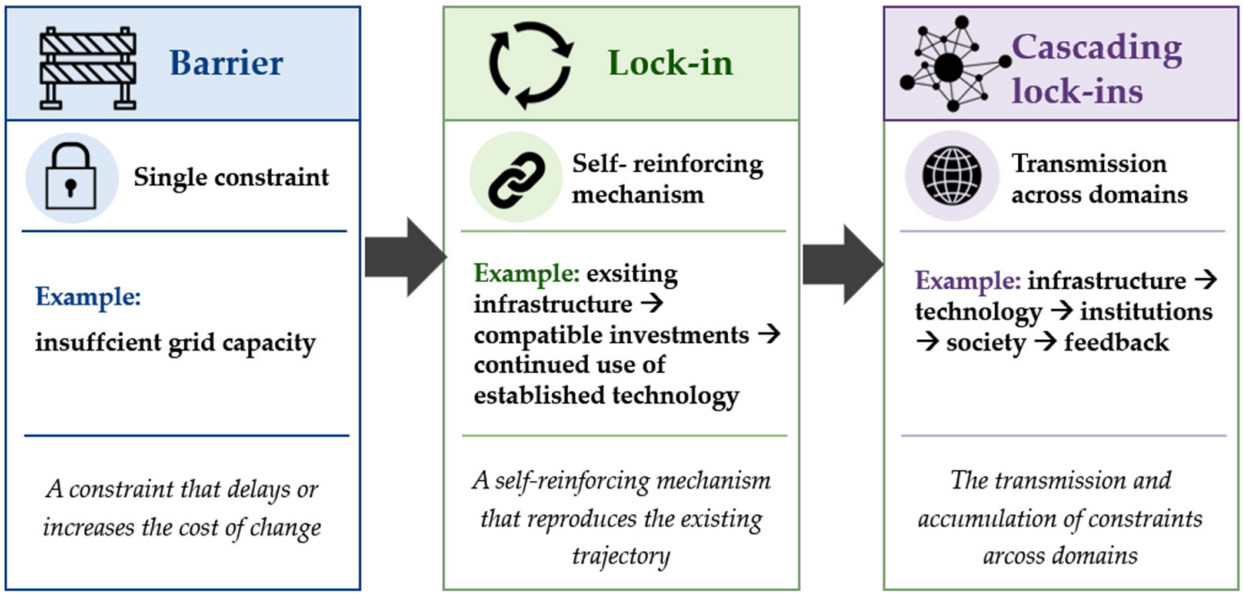

Figure 2. Conceptual distinction between a transition barrier, a self-reinforcing lock-in and cascading lock-ins.

A related pathway can be observed in the coal-dependent regions of Western Macedonia, Silesia and Stara Zagora. Comparative research indicates that insufficient stakeholder involvement can weaken local understanding, ownership and legitimacy of transition policies. Within the proposed framework, limited participatory capacity constitutes an institutional source mechanism that is transmitted into the social domain through inadequate recognition of local needs and expectations. The resulting distrust and reduced acceptance may obstruct the implementation of new economic and technological alternatives, which in turn reinforces institutional centralisation and continued dependence on established regional structures [2]. These examples represent cascading relationships because one lock-in mechanism contributes to the reproduction of another domain, rather than several barriers merely occurring simultaneously.

For example, infrastructure designed around centralised fossil fuel-based energy systems may favour technologies compatible with existing assets and networks. These technological choices may subsequently become embedded in regulations, financing arrangements, professional competences and administrative procedures. Institutional arrangements may then influence employment structures, vocational education, regional development priorities and social expectations. Concerns about employment, economic security or procedural fairness may subsequently generate political pressure to delay restructuring or preserve elements of the established system [3–6,9,10,18].

Such relationships may develop into feedback loops. Feedback occurs when an outcome produced in one domain subsequently reinforces the originating mechanism or another earlier dependency. Institutional support for established technologies may justify further investment in existing infrastructure, while social opposition may encourage public authorities to postpone institutional or technological change. Directional transmission and feedback are therefore analytically distinct: the former describes how a constraint moves across domains, whereas the latter describes how later effects reinforce earlier elements of the system.

The framework does not assume a universal sequence beginning with infrastructural lock-in. Infrastructure may be the dominant source of persistence where networks, industrial assets or district-heating systems strongly constrain technological alternatives. In other regions, however, institutional arrangements, financing systems, technological standards, labour-market dependence or political commitments may initiate the cascade. Its starting point, direction and intensity are therefore context-dependent and must be established analytically or empirically rather than assumed in advance.

This perspective helps explain why isolated interventions may produce limited or temporary effects. Renewable-energy investment may remain constrained not only by grid capacity or land availability, but also by planning regulations, financing procedures, skills shortages, conflicts over land use and low trust in investors [2,4,6,21,22]. Similarly, retraining programmes may fail when they are not connected to actual employment opportunities, economic diversification and institutional support for new sectors [4,5]. The formal availability of transition funds or low-carbon technologies therefore does not necessarily alter the regional trajectory if the mechanisms reproducing dependence remain active in other domains [4,9,10,18].

On this basis, the framework distinguishes four interrelated analytical domains:

1. Infrastructural lock-in, concerning material assets, networks, spatial configurations and technical interdependence;
2. Technological lock-in, concerning established technologies, standards, competences, supply chains and operational routines;
3. Institutional lock-in, concerning regulations, financing arrangements, organisational structures, decision-making practices and divisions of responsibility;
4. Social lock-in, concerning employment dependence, economic insecurity, identity, expectations, trust and social legitimacy.

These domains are analytically distinct but empirically overlapping. Their significance lies not only in their individual persistence but also in the transmission mechanisms through which constraints accumulate and reinforce the established regional trajectory. Section 5 examines the mechanisms operating within and between these four domains in greater detail.

5. Dimensions of the Cascading Lock-In System

The cascading lock-in framework distinguishes four interrelated analytical domains: infrastructural, technological, institutional and social. These domains are not successive stages in a fixed sequence. They represent areas in which self-reinforcing mechanisms may emerge, persist and transmit constraints to other parts of the regional transition system. Their analytical value lies not only in identifying where transition inertia is located but also in explaining how it is reproduced across domains.

5.1. Infrastructural Lock-In

Infrastructural lock-in refers to the persistence of material and spatial systems developed around mining and conventional energy production. In post-mining regions, mines, power plants, district-heating systems, transport networks, energy infrastructure, drainage

facilities and post-extraction sites may form interconnected configurations. Because these systems were developed over long periods and adapted to one another, modifying one component may require changes in several others, thereby increasing transition costs and complexity [9,10,18].

The principal self-reinforcing mechanisms include a high capital intensity, sunk costs, long asset lifetimes, technical interdependence and spatial rigidity. Existing infrastructure affects later investment decisions because new projects must either remain compatible with inherited systems or bear the costs of conversion, replacement or decommissioning. These conditions may favour incremental adaptation and continued use of established assets [7–10].

Infrastructural lock-in also has a territorial dimension. Former mining activity may influence land availability, network routes, settlement structures and the location of economic functions. Land instability, environmental degradation, fragmented ownership and reclamation requirements may further constrain new investment and increase risk [1,2,4].

Infrastructure may transmit constraints to the technological domain through compatibility requirements, operating standards and investment incentives. Where existing networks or installations were designed for conventional technologies, alternative solutions may require system redesign, additional infrastructure or coordinated investment across sectors [9,10,18].

Inherited infrastructure is not necessarily a barrier. Post-industrial sites, networks and underground facilities may provide resources for renewable-energy development, storage, heat recovery or new industrial activities. Whether infrastructure reinforces lock-in or enables transition depends on its adaptability, financing conditions and institutional context [1,2,4].

5.2. Technological Lock-In

Technological lock-in refers to the persistence of established technical solutions, standards, competences, operational routines and business models. In post-mining regions, mining and conventional energy technologies have shaped industrial organisation, professional qualifications, maintenance practices and perceptions of reliable energy production [5,7–10].

The main self-reinforcing mechanisms include learning effects, specialised skills, standardisation, technological compatibility, established supply chains and expectations regarding performance and energy security. Previous investments in knowledge, equipment and routines reduce the perceived attractiveness of alternatives, particularly where new technologies require different competences, organisational models or operating practices [7–10].

Technological lock-in therefore extends beyond physical installations. It also concerns the cognitive and organisational frameworks through which technological options are evaluated. Where regional development has historically been associated with large industrial facilities and centralised generation, distributed or flexible solutions may be perceived as less reliable or inconsistent with established regional capabilities [7–14].

Technological choices may transmit lock-in to the institutional domain when established solutions become embedded in regulations, financing arrangements, procurement practices, technical standards and education systems. Institutional support may then reinforce technological persistence by favouring familiar solutions and established actors [8–10,15,23,24].

Technological diversification therefore requires more than the installation of individual low-carbon technologies. It depends on the development of alternative capabilities, demonstration projects, new supply chains, reskilling and institutions capable of supporting experimentation and diffusion [11–14].

5.3. Institutional Lock-In

Institutional lock-in refers to regulations, financing arrangements, organisational structures, decision-making practices and divisions of responsibility that reproduce an established development trajectory. In post-mining regions, many institutions were historically developed to support mining, conventional energy and associated employment [2,4,5].

Institutional persistence may result from organisational routines, vested interests, established funding channels, sectoral policy structures and the distribution of authority among public and private actors. Even where formal policy objectives support decarbonisation, existing institutions may continue to favour established beneficiaries, familiar technologies and short-term stability [7,15,17,18,23,25].

Fragmentation is a central mechanism of institutional lock-in. Energy policy, spatial planning, labour-market policy, education, environmental protection, reclamation and regional development are often governed through separate procedures and administrative structures. This may generate inconsistent priorities, unclear responsibility, delayed decisions and weak coordination across levels of government [2,4,17–19,26].

Institutional arrangements also influence technological and social change. Education and labour-market institutions may remain oriented towards declining sectors, while financing and regulatory procedures may favour established technologies. At the same time, unclear responsibilities, limited participation and uncertain protective measures may weaken trust and reinforce social resistance [3–6,17–19,27].

Institutional lock-in may therefore transmit constraints in several directions: towards technology through standards and financing, towards skills through education and training systems, and towards society through the distribution of costs, benefits and decision-making power [8–10,15–19,28].

5.4. Social Lock-In

Social lock-in refers to self-reinforcing forms of economic dependence, identity, expectations and trust that increase resistance to structural change. In post-mining regions, mining often provided not only employment but also income security, occupational status, municipal revenues, community institutions and a basis for regional identity [3–6,29].

Employment dependence is one of its principal mechanisms. Mine closure and the contraction of conventional energy affect direct employees, suppliers, local services, household consumption and public revenues. Where alternative sectors are weak, the risks of transition are immediate and visible, whereas potential benefits remain uncertain [3–5,30].

Identity and recognition also matter. Occupational traditions, collective memory and regional belonging may reinforce expectations that mining-related employment and institutions should be protected. Transition strategies that disregard these meanings may be perceived as a rejection of regional history and social contribution [3,5,6,15,16,31].

Trust constitutes another self-reinforcing mechanism. Social acceptance depends on whether institutions are perceived as competent, transparent and fair and whether transition commitments produce credible employment and investment opportunities. Where previous restructuring programmes failed or decisions are perceived as externally imposed, distrust may become persistent [2,3,6,15,16,20–22,32].

Social lock-in is not merely the final outcome of other dependencies. It may generate feedback effects through public opposition, electoral pressure, industrial conflict or demands for employment protection. These responses may encourage institutions to postpone reforms, maintain transitional technologies or continue investing in established infrastructure [3–6,16,33].

5.5. Cross-Domain Transmission and Feedback

The four domains are analytically distinct but empirically overlapping. A cascading relationship occurs when a mechanism in one domain changes the incentives, capabilities, decisions or expectations operating in another.

Infrastructure may constrain technological choice through compatibility and conversion costs [9,10,18,34]. Technological systems may shape institutional support through standards, financing and skills requirements [8–10,15,23,35]. Institutions may influence employment, education, trust and the distribution of transition costs and benefits [2–6,17–19]. Social responses may subsequently affect political, technological and infrastructural decisions [3,6,15,16,36]. The relationships among the four lock-in domains, the principal transmission mechanisms and their cumulative effects are illustrated in Figure 3.

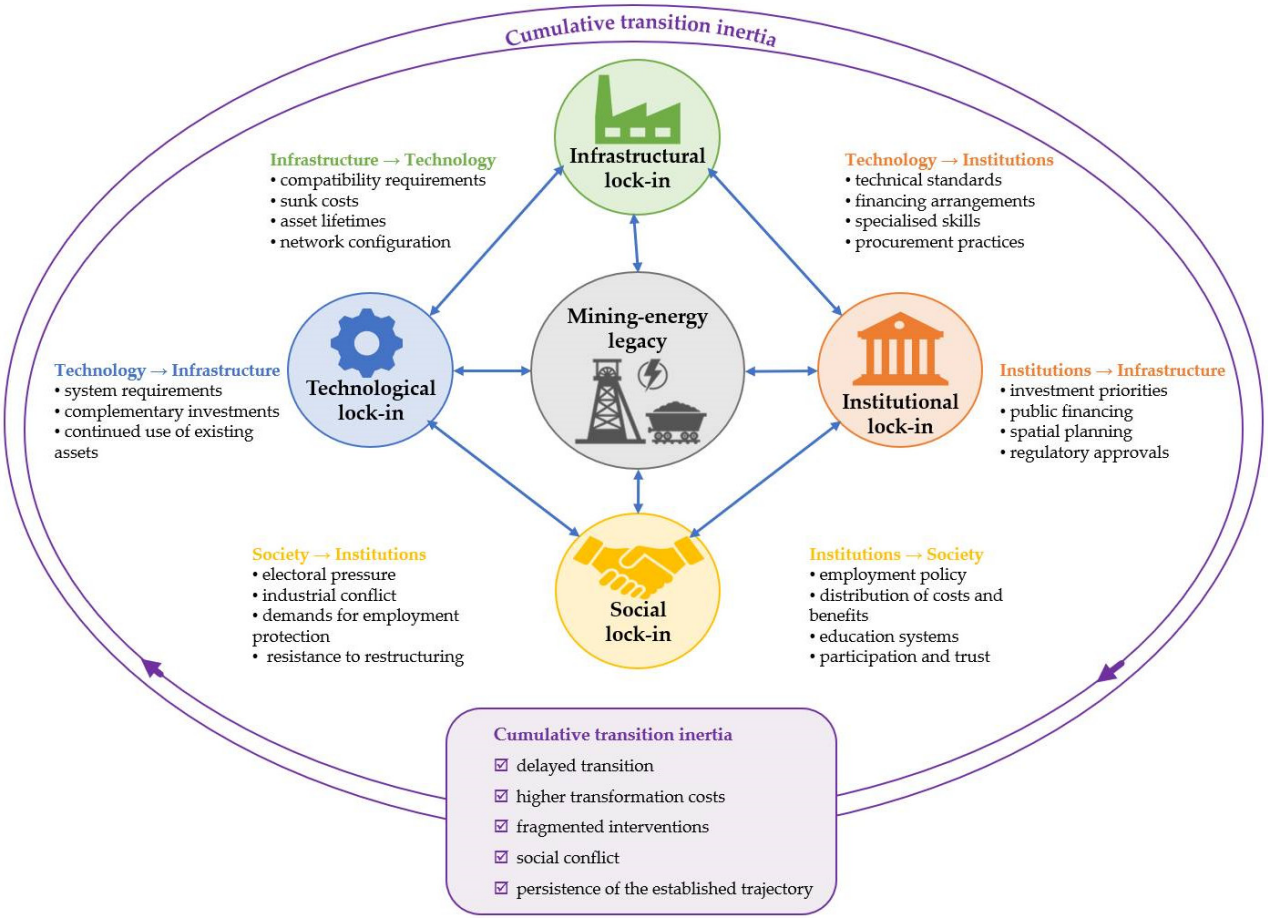

Figure 3. Conceptual framework of cross-domain transmission and feedback among infrastructural, technological, institutional and social lock-ins.

These relationships should not be interpreted as a universal sequence. Their direction and intensity depend on regional conditions, including infrastructure adaptability, economic structure, employment dependence, institutional capacity, access to finance, political commitments and the availability of credible alternatives.

The analytical purpose of the framework is therefore not to assign every barrier to one fixed category, but to identify how constraints are transmitted and reinforced across the regional system. This provides the basis for linking specific lock-in mechanisms with governance interventions in Section 6.

6. Cascading Lock-Ins and Their Implications for Transition Governance

To illustrate the relational logic of the proposed framework, Figure 4 presents an example of a cascading lock-in process in a coal-dependent regional energy system.

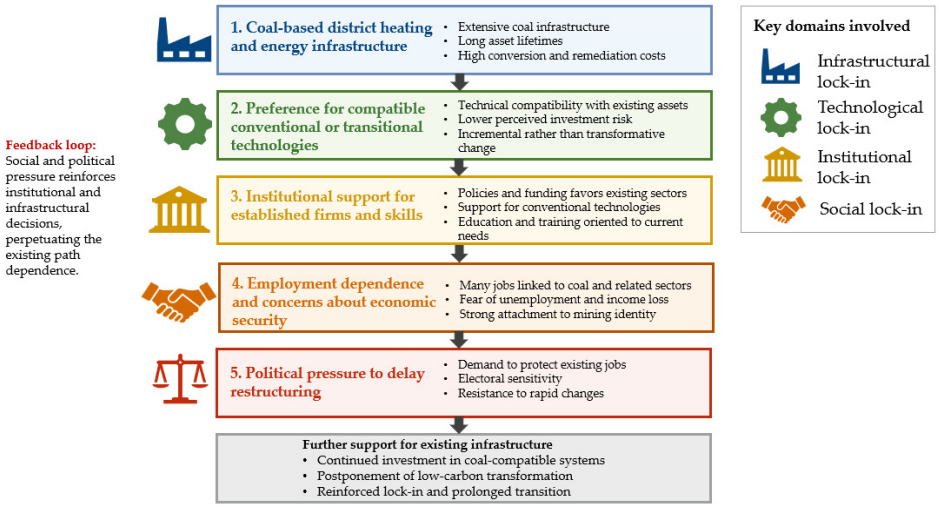

Figure 4. Example of a cascading lock-in process in a coal-dependent regional energy system: cross-domain transmission and feedback.

6.1. Linking Lock-In Mechanisms to Governance Interventions

The governance implications of the framework follow from the mechanisms through which lock-ins are reproduced. Integrated governance is required where a source mechanism, transmission pathway and reinforcing outcome extend across more than one policy sector, territorial level or stakeholder group. Governance responses should therefore be matched to the specific relationships identified in the regional system rather than applied as general solutions. Figure 5 links the four lock-in domains with corresponding governance interventions, responsible actors and the principal risks associated with implementation.

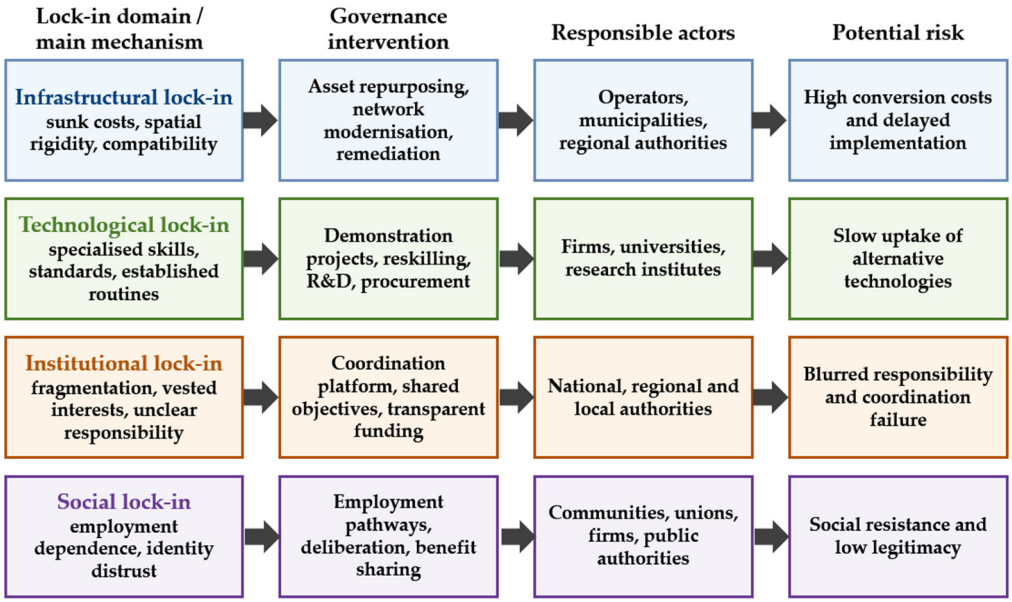

Figure 5. Linking lock-in mechanisms with governance interventions, responsible actors and potential implementation risks.

Infrastructural lock-in may be sustained by sunk costs, long asset lifetimes, technical interdependence, land constraints and compatibility requirements. Relevant interventions

include coordinated infrastructure planning, asset repurposing, network modernisation, land remediation, shared investment sequencing and mechanisms that reduce conversion risk. These interventions require cooperation among infrastructure operators, energy companies, municipalities, regional authorities, landowners, environmental institutions and financing bodies.

Technological lock-in may be reproduced through established standards, specialised competences, supply chains, operational routines and expectations regarding reliability. Relevant responses include demonstration projects, research and development, procurement reform, reskilling, support for alternative supply chains and regional capability development. These measures should be coordinated with infrastructure planning, education policy and labour-market development.

Institutional lock-in may result from fragmented responsibilities, established funding channels, sectoral policy structures, vested interests and unclear accountability. Governance responses should therefore include joint transition platforms, clearly assigned responsibilities, shared objectives, integrated financing arrangements, common monitoring systems and transparent procedures for resolving disputes among institutions and levels of government.

Social lock-in may be sustained by employment dependence, economic insecurity, occupational identity, distrust and concerns about the distribution of transition costs and benefits. Relevant interventions include credible employment pathways, income-protection measures, place-based economic diversification, recognition of mining heritage and meaningful participation in decisions concerning investment priorities and regional development.

The value of the framework lies in linking intervention design to specific mechanisms of persistence. Infrastructure investment alone may be ineffective where financing procedures, skills systems or low social trust continue to reproduce the established trajectory. Similarly, retraining programmes may have limited effects where economic diversification and actual employment opportunities remain insufficient.

6.2. Coordination, Trade-Offs and Conflict Management

The objectives of post-mining transition are not always mutually compatible. Infrastructure modernisation, rapid decarbonisation, economic diversification, institutional reform, employment protection and community participation may create competing demands for funding, time, authority and political support [37].

Infrastructure investment may provide long-term benefits but compete with short-term employment or income-protection measures. Rapid technological change may reduce emissions while increasing concerns about energy security, affordability or job losses. Economic diversification may create employment that differs from mining work in terms of qualifications, wages, stability and occupational identity. Institutional reform may improve coordination while redistributing authority and challenging established interests. Community participation may strengthen legitimacy but lengthen decision-making and expose conflicts among stakeholder groups [38].

These tensions should not be treated as implementation failures. They are inherent to regional transition and require explicit governance arrangements. Relevant mechanisms include negotiated transition agreements, sequencing of investments and protective measures, transparent assessment of trade-offs, shared monitoring indicators, compensation mechanisms and procedures for explaining why particular proposals are accepted, modified or rejected [39].

6.3. The Role and Limits of Polycentric and Deliberative Governance

Polycentric governance may support transition by mobilising multiple centres of knowledge and decision-making. National institutions may establish regulatory and financial frameworks; regional authorities may coordinate infrastructure, economic diversification and labour-market policies; municipalities may address land use and community participation; firms and infrastructure operators may implement technical investments; and universities, vocational institutions, trade unions and civil-society organisations may contribute knowledge, skills development, representation and monitoring.

However, polycentricity may also increase coordination costs, blur responsibility, reinforce unequal access to resources or deepen institutional fragmentation. Its effectiveness therefore depends on clear mandates, agreed decision rules, information-sharing procedures, accountability and formal conflict-resolution mechanisms [40].

Deliberative governance may improve legitimacy by allowing affected groups to influence transition priorities and by making competing interests, risks and expectations visible. Its usefulness depends on whether participation is connected to actual planning, investment and funding decisions. Deliberation may become symbolic, be dominated by organised interests or fail to influence outcomes where decision authority remains unclear [41–43].

Integrated, polycentric and deliberative governance should therefore not be treated as universally effective solutions. Their relevance depends on the specific lock-in mechanisms present in a region and on whether governance arrangements clarify responsibility, reduce rather than reproduce fragmentation and provide credible procedures for managing trade-offs. Table 1 illustrates how specific source mechanisms and transmission pathways may generate reinforcing outcomes across domains and indicates the governance responses, responsible actors and tensions associated with these relationships.

Table 1. Examples of cross-domain transmission mechanisms, governance responses and possible tensions.

Source Domain	Source Mechanism	Transmission Pathway	Affected Domain	Reinforcing Outcome	Governance Response	Key Actors	Possible Tension
Infrastructure	Sunk costs, long asset lifetimes and compatibility requirements	Existing systems favour compatible technologies	Technology	Continued use of established solutions	Asset repurposing, network modernisation and coordinated investment planning	Operators, firms, municipalities, regional authorities and investors	Modernisation expenditure versus short-term employment protection
Technology	Standards, specialised competences and established supply chains	Technologies become embedded in regulations, finance and training	Institutions	Continued support for familiar technologies and actors	Procurement reform, capability development, demonstration projects and reskilling	Firms, universities, training institutions and public authorities	Speed of innovation versus workforce adjustment
Institutions	Fragmented responsibilities and unequal allocation of costs and benefits	Unclear accountability weakens trust and credibility	Society	Distrust, opposition and reduced legitimacy	Joint transition platforms, transparent funding criteria and fair distribution mechanisms	National, regional and local authorities, unions and communities	Coordination versus institutional autonomy
Society	Employment dependence, distrust and political opposition	Social pressure affects policy and investment decisions	Institutions, technology and infrastructure	Delayed restructuring or prolonged support for established assets	Negotiated transition agreements, employment safeguards and meaningful participation	Communities, trade unions, public authorities and firms	Rapid decarbonisation versus employment security and procedural legitimacy

7. Conclusions

The energy transition of post-mining regions should be understood as the restructuring of regional development systems shaped by long-term reliance on mining and conventional energy. The persistence of these systems cannot be explained through isolated barriers alone. The framework illustrates that infrastructural, technological, institutional and social lock-ins may be transmitted across domains, accumulate over time and generate feedback effects that reinforce regional transition inertia.

The main contribution of the article lies not in identifying new categories of lock-in, but in providing a mechanism-based explanation for how existing forms of dependence interact. The framework distinguishes source mechanisms, transmission pathways, reinforcing outcomes and feedback effects. It therefore conceptualises cascading lock-ins as context-dependent cross-domain relationships rather than as a fixed or universal sequence.

This perspective helps explain why isolated transition interventions may produce limited results. Where constraints extend across several domains, infrastructure modernisation, technological diversification, institutional reform, skills development, economic restructuring and community participation require coordination. However, integrated, polycentric and deliberative governance should not be treated as universally effective solutions. Their usefulness depends on clear responsibilities, accountability, conflict resolution procedures and their connection to specific lock-in mechanisms.

This study has several limitations. It is based on a critical conceptual literature review rather than a systematic review or direct empirical analysis. The reviewed studies differ in geographical scope, terminology, methodology and level of analysis, which limits the possibility of determining the direction, strength and relative importance of individual relationships across all post-mining regions. The four lock-in domains should also be treated as overlapping analytical categories rather than as fully separate components.

Future research should empirically test the framework through comparative case studies, process tracing, expert interviews, document analysis and longitudinal regional assessments. Particular attention should be paid to the conditions under which cross-domain transmission and feedback emerge, the mechanisms that become dominant in different regional contexts, and the interventions capable of interrupting, redirecting or reversing cascading lock-ins.

Author Contributions: Conceptualisation, O.J. and A.G.; methodology, O.J.; formal analysis, O.J. and A.G.; investigation, O.J.; resources, O.J. and A.G.; writing—original draft preparation, O.J.; writing—review and editing, O.J., A.G. and J.K.; visualisation, O.J. and A.G.; supervision, J.K. and A.G.; project administration, O.J. and A.G.; funding acquisition, J.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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