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Economic Resilience of German Lignite Regions in Transition

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Abstract: This paper recalls the development of the German lignite regions Rhineland and Lusatia since 1945 to allow for a better understanding of their situation in 2019. We analyze their economic resilience, defined as adaptive capacity, using Holling's adaptive cycle model. We find that the Rhineland is currently in the conservation phase, while Lusatia experiences a reorganization phase following the economic shock of the German reunification. Key policy recommendations for the upcoming coal phase-out are to foster innovation within the Rhineland's infrastructures to avoid overconnection, and to expand digital and transportation infrastructure in Lusatia so that the structurally weak region can enter the exploitation phase. Future policymaking should take into consideration the differences between the two regions in order to enable a just and timely transition during which lasting adaptive capacity can be built.

Keywords: coal phase-out; energy transition; coal transition; sustainability transition; Energiewende; just transition; structural change; regional economic resilience; adaptive cycle model; Germany

1. Introduction

A global decline of the use of fossil fuels is crucial for reaching the 1.5 °C goal of the Paris climate agreement. At the same time, history has shown that past coal transitions have often had severe negative socioeconomic consequences on the affected regions due to poor management [1]. Consequently, literature has put an increasing focus on the just transition towards sustainable social-ecological systems [2–5].

In this context, the concept of resilience, especially the evolutionary perspective using the adaptive cycle model (AC) [6], has inspired useful insights on how regional economies withstand major disturbances [7,8]. We use this concept to address the situation of the two major German lignite mining regions that are currently undergoing sustainability transitions: the Rhineland in the western German state of North-Rhine-Westphalia (NRW), and Lusatia in eastern Germany in the former German Democratic Republic (GDR) (for the location of the regions see Figure 1).

To analyze the coal transition in the two regions, it is important to understand the current state of the energy transition in Germany. Climate protection advocates have long been calling for a coal phase-out, a claim which has since gained the support of the majority of the population [9]. As an attempt to comply with the Paris Agreement as well as a reaction to public opinion, the German federal government implemented a commission for growth, structural change, and employment (the so-called "coal commission") in 2018 with the mandate to develop a roadmap for the phase-out of coal, including

a fixed end-date. Its recommendation of phasing out coal by 2035–2038 [10] is a compromise between claims to phase out coal by 2030 to meet the Paris Agreement [11] and concerns of representatives of the lignite regions asking for sufficient time to manage the structural change. As of September 2019, the recommendations of the commission are currently being transferred and specified in the so-called Structural Enhancement Act (Strukturstärkungsgesetz), to be passed by the end of 2019.

Figure 1. Location of the study regions Rhineland and Lusatia.

Germany already has some experience with coal transitions, namely from the former hard coal mining regions in the Ruhr area and the Saarland in the western part of the country. While past structural change in those regions has not been without difficulties, they can generally serve as positive examples in comparison to other international experiences [12–14]. Other regions that have yet to face similar transition can learn from the experiences already made, the good ones as well as the bad ones. However, the differences between individual coal regions usually do not allow for direct transfer of successful strategies from one region to another [13–15]. Instead, an investigation of individual prerequisites and conditions is required for each region in order to derive meaningful policy recommendations.

To facilitate this process, we synthesize existing theories and frameworks on sustainability transitions and regional economic resilience in Section 2. In Section 3, we explain the methodology of the adaptive cycle model and its application to our specific case. We analyze our case study, the past development of German lignite regions, from a perspective of regional economic resilience in Sections 4.1 and 4.2. In Section 4.3, we then identify possible pathways towards a sustainable and resilient transition. We conclude with a discussion of the results in Section 5.

2. Sustainability Transitions and Regional Economic Resilience

Why is it so difficult for carbon-intensive regions to reduce their dependence on fossil fuels even if alternatives are available? Old industrial areas tend to be subject to two phenomena: path dependence and carbon lock-in. Path dependence occurs when past events, such as an important invention based on fossil fuels like the steam engine, lead to further carbon-based developments and inventions [16,17].

The concept of carbon lock-in is closely related; it denotes a situation where self-reinforcing mechanisms consolidate a society's dependence on carbon, seemingly creating increasing returns while putting up barriers for sustainable alternatives [18].

The research field of 'just transition' analyzes the question of how regions depending on fossil fuels can transform towards a low carbon economy. Research questions evolve around political economy questions of "who wins, who loses, how and why" [2]. Researchers analyze the existing distribution of energy, ask who lives with the side effects of energy extraction, production, and generation, and who will bear the social costs of decarbonizing energy systems and economies [2,3,19].

A distinction is made between two types of approaches to sustainability transitions: transition management and adaptive management. While both are closely related, they differ in their primary objectives: the former strives to steer change with a focus on creative capacity, while the latter aims to build resilience, focusing on adaptive capacity [20,21]. From a transition management perspective, Berlo et al. [22], Vögele et al. [23], and Leipprand and Flachsland [24] have analyzed the energy transition in Germany using the multi-level perspective (MLP) by Geels [25]. Foxon, Reed, and Stringer [20] propose to use both approaches, transition management and adaptive management, in a complementary way, combining the objectives of both. They propose that in the face of uncertainty, building resilience may help sustain the pathways developed in transition management.

In adaptive management, evolutionary interpretations of resilience are the most prevalent, which means that most studies reject the idea of equilibria from engineering and ecological resilience. By contrast to the latter two interpretations, where systems always strive to reach steady states, evolutionary approaches focus on the long-term capacity of the system to adapt to changing conditions [26].

This approach is widely used in the study of regions [7,8,26–28]. Boschma [26] proposes an evolutionary approach to regional resilience, where regions are resilient when they are able to overcome a trade-off between adaptation and adaptability in a situation of structural change. The more a region adapts to specific conditions, the more it has to forfeit its capacity to react to shocks or disturbances. Fath et al. [29] define resilience as the capacity of a system to successfully navigate all stages of the AC. From a regional economic perspective, Courvisanosae et al. [8] define adaptable resilient regions as demonstrating "change in the nature of industry over time without significant reduction in employment or income despite shocks (or perturbations)".

A widely used evolutionary model of resilience is Holling's [6] adaptive cycle (AC) model. According to the AC, systems pass four sequential phases determined by the variation of three parameters: potential, connectedness, and resilience. High resilience is equivalent to high adaptive capacity, this means the ability to flexibly respond to disturbances [7]. Originating from ecology, the AC can also be transferred to human systems, including regional economies [7,8,27,30,31].

The AC has since established itself to become a popular tool in resilience research, not only in its original field, but also in the study of human systems. Fath et al. [29] have further explored the AC in the context of the resilience of social systems, identifying key features for the success of a system as well as investigating the typical pathologies systems can experience in each phase of the cycle. Slight et al. [31] have identified leverage points for each phase of the AC that can help regional economies building adaptive capacity and successfully navigate the AC. Rogov and Rozenblat [32] propose an approach that determines urban resilience by the interplay of adaptive cycles on three different spatial scales.

3. Materials and Methods

We chose to focus on regional economic resilience because it offers a new and relatively un-researched perspective on the issues surrounding the structural change in regions experiencing coal transitions. This paper applies an evolutionary understanding of resilience using the AC, since we consider equilibrium interpretations of resilience insufficient to describe the complex dynamics of regional economies. We transfer Simmie and Martin's [7] framework of regional economic resilience to

our specific case. The results then serve as the basis for developing future policy recommendations concerning the management of structural change in the two major German lignite regions.

Since it is not an empirical, but a general model, the AC is intended to be used mainly metaphorically. The results of its application are supposed to encourage further research [30]. Therefore, this paper applies the AC as a complement to existing approaches using related methods such as the MLP.

The AC (Figure 2 and Table 1) is based on three key dimensions that determine the system's response to disturbances and other events: (1) potential for change, determining the range of possible options within the system; (2) internal connectedness, measuring system rigidity; and (3) resilience, determining system steadfastness to unexpected or unpredictable disturbances. The periodic change of these variables constitutes the four phases of the AC: the reorganization phase (α), the exploitation phase (r), the conservation phase (K), and the release phase (Ω). Systems have two different, sequential objectives, depending on the current stage of the AC: either the maximization of production and accumulation, or the maximization of invention and re-assortment [30].

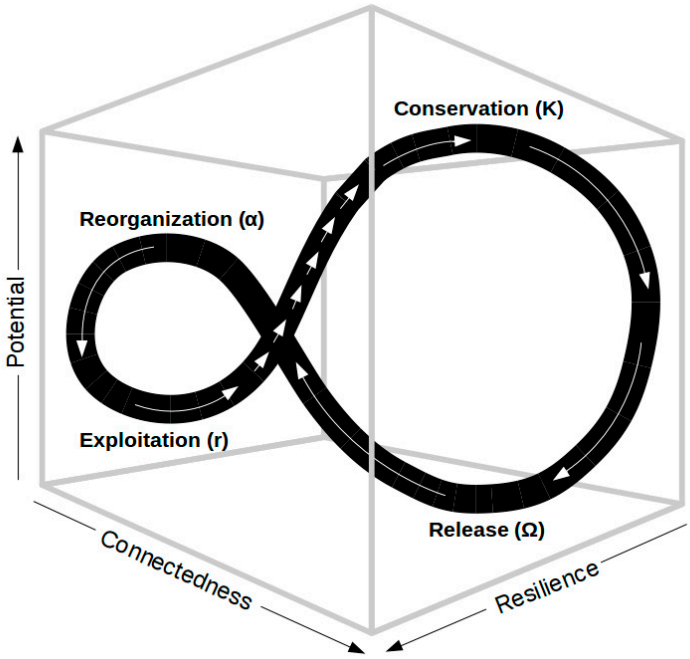

Figure 2. The adaptive cycle. Adapted from [30].

Table 1. Four phases of the adaptive cycle in a regional economy, the poverty trap, and the rigidity trap. Adapted from [6,7].

	Characterized by	Potential	Connectedness	Resilience
Reorganization phase (α)	innovation and restructuring	high	low	increasing
Poverty trap		low	low	low
Exploitation phase (r)	growth and seizing of opportunities	low	increasing	high
Conservation phase (K)	stability and increasing rigidity	very high	high	decreasing
Rigidity trap		high	high	high
Release phase (Ω)	decline and destruction	low	decreasing	increasing

Holling [6] describes the two most important dangers in the AC in case the system is lacking sufficient adaptive capacity: (1) the poverty trap and (2) the rigidity trap. Both are deviations from the original path of the AC. In the poverty trap, potential, connectedness, and resilience are low, keeping

the system from progressing to the exploitation phase. By contrast, in the rigidity trap, potential, connectedness, and resilience are high. This state of overconnection may hinder beneficial innovations, which cannot establish themselves without prior destabilization of the existing regime [33]. Moreover, the rigidity trap is fraught with an increasing risk of catastrophic breakdown in case of a disturbance affecting the higher-level system that the rigid system has adapted to [6]. An example could be the disappearance of a central actor that other actors depend on. Systems in the rigidity trap often try to avoid the release phase by unhealthy means such as a loss of outside connections and exhausting their internal resources in order to maintain the status quo [29].

To transfer the model to regional economies, Simmie and Martin [7] have translated the key attributes of the AC (see Table 2). In this work, we analyze the economies of the lignite mining regions in Lusatia and the Rhineland in a similar fashion to gain new insights about their resilience in the face of a disturbance, i.e., the impending coal phase-out. A result of this research shall be a conceptual framework applicable to other regions that are experiencing sustainability transitions.

Table 2. Characteristics of the three parameters potential, connectedness, and resilience of the AC [6,7].

	Holling [6]	**Simmie & Martin [7]**	**Application to Our Study Regions**
Potential	Inherent potential for change, determines the range of future options (the "wealth" of the system)	Internal competences of firms, skills of workers, institutional forms and arrangements, different types of infrastructures	Competences and skills in sustainable sectors (e.g., renewable energy), demographic structure
Connectedness	Internal controllability of a system, reflects the degree of rigidity of controlling variables and processes	Patterns of interdependencies among firms in the region	Diversity of regional economy, patterns of dependency on certain (esp. non-sustainable) industries
Resilience	Adaptive capacity, opposite of the vulnerability of the system to unexpected disturbances	Capacity for innovation among firms and institutions, actors' general inclination towards entrepreneurship and the formation of new firms, available investment or venture capital, willingness of workers to re-skill	Capacity for sustainable innovation, R&D expenditures, intensity and personnel

We apply this framework to a comparative case study of the German lignite regions, the Rhineland and Lusatia, drawing from existing research and descriptive statistics. The data and findings stem from available statistical information about the regional economy and industry, a review of academic and grey literature, and observations within the period from 2012 to 2019 that were made as part of three research projects, several visits of the regions, and interviews of involved actors. The period between the end of World War II and the final report of the coal commission in January 2019 was considered for the analysis since the developments during this period are the most relevant for understanding the current situation. We present a timeline comparing both regions' economic development and put it in the context of major events and disturbances. In addition, regional economic and demographic data is considered. This information then provides the basis for aligning each region's development to the different phases of the AC in order to investigate their regional economic resilience. We assess the risk of falling into the poverty or rigidity trap of the AC and derive policy recommendations for successfully navigating the AC against the background of structural change that is likely to come with the "Energiewende" and shut-down of the coal industry.

4. Results

4.1. Adaptive Cycles from 1945 until Present

Figure 3 shows the economic development of the two regions over time, featuring notable events and categorizing them into the four phases of the AC. The underlying data is presented in Table 3. For both regions, the end of World War II marked the beginning of a reorganization phase, which according to the AC is characterized by an increasing level of resilience, but also high uncertainty. In the post-war period, both German states made rebuilding their industries a priority. In the German Democratic Republic (GDR), lignite was the only domestic energy source available. While the Federal Republic commanded other resources such as hard coal, the lignite industry in the Rhineland remained important nonetheless [13].

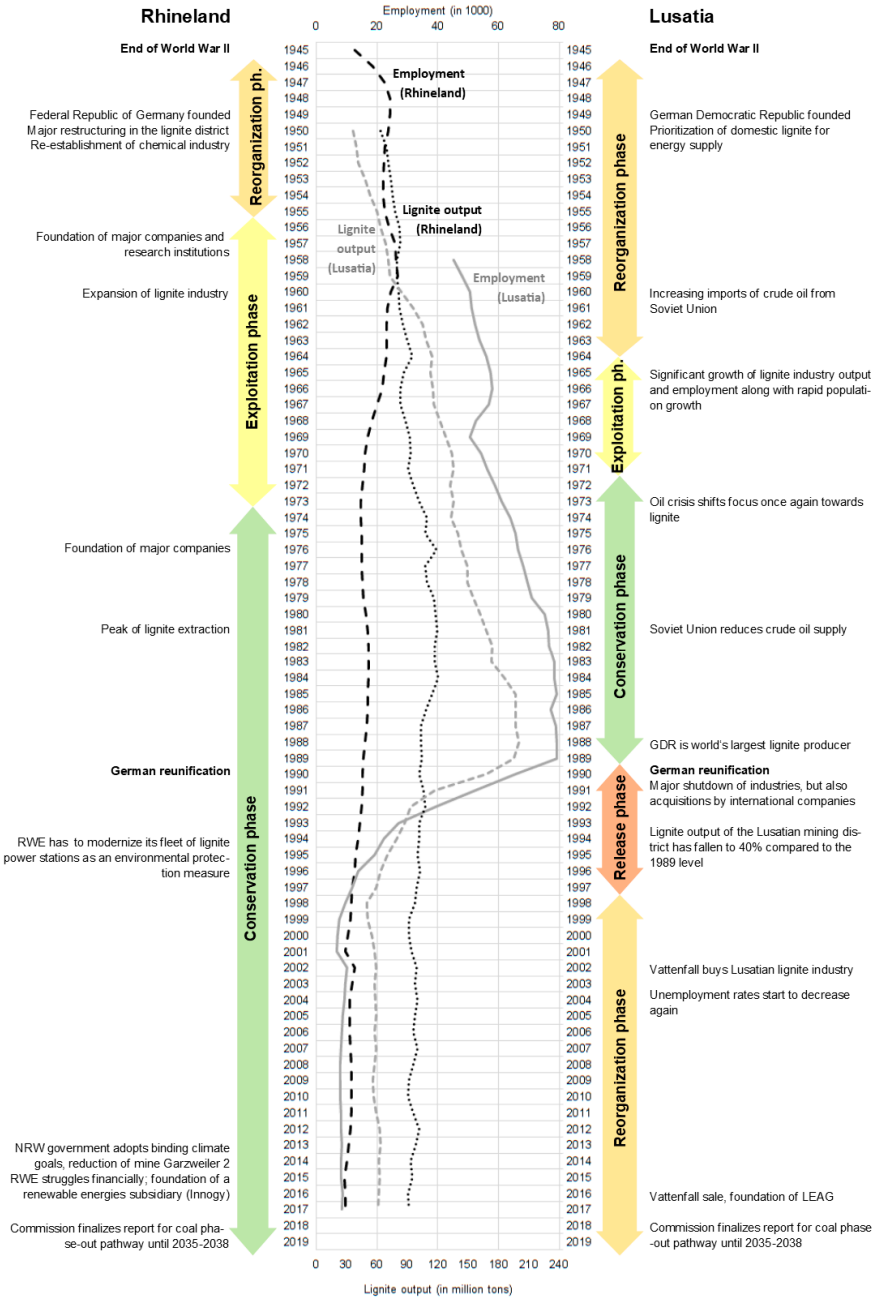

Figure 3. Adaptive cycles of the Rhineland and Lusatia (1945–2019), including a timeline and lignite industry data (until 2001: employment excluding power plants). Data source: [34–37].

Table 3. Characteristics of the regional economies of the study regions and their correspondence to the three parameters potential, connectedness, and resilience of the AC. Data sources: [34,36,38–44], partly own calculations based on data.

	Lusatia [1]	Rhineland [2]	Germany
Potential Competences and skills in sustainable sectors (e.g., renewable energy), demographic structure	**Low**	**Very high**	
Settlement structure, centrality	Rural, most districts are peripheral	Urban, all districts are very central	
Total population (2017)	1,157,609	2,440,995	
Population density	Sparsely populated	Situated in the densely populated state of NRW	
Population development	Reduction by almost 10% since 2000; aging population	Relatively stable population numbers; average age structure	
Unemployment rate in % (2018)	6.7	6.4	5.2
GDP in % p.a. (2005–2015)	3.2	2.6	2.8
Regional GDP in € p.c. (2015)	28,434	32,769	37,128
Trade tax revenue in 1000€ p.c. (2015)	332	251	560
Employment market	Few large employers except for LEAG and public sector	RWE largest employer; branches of many large firms	
Labor productivity in € per working hour (2015)	41.47	53.26	51.50
Available income in € p.c. (2015)	18,722	20,961	21,583
Number of STEM-employees per 1000 employees (2013)	37	45	37
Share of employees with an academic degree in % (June 2016)	12.1	13.1	15
Share of school leavers with a university entrance qualification in % (2011–2013)	31.1	48.1	35.3
Share of the population with access to public transport in % (2018) [3]	83.3	95.4 [4]	89.7
Broadband supply in % (2016)	52	87	75
LTE availability in % (2019)	67.7	76.1	77
Connectedness Diversity of regional economy, patterns of dependency on certain (esp., non-sustainable) industries	**Low to Moderate**	**Moderate to High**	
Lignite operator	LEAG (since 2016)	RWE	
Direct employment in the lignite industry (2017)	8,639	9,739	
Direct, indirect and induced employment (2016)	13,245	14,338	
Share of employees in the lignite sector among all employees subject to social security contribution (SSC) in % (2016)	2.03	1.13	0.06
Share of employees in the lignite sector (including indirect and induced employment) subject to SSC in % (2016)	3.3	1.8	

Table 3. *Cont.*

	Lusatia [1]	Rhineland [2]	Germany
Resilience Capacity for sustainable innovation, Research and Development (R&D) expenditures, intensity, and personnel	**Low but increasing**	**High but decreasing**	
Research intensity in % of GDP (2015)	0.5	1.04	2.01
Change of research intensity in % p.a. (2005–2015)	7.5	−1.5	1.8
R&D personnel intensity (share of employees subject to social security contribution) in % (2015)	0.34	0.86	1.32
Change of R&D personnel intensity in % p.a. (2005–2015)	4.5	−0.1	1.2
Company start-ups per 10,000 persons fit for work (2009–2012)	25.8	32.7	36.6
Share of high-tech start-ups (2009–2012)	5.7	6.9	7.0
Current phase in the AC	**Reorganization**	**Conservation**	
Number of AC phases since 1945	5 (one entire cycle; start of a new cycle)	3	

[1] Consisting of the administrative districts (Landkreise/NUTS-3 units) Dahme-Spreewald, Elbe-Elster, Spree-Neiße, Oberspreewald-Lausitz, Bautzen, Görlitz, and the city of Cottbus; [2] Consisting of Städteregion Aachen, Düren, Euskirchen, Heinsberg, Rhein-Erft-Kreis, Rhein-Kreis Neuss, and the city of Mönchengladbach; [3] Residence within a proximity of 600m (bus) or 1,200m (train) to a stop with a minimum of 20 departures daily; [4] Data for the whole of NRW (due to lack of data availability on district level).

In the 1950s, the Federal Republic experienced a period of unexpectedly strong economic growth—the "Wirtschaftswunder". In the AC, the "Wirtschaftswunder" happened alongside the exploitation phase, a time of great development opportunities and growth as well as a high level of resilience. Until 1973, the yearly growth of the Federal Republic's GDP was at least 5% [45]. Areas with a traditionally strong industrial sector, such as the Rhineland in the federal state of North-Rhine-Westphalia (NRW), especially benefited from this development.

In the 1950s and 1960s, the remaining lignite firms in the region merged with RWE, a major company in the energy and mining sector, partly owned by local municipalities. Consequently, RWE became the most significant producer of lignite in West Germany. The academic sector grew as well: among others, the research institute in Jülich was founded in 1956 and in 1966, the Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen expanded to become a full university.

By contrast, due to the planned economy of the GDR, the situation in Lusatia was much different. The standard of living was generally much lower than in West Germany. Nevertheless, the mid-1960s marked the start of the exploitation phase with significant growth of the lignite industry in terms of employment and lignite output (see Figure 3). Lignite mining and generation were (and still are) the most significant industries.

In the Federal Republic of Germany, the 1973 oil crisis abruptly halted the period of strong growth, initiating the conservation phase. The Rhineland, however, was able to keep its status as an attractive industrial region. While this is indicative of high potential, internal connectedness also increased and resilience started to decrease. As is typical for the conservation phase, most economic power is concentrated in certain industries that have shown a competitive advantage in the previous phases and cycles. In case of the Rhineland, this includes the lignite industry, but also the chemical, aluminum, automotive, and food industries. Their primary aim was now to increase their efficiency in order to achieve higher returns. Figure 3 shows that lignite production increased during the 1960s and 1970s, albeit not as strongly as in Lusatia [34].

For the GDR, the year 1971 marked a paradigm shift in economic policy due to the political change of power. The new government's first objective was to increase the standard of living, initially at the

expense of productivity gains. This can be interpreted as the start of the conservation phase, which is characterized by growing stability, but also increasing rigidity [7]. While the Federal Republic was able to compensate for the scarcity of resources caused by the oil crisis, the GDR had grown largely dependent on the Soviet Union for oil and gas imports. Its return to lignite once again gave special importance to the region of Lusatia, resulting in lignite production and employment increasing strongly. We argue that at this point, the system had fallen into a rigidity trap, a state of overconnection and adaptation to a dysfunctional higher-level system.

As was the case for large parts of East Germany, the German reunification caused the regional economy of Lusatia to suffer a considerable system shock that pushed it into a release phase. Large parts of the lignite industry were shut down within a short period due to being unable to compete with West German energy producers in an open market. Similar shocks also hit other industrial sectors in Eastern Germany. A period of very high unemployment rates ensued in Lusatia (and other parts of Eastern Germany), reaching their peak at around 21% in 2004 (own calculations based on [41]). Especially, young people left the region, causing a dramatic decline in population. This is an indicator for the plummeting of the system's potential, which is typical for the release phase.

Eventually, the regional economy of Lusatia progressed to another reorganization phase. The region's lignite output and employment in the lignite industry have remained relatively stable since the early 2000s, although at quite a low level compared to GDR times [35,36]. Lusatia is now the second largest lignite mining district in Germany, after the Rhineland. Other industries in the region are much smaller. Among the larger ones are the chemical industry and the railway industry. There are two universities in Lusatia today and public sector employment is a major factor as well [46].

4.2. Implications on the Resilience of the Regional Economies

4.2.1. Rhineland

The regional economy of the Rhineland has developed steadily since 1945 and it is now in the conservation phase. The region benefits from a notable locational advantage: it is situated in the densely populated state of NRW, within close proximity to the major agglomerations of Aachen, Cologne, Düsseldorf, and the Ruhr area. Access to public transport in NRW is above national average, as 95.4% of the population have access as compared to the German average of 89.7% [39,40]. Three important chemical parks and the German headquarters of various large international companies are located in the region. The level of education among the population, the share of employees with a background in science, technology, engineering, and mathematics (STEM), and the broadband expansion are above the German average [43]. Overall, these factors are indicative for a high potential for future development. Most other indicators are in line with the German average, such as GDP growth and labor productivity. Only a few indicators are below the German average: GDP, trade tax revenue, and available income per capita. Additionally, the unemployment rate, at 6.4% in 2018, is above average [43].

Connectedness is moderate to high in the region. Lignite operator RWE is the largest employer, but at the same time the regional economy is diversified and there are numerous other companies and industry branches in the region. There is a strong perceived dependence on the lignite industry, as several other major employers in the region are suppliers for RWE. Direct, indirect and induced employment of the lignite sector results in a total of 14,338 employees, who make up 10.2% of all employment subject to social security contribution in manufacturing industries, but only 1.8 among all sectors [43]. The conservation phase is characterized by a high degree of connectedness between the actors in the system. If the regional economy becomes overconnected, it is at risk of falling into the rigidity trap.

Resilience of the Rhineland is high but decreasing. As part of the Federal Republic and due to its close location to international markets (e.g., the Netherlands, France, Belgium, and the UK), the Rhineland has shown notable resilient capacity in the past and recovered from various disturbances, even from serious recessions following the oil crisis in the 1970s. At the same time, increasing

connectedness leads to decreasing resilience during the conservation phase. At present, innovative capacity in the Rhineland is in line with the German average while R&D intensity is stagnating [43] (for more detailed information, see Table 3).

4.2.2. Lusatia

Lusatia still suffers from the economic collapse following the reunification and its lasting impacts on other sectors and companies. Since Lusatia is now again experiencing a reorganization phase, the future is still largely open. Overall, it does not profit from as many economic privileges as the Rhineland and its potential can be characterized as relatively low. Lusatia is a quite sparsely populated, rural region with weak infrastructure. The largest city in the region is Cottbus, having 100,000 inhabitants. Larger cities, like Dresden, Berlin, or Leipzig, are relatively far away and poorly connected. In the district of Spree-Neiße, only 61.3% of the population have access to public transport, this district being the lowest ranking in in the eastern federal states. Overall, public transport accessibility in Lusatia averages at 83.3%, which is a few percentage points below the German average [39,40]. In addition, broadband and LTE coverage are far behind the German average [38,43]. As shown in Table 3, several economic key indicators, such as GDP per capita, labor productivity, and research intensity, are below the national average. However, other indicators suggest a narrowing of the economic gap between Lusatia and the rest of Germany. Unemployment rates have decreased significantly, from over 20% in 2004 to 6.7% in 2018, and the region exhibits an above-average GDP growth rate [43]. This reflects a positive economic development, especially in comparison with other regions in Eastern Germany [41,47]. However, the mentioned positive indicators should be taken with a grain of salt, since the reduction of unemployment is partly due to emigration, and the above-average GDP growth should be regarded in the context of its below-average basis.

Connectedness is low to moderate in the region. On the one hand, lignite operator LEAG (formerly Vattenfall, until 2016) is by far the largest employer in the region and there are not many other large employers except for the public sector. Overall, 3.3% of all employees subject to social security contribution are employed directly, indirectly in, or induced by the lignite sector, and their share among the manufacturing industries is even higher at 17.5% [43]. Hence, to a significant part of the population in Lusatia, the prospect of an impending coal phase-out feels like a major threat [48]. At the same time, the change of ownership in 2016 and the resulting uncertainty are indicative of low connectedness.

Generally, an increasing level of resilience is typical for the reorganization phase. This means that a region in the reorganization phase would likely be able to adapt to a new course of development in the face of a major disturbance. However, the region's innovative capacity is still rather low in comparison to the German average. In the past, the regional economy of Lusatia has not proven to be as resilient as that of the Rhineland. This appears to be largely due to the historical implications of the political system of the GDR [13]. This situation was aggravated by the fact that the region was almost solely dependent on the lignite industry and the absence of close-by international markets. Considering the region's structural problems and the impending coal phase-out, there is a great degree of uncertainty of future economic development, which corresponds with the reorganization phase. If resilience remains low, Lusatia may become at risk of falling into the poverty trap. However, the strong growth of R&D expenditures and personnel intensity, as well as the comparably strong regional GDP growth [43,47] might suggest that Lusatia might even have surpassed the poverty trap and is on its way into the exploitation phase (for more detailed information, see Table 3).

4.2.3. Comparability with Other Regions in Germany

With the Rhineland and Lusatia, we have analyzed two coal regions in different political systems over the same period. To facilitate contextualization, the following section briefly compares the two study regions with two other post-mining regions: Lusatia vs. the Central German coal district (Mitteldeutsches Revier) and the Rhineland vs. the Ruhr area. Table 4 gives an overview of key indicators.

Table 4. Comparison of the study regions with the Central German coal district and the Ruhr area. Data source: [34,36,42,43,47,49–51], partly own calculations based on data (data from 2015, unless otherwise noted).

Ruhr Area [1]	**Rhineland**		**Lusatia**	**Central Germany** [2]
5,113,487 (2017)	2,440,995 (2017)	Total population	1,157,609 (2017)	1,957,000 (2016)
Urban, very central	Urban, very central	Settlement structure, centrality	Rural, mostly peripheral	Heterogeneous; ranging from urban/central to rural/peripheral
31,394 (2016)	32,769	GDP in € p.c.	28,434	27,640
19.680 (2016)	20,961	Available income in € p.c.	18,722	18,163
8.9 (2016)	7.8	Unemployment rate in %	9.4	9.9
0 (2019) [2018: 3,371]	9,739 (2017)	Employees in coal mining industry	8,639 (2017)	2,414 (2016)
n.a.	1.13 (2016)	Share of coal mining employees in % [3]	2.03 (2016)	0.32 (2016)

[1] Consisting of Bochum, Bottrop, Dortmund, Duisburg, Ennepe-Ruhr-Kreis, Essen, Gelsenkirchen, Hagen, Hamm, Herne, Kreis Recklinghausen, Kreis Unna, Kreis Wesel, Mülheim a.d. Ruhr, Oberhausen; [2] Consisting of Altenburger Land, Anhalt-Bitterfeld, Burgenlandkreis, Halle (Saale), Landkreis Leipzig, city of Leipzig, Mansfeld-Südharz, Nordsachsen, Saalekreis; [3] Among all employees subject to social security contribution.

The Ruhr area once was Germany's most important hard coal mining region. Due to the coal mining and steel industry, the Ruhr area is the most densely populated region in Germany. However, already in the 1950s and 1960s, domestic hard coal mining became increasingly uneconomical, and the government of the Federal Republic decided to subsidize hard coal mining and initiate a gradual, linear phase-out process, which recently ended in 2018 with the closure of the last mine. The main reason for the prolonged subsidization was the protection of domestic coal production. Due to the slow and structured phase-out, social hardships for the miners could be largely avoided. However, it also resulted in very high costs and the region is still grappling with a lack of innovation and initiatives for future generations. Due to the region's dependence on the coal and steel industry, it was repeatedly affected by large unemployment rates, and a significant gap to the averages of NRW and Germany still prevails [13]. Within the 21st century, however, more diversified industries started to emerge especially in the southern part of the Ruhr area, increasing its resilience to future changes. The Rhineland, although not quite as densely populated, is an urban and very central region as well, and some parallels to the Ruhr area can be drawn which may aid the upcoming transition process.

The Central German coal district, like Lusatia, is a lignite mining region in the area of the former GDR. This region has started turning its back on lignite earlier than Lusatia for economic reasons after 1990, and only a few mines and power plants are left in the region today. Despite some similarities to Lusatia with respect to economic strength and potential for innovation, the Central German coal district exhibits a few advantages that Lusatia does not have. For instance, the region benefits from its proximity to the cities of Leipzig and Halle (Saale) as well as having a more diversified industrial sector of several chemical facilities. As a result, the share of lignite industry employees is much smaller than in Lusatia [43]. This indicates a higher level of resilience for the Central German mining district as well as a lower dependence on lignite compared to Lusatia. The comparison between the two regions underlines the peripheral location of Lusatia as one of the main challenges for the transition.

4.3. Policy Recommendations for Building Resilience

According to Holling [6], functional diversity among a system's components is essential for building resilience. The goal of the following policy recommendations is to help the regional economies to avoid or escape the typical traps and pathologies of their respective stages of the AC [29,52] and increase their adaptive capacity with the help of the leverage points identified by Slight et al. [31].

The leverage points are going to be translated into concrete policy measures that are applicable to the Rhineland and Lusatia.

4.3.1. Rhineland: Avoiding the Rigidity Trap

So far, the Rhineland appears to have successfully navigated all phases of the AC, which indicates high adaptive capacity. However, during the conservation phase, the regional economy must avoid overconnection, self-reinforcement, and inflexibility [52]. This might happen if too many actors in the region remain directly dependent on RWE's coal business.

In order to avoid the rigidity trap, Slight et al. [31] suggest increasing competition and promoting diversity within the system by traditional policy instruments such as subsidies or tax incentives, as well as retraining programs for workers, attracting small businesses, twinning agreements between communities, and the support of new product development in existing industries. Failing industries should not be subsidized as this causes merely a delay of the system's collapse.

Recent developments in the Rhineland point in the right direction and should be strengthened. In doing so, the region can benefit from the experiences made in the neighboring Ruhr area during the hard coal phase-out [53]. In the Rhineland, a strong infrastructure, a high density of universities and research institutes, as well as a diversified industry can be found [54]. Promoting networks between universities, research institutions, and companies may help create competitive and resilient structures, which keep companies in the region, attract new ones and lead to the foundation of start-ups out of university.

The regional economy of the Rhineland is likely to handle the coal phase-out well if it manages to avoid a state of overconnection. Further diversification of the economic structure is key for the municipalities, many of which largely depend on tax revenues by RWE and its contractors [54]. While the energy sector is likely to remain significant, its focus should shift towards more sustainable industries such as renewable energies, energy storage or energy efficiency. Another important factor that was often neglected in previous transformation processes is the role of soft location factors for the attractiveness of a region. "Action Program Ruhr" and the "IBA Emscher Park" of the neighboring Ruhr area are examples of how soft location factors can positively influence an entire region. Former industrial sites were transformed into landmarks and cultural sites in order to conserve the identification with the region and to facilitate the shift towards a new, more future oriented perception [13].

4.3.2. Lusatia: Entering the Exploitation Phase

The region of Lusatia has been in the reorganization phase for more than 20 years. This very long duration might be indicative of a poverty trap. According to Holling [6], the poverty trap is a departure from the adaptive cycle that occurs when potential and diversity are reduced to a point where all three parameters—connectedness, potential, and resilience—are low. As identified by Fath et al. [29], a lack of direction may prevent the system from exiting the reorganization phase. In order to enter the exploitation phase, a system needs activation energy and the capacity to grow. As a leverage point for the reorganization phase, Slight et al. [31] suggest to support emerging businesses so that they can progress into the exploitation phase. Possible economic instruments include supporting access to capital, private venture capital funding, and infrastructure renewal.

In the Lusatian case, the post-reunification period has clearly left its mark on the region due to the closing of many GDR companies and the emigration of a large portion of the younger and often more educated workforce. As structural data suggests, the region was not able to recover for many years. However, recent developments suggest that Lusatia is already on its way out of the poverty trap and moving towards the exploitation phase. For instance, the regional economy has started to diversify. This includes the foundation of a new entrepreneurship center in Cottbus, an innovation center in Senftenberg aimed at biotechnology and medical engineering start-ups, and a stronger focus on tourism. Besides the already popular Biosphere Reserve Spreewald, a second major holiday destination is emerging in the region: the artificial Lusatian Lake District, a restored post-mining area.

Renewable energies may not only serve as a replacement for lignite, but can themselves generate employment and be a motor for innovation [55,56]. The solar park in Senftenberg is one of the largest in Germany; two other major solar parks are located in Lieberose and Finsterwalde. In Lauchhammer, Vestas produces wind turbine blades for the global market.

While these developments towards a more diversified and sustainable regional economy allow for an optimistic outlook, further efforts are needed to get the structurally weak region back on track. Demographic effects lead to an increasing lack of skilled workers. Improving soft location factors can help encourage especially young people to stay or move to Lusatia. The region's remoteness poses further challenges. Lusatia is in urgent need of improved digital and transportation infrastructure in order to attract new businesses. A step in the right direction is the designation of Lusatia as a pilot region for the new mobile standard 5G. Research and development may be supported through means such as a cluster strategy, the establishment of new research institutions, increased support for the higher education institutions in the region, as well as the strengthening of their connections to companies. Post-mining landscapes should be restored in an environmentally responsible way in order to create new natural habitats and areas for recreation. Together, the three focus areas—renewable energies, science, and tourism—can be used to change the perception of Lusatia towards that of a 'green' region.

5. Discussion

The objective of this paper is to analyze the regional economic resilience of the two largest lignite mining regions in Germany, the Rhineland and Lusatia, by means of Holling and Gunderson's [30] adaptive cycle (AC) model and Simmie and Martin's [7] application to regional economies.

We use historical information and current economic data of the Rhineland and Lusatia in Germany in order to find out how successfully the regions have navigated the adaptive cycle, corresponding to the definition of resilience by Fath et al. [29]. We find that, since the end of World War II, the regional economy of the Rhineland appears to have experienced three out of four phases of the cycle and progressed to a phase of conservation. In the same period, the regional economy of Lusatia has gone through an entire cycle, with the economic shock following the German reunification having caused a release phase, followed by today's reorganization phase.

We argue that overall, the Rhineland has shown more adaptive capacity than Lusatia over the period from 1945 until present. The Rhineland should therefore foster innovation within existing infrastructures in order to reduce dependency on the lignite industry and avoid a state of overconnection (the rigidity trap). Possible measures are the promotion of networks between research institutions and companies, as well as the improvement of soft location factors. Lusatia, by contrast, is a structurally weak region that has had difficulties to enter the exploitation phase. In order to leave the poverty trap and improve its adaptive capacity, Lusatia needs to attract new companies and promote innovation. The comprehensive expansion of digital and transportation infrastructure therefore is an essential prerequisite, which may also strengthen the existing focus on tourism.

When comparing the regions, it becomes eminent that the Rhineland has had much more time than Lusatia to progress through the stages of the AC. For Lusatia, the upcoming coal phase-out is going to be the second major externally imposed transition within a much shorter period. This makes the situation more difficult economically and emotionally, especially since a considerable part of the population is going to have experienced both transitions. It is therefore even more important to manage the coal phase-out in a structured and just way in order to minimize the impacts on the affected population. By learning from previous energy transitions and considering resource peaks and the risks of climate change, future transitions may be achieved in a much faster and more coordinated way [57].

From an evolutionary perspective, a region is adaptable and resilient if it is able to overcome changes in the nature of industry without significant impairment of its overall economic situation [8]. Our results indicate that, given the prospect of an imminent coal phase-out, it is important to tackle the structural change wholeheartedly and immediately, to harness and increase the regions'

adaptive capacity and prevent them from suffering from major disturbances due to this transition. Our findings from the application of the AC thus support results from previous research as well as the recommendations for structural change from the coal commission [10,12,58].

The phase-out date of 2035–2038 suggested by the German coal commission in its final report lays down a timeframe of 20 years to manage the coal phase-out. The commission acknowledges the need for measures to support the structural change in the lignite regions, suggesting measures to improve infrastructure, research and development, and the expansion of renewable energies. In order to finance these measures, the regions are going to receive a total amount of 40 billion € over the next 20 years from the federal budget. If deployed in a sensible way, these funds can be a chance towards a sustainable structural change and a just transition within the regions. Therefore, the commission's recommendations need to be swiftly transposed into federal law, as scheduled, in order to create planning certainty for the regions and prevent them from maladaptation to dysfunctional circumstances. In order to allocate the funds and measures efficiently in the Structural Enhancement Act, the differences between the two regions should be considered, keeping in mind the increased difficulties that Lusatia faces compared to the Rhineland. Among the most important measures, especially in the structurally weak region of Lusatia, are the expansion of digital and transportation infrastructure as well as the promotion of research and development and the improvement of soft location factors. In both regions, structural support should be deployed towards the fostering of innovation in order to be as adaptable as possible and well equipped to handle future disturbances.

While this study has shown that the AC can be successfully applied to the regional economies of the Rhineland and Lusatia, the comparability between the economic resilience of both regions is still limited. The regional economy of Lusatia was largely influenced by the economy of the GDR that it was a part of. To some extent, the GDR history continues to have an effect on the region even today. In the AC, larger scales of time and space influence smaller ones and vice versa [7]. The economy of the GDR appears overall much less resilient than that of the Federal Republic. While the AC can serve as a tool to analyze and compare other coal regions around the world in further research, our policy recommendations for the Rhineland and Lusatia cannot be transferred one-to-one to other coal regions due to the important role of each region's individual history. Furthermore, not all aspects that make up the complexity of the regional economies and their transition could be considered, encouraging further research to investigate more factors that may affect a region's adaptive capacity.

Further limitations arise from the nature of the AC itself. The deterministic sequence of the four phases poses the question of whether the model is fully applicable to all systems including human foresight, such as regional economies. Holling and Gunderson [30] have attended to this question, but found no human system that could serve as an exception to the AC. Still, some studies choose to interpret the AC in a less deterministic way. Slight et al. [31] allow for the possibility of a system in the conservation phase to return directly to the exploitation phase by increasing its resilience. Salvia and Quaranta [27] address this issue by actively involving stakeholders in determining the phases of the adaptive cycle. Peter and Swilling [21] develop a new, probabilistic approach to sustainability transitions that synthesizes characteristics of the AC, the MLP, and related theories in a complexity framework.

Complementing existing literature on the topic, the AC offers a new perspective on the debate surrounding the coal phase-out in Germany looking back at the development of the lignite regions since the end of World War II and the upcoming phase-out within 20 years. Holistic approaches like the AC might even help reconcile the hardened fronts in this heated debate, since they view the lignite industry within the context of a larger system. Although most studies on structural change in the German lignite mining regions do not explicitly investigate or mention resilience, it is a concept which is crucial to the matter and which constantly resonates in the background. Now it is the turn of policy makers and stakeholders in the lignite regions and on the federal level to shape a sustainable future in the Rhineland and Lusatia and to build lasting adaptive capacity.

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