TRANSIENCE

TRANSITIONING TOWARDS AN EFFICIENT, CARBON-NEUTRAL CIRCULAR EUROPEAN INDUSTRY

Date: 30/06/2025

D3.9 – The twin transition from an innovation lens

WP3 – Characterising circularity and decarbonisation opportunities - generating model inputs

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Grant Agreement Number	101137606	**Acronym**	TRANSIENCE		
Full Title	TRANSItioning towards an Efficient, carbon-Neutral Circular European industry				
Topic	HORIZON-CL4-2023-TWIN-TRANSITION-01-36				
Funding scheme	HORIZON EUROPE, RIA – Research and Innovation Action				
Start Date	January 2024	**Duration**	48 Months		
Project URL	https://www.transience.eu/				
EU Project Advisor	Fátima GONZÁLEZ GÓMEZ				
Project Coordinator	Institute of Communication and Computer Systems (ICCS)				
Deliverable	D3.9 – The twin transition from an innovation lens				
Work Package	WP3 – Characterising circularity and decarbonisation opportunities - generating model inputs				
Date of Delivery	**Contractual**	30/06/2025	**Actual**	30/06/2025	
Nature	Report	**Dissemination Level**	Public		
Lead Beneficiary	Institute of Communication and Computer Systems (ICCS)				
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Keywords	sociotechnical transitions; industrial transitions; industrial clusters; industrial symbiosis steel, cement; chemicals; hydrogen; circularity; CCS; MLP; TIS; innovation				

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PROCESSES4PLANET

EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

This report is intended for policymakers and other industrial actors in the three regions analysed (Rhine-Ruhr, Port of Rotterdam, Basque Country) to shed light on system dynamics influencing decarbonisation efforts. Stakeholders from other regions, or those involved in broader industrial transformation, may also find the insights transferable to different contexts. Additionally, the findings can be useful to modelling scientists and other researchers (including from the Social Sciences and Humanities), to inform and/or adapt exercises based on the insights presented.

3. Short summary of results

Energy-intensive industries are among the largest contributors to greenhouse gas emissions. Decarbonising these sectors is therefore crucial for meeting global climate targets. However, such a process is complex given different development priorities, like maintaining economic competitiveness alongside addressing climate change, while the lack of mature mitigation options remains a critical barrier. The role of industrial clusters as areas of enhanced industrial activity and potential innovation hubs is critical.

In this research we perform three empirical sociotechnical analyses in the industrial clusters of Rhine-Ruhr (DE), Port of Rotterdam (NL), and Basque Country (ES) focusing on past and current trends to understand the rules, processes, system dynamics, and actor interactions that are embedded in the current system configuration, and the role of radical, disruptive innovations. We focus on the key EIIs of iron and steel, cement, chemicals, and the mining industry to shed light on transition implications at different scales based on contemporary dynamics that are part of the sectoral systems. We then take a forward-looking approach, shifting focus onto the diffusion and market formation of low-carbon innovations, such as hydrogen, CCS, bioenergy feedstock, as well as circularity performance approaches, mapping their role within the transition pathways. By diving into the complexities of specific sectors and innovations, we identify what the transition entails in their context but also understand the interplay of the transitions of different sectors, and consequently implications to the entirety of industry.

We highlight potential challenges such as spatial limitations required for extensive infrastructure expansion, differences in the existing capacities and organisational structures of the clusters, as well as enabling factors in the form of ongoing innovation efforts, all potentially affecting the industrial transition in the regions, and the European industry in general. Our analysis also sheds light on the perceived role of core mitigation options widely discussed, such as hydrogen and CCS, along with significant opportunities and caveats.

4. Evidence of accomplishment

This report.

Preface

The need to approach climate action, resource efficiency, and circularity performance as integrated, economy-wide, cross-cutting issues is growingly gaining attention in the policy world, stimulating the development of new industrial policies in Europe and worldwide. Currently, however, there is little progress in conceptualising the circular economy and understanding its interactions with climate action. State-of-the-art modelling capacity to capture the interplay of the two agendas and their implications for energy-intensive sectors as well as to represent the European industry's transformation in line with the region's vision for climate neutrality is not yet fully developed. TRANSIENCE will undertake a comprehensive characterisation and assessment of circularity principles and measures vis-à-vis decarbonisation, by looking at the twin transition of European industries through the lenses of global competitiveness, innovation, and holistic sustainability. It will then produce MIC3, a consistent, fully open-source model ecosystem to assess industrial circularity, decarbonisation, and sustainability. A series of interoperable modules on the socioeconomic, service and product, material, industrial, energy-system, and environmental perspectives of the transformation of European industry will be developed and integrated, building on and opening the code of leading modelling tools. MIC3 will finally be used in extensive scenario modelling to produce diverse pathways toward a material-efficient, circular, climate-neutral, sustainable European industry. Transparency, openness, and knowledge sharing will be promoted, and technical capacities will be developed in four industrial agglomerations in the EU, moving beyond stakeholder consultation, onto model co-development, continuous validation of assumptions, co-creation of scenario modelling, evaluation of the desirability and usability of the developed model and insights, and eventually co-production of science and action.

ICCS – Institute of Communication and Computer Systems	EL
CEPS – Centre for European Policy Studies	BE
E3M – E3-Modelling AE	EL
Fraunhofer – Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.	DE
HOL – HOLISTIC IKE	EL
PIK – Potsdam Institut für Klimafolgenforschung e.V.	DE
PNTEC – Park Naukowo-Technologiczny Euro-Centrum Spolka Z Ograniczona Odpowiedzialnoscia	PL
TECNALIA – Fundación Tecnalia Research & Innovation	ES
UU – Universiteit Utrecht	NL
WI – Wuppertal Institut für Klima, Umwelt, Energie gGmbH	DE
PSI – Paul Scherrer Institut	CH
UCL – University College London	UK

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Executive Summary

Energy-intensive industries (EIIs) are among the largest contributors to greenhouse gas (GHG) emissions. Decarbonising these sectors is therefore crucial for meeting global climate targets. However, such a process is complex given different development priorities, like maintaining economic competitiveness alongside addressing climate change, while the lack of mature mitigation options remains a critical barrier. The role of industrial clusters as areas of enhanced industrial activity and potential innovation hubs is critical.

In this research we perform three empirical sociotechnical analyses in the industrial clusters of Rhine-Ruhr (DE), Port of Rotterdam (NL), and Basque Country (ES) focusing on past and current trends to understand the rules, processes, system dynamics, and actor interactions that are embedded in the current system configuration, and the role of radical, disruptive innovations. By applying the Multi-Level Perspective (MLP) on the key EIIs of iron and steel, cement, chemicals, and the mining industry we shed light on transition implications at different scales based on contemporary dynamics that are part of the sectoral systems. Then, through the Technological Innovation Systems (TIS) and niche analysis, we take a forward-looking approach shifting focus onto the diffusion and market formation—including the barriers and enablers towards creating demand—of low-carbon innovations, such as hydrogen, CCS, bioenergy feedstock, as well as circular economy approaches, mapping their role within the MLP system transformation pathways.

Overall, our regional-sectoral focus offers a comparative advantage over viewing such transitions in isolation. On the one hand, we perform a deep dive into the complexities of specific sectors and innovations, identifying what the transition entails in their context. On the other, by focusing on industrial clusters that feature activities transcending the borders of one specific sector, we aim to understand the interplay of the transitions of different sectors, including synergies and conflicts, hence enabling us to translate the contribution of shifts in standalone systems to the entirety of industry.

During our analysis of the three empirical case studies, we identified common elements as well as notable differences, which can be crucial when attempting to understand the decarbonisation of European industry from a holistic perspective. Understanding the impact of solutions that might work on numerous different contexts, while also respecting the particularities of each region will be an important aspect of efficient sustainability planning. Notably, we highlight potential challenges such as spatial limitations required for extensive infrastructure expansion, differences in the existing capacities and organisational structures of the clusters, as well as enabling factors in the form of ongoing innovation efforts, all potentially affecting the industrial transition in the regions, and the European industry in general. Our analysis also sheds light on the perceived role of specific core mitigation options that are widely discussed, such as hydrogen and CCS, along with significant opportunities and caveats. Crucially we note bottlenecks related to CCS, in the form of public opposition as well as cancellations of existing pilot projects, seemingly limiting the scope of use in selected industrial applications.

We finally discuss how the empirical findings based on the secondary sources collected and analysed through a socio-technical lens can be combined with primary data elicited through stakeholder engagement in the workshops organised by the project, to influence model development and use, by providing the necessary socio-technically informed parametisation and/or the creation of socially desirable scenario narratives.

Contents

Table of Figures

Table of Tables

1 Introduction

The global shift from fossil fuel-based energy systems to cleaner sources is crucial to reduce GHG emissions and mitigate climate change. Achieving such a sustainable transition requires urgent and coordinated global efforts to efficiently exploit the multiplicity of mitigation options (Word Economic Forum, 2024) and should be tailored to the needs of specific sectors, industries, and regions to have effective results (IEA, 2023). Crucially, the transition should be affordable, inclusive, and supported by policies that enable firms (especially smaller ones), as well as other system actors (even at the citizen level), to adopt clean energy technologies without undermining their competitiveness (Rehman et al., 2023), while at the same time increasing their resilience in the light of potential significant economic pressures (IEA, 2023).

A robust foundation for a sustainable transition entails urgently prioritising interventions that aim to decarbonise major sources of emissions in the economy. Heavy industry has been repeatedly perceived as one of the hardest sectors to decarbonise, mainly due to its heterogeneity, GHG emissions intensity, trade exposure, investment-relied nature, and long-lived facilities (Bataille et al., 2018). Production of commodities by energy-intensive industries (EIIs) is responsible for approximately a third of annual global GHG emissions (Bataille et al., 2018), and account for 38% of total final energy consumption—in comparison, buildings account for 30%, while transport for 26%. Specifically, the steel and cement industries, along with the production of chemicals, paper, and aluminium are the most carbon-intensive sectors, responsible for around 17% of global GHGs, demanding nearly 90% of coal, 70% of crude oil, and 55% of natural gas used in industry (IEA, 2023).

Decarbonising EIIs is a complex task due to stronger climate policies long exempting hard-to-abate sectors from environmental regulations (i.e., higher carbon prices), fearing they would risk competitiveness (Bataille et al., 2018). In addition, industrial strategies towards sustainability are bound by developments at the regional, national, and international level (i.e., energy prices, trade tariffs), usually prohibiting policymakers from formulating clear and coordinated visions or pathways (Åhman et al., 2017; Bataille et al., 2018) across all levels of governance. Stakeholder-oriented pathway processes have thus been proven as important tools towards creating inclusive and realistic visions for spatially and regionally informed industrial sustainable futures that feature socially legitimised solutions (Lechtenböhmer et al., 2015; Weber & Rohracher, 2012). However, more than half of EIIs' emissions reductions must come from technologies that are not yet market-ready, despite their proven effectiveness (IEA, 2024). Therefore, fully developed pathways require long-term dynamic strategies that include the whole innovation chain, ranging from the funding of research and development (R&D) as well as pilot and demonstration of projects, to market-formation regulations and standards (Åhman et al., 2017; Wesseling et al., 2017). Such considerations should follow a place-based approach (Sovacool et al., 2024), as most groundbreaking initiatives (i.e., testing or adopting innovative processes, technologies, and approaches) will naturally need to occur in regions with a strong industrial presence, like the industrial clusters included in TRANSIENCE that are active across multiple value chains.

Research on sociotechnical transitions has become a core framework to analyse transformative changes, while within the context of transitions towards sustainability—henceforth sustainability transitions—efforts have focused on several sectors including energy, buildings, mobility, and agri-food systems (Sovacool et al., 2020). However, applications of such frameworks in industrial and energy intensive sectors remain scarce (Koasidis et al., 2020) or not always aligned with the needs of regions featuring such activities (Sovacool et al., 2024). Yet, the emergence of radical low-carbon innovations, especially those with a potential use in industrial applications (e.g., hydrogen; Rosenow, 2022) has been urgently demanded by societies and industries that are now facing climate change consequences in various parts of the world. Two sociotechnical frameworks that can be thoroughly and empirically applied to analyse such eminent transition processes are the multi-level perspective (MLP) and the technological innovation systems (TIS). The two qualitative approaches have been progressively adapted to map the diffusion of low-carbon innovations as well as their systemic and societal embedding (Sovacool et al., 2020). Sociotechnical approaches study the interactions of technological, cultural, and social changes during transitions towards sustainability (Markard et al., 2012). Such approaches in sustainability transition research have led to a typology of multiple transition pathways guided by the variations of timing and the nature of sociotechnical transition processes (Geels & Schot, 2007a). Within this framing, leveraging the socio-technical sustainability transitions perspective is crucial to analyse and understand industrial transition pathways and the potential diffusion of low carbon innovations, including uncovering the systemic and technological complexities integrated in developing pathways for a sustainable and competitive European industry.

Within this context, in this research we perform three empirical sociotechnical analyses in the industrial clusters of Rhine-Ruhr (DE), Port of Rotterdam (NL), and Basque Country (ES) focusing on past and current trends to understand the rules, processes, system dynamics, and actor interactions that are embedded in the current system configuration, and the role of radical, disruptive innovations. By applying the MLP on the key EIIs of iron and steel, cement, chemicals, and the mining industry we shed light on transition implications at different scales based on contemporary dynamics that are part of the sectoral systems. Then, through the TIS and niche analysis, we take a forward-looking approach shifting focus on the diffusion and market formation—including the barriers and enablers towards creating demand—of low-carbon innovations, such as hydrogen, CCS, bioenergy feedstock, as well as circularity approaches, mapping their role within the MLP system transformation pathways. Overall, our regional-sectoral focus offers a comparative advantage over viewing such transitions in isolation. On the one hand, we deep dive on the complexities of specific sectors and innovations, identifying what the transition entails in their context. On the other hand, by focusing on industrial clusters that feature activities transcending the borders of one specific sector, we aim to understand the interplay of the transitions of different sectors, including synergies and conflicts, hence enabling us to translate the contribution of shifts in standalone systems to the entirety of industry.

The rest of the report is organised as follows. In Section 2, we discuss key theoretical aspects of socio-technical transitions and frameworks, and we present the adopted MLP-TIS framework used for the empirical analysis of the industrial clusters, as well as elaborate on the selection of secondary sources. In Sections 3, 4, 5, we present the core case studies for Rhine-Ruhr, the Port of Rotterdam, and the Basque Country. Section 6 offers a synthesis of cross-cutting themes identified from the different case studies, entry points to modelling, and concluding remarks.

2 Methodology

2.1 Sociotechnical transition theory

2.1.1 Sociotechnical transition: an innovation process

A sociotechnical transition involves a set of processes leading to a fundamental shift from one sociotechnical system configuration to another (F. W. Geels & Schot, 2007a). Sociotechnical systems consist of networks and institutions as well as material artifacts and knowledge (F. W. Geels, 2004; Markard et al., 2012; Weber, 2003). Networks can be developed by individuals, firms, and organisations while institutions present the regulations, standards and good practices, and societal norms existing in a sociotechnical system. Material artifacts and knowledge are the manifesting elements of possible changes in sociotechnical systems. For one system to shift into another, radical changes must take place along multiple dimensions: technological, material, organisational, institutional, political, economic, and socio-cultural, encompassing a multi-actor interplay of interactions between businesses, firms, user groups, scientists, policymakers and special interest groups (F. W. Geels & Schot, 2007a). This interplay brings about the emergence of new products, services, business models, and organisations, commonly framed as technological or social innovations (Markard et al., 2012), which may partly complement and/or substitute the previous (existing) ones and to which societies and markets under transition need to adapt to.

Transitions should be conceived as long-term processes that unfold over a lengthy time spans, although breakthroughs may be relatively faster (Geels & Schot, 2007a; Markard et al., 2012). Accordingly, sustainability transitions are long-term, multi-dimensional, transformative processes that shift socio-technical systems into a sustainable means of production and consumption (F. W. Geels & Schot, 2007a), despite the urgency of mitigating climate change (Geels, 2019). Regulatory frameworks, institutional support as well as political actors play a crucial role in sustainability processes (Smith et al., 2005).

2.1.2 Sociotechnical dynamics in sustainability transitions

Sociotechnical transition frameworks study how change affects existing sociotechnical systems by assessing the attempts of innovations to diffuse into the sociotechnical system (Markard et al., 2012). Sustainability transition processes examine the development and diffusion of innovative sustainable technologies, and notably the interactions of technological, cultural, and social changes during transitions towards sustainability (Markard et al., 2012). Sociotechnical transitions, and in particular sustainability transitions, have been increasingly studied by social scientists during the last decades, arguing that sustainable development does not only depend on technological solutions but also derives through social and cultural change (Geels & Schot, 2007a). Such approaches distinguish between the sociotechnical regime and the niche level. On the one hand, the regime reflects the scientific knowledge, the engineering practices, and the process technologies that are socially embedded and strongly associated with the expectations and skills of technology users, institutional structures, and with broader infrastructures (Kemp et al., 1998); in other words, sociotechnical regimes reflect the logic of established development pathways directing incremental sociotechnical changes (Markard et al., 2012). On the other, the niche level refers to protected spaces such as domains of application, i.e., markets, in which radical innovations (i.e., novel technologies) can develop without being subject to the selection pressure of the prevailing regime (Kemp et al., 1998; Markard et al., 2012). Niche markets, actors, and networks can develop new technologies, business models, or practices irrespectively of the established regime, introducing new expectations and challenging dominant

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technologies (Geels & Raven, 2006).

2.2 Common Sustainability Transition Frameworks

2.2.1 The Technological Innovation Systems (TIS) explained

The TIS framework investigates the factors influencing the development and diffusion of sustainable innovations systems within a specific time and place (Hekkert et al., 2007). Innovation systems consist of a set of organisations and networks of actors and institutions that foster the development, diffusion, and utilisation of novel innovations (Hekkert et al., 2007). The framework is commonly employed to produce policy recommendations, such as technology-push initiatives, facilitated, for example, through subsidies, to introduce new technologies. Both the scientific and policy making communities increasingly acknowledge that understanding technological change is best achieved by considering the emergence of innovation technologies as the outcome of innovation systems (Hekkert et al., 2007). The concept of TIS can be perceived as a heuristic attempt studying all societal subsystems, actors, and institutions contributing in any manner - directly or indirectly - consciously or unintentionally, to the emergence or production of innovation (Hekkert et al., 2007). Therefore, the TIS framework perceives sustainable technological change as a dynamic process.

Actors and networks can be firms, governmental agencies or non-governmental organisations, universities, research facilities, or sectoral associations. Institutions refer to the laws and regulations, sociocultural and technical norms, practice patterns and shared expectations. TISs are created when actors, networks, and institutions interact within the context of a specific sector and infrastructure, participating actively in the generation, diffusion, and utilisation of a particular technology (Hekkert et al., 2007; Markard & Truffer, 2008). Despite the interdependence of these interactions (between actors and institutions), actors maintain the freedom to choose whether to transform, adapt, or even create new institutions to promote their development (Markard & Truffer, 2008).

Within the TIS framework, assessing innovation processes evolves around their functions (Markard & Truffer, 2008). Functions detect the determinants of change by carefully mapping the activities taking place within the system showing high or low performance: they reveal possible ways to influence innovation development and increase innovation speed (Hekkert et al., 2007). In a sense, functions determine the technological development within a system (Hekkert et al., 2007). Hekkert et al., (2007) amongst others, have proposed a set of indicative functions (see Figure 1).

Function	Definition
F1: *Entrepreneurial activities*	Entrepreneurial activities involve company engagement in projects, high technology readiness level product testing, diversification into new industries, new entrants and commercial activity
F2: *Knowledge development*	Knowledge development occurs in private, in-house R&D departments or in publicly funded research institutes or universities. It focuses on basic research and low technology readiness levels
F3: *Knowledge diffusion*	Knowledge diffusion occurs through the exchange of information via networks, partnerships and shared project experience/collaboration
F4: *Guidance of the search*	Guidance of the search comes from both the government, in the form of discourse and policy visions/targets, and company/private sectors visions
F5: *Market formation*	Market formation is set by government market policy, tax exemptions, market regulations and consumer and private sector demand
F6: *Resource mobilization*	Government funds supplied for R&D and market subsidies as well as private investments in human and financial resources
F7: *Legitimacy / counteract resistance to change*	Legitimacy is driven and supported by the government, consumer acceptance and private lobbying activities

Figure 1. TIS Functions and their definition

Source: (Bergek et al., 2008; Hekkert et al., 2007; Hekkert & Negro, 2009; Wieczorek & Hekkert, 2012)

Function 1 (Entrepreneurial activities) maps the number of new entrants pursuing business opportunities in new markets or incumbent companies that reconfigure their business strategy to take advantage of innovative technologies. Entrepreneurial activities and/or firm interactions are primary indicators of a system's performance in a well-functioning TIS.

Function 2 (Knowledge development) maps research and development (R&D) projects and patents (learning by searching and learning by doing) as well as their relevant investments.

Function 3 (Knowledge diffusion) maps the exchange of knowledge/innovation (learning by interacting, learning by using) within collaborative networks, identifying their size and intensity over a certain period. Workshops and conferences devoted to a specific topic/technology could also provide diffusion-relevant indexes.

Function 4 (Guidance of search) displays the direction of learning processes, including shifts in societal preferences, technology users' expectations, policy ambitions and/or long-term goals (e.g., GHG emission reduction targets) that could incentivise novel technological shifts and raise expectations upon a certain technological path. Mapping the dominant narratives stemming out of scientists, businesses, and policymakers could illustrate those expectations.

Function 5 (Market formation) tracks the number of niche markets introduced to map policy-relevant incentives (e.g., specific tax regimes, new environmental standards, carbon pricing etc.) enabling those markets to become operational.

Function 6 (Resources mobilisation) maps the allocation and/or the actors' accessibility to sufficient resources (e.g., human capital, financial capital) necessary to promote niche innovation developments.

Function 7 (Creation of legitimacy) maps the activities of emergent organisations, lobbies, and interest groups supporting or resisting innovation technology paths, with the potential to influence policymaking, and thus guide developments in other functions.

The functions described above should not be conceived as linear processes but instead as interactive schemes featuring both temporally and spatially relevant successions of activities or gaps in niche-level developments.

2.2.2 The Multi-Level Perspective (MLP) explained

The multi-level perspective (MLP) aims to identify regime-level shifts in terms of technologies, knowledge, technical artifacts, policies, markets, supporting infrastructure, systemic structures as well as user practices (F. W. Geels, 2002; Markard & Truffer, 2008). These changes are conceived as taking place in vertical and horizontal axes, referring to three distinct levels, namely the regime, the niche and the landscape level (see Figure 2), in heterogenous sociotechnical structures (Geels & Schot, 2007a). By examining the trajectories within and between these three axes of the transition process, the dynamics of each MLP level can be illustrated. While sociotechnical system trajectories co-evolve, tensions may appear if changes are not properly adjusted within the regime level or there is lack of synchronicity with landscape pressures (Geels & Schot, 2007a). These tensions create "windows of opportunity" for niche-innovations to breakthrough beyond the niche level. Hence, the MLP framework interprets the interacting processes as well as the alignments creating tensions triggering windows of opportunity for niche-innovations (Geels & Schot, 2007a).

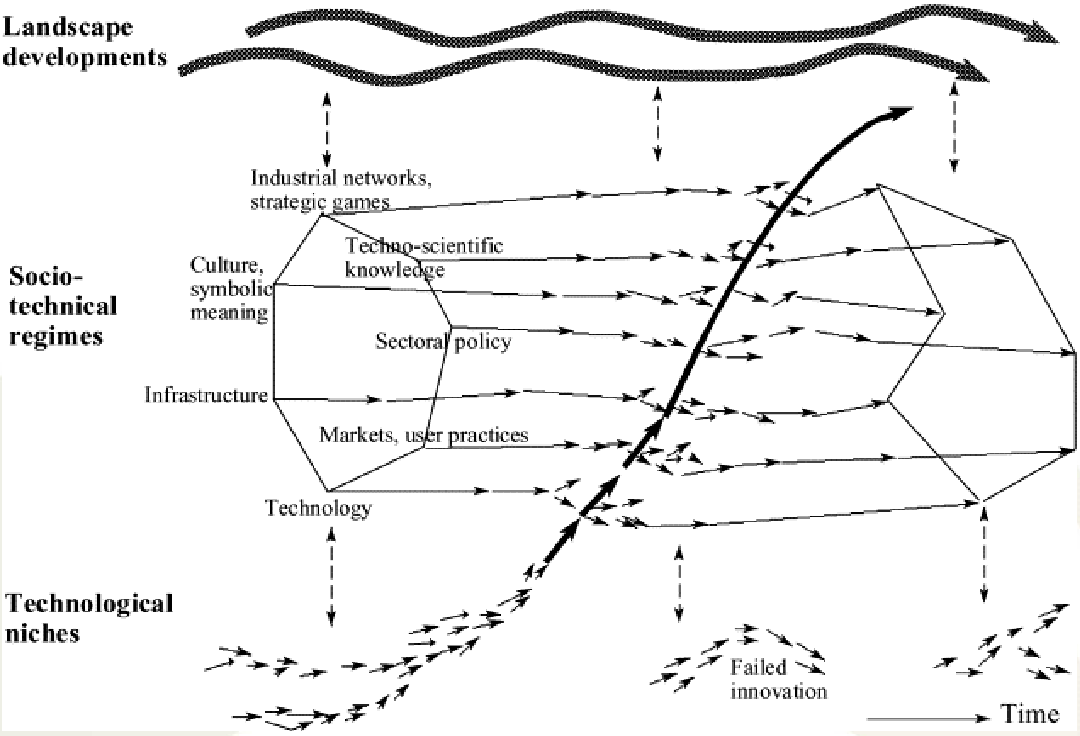

Figure 2. The MLP framework

Source: (Geels, 2002, 2005)

The sociotechnical regime is conceived as a tightly bound meso-level with a concrete structure that consists of established products and technologies, knowledge stockpiles, user behaviours, expectations, norms, and regulations (Markard & Truffer, 2008). Influenced from evolutionary theories, the regime-level portrays the context of technological development acting as a barrier for the diffusion of radical innovations with the potential to disrupt it (Markard & Truffer, 2008). Landscape factors influence a stable regime only incrementally, giving it the time to adjust to transition processes. However, when landscape factors exert intolerable pressure upon the regime, they can potentially disturb its coherent structure and eventually, destabilise it. This explains why the framework primarily conceives radical innovations as disruptive developments (Markard & Truffer, 2008). Niches represent the micro-level, protecting the development of radical innovations at the early stages from the regime resistance and/or landscape pressures (Markard & Truffer, 2008).

The framework has been used to analyse both historical (Berkers & Geels, 2011; Geels, 2002, 2005, 2020;

Geels & Schot, 2007b), current, and future sustainability transitions (Geels, 2020; Nykvist & Nilsson, 2015; Van Bree et al., 2010). The concept highlights both radical change and dynamic stability (Geels, 2020). Radical change is reflected through the concept of niches as spaces incubating radical novelty, while the regimes illustrate established structures. The landscape level refers to externalities that can influence both these regime structures and protected niches. Destabilisation delving from landscape pressure, offers possibilities for the diffusion of niche-innovations in an either symbiotic relationship with ongoing regime processes or a competitive one, ultimately resulting in regime's substantial disruption. Niche-innovations could only increase momentum if niche-relevant learning processes, price and performance improvements, and expansion of social networks is promoted (Geels & Raven, 2006).

The MLP framework can reveal the level of autonomy and/or dependency amongst different groups of actors or networks diagnosing the key players of different trajectories. As these trajectories co-evolve, tensions may appear if changes in trajectories are not properly adjusted (within the regime level) or there is lack of synchronicity (with landscape externalities) (Geels & Schot, 2007a). These tensions create "windows of opportunity" for niche-innovations. Hence, the framework can reflect both the interactions and the alignments between the three levels. Considering niche innovations as the "seeds of transition process", whether these seeds will sprout is determined by their respective landscape (Geels & Schot, 2007a). In case sustainable technological developments lose track, this is due to the dynamics in both the regime and landscape level, 'trapping' innovations within the niche level, potentially for a prolonged period of time (Geels & Schot, 2007a). This multi-level approach can thus illustrate the possibilities of strong regime resistance or niche-innovations mismatch with incumbent regime structures. At the same time, windows of opportunities can be useful to evaluate the performance of protected niche-innovations.

2.2.3 Existing industrial applications of sociotechnical transition frameworks

These sociotechnical approaches have been extensively applied for the analysis of sustainability transitions and innovations within several sectors, including the transport and energy sectors. Both the MLP and TIS frameworks—amongst other sociotechnical approaches (e.g., strategic niche management, transition management, etc.)—have been particularly applicable to these sectors due to their comprehensive nature, focusing on various scales (e.g., eco-industrial parks, electronics sector, single plants, waste management systems) and various spatial and temporal contexts.

Some indicative MLP analyses include the analysis of the diffusion process of social innovations within the sustainability vision of the German 'Energiewende' in North Rhine-Westphalia (Hölsgens et al., 2018), a highly industrialised region of relevance to TRANSIENCE, the post-lignite transition in Greece (Nikas et al., 2020), the lock-in and emerging regime tensions in Sweden's heat-energy system (Dzebo & Nykvist, 2017), and the adoption process of biofuels within the fossil fuel-based aviation industry (Kim et al., 2019). Accordingly, indicative TIS analyses have highlighted the barriers (i.e., strict investment criteria) obstructing the diffusion of industrial heat pumps in the Netherlands (Wesseling et al., 2022), or hydrogen-based direct reduced iron (DRI) in the Swedish steel industry (Kushnir et al., 2020), the 60-year long development of hydrogen fuel-cell innovation in the UK (Hacking et al., 2019), or Taiwan's biodiesel innovation system (Chung, 2018), the lack of support to create new markets and value chains for concentrating solar power (CSP) technology (Lilliestam et al., 2021).

2.3 Towards a definition of industrial sustainability transition pathways

The MLP has been applied to analyse both historical (Berkers & Geels, 2011; Geels, 2002, 2005, 2020; &

Schot, 2007a), and future sustainability transitions (Geels, 2020; Nykvist & Nilsson, 2015; Van Bree et al., 2010), emphasising both radical change and dynamic stability. By highlighting the transition trajectories within existing regimes, the framework can be used to diagnose different transformation pathways (Geels & Schot, 2007a). Indeed, Geels and Schot (2007) have further refined the MLP framework introducing a typology of multiple transition pathways based on variations of timing and the nature of multi-level interactions. Specifically, the authors have tried to counter a presumed bottom–up, niche-driven bias within the socio-technical system framework, proposing a range of stylised transition pathways that describe niche-innovations replacing, merging with, or co-existing with existing regime structures, implying that entire and/or partial replacements of incumbent regimes are not commonly met in real-world cases. This typology (Geels and Schot, 2007) includes four different transition pathways: transformation, de-alignment and re-alignment, technological substitution, and reconfiguration, while proposing a standard reproduction pathway (no external landscape pressure; regime remains dynamically stable and reproduce itself) along with a fifth option to include a sequence of transition pathways proposed above.

Transformation entails moderate landscape pressure at a moment when niche-innovations have not been sufficiently developed. When regime actors/networks perceive and act upon landscape pressure, they adjust by proceeding with the necessary reorientation of their activities to respond to these changes. Niche-innovations cannot take advantage of landscape changes. Yet, regime insiders tend to neglect negative landscape externalities. Outsiders are important in this case, since they can provide with timely 'translations' of negative externalities and thus protect incumbents. In this pathway "new regimes grow out of old regimes through cumulative adjustments and reorientations" without disrupting established regime structures.

De-alignment and re-alignment entail large or sudden disruptive landscape change leading to the eventual erosion of the regime. If niche-innovations are not sufficiently developed, then space is created for the emergence of multiple competing niche-innovations, carried out by outsiders or diversifying regime actors, de-aligning the regime structure and creating uncertainty. The re-alignment of a new regime would eventually happen when one of these niche-innovations becomes dominant.

Technological substitution describes an avalanche change occurring through intense landscape pressures when niche innovations have already been adequately developed but haven't previously been able to disrupt a stable regime structure. In this case, regime incumbents pay little push for incremental changes (as in the case of the transformation pathway) but cannot sustain landscape pressure causing major regime tensions and leading to windows of opportunity for niche-innovations.

Reconfiguration refers to the symbiotic relationship between regime and niche-innovations adopted to provide local solutions. Initially not disruptive, niche-innovations may trigger further developments affecting the basic architecture of regime structures. Regime's co-evolution with a multiplicity of technical novelties under the influence of landscape pressure, can thus lead to regime changes. In this pathway, the new regime grows out of the old regime, but it is subjected to major reconfigurations (and hence diverges from the transition pathway).

This typology insists on the slow speed of disruptive change, unless the landscape is subject to a shock, suggesting that a sequence of transition pathways would be the best framework to analyse transitions. This is because, in real-world cases, actors perceive only moderate change and are thus drawn more towards transformation and reconfiguration pathways. As pressure continues to build towards a dominant direction then landscape pressure becomes more disruptive, possibly leading to substitution or re-alignment.

Based on the definitions of the transition pathway typology described above, the empirical sociotechnical analyses produced within TRANSIENCE across different geographic boundaries among the four case studies targeted in the project (including the Rhine-Ruhr, Port of Rotterdam, Basque Country, and Silesia industrial clusters) under D3.9 will provide regionally specific and timely-informed qualitative backgrounds toward better informed modelling. Analysis with such frameworks at different scales will shed light on the role of radical, disruptive innovations, with a focus on key EIIs (iron and steel, cement, chemicals, etc.) as well as sectoral, regional, and international contexts, understanding rules, processes, system dynamics, actor interactions accompanying a shift to a climate-neutral, circular industry. As transitions have different meanings for each value chain, sector, technology, our focus will be drawn towards understanding the contribution of shifts in standalone systems to the entirety of each cluster's environment, to conceptualise and synthesise a broader transition to industrial climate neutrality and circularity, guiding quantitative modelling.

The process of developing coherent decarbonisation pathways for EIIs primarily relies upon recent technological developments such as renewable energy, hydrogen, and CCUS. However, their competitive advantages and potential markets heavily depend on technological readiness levels, established or planned infrastructure, knowledge development, cooperation initiatives, investment incentives, supporting regulation, and public acceptance.

At the same time, industrial decarbonisation can be facilitated through international and regional initiatives that foster collaboration across industries and regions to exchange best practices and create demand for near-zero emissions products (IEA, 2023). Coordinated efforts across various sectors can be influenced by the strength of relationships and the flow of information between actors. Configurations that have hitherto been based on industrial symbiosis are particularly relevant for heavily industrialised regions, since existing networks and innovation diffusion flows consist of separate entities located in proximity, which are willing to engage in a collective approach involving physical exchange of materials, energy, water, and by-products for their competitive advantage (Chertow, 2000).

These crucial factors for industrial transition pathways can be explicitly targeted analytically within the two sociotechnical transition frameworks, MLP and TIS, and are going to determine the technology, policy mix, and configuration transformations that are both feasible and hoped for in each specific industrial region towards achieving climate goals without jeopardising economic growth (Neves et al., 2020).

2.4 The adopted framework for the TRANSIENCE pilot regions

2.4.1 Common critiques of sociotechnical transitions frameworks

Sociotechnical transition frameworks are widely employed to unfold future sustainability transitions. The global mandate for CO_2 reductions forces EIIs to decarbonise, while at the same time industrial stakeholders aim to balance the pace of their demand/supply chains and their efforts towards sustainable innovations globally. The MLP framework encompasses both a 'global' and a 'local' model component to outline the overarching course of sustainability transitions and specify the causal mechanisms within multi-level interactions (Geels, 2019). By understanding 'large-scale' change as 'transition', the MLP can address long-term sustainability effects demonstrating that life-cycle analyses or other relevant models are not the only approaches used to identify sustainability outcomes (Geels, 2019). Furthermore, it is the only framework able to identify possible transition pathways (Geels & Schot, 2007). However, critics have pointed out its limited attention to politics, power dynamics, and cultural meanings (Lockwood et al., 2017). In response, scholars have been increasingly incorporating political science theories to detect the potential for policy developments at the regime and niche levels (F. W. Geels, 2019), advocating for more robust governance analyses (Turnheim et al., 2015). Geels and Schot (2010) had already diagnosed the need for incorporating more theories to produce precise explanations of relationships among technology, policy, and economics, later calling for the framework's flexibility to integrate interdisciplinary insights (Geels, 2019).

A consistent criticism over both frameworks revolves around their emphasis on bottom-up disruption pathways (Markard et al., 2012). At the same time however, others have claimed that the frameworks lack a careful examination of specific processes of technology generation, development, and diffusion (Weber & Rohracher, 2012). For instance, MLP is accused of ignoring the potential of incumbent actors for incremental change offering only a blur portrayal of system destabilisation (Hodson & Marvin, 2009). The TIS framework relies heavily on its functions to analyse a transition process by explicitly referring to innovation generation, development, and diffusion indexes. Diverging from the MLP's emphasis on the levels of development, TIS relies mostly on transition agents, the primary actors of pursuing technological innovations. Nonetheless, TIS is neither expected to offer holistic overviews of radical innovation processes nor provide long-term forecasts (Markard & Truffer, 2008). Instead, the framework's aim is to identify the micro-level of niche technologies within an established system, its expertise lying in integrated market dynamics (Weber & Rohracher, 2012). TIS examines how entrepreneurs identify market opportunities and mobilise resources to bring innovative technologies to the market (Geels, 2002, 2005). It explains how key R&D agents can advance with new knowledge and technologies through developing prototypes and conducting research (Geels & Schot, 2010; Weber & Rohracher, 2012). Hence, collaboration, competition, knowledge exchange, and resource allocation are under the framework's microscope (Weber & Rohracher, 2012).

Hölsgens et al., (2018) alleged that, because sustainability transitions impose widespread transformations of energy systems into new co-existing conditions, single sustainability research frameworks confront difficulties to interpret both the micro- and the macro-level of the transition processes. Each sustainability transition approach individually provides different and exclusive transition aspects according to their core examination methodology. As efforts are being made to fully capture the transition processes, researchers tend to shift to more inclusive, and notably flexible and efficient approaches (Markard et al., 2012), with the literature increasingly including integrated methodology frameworks that can adapt to the emerging transition processes (Markard et al., 2012; Markard & Truffer, 2008).

2.4.2 The adopted integrated MLP-TIS framework

Markard and Truffer (2008) were the first to propose an integrated approach combining both the MLP and the TIS framework, arguing that their integration provides an articulation of both the transition and the system's components. Weber and Rohracher (2012) further encouraged this integration highlighting the complementarities and the common goals for policy legitimation and innovation dynamics. Overall, integrated approaches gain higher acceptance in policy circles as they include demand and supply variables in justification for policy intervention (Markard et al., 2012), particularly in complex sustainability transitions (Weber & Rohracher, 2012). By building a bridge between transition thinking and more established innovation policy approaches (Markard & Truffer, 2008; Sharif, 2006), the complementarity of TIS and MLP relies upon MLP's long-term perspective and TIS's micro-level of niche development inside an established regime. In addition, an integrated MLP/TIS approach makes each framework's application domain unambiguous (Nikas et al., 2022) while developing consistent performance comparisons (Markard & Truffer, 2008) to propose ways to support the development of technological innovations. At the same time, both approaches employ a systematic identification and assessment of the broad range of factors affecting innovation process (events, developments, institutional effects, actor behavior) (Markard & Truffer, 2008). However, it always depends on the research objective whether these approaches shall be combined. When integrated though, MLP and TIS can demonstrate the interactions between the system and its surroundings holistically (Markard & Truffer, 2008).

There are several examples of an applied integrated MLP/TIS approach in the literature. For example, Nikas et al. (2022) employed both approaches to examine the historical evolution of sustainability transition processes as well as diffusion levels and establishment of biodiesel in the transport system of Argentina and Brazil. Miedema et. al. (2018) examined the application of biomass gasification to the Dutch residential sector using TIS and then, applied MLP to map the sectoral configuration of the natural gas regime and renewable heat diffusion. To study wind energy in Colombia, Edsand (2017) employed TIS to examine the slow diffusion of the technology and MLP to understand the influences of broader landscape pressures.

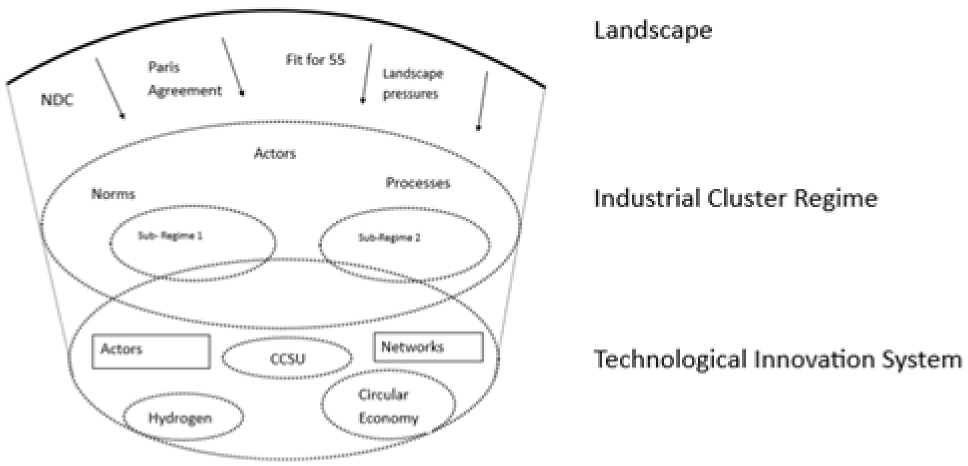

Figure 3. Indicative conceptualisation of the integrated MLP-TIS framework in industrial clusters.

Adapted from Nikas et al. (2022)

Given the complexity of industrial transitions—and crucially both the focus on technological developments of innovations that are not yet commercially available for large-scale implementations and overall configuration factors like industrial symbiosis—an integrated MLP/TIS approach (see Figure 3) will be applied for the sociotechnical analyses of selected industrial case studies. Following a consistent literature review process, tailored to each EII and region, we aim to demonstrate the most prevailing interdependencies between local actors and institutions engaged in low-carbon industrial decarbonisation and circularity, also acknowledging niche-innovation-relevant knowledge exchange trends. Specifically, we will trace MLP dynamics through the historical dependency of industrial clusters on fossil fuels and try to reveal the landscape pressures imposed on incumbent regime structures. MLP will also be applied to portray the overall progress of each industrial region towards sustainability. Then, the TIS framework will be used to map and evaluate the emergence of industry-relevant technological innovations (i.e., hydrogen, CCUS). By applying the TIS functions (described above) we will provide insights of each cluster's innovation and institutional capacity. The exact analytical approach employed in each case study depended on the insights reflected in the elicited literature (e.g., in the Basque country a niche-based analysis was preferred to a TIS one for the micro-level of the MLP which was more appropriate given the progress of transition and the discussions in the literature). Overall, we aim at juxtaposing and equally highlighting each region's long-term sustainability strategies with their most recent niche-innovation developments to produce regionally specific insights to guide and inform conceivable scenarios towards, and policy insights for, future trajectories and decarbonisation strategies.

2.4.3 Process for the collection of secondary sources

Building empirical socio-technical analyses entails collecting a plurality of information—mostly from secondary sources—to map all dynamics embedded within a system or a transformation process, whether historical, contemporary or forward-looking. To achieve this, we constructed a review protocol aimed to collect information on the three case studies of interest. While the review was not explicitly conducted as a systematic literature review, e.g., following the PRISMA guidelines, it was informed by core principles of systematic reviews such as clear queries, inclusion/exclusion criteria, documentation of sources etc.

In particular, we used Google Scholar for the identification of relevant sources. This selection, instead of e.g., using Scopus or Web of Science that are typically employed in reviews, was based on the fact that critical material and information are included in industry-led, hence not purely academic, reports as part of the grey literature, which Google Scholar assisted towards accessing more easily. The queries used were based on the following core string:

- (Potential methods) AND (Sectoral focus) AND (REGION)

For example, a universal query found useful was the following:

- ("MLP" OR "Multi-level Perspective" OR "TIS" OR "Technological innovation system") AND ("Energy Intensive Industries" OR "Energy Intensive Industry") AND ("Rhine-Ruhr" OR "Port of Rotterdam" OR "Basque Country").

We note however that in many cases the query required adaptation, e.g., to include the different names used for the Rhine-Ruhr region, while in some other cases also including the country instead of solemnly the region was necessary to avoid missing information.

After the first elicitation, we applied the following inclusion/exclusion criteria:

- The types of studies included are scientific papers, industry reports, and policy documents. However, these should be in English. Although it is possible that some reports may be in local languages, the risk of missing information is mitigated given the international focus of the three clusters.
- For each case independently, the region of interest should be explicitly analysed or brought into context within the national framing.
- The same was also applied to the sectoral aspect, focusing on papers that explicitly delt or significantly commented on one or more energy intensive industries.
- Although we avoided imposing a strong exclusion criterion based on papers following socio-technical methodologies, we required papers to include in part core socio-technical terms and dynamics to build a strong basis for our analysis.
- The review was conducted between October 2024 – April 2025 (depending on the case study). Given that the transition of industry is not yet experiencing the speed of the transition in other sectors (e.g., power generation), no cut-off date was placed on the sources.

The technological dimension was approached as a dependent variable in the review protocol, allowing the literature itself to bring forward the technologies prominently featured in ongoing discussions within the clusters. This carries a potential selection bias risk (i.e., missing on technologies that are currently under-discussed). However, we mitigated this risk by coding a wide range of potential technologies/options identified in the literature. That said, since our core aim is to focus on innovations with an expanding TIS, the main analysis concentrated on technologies more prominently featured in the literature included.

Titles were progressively filtered by title and abstract, then by accessing the full text. This process finally led to the inclusion of 65 papers for the Rhine-Ruhr or the broader North Rhine-Westphalia, 53 papers in the Port of Rotterdam, and 45 papers in the Basque Country.

3 The Rhine-Ruhr case study

3.1 Background

The Rhine-Ruhr region is located in western Germany, near the borders of Belgium and the Netherlands, and includes the administrative districts of Düsseldorf (NUTS2 Region DEA1) and Cologne (DEA2), which are part of the Federal State of North Rhine Westphalia (NRW). Düsseldorf and Cologne are among the most densely populated districts in Germany with a high urbanisation level. The GDP per capita in the Rhine-Ruhr region was around €44in 2023, which is 5% less than Germany's national average. The two regions in the NRW area constitute the bulk of what is termed as the Rhine-Ruhr industrial cluster, with Ruhr (Düsseldorf) featuring primarily steel-related activities, and Rhineland (Cologne) the chemical industry—after a transition from a coal-based economic development.

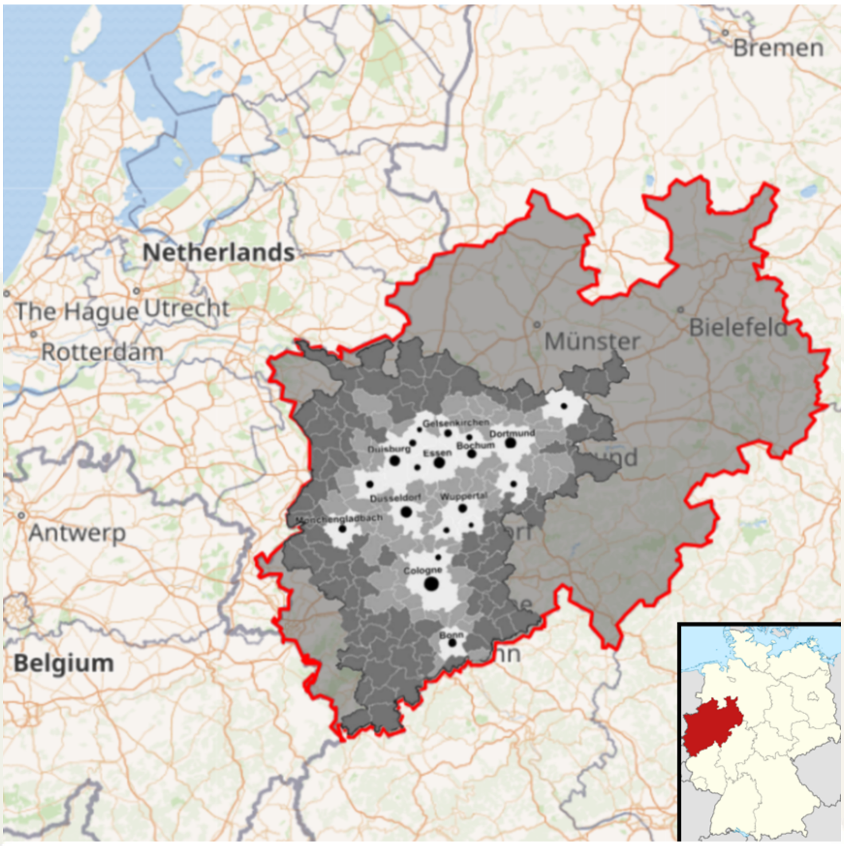

Figure 4. The Rhine-Ruhr metropolitan region (with most populated urban areas in white) within the State of NRW boundaries shown in red

A major German industrial hub, the NRW State is responsible for the production of 30% of cement, 30% of chemical, and 40% of steel and the highest total and per capita electricity consumption in Germany (Abdelshafy & Walther, 2022b). This industrial system, which is mostly concentrated along the Rhine-Ruhr corridor, is shaped through major economic, technological, and political changes over the last two centuries and a long industrial history, centred around its abundant coal resources—which are, historically, strongly associated with the economic interests of big electricity providers. While coal mining in Germany experienced a continuous, controlled decline over six decades, due to non-competitive coal prices, joint resistance of mining companies, politicians, and trade unions sought to delay restructuring and argued for the modernisation of the established steel and coal mining sectors instead of pursuing new economic possibilities (Oei et al., 2020).

Primary steel is a significant industry in NRW, producing approximately a third of Germany's total steel production, 85% of which at the Ruhr area (Abdelshafy & Walther, 2022b). Named after the river flowing through it, the Ruhr area is a polycentric urban region of 5.1 million inhabitants (in 2019) (Hassink & Kiese, 2021). Duisburg, in the administrative district of Düsseldorf, is the heart of Germany's steel industry, counting more than 40,000 employees. Primary steel production activities are generally performed by integrated plants that produce a wide range of final high-quality steel products, usually tailored to service the automotive and mechanical engineering sectors, which are also both located in NRW. The proximity of steel supply and use and the symbiotic nature of industrial activities formed around it is an important asset of the region's industrial capacity and competitiveness.

Rhineland, the biggest lignite region in Germany, continues to produce lignite, however production is already been gradually reduced, following Germany's decision for an early lignite phase-out in the Rhenish mining area until 2030 (Wegener et al., 2023)[1], and the decoupling of its industrial capacity and regional economy from fossil fuels (Hermwille et al., 2023). The region, located to the south and north of Cologne along the Rhine, was forced to shift its coal-based fuel production to petroleum-based chemical industries in the 1950s, since most of its production facilities were destroyed during Worls War II (Scholz et al., 2024)., Today, Rhineland is favoured by its advantageous location and notably its existing inland and transnational pipeline connections with other major chemical industries and petrochemical clusters. The Rhineland chemical cluster, also part of the chemical supercluster of Antwerp-Rotterdam-Rhine-Ruhr Area (ARRRA) that is considered the largest chemical region in Europe, currently hosts 260 chemical companies and 70,000 workers, collectively generating €30 billion in sales—amounting to 22% of Germany's total chemical revenue (Scholz et al., 2024).

Lignite mining is still extracted there for the needs of 13 adjacent power plants, supplying 44% of NRW's electricity production. On the other hand, hard coal mining, historically located in the Ruhr area, has phased out since 2018. To replace the closed domestic sources, Germany currently imports hard coal from the U.S., Colombia, and Russia (Coggio & Gustafson, 2019). Coal companies and trade unions, that were initially pushing the government towards policy measures against brown coal phase-out, have gradually been in support of the restructuring process. Their main arguments have included security of supply and safeguarding local jobs and municipal revenues that were dependent on the local power companies' financial profitability (Brauers et al., 2020).

Overall, NRW is responsible for about a quarter of Germany's GHG emissions (a level equivalent to large European countries such as Spain), 50% of which come from the power sector and 21% from the industrial sector (Abdelshafy & Walther, 2022b); in fact, RWE and E.On, two major German energy companies based in NRW, were amongst the top emitters in the EU Emission Trading System (EU-ETS) database (Rentier et al., 2019). Compared to the 20% contribution of NRW to the national GDP in 2023 (CEIC, 2010; Fitch Ratings, 2024), this reflects the State's significance in meeting national and European climate targets.

[1] Other mining regions in Germany may legally continue to operate until 2038.

3.2 Regime

3.2.1 Historical restructuring of the Rhine-Ruhr region

The Rhine-Ruhr industrial cluster historically featured extensive mining activities and heavy-industrial production, which eventually raised Germany's most severe debates and environmental conflicts around the use of fossil fuels, climate justice, and energy prices during the 1990's and early 2020's (Weber & Cabras, 2017). The State's efforts aimed to prevent de-industrialisation and/or industry relocation to ensure the economic competitiveness of the region. In those terms, the region aspired to transition towards a "knowledge economy" with a focus on industrial economic growth, mostly driven and funded by governmental (both Federal and State) action (Oei et al., 2020).

In the case of the Ruhr area, this restructuring process was initially state-led and managed with a "reindustrialisation and lock-in" outlook lasting until the mid '80s (Arora & Schroeder, 2022). In a sense, this period saw efforts to combine NRW's goal for Ruhr's economic diversification and low-carbon investments in industry as expressed in the "Development Program Ruhr" that set aside €32 billion, along with activities to preserve hard coal- and steel-related operations and coalitions through national government subsidies amounting to €126 billion, accompanied by generous redundancy payments to ex-miners reaching €223 billion (paid by the federal government) (Arora & Schroeder, 2022).

During the '00s, European and international pressure started amounting, with countries, alliances, and platforms pushing for efforts to tackle climate change and minimise socioeconomic impacts from coal phase-out (Oei, 2018)[2]. European support—mainly via the European Regional Development Fund—and dedicated cluster policies provided another boost for economic competitiveness and diversification during that period. This pushed market and innovation strategies away from coal-based activities in an effort to overcome industrial lock-ins (Michie et al., 2019).

In 2013, the State issued its Climate Protection Law (CPL) and legally adopted a Climate Protection Plan (CPP) which was deliberated with industrial and other relevant stakeholders', setting a target of emissions reductions in the State of 25% by 2020 and 80% by 2050 (Lechtenböhmer et al., 2015). Based on this plan, NRW became the first German State to adopt such regulation in line with broader EU targets and efforts. It should be noted that the German equivalent legislation was voted later in 2019, after the consolidation of a national Climate Protection Plan in 2016.

Joint discussions on the State's restructuring towards cleaner industries intensified prior to the 2019 national elections upon the "expiration date" for hard coal extraction in 2018 (Oei et al., 2020), under the influence of the Fridays for Future mass mobilisation that called for climate change action I(Hermwille & Kiyar, 2022). In the same year, the German government assigned the Commission on Growth, Structural Change and Employment (WSB Commission, also known as the Coal Commission) to design an entire lignite power phase-out plan by 2038 (Breul, 2022), a target which was later revised to an earlier phase-out by 2030 for the Rhenish lignite district (Wegener et al., 2023). A core outcome of the process was the Structural Strengthening Act, which was passed by the Coal Commission in 2020, allocating around €40 billion—

[2] Examples are the COP23 (2017) alliance "Powering Past Coal" and EU's "Coal regions in Transition Platform" (2017) (Oei, 2018)

including €14 billion for investments and €26 billion for support through national programs and infrastructure projects (Cirillo et al., 2024)—until 2038 to affected States, including NRW among others (Lower Saxony, Saarland, Bremen, Hamburg, Brandenburg). The Coal Commission was a multi-stakeholder body backed by broad social consensus on coal phase-out, with 63% of Germans—and a majority in coal mining regions—supporting phasing out coal production (Coggio & Gustafson, 2019). Drawing from this support, the Commission was tasked with both ensuring the closure of coal and lignite plants and boosting regional development. This second transition phase, which is reflected in current efforts for structural change, was based on bottom-up regional cooperation, social partnerships, and consensus-seeking among trade unions, environmental groups, industry, and academics involved in the Coal Commission (Arora & Schroeder, 2022)—in stark contrast to the mostly top-down approach followed before the '00s.

To achieve a consistent regional restructuring for the coal phase-out, NRW aimed to grant both the Ruhr and Rhineland an advanced role in planning and decision-making. However, neither region reflects a single administrative entity, while the Ruhr area is even embedded within 4 different district authorities, which risked the prevalence of bureaucratic bottlenecks. Consequently, in 2019, the NRW transferred all planning initiatives to Ruhr's regional planning authority, Regionalverband Ruhr (RVR) and its affiliated economic development subsidiary, the Business Metropole Ruhr (BMR). These newfound actors were in charge of coordinating the region's master plans as well as regional business development and to voluntarily support climate mitigation and energy transition policies (Roelfes et al., 2018). This profound restructuring process successively alleviated pressures on Ruhr's employment, infrastructure, knowledge base, environment, and quality of life, also initiating local stakeholder engagement that eventually brought broad consensus upon the imperative of the area's restructuring and industrial transition (Michie et al., 2019).

On the other hand, the Rhenish lignite mining area currently hosts three large lignite open-cast mining areas (Inden, Garzweiler, and Hambach) spanning across 65 different municipalities. As early as in 2010, the government of NRW had emphasised starting an "action programme" for the Rhenish lignite mining area (Wegener et al., 2023). Building on an enabling political landscape that featured the coalition between the social democrats and the green party at the Federal level, a regional development agency, the Future Agency Rhenish Region Agency (ZRR) was formed in 2014, including shareholders from municipalities, business associations of the region, and the trade union for the industrial sectors mining, chemical industry, and energy (IGBCE). ZRR gained momentum as a strong intermediary actor aiming for the development of a European pilot region for sustainable energy production and resource management, strengthened by active support from the European Regional Development Fund with €8.9 million for personnel and financial equipment (Wegener et al., 2023). ZRR has no legal or executive power, but works as the de-facto project managing organisation for much of the transition funding while it serves as an important connector of regional stakeholders and is consequently considered a "key player with regard to decarbonisation" that exerts pressure from status quo coal defenders, namely the coal industries (RWE, Steag, MIBRAG, Vattenfall, LEAG), industry associations (DEBRIV, BDEW), and trade unions (in particular IGBCE) (Roelfes et al., 2018). The region has outlined its own decision-making structures and defined its most appropriate investment plans (Michie et al., 2019), supervised by the Federal Ministry for Economic Affairs and Energy at the federal level. The Rhenish region eventually published its Economic and structural program (WSP) in 2021 featuring a vision for the transition. This strategy includes the promotion of different regional industrial pathways, considering both its industrial capacity's modernisation (e.g., resource efficiency and circular economy, digitalising production) and expansion (e.g., the hydrogen industry, battery and fuel cells manufacturing) (Breul, 2022).

The national government's plan is to provide financing for the measures of the Structural Strengthening Act (2020) through the EU's Just Transition Fund, launched in 2022, to support the adaptation of workers and enterprises (mostly through employment and social policy measures) albeit without increasing the funding allocation already mutually agreed upon with the mining regions (Cirillo et al., 2024). In NRW, Just Transition financial resources are focused on lignite mining land restoration, new SMEs and start-ups in resource efficiency and circular economy, and job retention. Approximately €120 million are allocated to support labour market interventions in the Rhenish lignite mining district and the northern Ruhr area, making NRW the first coal-dependent state to initiate job up-skilling and re-skilling projects. For example, the Coach2Change project, initiated in 2024, offered individual coaching for local employees in SMEs (Cirillo et al., 2024).

Once identified as the backbone of Germany's economic success and now included in UNESCO's World Heritage list for its historic "industrial culture", Ruhr signifies a model case of Germany's industrial reorientation. However, large unemployment rates and lack of innovation initiatives still prevail, despite recent industrial diversification efforts, especially in the southern parts of the area (Stognief et al., 2019) where coal ended earlier, and which saw many universities and technology centres successfully being established (Dahlbeck & Gärtner, 2019). Such barriers highlight the difficulties in achieving a just transition and an industrial transition even in a "model case" such as the Ruhr.

On the contrary, the Rhenish open-cast lignite mining continued to provoke opposing positions, as traditionally reflected at the federal level between the Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety and the Federal Ministry for Economic Affairs and Energy (Leipprand & Flachsland, 2018): the area was affected by extended resettlement causing social conflicts and protests by environmental groups, climate and local citizens initiatives, and more recently trade associations (Hermwille et al., 2023). At the same time, lignite power stations were until recently perceived to be indispensable to compensating for renewable energy fluctuations, guaranteeing availability and price stability, as well as energy security to avoid geopolitical risks (Overhoff et al., 2018). However, both lobbies felt they have not been adequately included in the decision-making process of the transition (Brauers et al., 2020).

3.2.2 Incumbent industrial actors and their activities in Rhine-Ruhr

The way the transition has shaped—via calls for diversification and resistance from the existing regime—has seen existing companies, or their mergers, secure their position within the regional sustainability vision of the Rhine-Ruhr. Arguably the biggest incumbent in the region is the power company RWE (Rheinisch-Westfälisches Elektrizitätswerk AG), a company with significant influence and impact in the future orientation of the transition process of Rhine-Ruhr. RWE enjoys a solid position, as Germany's largest energy producer and the main employer and landowner in the region. Historically, the company has made significant technological breakthroughs in lignite power generation, investing in modern lignite-fired power plants with optimised plant technology and retrofitting or upgrading existing power plants since the beginning of 2000—these advancements have led to achieving a net efficiency of over 43% (Overhoff et al., 2018). RWE recently announced its commitment to phase out coal, committing to transition the wider region "from the coal powerhouse to a sustainable region", hence, to locally invest in renewable energy sources (RES) (Wegener et al., 2023). However, concerns have been expressed over barriers to entry in the region's market, since new actors in renewable energy would have to buy land from a powerful competitor (Kolde & Wagner, 2022).

In terms of local steel production, Duisburg, a major Ruhr district, hosts two integrated pig iron and raw steel production plants run by Thyssenkrupp Steel (TKS) and Hüttenwerke Krupp Mannesmann (HKM) both operating blast furnace (BF) and blast ocygen furnace plants (BOF), and a small BOF facility run by ArcelorMittal (Abdelshafy & Walther, 2022b). The rest of the steel production (1Mt) is produced in two electric arc furnace (EAF) plants (secondary steel) located in the city of Witten, near Dortmund (ibid). Standard primary steel production is based on the blast furnace-basic oxygen reduction (BF-BOF) method that reduces iron ore to iron using coal and coke. In general, half of Europe's primary steel production uses this emission-intensive route and most probably will continue to use it for a transitional period until assets are dismissed by 2040. The sector is known to face high fixed costs and long investment cycles with low profit margins, with few, usually merged incumbents leaving no space for new players. Under these circumstances, sustainable steel innovation evolves at a slow pace, promoting energy and resource efficiency as supporting decarbonisation options while retaining main assets and standard production streams (Lechtenböhmer et al., 2018). Secondary steel production is primarily done in an electric arc furnace (EAF) currently providing a third of the European manufacturing value chain input. Both old and new steel scrap generated reached 2.9Mt and considering its low recycling rate in NRW (6.4% compared to a national average of 30%, and the EU one at 40%) a large amount of it is exported (ibid). By-products of the primary steel production process are energy (in the form of various gases) and slag, which to a large extent is used as input for the production of cement (grades CEM II and CEM III) in the cluster's cement plants—see also the discussion below.

Cement production takes place in 11 cement clinker plants in the North and East of the state, outside the Rhine-Ruhr cluster which hosts 5 cement (no clinker) plants. Several medium-sized German and multinational companies are based in the region (Heidelberg Cement, Dyckerhoff, Cemex, Lafarge Holcim) (Lechtenböhmer et al, 2015c). The State's power plants generate large quantities of secondary resources, namely fly ash and secondary gypsum, both useful to the construction industry. Both cement and recycled construction and demolition waste (CDW) are feeding the domestic construction industry and also exported (37% of production) to other EU countries (mainly the Netherlands and Belgium).

The Rhineland chemical cluster hosts a diverse product portfolio, with strong emphasis on basic chemicals, including high value chemicals (HVC) such as ethylene, propylene, and butadiene, which are primarily produced through naphtha steam cracking, as well as propylene, which is produced via fluid catalytic cracking (FCC) at the two Shell refineries, in Godorf and Wesseling (Scholz et al., 2024). The disintegration of large chemical firms like Bayer, Höchst, and Hüls has led to the consolidation of four chemical parks in Wesseling, Knapsack, Leverkusen, and Dormagen, hosting over 260 SMEs (80% of existing chemical companies) that took over parts of the existing production chains (Scholz et al., 2024). However, major petrochemical multinationals, such as Shell, BASF, LyondellBasell, Covestro, and Evonik, also participate in regional innovation projects. The cluster's location has been a reinforcing factor in its success story, since the wider Rhine-Ruhr area offers a large sales market, and its rivers have provided a vital transport route to the major chemical sites of Rotterdam and Antwerp. Today, crude oil as well as naphtha and other liquid products are obtained from the tank terminals at the port of Rotterdam via pipelines to steam crackers in Wesseling and Dormagen, owned by Shell, LyondellBasell, and Ineos. The produced olefins are then distributed to the chemical industries and are also exported back to feed the ARRRA supercluster (Scholz et al., 2024).

Aluminum is also a growing energy-intensive industry (EII) in Rhine-Ruhr and, although it does not involve primary production capacity, a broad set of products is provided by major industrial players (Trimet, Aluminium Norf, and Hydro) located in NRW. Aluminium processing (heat treatment and smelting) is increasingly supported by a broad network of regionally active research and development actors such as the Technical University of Aachen (RWTH Aachen) as well as the Gas and Heat Institute Essen (GWI) (Lechtenböhmer et al 2015b).

Another important EII in the region is the automotive industry, mostly represented by a major production plant of the Ford Motor Company in Cologne, a major production facility for Mercedes Sprinter commercial vans in Düsseldorf, as well as many automotive suppliers throughout the region. Increasing coordination between the automotive and energy sectors over hydrogen and fuel cells (H&FCs) at the national level since 1990, led to a policy forum known as the Transport Energy Strategy (TES) including big transnational automotive companies (Ford excluded) and German power operators, including RWE. These developments, also driven by public expectations for greener car fuels, urged investments in hydrogen and fuel cell infrastructure and secured funding within the H2Mobility programme, aimed to proceed with mass-produced H&FC vehicles by 2015. However, public Federal funding in H&FC infrastructure was paused in 2016 (Hacking & Eames, 2012), whereas the Ford Motor company only recently (2023)[3] implemented a 3-year H&FC transit trial, to deliver van operators.

3.2.3 Infrastructure

NRW is the state with the highest electricity consumption in Germany. At the same time, however, locally produced electricity via existing power plants enables the region to act as net exporter of electricity to other German regions, securing additional profits while ensuring that established EIIs are connected to a strong and reliable electricity grid (Schneider & Lechtenböhmer, 2018a). Adaptations, nonetheless, will be necessary to accommodate the increased penetration of RES that will inherently increase production fluctuations (Ausfelder et al., 2021).

As part of the ARRRA supercluster, the region is also particularly supported by an excellent infrastructure connection via a complex natural gas, fuel and industrial gas pipeline grid with refineries, as well as major seaports, road, rail, and inland waterways.

Specifically, Germany features an unprecedently complex gas network compared to other European countries, including a transportation network run by 16 different operators and a gas distribution network by more than 700 operators (Oberle et al., 2021). As far as Rhine-Ruhr is concerned, it should be noted that its chemical sector is well connected to the gas transportation network (Oberle et al., 2021). The chemical sector is the biggest consumer of natural gas since this is used both for electricity and steam production in combined heat and power (CHP) plants, and as feedstock for ammonia and methanol production. In 2020, the iron and steel industry, natural gas covered less than a third of fuel consumption (with the remaining two thirds being coal. The cement sector requires natural gas mostly for clinker production, which is not relevant to Rhine-Ruhr. Crude oil is transported via pipelines to the region's refineries that also distribute generated and imported steam cracker feedstocks. The produced olefins are circulated back to the ARRRA sites utilising pipelines and inland river waterways (Scholz et al., 2024). Additionally, Rhine-Ruhr features an established regional hydrogen grid connecting the refineries with the chemical industries for domestic

[3] https://media.ford.com/content/fordmedia/feu/en/news/2023/05/10/ford-explores-three-year-hydrogen-fuel-cell-e-transit-trial-that.html

feedstock uses.

Therefore, the connection to the pipeline grid and inland shipment routes can offer a large boost to Rhine-Ruhr's decarbonisation prospects. Yet challenges remain from an infrastructure perspective that could impact the future resilience of the cluster, since both the steel and chemical industrial clusters are geographically located in a way that does not align well with where low-carbon energy or feedstocks can be generated or supplied (Scholz et al., 2024). This is posing a great fossil fuel lock-in challenge if a low-carbon transition were to render the current interconnection status obsolete. To cover both the expected high energy demand for the decarbonisation of EIIs and the necessary production reconfiguration with non-fossil feedstocks, major clusters in the ARRRA supercluster will need to jointly take action towards coordinated efforts and pathways to upgrade and adapt their integrated infrastructure and address related challenges (Ausfelder et al., 2021; Merten et al., 2020). These challenges mostly refer to the expansion of already existing grids for electricity, hydrogen, and CO_2. In 2024, Germany has adopted a Hydrogen Grid Core Grid Strategy as an attempt to resolve this issue, however, no simiral planning exists for CCS infrastructure yet[4]. NRW lacks CO_2 underground storage, while most available porous aquifer storage options are spatially located at a great distance from the emission-intensive industrial activities (Rhoden et al., 2021). This requires developing a new CO_2 transportation network, either via shipping or with dedicated pipelines, the specifics of which will be immediately dependent on the development of other storage options (on-/offshore) or imports. Such large-scale development could give incentives to emission-intensive industries to relocate closer to CO_2 pipeline nodes.

Offshore wind and storage capacity in the North Sea is viewed as critical since industrial hotspots in ARRRA have limited potential for hinterland RES due to unfavourable natural and climatic conditions and either are regionally dispersed or do not offer storage facilities (Samadi et al., 2021). CCS technology, exploiting the Dutch CO_2 offshore storage sites and/or the Norwegian North Sea offshore facilities, is found plausible in possible energy infrastructure pathways (electricity imports, hydrogen generation/imports) (Merten et al., 2020). However, the strategic orientation of the steel and chemical industry accompanied by a rigorous circular economy strategy—including material efficiency, reuse, recycling, and process changes—in the wider North-West Europe might avoid large scale deployment of such an option, apart from the concrete sector where CCS might still be necessary due to a large share of emissions that are process-related (Merten et al., 2020).

3.2.4 Research & Development

According to the German start-up Monitor 2022, NRW is the Federal State with the most start-ups in Germany. Cologne and Düsseldorf are identified as the main start-up hotspots (mostly focusing on software), 47% of which have a clearly technology-driven orientation, driven by RWTH Aachen University. The State features an elaborate R&D environment including 67 universities, 14 centres of Fraunhofer Society, 12 centres of the Max Planck Institute, and more than 50 research institutes located at universities of applied sciences (Wegener et al., 2023). NRW is also considered a leader in research evaluating the potential of Industry 4.0 processes to provide flexible energy demand, with RWTH Aachen and TU Dortmund involved in the most related publications (Nolting et al., 2019). However, this strong R&D capacity does not

[4] https://fnb-gas.de/en/hydrogen-core-network/

seem to be reflected in regional economic growth (Wegener et al., 2023), considering increased unemployment levels (relative to national levels) and workforce skill shortages.

The Ruhr is often identified as Germany's less prominent region in terms of its knowledge-based economy (Hassink & Kiese, 2021). ThyssenKruppSteel, a major steel company, maintains close collaboration with the region's academic institutions like University of Duisburg-Essen and Ruhr University in Bochum. Other research activities devoted to steel innovation are provided by the Steel Centre in Düsseldorf that hosts the Research Association for Steel Utilisation (FOSTA), Max Planck Institute for Iron Research (MPIE) as well as the Steel Information Centre (S-I-Z) (Espert et al., 2016). In addition, the SMS Group, one of the world's leading engineering firms and equipment manufacturers for the steel industry is also located in the region. Given the economic importance of the region's steel industry for the national and European aggregate economy, it is actively supported by established national actors and autonomous institutions, mostly dedicated in applied research towards innovation technologies. The German Steel Association (WV Stahl) is also a significant political influencer, working closely with institutes like the VDEh Steel Institute, the VDEh Institute for Applied Research, the Research Association for Steel Application, the Information Center Stainless Steel, and the Max-Planck-Institut. This R&D environment sustains an active collaboration landscape that promotes technological change and ensures the sector's competitiveness at the global level (Koasidis et al., 2020). Within this context, further support for neutral hydrogen-based steel production processes (i.e., DRI or EAF) as well as the promotion of secondary production routes, has been a vision shared by the European steel association Eurofer (Schneider, 2022).

R&D activities in the Rhineland region are also among the core enabling factors for the transition. RWTH Aachen University and the large European research institution Jülich Research Center, are both located in the region, as are universities of the surrounding major cities, Cologne, Düsseldorf, and Bonn. Local academia has already demonstrated close cooperation with trade unions through the NRW 2020 programme, launched by DGB NRW, the NRW Office of the German Trade Union Confederation (Kolde & Wagner, 2022)[5]. However, the strong technology-oriented academic landscape of the region might also be regarded as a problem in recruiting new highly skilled workers, as brain drain is a real challenge in the region. Specifically, the Rhenish lignite district is currently considered as a "field of experimentation" for new start-up companies (Kolde & Wagner, 2022). However, a major challenge faced by the local chemical R&D is subjected to the operating multinational companies' priorities (e.g., Bayer, BASF, Covestro, and Evonik).. The same applies to cement multinationals, favouring prospective abatement technologies, such as CCS (Lechtenböhmer et al, 2015c).

3.2.5 Established Public-Private Partnerships and cooperation culture in Rhine-Ruhr

NRW was the first German State to adopt its own climate law (Climate Protection Act) proceeded by the development of a regional sustainability vision in 2016, Sustainability Strategy NRW, and accompanied by a research project of the Wuppertal Institute for Climate, Environment and Energy. These developments went

[5] Whereas DGB NRW constitutes the main representative body from the labour policy side, its divisions, IG BCE (the Mining, Chemical and Energy Industrial Union), representing the interests of employees in open-cast mines and the Ver-di (the United Services Union) representing employees in power plants, specifically deal with employment protection issues at a company level (Kolde & Wagner, 2022).

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through a participatory multi-stakeholder process, the Platform Climate Protection and Industry North-Rhine Westphalia involving stakeholders from six EII sectors (aluminium, cement, chemical, glass, paper, steel) and their respective industry associations. The aim of the platform was to increase the knowledge base in low-carbon technologies (including breakthrough technologies) for future industrial developments (Espert et al., 2016). Other stakeholders that are active in the decision-making process of the NRW industrial transition include Agora (a think tank dedicated to Energiewende), Dechema (an industry-academia network focusing on chemicals and biotechnology), and Prognos (a Swiss consultancy also based in Düsseldorf, conducting research on energy and macroeconomic modelling. In addition, the NRW government encouraged the growth of a hydrogen and fuel cell (H&FC) cluster based on the North Rhine-Westphalia Fuel Cells and Hydrogen Network (NBW-NRW) in Düsseldorf. The Network includes a large number of local, national, and foreign enterprises linked to H&FCs as well as strong representation of regional and national academic and research institutions (Hacking & Eames, 2012).

Organisationally, the steel and chemical industries feature densely clustered multi-sectoral collaborations, in comparison to the other industrial sectors in the region (cement, paper and glass, aluminium) that are dominated by regionally dispersed SMEs; This particularly benefits the Rhineland chemical cluster strengthening its networks and enabling cross-sectoral synergies, despite the fact that the sector is also dominated by SMEs. At the same time, however, even closer cluster integration would suggest broader and more complex discussions and networking among industrial players (Espert et al., 2016).

The most notable cross-sectoral attempt to innovation in the region was Carbon2Chem, exploring long-term prospects of the conversion of off-gases from the blast furnaces to raw materials for chemical products. A pilot plant started operating at the steel production site in Duisburg in 2018 to produce ammonia, methanol, and higher alcohols using both CCU and hydrogen (Di Molfetta, 2022). The project, established in 2016, was an initiative by steelmaker giant Thyssenkrupp and two research institutions—Fraunhofer Institute for Environmental, Safety, and Energy Technology and Max-Planck-Institute for Chemical Energy Conversion—and soon included more partners from science and industry, such as the large chemical producers BASF, Covestro, and Evonik. Although a private initiative, the project would not be realised without the initiative to bring the steel and chemical industries together cultivated at the NRW government level (Tönjes et al., 2020). The Carbon2Chem was deemed crucial for NRW as a cross-industry collaboration paradigm that inaugurated a dense industrial multi-stakeholder exchange platform under the IN4Climate.NRW initiative (Tönjes et al., 2020).

IN4Climate.NRW is an initiative of the Federal State NRW to provide a collaboration platform between government, science, and industry stakeholders involved in the region. It consists of a complex structure aiming to cover all represented fields of expertise and foster cross-industry alliances towards maintaining NRW's industrial competitiveness and growth in a climate-neutral future (Roelfes et al., 2018). While fostering a continuous dialogue process between its partners, the platform also manages the SCI4climate.NRW research project carried by six leading research institutes: Wuppertal Institute, Fraunhofer UMSICHT, German Economic Institute, RWTH Aachen University, VDEh Institute for Applied Research and the German Cement Manufacturer's Association. Set up in separate working groups, the project has collaboratively explored the role of hydrogen as well as the prospects of chemical recycling for plastic waste as a circular economy component (Tönjes et al., 2020).

Circular Valley based in Wuppertal, a collaborative initiative targeting the greater Rhine-Ruhr area, aims to work as an accelerator of circular start-ups (Circular Economy Accelerator Program) with a clear focus on chemicals, characterised as "high impact intermediary products". The NRW Environment Ministry also established The Round Table Circular Economy NRW to promote CE knowledge exchange among industry, research, and government stakeholders (Wegener et al., 2023).

An innovation-forward approach could further enhance cross-sectoral research, focusing on industrial symbiosis aspects, extending the already existing cooperation between the steel and chemical sectors, a prospect that would nevertheless increase the number of parties involved and thus require more complex deliberations.

3.2.6 Key policies and strategies for the decarbonisation of EIIs in Rhine-Ruhr

At the national level, industrial policies seem to address the core decarbonisation technologies for the industry sector, namely hydrogen, electrification, and CCU/S. Three main programs, CO_2 Avoidance and Use, Hydrogen CCfDs (Carbon Contracts for Difference), and IPCEI for hydrogen (Important Projects of Common European Interest), aim towards the construction of new large-scale plant facilities. Strategically, Germany also aims to increase its electrolysis capacity by 2030, drawing from the increasing RES-based (green) hydrogen demand and the renewables sector expansion (Fleiter et al., 2021).

NRW has taken a clear orientation to hydrogen technology, publishing its own Hydrogen Roadmap in 2020, acknowledging the State's intention to join the European Alliance for Clean Hydrogen, since many energy-intensive steel and chemical industries are in the greater region of Rhine-Ruhr. Although the prospect of a green hydrogen economy is identified as a "crucial avenue for achieving sustainable transformation" and reflected in the National Hydrogen Strategy (2020), the regional roadmap's focus is primarily focused on economic growth and job creation rather than climate neutrality goals (Lu, 2021). This is clearly reflected by NRW's plans to also make use of grey, blue, and turquoise hydrogen[6] to accelerate its market ramp-up. TheFederal government has recently agreed to use all colours of hydrogen when ramping up the hydrogen market providing major funding (€3.4 billion) for investments through public-private partnerships.

Overall, there seems to be a non-negligible aspiration to transform NRW into a Hydrogen Valley, also supported by the recent Hydrogen Core Grid Strategy (2024), meaning a region aiming to cover the entire hydrogen value chain. As mentioned above, hydrogen can be used both as an energy carrier to provide high-temperature process heat and as feedstock for the chemical industry. It could also be used as an energy storage medium to balance fluctuations from RES (Neuwirth et al., 2022). Currently, 26 regional private firms from different sectors have taken up such initiatives, demonstrating a bottom-up paradigm shift in hydrogen adoption (Gill, 2024). Thyssenkrupp is currently building a hydrogen-based Direct Reduced Iron (DRI) plant in Duisburg, with a goal to produce 3 Mt of primary green steel by 2030 (Di Molfetta, 2022). However, there is currently no hydrogen generation capacity to cover for its planned large-scale use. Furthermore, the cost of such a development prospect can hardly be calculated since the lack of infrastructure in the region (i.e., hydrogen pipeline networks, storage facilities) does not foster investment incentives. As a result, the bid to procure hydrogen for the DRI plant has been put on hold, due to high offered prices, challenging the viability

[6] The different "colours" of hydrogen suggest its production methods and its energy uptake. Green hydrogen is entirely climate-neutral using RES, grey is generated from natural gas or methane, blue is fossil-based combining CCS, and, finally, turquoise refers to methane pyrolysis process generating solid carbon that could then be re-used in other applications (i.e., tyre manufacturing, soil improver substance).

of such initiatives[7].

A national-scale project named AquaDuctus is aiming to bridge this gap involving more than 45 private firms, research institutions, and organisations to install, produce, and transport green hydrogen from the German North Sea (Lu, 2021). Additionally, it is estimated that renewables will contribute up to 60% to the hydrogen economy's production costs and will therefore drive its development (Lu, 2021).

A study commissioned by the Federation of German Industries (2018) has proposed the use of biomass and CCS as most cost-effective strategies, prioritising existing assets and processes over profound restructuring (Samadi & Barthel, 2020). With the bioeconomy being demonstrated as the shared vision for Germany's strategy towards climate neutrality, it is natural that the greater Rhineland region which comprises significant rural areas besides the urban centres of Cologne and Düsseldorf, is expected to provide a diverse range of biomass feedstocks, as well as support activities such as processing, trading, and recycling, feeding bio-technology companies and start-ups as well as the chemical cluster (Venghaus et al., 2022). Besides ZRR (the regional development agency) and the German Bioeconomy Council, the key stakeholders involved in biomass production research and development in Rhineland include the Research Center Jülich, the German bio-technology firm BRAIN AG, farmers' associations, environmental and consumer associations as well as international giants like BASF and Bayer (Venghaus et al., 2022). Nevertheless, the vision for Germany's transition towards the bioeconomy places a limited focus on industry (Fleiter et al., 2021). Additionally, support on biomass and the bioeconomy in general has been subject to conflicts, raising resource and environmental concerns (e.g., on food availability) (Nikas et al., 2022), requiring a clear legislative framework that will secure the system's sustainability (Venghaus et al., 2022). These concerns are also backed with criticisms over transparency issues and citizen participation deficits (Hilgert et al., 2025).

Moreover, material efficiency and circular economy measures do not seem to be adequately met by the country's main financial instruments, namely the German Resource Efficiency Program ProgRess III. The instrument provides funding for R&D projects, mostly to support SMEs and lighter industries, mainly directed towards construction and plastics (including chemical recycling). Already having missed resource productivity targets from 1994 to 2020, it is contested whether this funding mechanism can guarantee relevant market formation or sufficient financing for innovation technologies (Fleiter et al., 2021). Instead, circular economy policies traditionally continue to target the collection and recycling of waste, without mobilising emission-intensive secondary production routes. Replacing primary steel production with secondary production (steel scrap) and providing the infrastructure and market incentives for the circularity of plastic and concrete production with alternative feedstocks (i.e., chemically recycled waste) and materials can offer a viable decarbonisation strategy for Rhine-Ruhr (Fleiter et al., 2021), but pursuing such options currently remains under pilot development. As a counterargument though, material flow analyses show that climate-neutral production processes can severely put at risk the current cross-sectoral interdependencies, which can be affected by the supply and demand of alternative resources/feedstocks; as such, there is a potential threat that this could either drive the cluster towards greater import reliance or lead to other emission-intensive solutions (Abdelshafy & Walther, 2022b).

[7] https://eurometal.net/thyssenkrupp-steel-pauses-german-green-hydrogen-tender-on-high-prices/

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3.3 Landscape

3.3.1 The challenge of high energy prices and EIIs' increased energy demand

European efforts towards climate neutrality and clean innovation, as expressed in the European Green Deal, as well as national efforts, reflected within the Energiewende (aiming for net zero by 2045), identify green growth, clean energy, efficiency, and competitiveness as core priorities. Combating de-industrialisation and preventing industrial relocation while at the same time reaching ambitious emissions cuts emerge as key challenges. The EU's and Germany's shared vision and financial support for RES imply a commitment to driving domestic and energy capacity (Lu, 2021). The main EU policy mechanism for the decarbonisation of EIIs, however, the EU ETS, had until recently had little effect on sectoral investments in green innovation technologies (Fleiter et al., 2021). Germany's legislation, traditionally focusing on energy efficiency improvements in SMEs and lighter industries, used the innovative CCfD mechanism to accelerate the transition of heavier industries towards decarbonisation, compensating for both CAPEX and OPEX costs. The flaws of EU-ETS were also stressed by coal-regime defenders in Germany, who would argue against its reinforcement, while opposing stronger national action (Leipprand & Flachsland, 2018). At the same time, Germany's chronic reluctance to proceed quickly with the coal phase-out caused uncertainty over the region's transition pathways, while arguably keeping Germany's climate goals out of reach (Coggio & Gustafson, 2019).

The recently unveiled Clean Industrial Deal (February 2025) aims to act decisively towards ensuring the competitiveness of its net-zero industries, pushing for a global green innovation rally through targeted funding and subsidies to encourage investments. The Deal's biggest challenge is to reduce energy prices, with efforts lagging those in USA and other leading economies (Hermwille et al., 2025). Therefore, production of domestically generated clean energy proves to be among the crucial elements for the decarbonisation of EIIs, shifting funds from fossil fuels procurement towards more environmentally effective investments, such as coordinated cross-border infrastructure investments that support cleaner technologies needed in industrial processes. Initiatives like the Carbon Border Adjustment Mechanism (CBAM) and sustainability-based public procurement standards aim to foster clean trade partnerships and boost EU green markets respectively. Circularity performance and workers' reskilling have been suggested as inclusive and equitable transition measures that are critical to the Deal[8].

EU incentives towards an integrated European grid and demand-side flexibility are pushing for increased electrification shares in the power and EII sectors (Hermwille et al., 2025). Findings from a recent study (Compass Lexecon, 2024) for the EU manufacturing suggest that scalable electrification could decarbonise 90% of industrial processes across sectors, including chemicals and steel, by 2035, although it is acknowledged that electric industrial heating for high-temperature processes may face challenges. In Germany, electrification is not yet proclaimed as a standalone industrial decarbonisation option because electricity prices in the country are not expected to be competitive compared to other regions with higher potential for wind and solar RES, and because domestic technological processes (e.g., large share of BF-BOF in steel production) currently in place are not yet compatible with such a path (Samadi & Barthel, 2020).

[8] https://www.euractiv.com/section/eet/news/revolutionary-clean-industrial-deal-needed-for-a-sustainable-and-competitive-europe/

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Indirect electrification through green hydrogen generation is therefore viewed as a more feasible alternative, given also the capacity to store energy to power batteries (i.e., battery electric vehicles), heat pumps, and electric boilers and/or furnaces (Schneider & Lechtenböhmer, 2018a).

EU policy packages and strategies such as Fit-for-55 and RePowerEU have particularly targeted green hydrogen technological developments (electrolysis, grid infrastructure) towards decreasing its high price and therefore introducing competitive electrification pathways for the decarbonisation of energy-intensive steel and ammonia (Altenkirch, 2024). The utilisation of hydrogen is also thought of as an energy storage medium, providing flexibility to shift increased electrification and energy imports from other EU member states and economic community countries (Altenkirch, 2024).

The EU recognised steel's relevance towards a net-zero Europe, drafting emergency strategic plans for this and other critical sectors. Abatement of GHG emissions in the primary steel sector points towards new production processes using reduction methods that require alternative fuels to coal, coke, and natural gas.

Steel's strategic role in the European economy signifies the sector's critical contribution to exports and jobs, creating about €140 billion gross value added in 2019in the EU. However, the sector is also responsible for 7% of global GHG emissions making it the largest single emission source (European Research Executive Agency. & Green Steel for Europe., 2022). While it is estimated that steel demand will continuously increase globally, Europe is considered as a saturated steel producer and will be facing a steady primary steel production decrease, substituted by secondary production routes. It is thus expected that steel scrap will soon make up for the majority of its steel demand (Lechtenböhmer et al., 2018) What is more, one of the main global challenges of steel decarbonisation is the sector battling increasing competition from lighter alternative materials or products (Espert et al., 2016). At the same time, however, the EU's reliance on electrification as an appropriate decarbonisation option requires steel and cement cross-sectoral cooperation, due to their contribution as key providers of materials needed for wind turbine construction[9].

Decarbonisation of the chemical industry may offer only moderate emissions reductions—mainly achieved in its energy uptake—without alternative feedstock technologies and infrastructure, considering the expected deployment of bioeconomy (for biobased feedstocks) and recycled waste capacity that could potentially be in place by as early as 2030 (Kloo et al., 2023). Yet, it seems difficult to conceive of a clear net zero path for the sector as a result of high structural complexity and process diversity (Kloo et al., 2023). This prospect is further challenged by an expected increase in energy demand due to electrification and hydrogen processes uptake, driving the chemical sector away from its fossil-based stability towards growing dependence on electricity prices as well as the global renewable feedstock market (Kloo et al., 2023). The dependence of the chemical sector on energy prices is expected to increase and may therefore expose domestic production to competition with other parts in the world that benefit from structural advantages (e.g., RES capacity in other EU countries, shale gas in the USA) to produce their products with cheaper energy supply (Espert et al., 2016). When compared to global developments, the EU's chemical industry in general might seem stagnant or even declining, with most investments placed in China, the Middle East, and the USA. Among core advantages that have so far ensured the competitiveness of the sector are skilled workforce, existing infrastructure, and integrated clustering (Ausfelder et al., 2021). In this context, it is not

[9]https://www.euractiv.com/section/eet/news/industry-calls-for-collaboration-to-deliver-strong-and-actionable-clean-industrial-deal/

surprising that chemicals have recently been added to the emergency strategic plans of the Clean Industrial Deal, suggesting the sector also faces considerable challenges for decarbonisation. Global industry digitalisation and artificial intelligence trends will also critically increase Germany's energy demands (Nolting et al., 2019).

Nevertheless, geopolitical tensions are pushing the EU to primarily focus on domestic energy and resources security/efficiency measures pointing towards enhanced circular practices. This is pushing towards further EU-coordinated action within its Ten-Year Network Development Plans for electricity network expansion (Merten et al., 2020).

3.3.2 Germany's spatial heterogeneity challenge

The Energiewende had been part of the energy transition discussion in Germany since the late 70s[10] but was officially legislated much later, in 2010, a few months before the Fukushima nuclear accident in 2011. The plan set a goal for Germany to withdraw from both lignite and nuclear energy and outlined long-term GHG emissions reduction targets, which were revised in 2021 to reach emissions reductions of at least 65% by 2030 compared to 1990 levels, 88% by 2040, and net zero by 2045. By 2015, the share of renewable energy in electricity consumption had increased impressively, from 3% to over 30%, laying the groundwork for further progress through support policies and strong lobbying from renewable energy companies. Perceived as a success story, the Energiewende soon became the mainstream narrative of Germany's energy transition, ensuring not only environmental protection but also the modernisation of the industrial system, job creation, and competitiveness (Leipprand & Flachsland, 2018). As a result, 90% of the German electorate, and the majority of the country's political parties, soon pushed for more ambitious renewable targets, believing that the implementation of the Energiewende is too slow (Fischer et al., 2016), although concerns were also raised over its ability to promote a general attitude shift towards technology, consumption, or equity (Weber & Cabras, 2017).

The German Federal States played a key role in the Energiewende as both drivers and implementers of global and national climate policies (Oei, 2018). Their interest in proceeding with the expansion of RES (mostly photovoltaics and wind turbines) in their territories lied in the subsidies they could and still can access through the German Renewable Energy Act (EEG). At the same time, they are confronted with the technological, economic, and social challenges of the intensification of RES integration within their constituencies. In NRW particularly, major inconsistencies can be identified throughout the pursued direction. On the one hand, the federal government refrained from committing to fast lignite power generation phase-out, continuing mining extraction and adding to CO_2 emissions, with controversy surrounding lignite mining districts on issues of employment, home relocation, and environmental aspects perpetuating citizens' initiatives and environmental justice organisations' resistance (Oei, 2018). On the other hand, subsidies for renewable energy under the EEG undercut natural gas prices, pushing utilities towards coal while disproportionally increasing electricity prices for households compared to industrial and commercial customers, rising energy poverty in densely populated urban areas (Fischer et al., 2016; Weber & Cabras, 2017). The EEG Special Equalization Scheme provided for a reduction of the EEG levy for certain energy-intensive companies, which have to compete internationally. This cost reduction implicated that the

[10] https://www.carbonbrief.org/timeline-past-present-future-germany-energiewende/

price for "non-privileged" electricity consumers (i.e., households, non-privileged industries and businesses) rises e e.g., by about 1 EUR-Cent/kWh in 2015. Those sectors passed down the higher electricity costs to the consuming households, which also had to bear the higher end consumer prices caused by the scheme. Eventually, the EU Commission questioned the legitimacy of this compensation scheme but revolved the conflict with the German Government in 2014 (Fischer et al., 2016). The controversial EEG surcharge (or levy) on consumer power bills was finally removed on 1 July 2022.

This precedence hints that the macroeconomic impacts of the Energiewende do not spread evenly throughout the 16 German federal states (Fischer et al., 2016). Some states offer favourable conditions for RES investments, either in terms of natural resources such as wind potential and land availability or in the form of structural enablers such as agricultural activities for bioenergy, thus, featuring strong regional gross employment effects (Fischer et al., 2016). Nonetheless, the positive effects of this "renewable energy job miracle" were not evident in mining states like NRW, consolidating the winners (federal states generating significant levels of renewable energy) and the losers (federal states with low generation levels but high electricity demand) of the transition (Fischer et al., 2016).

Consequently, one of the most challenging aspects of NRW's decarbonisation is related to Germany's spatial heterogeneity in terms of its energy transition potentials. On the one hand, the nation's EIIs—namely primary steel and aluminium production, crude oil refineries, and basic chemicals—are mainly located at a few integrated large-scale manufacturing sites in the West and South-West parts of the country (Neuwirth et al., 2022). On the other, the leading role of solar and wind renewable energy in Germany's energy transformation mostly favours the coastal North (Rhoden et al., 2021). At the same time, local availability and/or large-scale infrastructure required to support the import or generation of other CO_2-neutral energy carriers like hydrogen or other green gases has not yet been in place, causing high levels of uncertainty to the private companies eager to invest in greener technologies (Fleiter et al., 2021). As previously discussed, this also applies to CO_2 transportation. Rhine-Ruhr's industrial competitiveness risks being severely affected by such spatial disparities and lacking infrastructure, attesting to the critical importance of Germany's infrastructure planning to the regional industrial policy mix (Fleiter et al., 2021).

3.3.3 Diverging visions in industrial decarbonisation pathways

Decarbonisation technologies have seen mixed reactions in Germany and thus associated with occasionally conflicting directions for the transition. For example, Germany's electrification capacity from wind and solar RES currently falls behind, requiring major electricity imports (Altenkirch, 2024), while any plans for RES expansion are perceived from a 'winners and losers' perspective (Aniello et al., 2019; Rhoden et al., 2021). Interestingly, RES expansion was never confronted by the German environmental movement that mostly engaged with forest protection and nuclear phase-out (Weber & Cabras, 2017). Additionally, although biomass is also expected to play a growing role in many industrial processes globally, Germany has featured an overall lack of consensus over the availability and appropriate use of sustainable biomass (Samadi & Barthel, 2020). Carbon capture and storage (CCS) has been a dividing subject in the German industrial, political, and social context, mainly due to its association with fossil-based industries and thus perception of antagonistic to cleantech. Finally, the perspectives of material efficiency and circular economy (CE) have only recently albeit partially been introduced as emissions abatement options for EIIs, since CE has traditionally focused on waste management.

The implementation of the EU Directive on CCS in German legislation in 2012 was a controversial process, resulting in a compromise to only allow CCS plants for pilot development but not for commercial use in the country (Fischer, 2015). Initially objecting to the technology, environmental NGOs and the Green party gradually showed willingness to accept CCS as a "bridging technology" to combat industrial process-related CO_2 emissions (Fischer, 2015). However, their reluctance is still shared by a large part of the public. The Federal Ministry for Economic Affairs and Energy and the Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety have formulated a National CCS Act, although concerns have been raised over the conflicting aspirations for the transition (Fischer, 2015), and as a result the Act was finally not adopted Several R&D projects have been implemented on different storing technologies, most of whom are focusing on the pilot storage site of Ketzin in Brandenburg (Fischer, 2015, p. 259). NRW previously saw a CCS power plant being cancelled in Hürth due to the State's failed plan to connect it via a new CO_2 grid back in 2008 (Fischer, 2015). Pressure from EU's Net-Zero Industry Act towards CO_2 storage could orient NRW industries, specifically the petrochemical sector, to direct their assets and R&D towards this decarbonisation option.

Another challenging aspect of the industrial decarbonisation in Germany is related to biomass and the prospect of a planned national bioeconomy strategy, which entails the replacement of fossil-based resources with bio-based alternatives in a circular economy setting. The ZRR has declared its vision towards the bioeconomy transition of the Rhenish lignite district, mainly counting on the potential for new jobs (Hilgert et al., 2025). However, support from the Federal Government has proven insufficient. At the same time, misalignment between the involved regional ministry authorities (Ministry of Economic Affairs, Industry, Climate Action and Energy (MWIKE) the Ministry of the Environment, Nature Conservation and Transport (MUNV), the Ministry of Agriculture and Consumer Protection (MLV)) may even act as a deterrent of potential investments. Consequently, the shape of the regional bioeconomy strategy still remains vague (Hilgert et al., 2025).

Echoing the position taken by the Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety, there is apparent scepticism over chemical recycling as well (Fleiter et al., 2021), although recent demonstration initiatives are now undergoing by LyondellBasel. However, it is perceived as less environmentally friendly due to its high energy demand and thus is only considered a viable option for recycling/energy recovery of contaminated plastic. Similarly, environmental organisations like Greenpeace and Nature and Biodiversity Conservation Union question its economic and ecological advantages, considering it as an argument for more plastic production. Finally, European industrial associations demand that chemical recycling should be officially classified as recycling in Germany, in the same way it is defined at the EU level (Fleiter et al., 2021).

3.4 Key technological innovation systems (TIS) in Rhine-Ruhr

3.4.1 Hydrogen TIS

3.4.1.1 Entrepreneurial activities/Knowledge development

NRW, and particularly Rhine-Ruhr, face geospatial limitations for high levels of RES domestic generation. However, it features good infrastructural connections qualify for the option of electrification for its industrial decarbonisation, closely intertwined with green hydrogen developments. However, given hydrogen's infrastructure infancy status, this will only be possible after critical investments and market formation.

A crucial example for a soon-to-be established hydrogen installation relates to the construction of a large-scale DRI plant in Duisburg, by ThyssenKrupp[11], with an integrated smelting unit, planned to start operation in 2027 to produce primary green steel. As an alternative to fossil-based primary steel production, DRI is a process that avoids the use of blast furnace (and thus coal and coke use) to produce sponge iron, which is then melted and refined into steel, often using additional steel scrap in an EAF—a process that smelts recycled steel scrap into liquid steel using electricity, although some coal and natural gas might be required to provide additional heat. However, a standalone EAF route is challenged by the lack of availability of quality steel scrap. As such, DRI could complement the EAF route to produce better quality steel scrap. This process could result in nearly zero emission steel production if DRI uses green hydrogen (H-DRI). Combined with EAF, H-DRI would then require both RES-based energy and electrolysis capacity.

At the same time, the current regional hydrogen generation capacity, mainly as a chemical by-product (chlorine production) should not be disregarded. A power-to-liquid demonstration plant in Shell's converted refinery in Wesseling resulted in a €10 million financial support from the Clean Hydrogen Partnership to continue producing synthetic fuels and hydrogen using a proton exchange membrane (PEM) electrolyser[12]. Large-scale hydrogen electrolyser plants for green ammonia and methanol production are about to follow in the Ineos site in Cologne, having secured funding from the IPCEI ChemCH2ange project. Although all the above demonstrations use water electrolysis, a pyrolysis pilot plant for hydrogen production, has also been developed by Fraunhofer UMSICHT in the RWE Innovation Center in Niederaussem, one of RWE's last remaining large lignite fired power plants. close to Cologne[13]. Pyrolysis is a process usually related to chemical recycling with currently low technological maturity (Ausfelder et al., 2021).

Within NRW, hydrogen is also being tested for additional industrial sectors, like cement and foundries as well as less energy-intensive applications in glass and tile and brick (Di Molfetta, 2022). Regional RES energy generation (i.e., in Duisburg and Rhein-Kreis Neuss) currently under subsidies of the German Renewable Energy Act, could also provide the necessary power to further enhance local hydrogen generation, although these subsidies are expected to be gradually withdrawn (Di Molfetta, 2022).

3.4.1.2 Resources mobilisation

Hydrogen grids have already been established in the NRW, especially in the Rhine-Ruhr region, to support the transportation of hydrogen as a by-product of refining processes. However, this is both generated and consumed on site as an input for the chemical industry (chlorine production), and thus there is hardly any market for the transportation network developed yet (Lambert & Schulte, 2021). Gas producer Air Liquide currently operates this infrastructure network, researched within the H2NRW project.

[11] https://www.thyssenkrupp-steel.com/en/newsroom/highlights/push-for-climate-protection.html
[12] https://energycentral.com/c/cp/refineries-and-hydrogen-oil-and-gas-refining-and-chemical-sectors-2
[13] https://www.umsicht-suro.fraunhofer.de/en/press-and-media/press-releases/2023/pilot-plant-for-the-production-of-sustainable-hydrocarbons.html

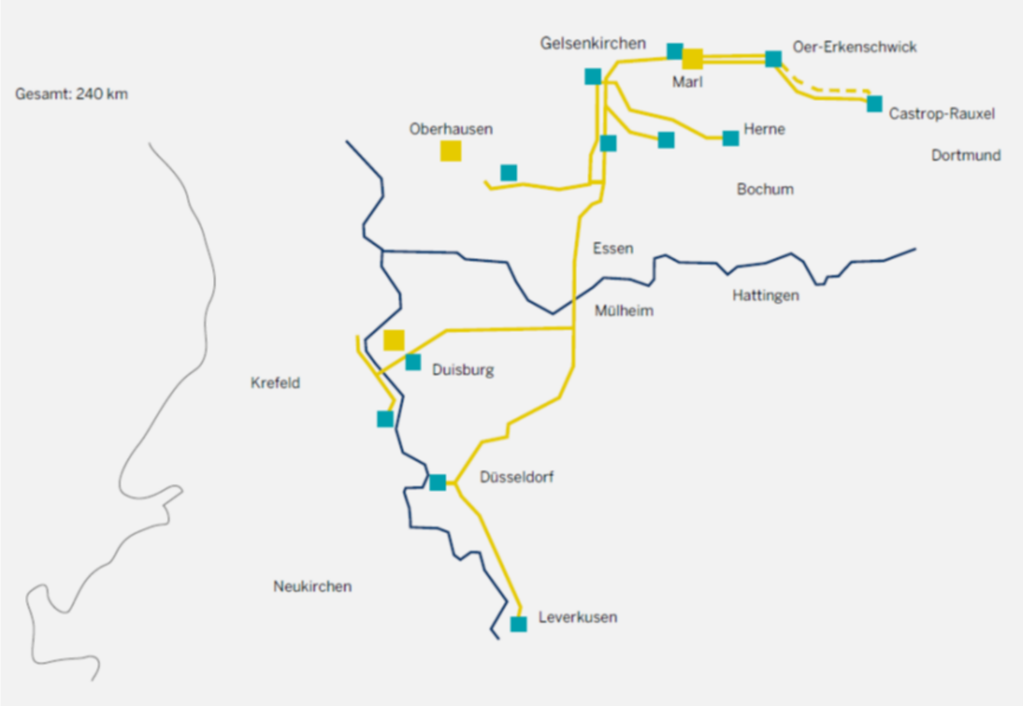

Figure 5. Existing hydrogen network (Air Liquide) in Rhine Ruhr area, NRW. Current production (yellow) and consumption (green) sites can be observed

Source: (Di Molfetta, 2022)

Although the Rhine-Ruhr industrial cluster has already established a regional hydrogen grid, it is clear that it is one of the first industrial clusters to be connected to an additional long-distance new hydrogen grid, connecting the refineries and the steel mills with hydrogen generation (possibly in the North Sea coast) or import hubs outside the cluster (Schneider & Lechtenböhmer, 2018a; Scholz et al., 2024). Green hydrogen production most often involves water electrolysis using RES energy input. Due to RES fluctuations and intermittency, this process requires hydrogen storage and grid infrastructure able to accommodate both inland generated and imported hydrogen and green hydrogen products (i.e., ammonia), along with new electrolyser facilities (Ausfelder et al., 2021). The absence of large-scale hydrogen pipeline infrastructure in Germany is a critical obstacle for the country's hydrogen economy aspirations, since retrofitting the existing natural gas network to accommodate hydrogen is associated with technical restrictions. Thus, the construction of new pure hydrogen pipelines is advocated to support green hydrogen production (Tholen et al., 2021). As part of the sector's decarbonisation, this network will need to be retrofitted to support hydrogen infrastructure and consequently drive new business opportunities for local distribution network operators (Oberle et al., 2021).

3.4.1.3 Market formation

Consequently, it can be assumed that the costs related to green hydrogen generation as well as those of hydrogen-based industrial processes are currently higher than those of standard fossil-based fuels. The implementation of the amended national Renewable Energy Sources Act (EEG) in 2021, aimed at bridging this price discrepancy by exempting green hydrogen from the EEG surcharges. However, it should be noted that less than half of the electricity mix in Germany is currently based on RES, and electrolysis will continue to produce higher emissions from conventional hydrogen production through methane steam reforming (blue hydrogen) in the near term (Tholen et al., 2021). At the same time, the German government does not yet consider additional electricity capacity for hydrogen generation while struggling to meet national targets for RES expansion. Germany is believed to have enough RES to meet capacity targets for electrolyser installations, giving a straightforward message to investors to proceed quickly with green hydrogen developments (instead of blue or grey hydrogen). However, recent studies reveal a gap in domestic hydrogen generation capacity failing to reach the national target of 5GW by 2030, with a further 5 GW increase planned between 2035 and 2040, thus emphasising the need for RES-based hydrogen imports as well (Lambert & Schulte, 2021). Naturally, both the construction of new hydrogen infrastructure and the generation capacity, along with the major changes in the energy system to proceed, are under scrutiny. Regions with high hydrogen capacity require complex technological developments—primarily with regard to the need for sufficient and guaranteed supply of renewable electricity (Neuwirth et al., 2022). The diversification of energy-intensive industries in the Rhine-Ruhr cluster (refineries, chemical, and steel plants), the highly integrated pipeline infrastructure base and its future development plans, and the existing inland waterway transportation routes are all enabling characteristics for the adoption of hydrogen.

Nevertheless, Rhine-Ruhr's role in Germany's industrial sustainability and competitiveness is pointing towards prioritising hydrogen industrial applications mostly in the steel and chemical sectors (Tholen et al., 2021). Indeed, NRW is expected to be a hydrogen hotspot-driven demand for the fuel in these two sectors, and its application will mostly focus on primary steel DRI and methanol to olefins process, a very energy-intensive route for the production of plastics (Neuwirth et al., 2022). The chemical and steel industries in NRW already require significant hydrogen inputs, a demand that is expected to grow over the next years featuring the highest demand at a national level (Di Molfetta, 2022). Public procurement and green steel labelling have often been proposed as market formation instruments, while product design could reduce the amount of steel required, compensating for higher prices and materials (Lechtenböhmer et al., 2018).

3.4.1.4 Guidance of search/Knowledge diffusion through networks

Existing hydrogen pipeline and storage infrastructure located in the Rhine-Ruhr is already an asset that will soon be complemented by natural gas pipeline grids that could be converted to transport hydrogen. A realistic hydrogen pathway for the efficient mobilisation of existing resources is to couple green hydrogen with the existing conventional generation and grid infrastructure facilities first. Hotspots can then be created to drive further demand from adjacent industrial sectors (Neuwirth et al., 2022).

Both the German National Hydrogen Strategy and the European Hydrogen Strategy 2020 promote European cooperation for domestic green hydrogen applications and transport. This goal has been actively pursued via the selection of 62 German research projects such as IPCEI, securing €8 billion of funding within a total of over €33 billion of investments for hydrogen. 15 of those projects are solely focused on hydrogen infrastructure and storage, aiming to extend and repurpose the existing natural gas grid, and aiming to provide a total pipeline length of about 6300km to be operated by 2032. Plans of gas pipeline operators in Germany foresee an addition of 1.2 km of new hydrogen grid pipelines, named H2 Start Net 2030, expected to operate from 2030 onwards. The expansion of hydrogen grids towards the North of Germany and the North Sea—combined with the regional inland waterways—might prove necessary to connect the region's heavy industrial capacity to hydrogen generation centres that are close to offshore wind energy sources. If implemented, it will consist of the largest hydrogen pipeline in the world, demonstrating Germany's confidence in the hydrogen economy (Lu, 2021).

This core network will connect German EII regions (including Duisburg) with Eastern and Western neighbouring countries, such as Poland, the Netherlands, Denmark, and France, ensuring import and export capacity (Müller-Kirchenbauer et al., 2025). For example, NRW's Hy3 and RH2INE projects are currently exploring hydrogen imports and exports via the Port of Rotterdam (Di Molfetta, 2022). Indeed, Rhine-Ruhr's relevance within the ARRRA supercluster is explicitly projected as "a crucial step in accelerating and completing the energy transition" (Namazifard et al., 2024).

3.4.1.5 Creation of legitimacy

The delayed development of the hydrogen infrastructure that is long awaited by private industrial companies to proceed with hydrogen applications, as well as the green hydrogen heavy reliance on RES costs—despite these being expected to decrease—is causing increased uncertainty in private investments. Until recently, the lack of a clear green hydrogen taxonomy or standards was causing further investment stagnation since access to funding or other financial options (i.e., loans) from institutions such as the International Monetary Bank, European Investment Bank, Green Development Banks, etc., are available based on specific environmental and sustainable criteria. Currently, investors are confronted with the unknown viability of short- to medium-term hydrogen developments, since the actual efficiencies and costs of hydrogen pipelines and/or networks, storage facilities, and hydrogen-powered generation facilities (i.e., electrolysers) are hard to be estimated (Lu, 2021). In other words, private firms are reluctant to rush their investments towards the hydrogen economy, based on the expectation that these costs may significantly decrease soon and, thus, are prone to wait.

Another main obstacle seems to be Hydrogen coalitions at the EU level have been calling for stricter rules for hydrogen in the proposed Sustainable finance package under the EU Taxonomy Climate Delegate Act. Green Hydrogen Certificates (GHC) are being implemented within a guarantee of origin scheme project called CertifHy that audits and certifies hydrogen producers and therefore works as an initiative to de-risk investments (Lu, 2021). In that sense, possibly combined with Hydrogen Purchase Power Agreements (HPPAs), GHCs are expected to greatly improve this investment stalemate.

3.4.2 Carbon Capture and Transport (CCT) or Utilisation (CCU) TIS

3.4.2.1 Guidance of the search/ Market Formation

For the steel sector, aligning the established BF-BOF route with a low-carbon emission pathway will often require CCT in order to retain existing plant configuration and processes, especially until/if hydrogen-based steel production faces extended delays (Lechtenböhmer et al., 2018). However, the hot rolling facilities (i.e., shaping etc.) that are necessary for later stages of steel value chains mean that the sector would also strongly depend on electrolyser technology anyway (i.e., on RES and hydrogen developments). For instance, Germany accommodates 18 isolated hot-rolling steel mills. Only the Duisburg site is equipped with integrated steel production (Schneider & Lechtenböhmer, 2018b). Increasing the share of secondary steel scrap using EAF would further commit the sector to require clean electricity supply. At the same time, going for a more elaborate CCT pathway could shape new connections between the steel and chemical sectors, under the condition that the infrastructural resources (i.e., CO_2 grid network) are in place.

Inherently, this implies that the evolution and expansion of the green hydrogen and CCS TISs innovation systems are not necessarily independent from each other. Crucially, applications of CCS could potentially reduce the required amount of clean energy and hydrogen supply required, addressing concerns of the fuel's affordable availability. At the same time, use of green hydrogen could reduce the dependence on CCS, which is also faced up against with challenges in large-scale deployment.

The Rhine-Ruhr cluster is profiting both from the proximity to the Port of Rotterdam and the capacity of the Rhine River to circulate large, imported cocking coal and iron ore quantities (i.e., from Brazil and/or Australia). In addition, the cluster features strong trade relations with other European steel clusters since 45% of steel exports stay within north-west European countries (Schneider, 2022).

The cement industry requires clinker or lime production to be processed into cement to produce various construction products like ready-mix concrete or precast concrete, which takes place in more than 270 plants within the federal state. The waste concrete that is generated through this process, combined with obsolete construction materials, is then fed into concrete recycling plants, also regionally located. The Rhine-Ruhr cluster does not accommodate any clinker plants nor reinforced precast production—both among the most emission-intensive processes of the sector—since these are clustered at the northern and eastern parts of NRW. However, most lime plants, located inter alia in Rhine-Ruhr, profit by their proximity to concrete producers and recycling plants, as well as the highly urbanised cities of Düsseldorf and Cologne, where most of construction and/or demolition that produces concrete waste takes place (Abdelshafy & Walther, 2022a). In addition, the region exhibits higher market shares for non-reinforced precast concrete products, rendering them eligible for recycling, with NRW featuring higher levels of concrete circularity (70%) than the German average (40%). However, the sector is rather fragmented due to the multiplicity of smaller-scale private firms (there are more than 140 RMC plants, 120 precast plants, and 160 recycling plants in NRW) making coordination towards CCU innovation technologies challenging in terms of the number of stakeholders involved as well as of the low sequestration capacity of such (dispersed) production scale (Abdelshafy & Walther, 2022a).

The chemical industry is known to proceed slowly towards cutting emissions and reaching climate neutrality due to its high dependence on fossil resources to provide both energy and feedstock demands, particularly in the petrochemical industries. The chemical value chain is therefore immediately affected by the de-fossilisation of the energy sector as well as by the efforts towards greener feedstock alternatives (Kloo et al., 2023). Any pathway proposing alternatives for the feedstocks and energy used to support the transition of the chemical sector needs to take into consideration that the sector production rates are expected to rise, creating additional needs for emission reduction strategies (Kloo et al., 2023). Currently, the available options for a climate-neutral chemical sector focus on recycling, biomass, CCU/H2, electrification, CCS, and other means of efficiency improvements.

CCS is most often excluded in national pathways for the chemical industry (contrary to other industrial sectors) while biomass technologies are expected to be available later than CCU/S (Kloo et al., 2023). On the contrary, CO_2 utilisation as raw material will continue to be needed as one indispensable feedstock resource for the chemical industries. Sourcing carbon could become a complicated process since all available alternative options, recycled feedstock, biomass, and captured CO_2 do not always provide the energy density of their fossil equivalents. As re-activation of the energy potential of CO_2 could happen with hydrogen, its regional resources and usage possibilities also affect the overall decarbonisation of the sector (Schüwer, 2015). A large-scale CO_2 network of dedicated pipelines at the national level is expected to reach out to hard-to-abate industrial clusters with no storage capacity, like NRW, possibly giving incentives for the relocation of industrial facilities closer to it (Rhoden et al., 2021).

3.4.2.2 Creation of legitimacy/Resources mobilisation

Germany demonstrates strong opposition to CCS in all its forms (geological onshore/offshore, mineral). This tendency stems mostly from regulatory and distributive concerns, rather than ecological ones (Rhoden et al., 2021). Initially conceived as a supplement to coal-fired power plants, it is unclear whether it can be re-introduced as an indispensable process-related emissions mitigation option to avoid the public's reluctancy. This is because the public associates CCS with CO_2 emitting industries and a "a fig leaf for continued coal-fired generation" rather than infrastructure in itself (Dutton et al., 2020). The spatial discrepancy between emission-intensive and CO_2 storage capacity in the German territory might give rise to further CCS opposition, especially between regions bearing the (environmental) costs of CO2 storage and those emitting, capturing, and opting to store CO_2 elsewhere.

Germany's renewed target to reach climate neutrality by 2045 drove a gradual shift in embracing CCS that has been observed since 2023, when Germany repositioned it as part of its climate and industrial agenda. This was also confirmed by the German Federal Ministry for Economic Affairs and Climate Action national Carbon Management Strategy in 2024, that coincided with the EU's approach. The German strategy highlighted the importance of both CCS and CCU with an explicit intention to amend the existing Carbon Dioxide Storage Act that was restricting major technological developments by posing restrictive storage application deadlines and the possibility to ban onshore storage offered to the Federal States (Blanchard et al., 2024). Currently, many projects are under development, most of which directed towards the transportation of CO_2 away from hard-to-abate industrial sectors towards offshore hotspots. These projects are industry-led with support mainly coming through cross-border bilateral or multi-lateral partnerships with other European counterparts. NRW had already published its own regional Carbon Management Strategy in 2021, including provisions for CO_2 infrastructure planning, aiming to push the Federal Government to proceed with the Act's amendment.

Germany pursues collaboration with Norway, with the two countries signing a joint feasibility study to explore hydrogen combined with CO_2 pipeline connection. Important industrial stakeholders like the Federation of German Industries (BDI) and the German Trade Union Confederation (DGB), also followed by environmental organisations active at both the national and the regional level, such as Nature And Biodiversity Conservation Union (NABU) and the World Wildlife Fund (WWF), as well as the Green Party clearly endorse CCS/CCU to address hard-to-abate sectors like cement (Blanchard et al., 2024). The Rhine-Ruhr cluster participates in some projects that currently explore this option. Major German firms like Heidelberg Materials and BASF, producing cement and basic chemicals respectively, explore carbon capture applications to align with the next phase of EU-ETS that saw emission allowances reduced. The Delta Rhine Corridor project[14] intends to construct a CO_2 pipeline network using the Rhenish lignite mining area as a transportation node connected to the Port of Rotterdam and other chemical clusters in between, namely in Antwerp (Belgium), the Chemelot site (The Netherlands), Gelsenkirchen and Cologne in Rhine-Ruhr, and Ludwigshafen (outside NRW). The project initiated by a partnership between Shell, gas grid operators (Open Grid Europe (OGE), Gasunie), and BASF, a chemical company, has been approved by both the Dutch and German Governments. The grid is intended to transport captured CO_2 emissions to the North Sea while also providing new hydrogen pipelines on the same grid dedicated to imports, again mainly from hydrogen generation hotspots in the North Sea. Another CO_2 grid project also developed by OGE is the WHVCO2logne[15] that aims to transport the cluster's industrial CO_2 emissions, this time towards the energy hub of Wilhelmshaven, a coastal town in Lower Saxony in the north of Germany. These two overlapping

[14] https://www.delta-rhine-corridor.com/en
[15] https://oge.net/en/co2/co2-grid

projects increase the prospects of a CO2 transportation strategy in the Rhine-Ruhr area (Block et al., 2024).

Carbon capture and utilisation (CCU) instead is often considered as an alternative to CCS applications that could leverage the public's opposition and legislative reluctancy towards carbon storage or could even be used in cases with land use restrictions. Additionally, CCU can avoid cost-related scepticism related to CCS infrastructure developments or CO_2 purification processes (Abdelshafy & Walther, 2022a). In terms of CCU, the most challenging development seems to be supporting uses and processes with long-term storage (Fleiter et al., 2021), which would require a regional CO_2 pipeline network that in the case of NRW has been implemented since 2009 but never operated due to local opposition leading to legal dispute/litigation (Herzberg & Kircher, 2024). However, according to the Regional Innovation Network (RIN) Material Flows, funded by NRW's Ministry of Science (MKW), all material flows available in the region (e.g. municipal waste or CO and CO2 emissions from the process industry, waste recycling and agriculture) could potentially form closed carbon cycles, increase resource efficiency and save raw materials (Herzberg & Kircher, 2024).

Among the available CCU techniques, there is potential for active carbonation in the NRW, a CO_2 sequestration process of concrete or lime products and concrete waste. In addition, given the fact that the chemical industry is dependent on CO_2 as a feedstock, CO_2 utilisation offers a straightforward opportunity to reduce emissions and at the same time the consumption of fossil raw materials. In other words, carbon emitters can be transformed into carbon suppliers, turning CO_2 into a regionally abundant raw material (Herzberg & Kircher, 2024). Cooperation potential between the steel and chemical industries, as already proven by the Carbon2Chem project in Rhine-Ruhr, as well as its exploration in other cross-sectoral applications, is featured as a good practice decarbonisation option for a sustainable/circular alternative future. However, the widespread application of CCU in such production processes remains a challenge and would soon require the use of bio-based carbon at great extent since the imported fossil-based raw feedstocks currently used (crude oil, natural gas) are expected to significantly decrease following the feedstock transition of heavy industrial sites.

3.4.2.3 Entrepreneurial activities/Knowledge development

In terms of the utilisation of CO_2 as a feedstock for petrochemical production, other projects like the Carbon2Cem that has already established a pilot for steel-chemical cooperation in Rhine-Ruhr have taken place regionally or within the ARRRA region. For example, the Dream Production project, initiated by Covestro and Bayer Technology Services partnered with RWTH Aachen University and its CAT Catalytic Centre, developed and started industrial production of polyether polycarbonate polyols (PPPs) from 20% CO_2 feedstock at its Dormagen site. Using CO_2 by-products from a neighbouring chemical factory, this application eliminates crude oil and the energy to process it while no additional energy is needed to make the CO_2 react[16]. ArcelorMittal announced the industrial production of ethanol in Ghent (Belgium) in 2023, following its demonstration in a CO-based ethanol project. This process captures industrial gases from steel production to biologically convert them using a carbon bio-recycling process[17]. Similarly, BASF initiated a CO2 to Methanol project in Ludwigshafen (in Rhineland-Palatinate, another German Federal State

[16] https://www.plasteurope.com/news/detail.asp?id=234342

[17] https://corporate.arcelormittal.com/media/news-articles/arcelormittal-announces-the-first-industrial-production-of-ethanol

neighbouring NRW).

3.4.3 Circularity TIS

The current transformation agenda in the Rhineland chemical cluster mainly focuses on demonstrating alternative feedstocks and proceeding with energy efficiency improvements (Scholz et al., 2024). Recycled feedstocks require mechanical or chemical recycling mainly from plastics through technologies already developed (i.e., solvolysis, pyrolysis and gasification). For example, the big Wesseling refinery owned by Shell, planned to be discontinued within 2025, will be replacing fossil fuels with biomass and plastics pyrolysis, and imports and production from the neighbouring plant in Köln-Godorf. Also, they are building a 100mw electrolyser at the site. Other company initiatives mostly operate pilot plants for onsite or cluster-oriented energy efficiency efforts. For example, Covestro uses chemical recycling of polyurethane foam mattresses, Lyondellbasell uses bio-based hydrocarbons from Neste (producer of sustainable aviation fuel and renewable diesel) to produce food packaging, while it has already started construction of a 250mln Euro demonstrator chemical recycling plant in Wesseling and Dormagen, partnering with Ineos and other public and private entities in 2024.

However, these options are challenging mainly due to low collection rates in the EU (35% currently), the high level of sorting required for the mechanical recycling processes, and the energy-intensiveness of chemical recycling. Similar technologies are required for sustainable biomass-based feedstocks, deriving mostly from agricultural or forestry residues, other woody biomass, starch, or food waste. As previously discussed, chemical recycling and bio-based feedstocks both face disruptive arguments and low societal acceptance mainly for environmental reasons (e.g., food security, deforestation). As such, they are either perceived within the context of a cluster-constrained environment or expected to be market-ready much later. Specifically, despite accounting for 13% of chemical processes in Germany (Herzberg & Kircher, 2024), bio-based feedstocks are considered low-energy raw materials for low-scale decentralised facilities. Interestingly, while biomass increases in industry's final energy demand in most European and global scenarios, this is not the case for respective German scenarios (Samadi & Barthel, 2020). Additionally, bio-based processes (i.e., biogas plants) emit considerable amounts of CO_2 and CH4 and would therefore require additional emission abatement efforts (Herzberg & Kircher, 2024).

The third option for carbon sourcing for chemical feedstocks is collecting CO_2 captured from industrial processes, energy production, waste incineration, or direct air capture (DAC), adding hydrogen to turn into hydrocarbon, and then using it to produce intermediate products (e.g., methanol, ethanol, syngas), which can then also be further processed (Kloo et al., 2023). This option has to some extent already been implemented in Rhine-Ruhr, as a synergy between the steel and chemical sectors. Therefore, it is featured as a real case of an immediate solution for the decarbonisation of the chemical sector of Rhineland, also promoting circularity as an industrial practice.

3.5 Discussion

Rhine-Ruhr is a densely populated and highly industrialised region, having faced major restructuring led by strong policymaking initiatives, either at the regional or even the national level (e.g., through Energiewende's imperative for a clean energy transition). The region has been recognised as a success story, mainly based on enabling characteristics embedded within its regime, such as diversified industrial composition, good interconnection—via complex grid pipelines, inland waterways, rail, and road—extensive technology-oriented and industry-connected R&D capacity, and a public-private cooperation culture.

NRW has been aiming to manage the transition process towards a regional sustainable industrial future, which requires reconciling incumbent's hesitance towards coal phase-out and an inherent trend to reproduce existing system configurations, with the diffusion of low-carbon innovations. The need to ensure the resilience of existing actors has made the entrance of new green technology players more difficult, also hindered by incumbent's land ownership status.

In our analysis, primary steel making and (petro-)chemicals emerged as the region's most crucial sectors, since the Ruhr is responsible for a third of Germany's total steel production, while Rhineland is embedded within the ARRRA supercluster, the largest chemical cluster in Europe. Established production routes are still heavily dependent on fossil fuels, with industrial production processes featuring a high level of cross-sectoral synergies between the two sectors. This has progressively encouraged the consolidation of long-term interdependence, empowering public-private partnerships and overall cooperation. However, these intertwined practices make the transition more complex, risking exposing the cluster to carbon lock-in. This risk is further amplified by NRW's lack of access to limited green energy and feedstocks, since the EIIs of the cluster are located away from areas with large renewable energy source potential (mainly wind), storage options (for CCS), which are both available offshore in the North Sea. Crucial pipeline grid extensions are needed to compensate for such a locational disadvantage.

At the same time, decarbonising both the steel and the chemical sector would heavily increase green electricity demand, both for electrification and hydrogen-based processes (H-DRI and EAF for steel, CHP for chemicals, etc.), potentially combined with CCS, but these options would also entail major reconfigurations on established production routes and assets. In addition, the growing secondary steel production, mandated at the European level, would further increase electricity demand. On the other hand, decarbonising the concrete sector would largely depend on CCS, inter alia due to process-related emissions. Therefore, Rhine-Ruhr is facing major needs and options to implement a sustainable path, hence crucial decisions need to be made on the speed and prioritisation of relevant investments. These entail large infrastructure investments, mostly in pipeline connections towards the North Sea to support offshore wind, carbon capture, and biomass imports to produce renewable feedstocks mainly via chemical recycling. Additionally, major production process reconfigurations are needed towards the ramp-up of hydrogen, again requiring major infrastructure investments for retrofitting existing grid interconnection as well as hydrogen generation capacity—via large-scale electrolyser construction. Although these options can compliment each other, they require major investments, clear timelines and a careful consideration of risks associated with a high level of dependence on North Sea-based investments. As such efficient planning, which can be supported by the MIC3 modelling exercises, will be vital to outline the cluster's path towards sustainability.

Contextualising Rhine-Ruhr's existing technological capacity and prospects for the diffusion of innovation, our analysis based on the systems of innovation reveals specific tendencies that have recently been shaping the cluster's low-carbon transition and could therefore inform—in parallel with modelling exercises—investment planning decisions. First, hydrogen adoption is widely accepted both by system actors and the public, with high expectations existing over the potential of domestic generation (electrolyser capacity), as well as the prospect of expanding infrastructure developments (Hydrogen Core Grid Strategy) building on existing assets (internal distribution grid). Such initiatives fit well with EU priorities, which makes it easier to attract funding options. In contrast, CCS has been met with reluctance within the German landscape, both by policymakers and the public. Large-scale deployment could eventually prove to be in competition with hydrogen adoption (i.e., need for CO_2 storage in the North might make it more difficult to expand offshore wind capacity needed for green hydrogen generation), hampering the complimentary of the options discussed above. However, the prospect of expanding closed carbon cycles as a transitional option, could support the transition of the refinery and cement sectors and benefit the domestic chemical sector, without necessarily relying on offshore storage. This would discharge technology competition and further enhance the circular model, possibly introducing more prospects for cross-sectoral cooperation.

Overall, the diversification of the region's industrial outputs would require expanding established/prospective cross-sectoral synergies as a single technological pathway might not be effective towards both decarbonising the sector and ensuring competitiveness. In that sense, both hydrogen and CCUS innovation systems, complimented by other circular processes, are going to play a role towards the cluster's industrial decarbonisation.

4 The Port of Rotterdam case study

4.1 Background

Located at the end of the river Rhine and projecting into the North Sea, the Port of Rotterdam (PoR) spans through a ribbon-like development area of 1 to 2 km wide and about 40 km long, making it the largest port in the world until the early 2000's (Baas & Korevaar, 2010), and now hosting one of Europe's largest industrial cluster. PoR occupies approximately 12,500ha (land and water), of which over 6,000ha host the Rotterdam Harbour industrial complex (RHIC). Among the most energy-intensive industrial sectors hosted within the Port area are oil refining, petrochemicals, and power and steam generation (Schneider et al., 2020). RHIC was established near the North-West German border to facilitate world trade after the Second World War, although the port itself has been there for centuries (Baas & Korevaar, 2010; Vroomans et al., 2022). The cluster's competency to supply coal and iron was based on its strategic position near the Ruhr area, which was vital for the reconstruction of post-war Germany. During the 50's and the 60's, RHIC further developed as a result of world trade increase, establishing the port as a transport hot spot during the early 70's, to import and process crude oil (Vroomans et al., 2017). Today, PoR receives approximately 438M tonnes of cargo a year, carries out port activities for dry and wet bulk goods, handles 28,000 sea vessels and 90,000 inland vessels annually, while RHIC features an advanced and diverse complex of industrial facilities (Samadi et al., 2016). The national added value of PoR has been significantly increased during the last two decades increasing from €13 billion in 2013 to €45.6 billion in 2020 (Gianoli & Bravo, 2020). According to the PoR Authority, although direct contributions from regional industrial activities has been in decline, the port's broader economic impact now exceeds €60 billion. These growth rates reflect the port's critical role in facilitating supply chain optimisation, and establishing as a major port in international trade withing the EU and wiith international partners, with relevant spillovers effects for the whole EU economy due to its global relevance (Gianoli & Bravo, 2020). Among critical factors explaining RHIC's economic competitiveness and performance reduced transportation needs, specialised workforce, and a well-developed industrial ecosystem with synergies among industrial firms have been highlighted (Gianoli & Bravo, 2020).

The PoR is one of the largest fossil fuel hubs in the world while half of its own production processes is focused on fossil fuels, supplying 50% of North-Western Europe's fossil-fuel demand(Bosman et al., 2018). Additionally, RHIC is ranked first among Europe's GHG hotspots, and, therefore, despite efforts made in the last decade to accelerate decarbonisation through a combination of strategies that focus on promoting the switch to alternative fuels and energy efficiency, the PoR still bears a large responsibility towards both Dutch and European industrial decarbonisation (Schneider et al., 2020). Maritime supply chain emissions were estimated at 13.7 Mt of CO_2, making it the largest contributor to climate change among European ports[18]. Housing 45 petrochemical companies and five oil refineries, RHIC is responsible for approximately 20% of Netherland's total CO_2 emissions (Gianoli & Bravo, 2020), exceeding 30 Mt annually (Haas & Dril, 2022). The cluster's GHG emissions almost doubled within the last three decades, as the activities expanded, following similar trends of those of energy sector emissions (Schneider et al., 2020). Despite this, emissions from coal-fired power plants dropped from 30.7 Mt in 2015 to nearly 17.3Mt in 2020 but rose again to 24.6Mt in 2021

[18] https://www.statista.com/statistics/1310353/most-polluting-ports-europe/

and 2022 due to the sharp increase of natural gas prices after the Russian invasion in Ukraine[19]. Although the Netherlands has committed to reduce its coal consumption by 2030 through regulatory measures, the PoR has been relying on two considerably new coal-powered plants operated by Engie (previously GDF Suez) and E.ON since 2016 (Schneider et al., 2020), postponing the cluster's coal phase-out while the switch of alternative fuels and biobased fuels also progresses. During the same period, GHG emissions from natural gas power plants, operating as an alternative to coal-fired ones, surpassed in absolute terms those from coal (Carmona-Martínez et al., 2024). Nevertheless, only 10% of the coal imported to PoR is consumed domestically, while the remaining 90% is shipped across Europe..

The PoR Authority, a semi-public organisation, responsible for the smooth operation, development, and a crucial player in the port's decarbonisation efforts, has officially committed for CO_2 emission reductions since 2016, targeting a 50% reduction by 2025 and an overall 60% reduction by 2030 compared to 1990 levels (Samadi et al., 2018). At the same time however, in 2019 the RHIC's emissions have only managed to reduce industrial emissions by 20% compared to 2016 levels, reflecting the cluster's persistent reliance on fossil fuels until at least 2030 when coal phase-out should be accomplished and refinery operations are expected to decline (Samadi et al., 2016). Currently, according to the PoR Authority, emissions have been further reduced reaching 19.2Mtons in 2024, from 31.5Mtons in 2016[20].

4.2 Regime

During the last decade, the sustainability of the port's maritime and logistics sectors has improved through electrification and digitalisation processes, according to PoR Authority[21]. For instance, the Maasvlakte platforms responsible for distributing international breakbulk cargo across Europe and for logistics operations, including container handling, have been fully electrified using to a larger extend renewable resources. The relocation of deep-sea container handling to Maasvlakte II in 2013, created additional space for port activities, allowing companies to streamline their operations and introduce new green initiatives. This allowed the Eemhaven terminal to focus on its role as Europe's largest short sea facility, featuring over 200 connections across the UK, Ireland, Scandinavia, the Baltics, and the Mediterranean. Creating infrastructure flexibility was an important pillar to ensure compliance with quarantine and trade regulations as well as with sustainability standards, not only to enhance supply chain efficiency but also to solidify the port's position as a leader in green logistics. Eemhaven also expanded its empty depot capacity to enhance container storage, fumigation facilities, and handling operations (PoR Authority, 2024). The Rotterdam Cool Port, a cutting-edge cross-dock for refrigerated and frozen cargo, offers state-of-the-art packaging, sorting, and distribution facilities, with multimodal transport integration. Additionally, the Rotterdam Shortsea Terminals (RST) at Eemhaven, the largest short-sea terminal in Europe, has invested in solar panels, electric

[19] https://www.portofrotterdam.com/en/logistics/cargo/dry-bulk/coal

[20] https://www.portofrotterdam.com/en/news-and-press-releases/greenhouse-gas-emissions-companies-port-rotterdam-down-8#:~:text=Greenhouse%20gas%20emissions%20at%20companies,to%2019.2%20Mton%20in%202024.https://www.portofrotterdam.com/en/port-future/energy-transition/making-logistics-chains-more-sustainable

[21] https://www.portofrotterdam.com/en/port-future/energy-transition/making-logistics-chains-more-sustainable

vehicle (EV) fleets, and shore power infrastructure, to reduce CO_2 emissions per container by 50% by 2025.

The sophisticated logistics infrastructure of PoR draws upon its network routes to guarantee efficient movement of goods, raw materials, and energy (Carmona-Martínez et al., 2024; Gianoli & Bravo, 2020). Bulk cargo management, warehouses, port infrastructure, pipelines, and vessel transportation lines are actively reducing energy costs while pursuing increased operation efficiency, cluster flexibility, and synergy effects (Gianoli & Bravo, 2020). This is one of the main reasons why PoR distinguishes as a hub for international trade and distribution, connecting major European and international markets and adding strategic value for regional and peripheral industrial facilities in Northwestern Europe, strengthening the port's role in supply chains and making it less vulnerable to disruptions. Obviously, RHIC benefits from the long-established multiple connections of PoR to other European industrial regions in the hinterland. Additionally, the industrial cluster features good cluster integration and infrastructure that can work in favour of both ambitious decarbonisation and circularity measures. In fact, the Authority considers a multi-faceted approach combining technological innovation infrastructure projects, including biomass, renewable electricity as well as carbon capture utilisation and storage (CCUS), and policy interventions as the best suited mitigation approach to reach net-zero industry operations by 2050 (Carmona-Martínez et al., 2024; Haas & Dril, 2022; Sovacool et al., 2020).

4.2.1 EII sectors in RHIC

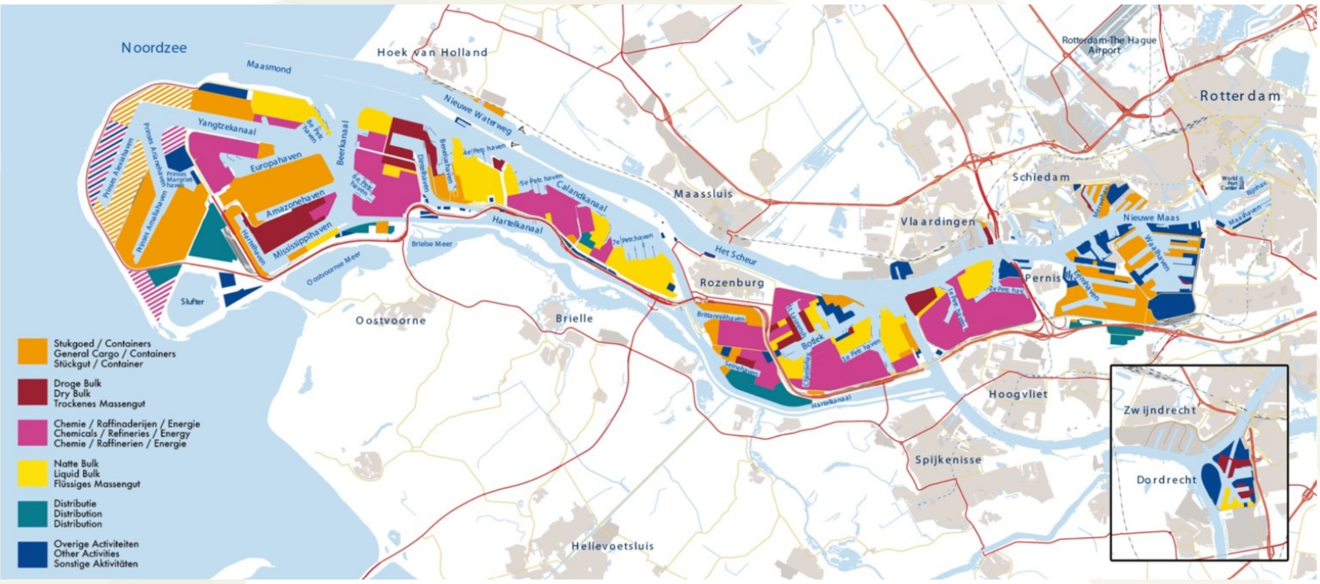

Figure 6. Map of facilities by activity in PoR

Note: Map adapted from https://rotterdamtransport.com/maps-port-of-rotterdam/)

RHIC hosts five main oil refineries operated by Shell, ExxonMobil, BP, Gunvor, and VARO Energy, most of which are also involved in chemical production. In Pernis, Shell runs the largest oil refinery in Europe, maintaining crucial infrastructure facilities producing a wide range of petrochemical products including plastics, lubricants, and solvents. Shell Pernis plays a central role in the cluster's refining capacity and is linked with an extensive pipeline system to Botlek and Europoort terminal facilities. ExxonMobil and BP operate in Europoort, processing crude oil into fuels and chemicals. Gunvor Energy Rotterdam (GER) is a traditional refinery and terminal with 60 years of presence in RHIC, producing and distributing finished and intermediate products of LPG, naphtha, diesel, and gasoline. Vopak and Evos do not operate refining in Europoort anymore, but manage their huge storage facilities for oil, chemicals, and refined products. The strong presence of key carbon emitting players, like Shell and ExxonMobil, is critical to the cluster's industrial decarbonisation efforts, with the companies manifesting a particular emphasis on CCS developments for mitigating GHG emissions (Haas & Dril, 2022; Sovacool et al., 2022).

Botlek is associated with the cluster's petrochemical sector since several finished petroleum-based products (such as gasoline, diesel, jet fuel etc.) are distributed across the North Sea and towards the European hinterland through its facilities. Botlek is one of the most important industrial facilities within RHIC and home to a mix of storage tank terminals, chemical feedstocks production, and storage such as olefins, polyurethane, polyester, chlorine as well as important utilities for the distribution of electricity, steam, natural gas, and industrial gases[22]. Most of RHIC's petrochemical companies actively operate in the storage and processing of chemicals within the area. Botlek serves as a major petrochemical hub since the final products are then transported via pipelines to storage tanks, distribution terminals, and other facilities across Europe through critical rail, road, and water connections (Haas & Dril, 2022). Shell and Exxon Mobil, Evos, and Kuwait Petroleum operate in this highly energy intensive industrial harbour area while BP has ceased its operations in Botlek relocating in the nearby Europoort area, where chemical production also takes place.

Botlek is also associated with the production of alternative industrial chemicals, housing Alco Energy Rotterdam, the largest bioethanol plant in Europe with an annual production capacity of 650 million litres of bioethanol as well as 450 thousand tons of protein-rich animal feed and 300 thousand tons of CO_2 re-used in greenhouses per year. In 2019, Vopak sold its oil storage terminals in Botlek to First State Investments, now called First Sentier Investors, which led to the creation of Evos, a company formed to manage these acquired assets, as part of a strategic shift to sustainable and alternative fuels. Evos also uses liquid organic hydrogen carriers (LOHC) that can reversibly store and release hydrogen, enabling safe and efficient storage and transportation.

Table 1. Fuel and feedstock uptake in RHIC in 2015

Input	Process	Output	Market Use
Crude oil	Refining	Oil products and residue	Fuel and feedstock
Natural Gas	Steam Reforming	Hydrogen	Air Liquide H2 Grid (Rotterdam-Antwerp-France)
	Power Generation	Electricity	Electricity
Biomass, Coal, Waste	Heat/Cogeneration	Heat/Steam	Industrial and Residential usage
Naphtha	Steam Cracking	Ethylene, Propylene	Petrochemical products (e.g. plastic, solvents, etc.)
Ethylene, Propylene	Further Processing	Chemical products Plastic components Polyethylene (PE)	Chemical industry

[22] https://chemicalparks.eu/parks/port-of-rotterdam

		Polypropylene (PP)	
		Plastic components	Renewable energy sources construction
		Polyethylene (PE):	Plastics
		Polypropylene (PP)	

Source: (Samadi et al., 2016)

4.2.2 RHIC transition efforts

The Netherlands seek to pioneer in implementing climate-conscious policies within the EU, being one of the first countries to develop a climate policy in the early 1990s and pushing for stronger integration between environmental and spatial policy (Lenhart et al., 2015). Due to heavy resource consumption of its port, Rotterdam became one of the first Dutch cities to "put sustainability on the map" (Lenhart et al., 2015).

PoR's fossil-fuel cluster has served as Europe's gateway since the late nineteenth century, firstly due to the emergence of automobile industry and later addressing post-war oil demands in the 1950's (Haas & Dril, 2022). It established as a petrochemical cluster during that time (Rattle & Taylor, 2023) and ever since, has shown growing investments in both physical and knowledge infrastructures, mostly concentrated on cluster developments (Rattle & Taylor, 2025). The history of RHIC's transition process is ultimately bound to industrial symbiosis (IS) developments bringing RHIC to the forth as a pioneer in technological and infrastructural advancements towards deep decarbonisation prospects (UNIDO, 2024).

The Dutch Climate Agreement (2019), initiated by a collaborative process involving government, industry, and civil society focusing on hydrogen, electrification from RES, CCUS, and better employment rates for established industrial clusters. The Agreement demonstrates the State's strong dedication to reduce industrial emissions and foster cross-industry collaboration practices (Janipour et al., 2020), clearly identifying industrial clustering as "catalysts for low-carbon transition" able to drive innovation (Rattle & Taylor, 2025). The country aspires to align with European targets while also leading industrial decarbonisation efforts by committing to achieve a 55% reduction in GHG emissions by 2030, reaching net-zero by 2050.

Currently, industrial collaboration has become interestingly relevant in decarbonisation discussions due to the importance of industrial symbiosis principles for circular economy processes (Domenech et al., 2019). Within industrial symbiosis complexes, businesses can leverage underutilised resources, like energy, water, and materials, through mutually beneficial exchanges (Domenech et al., 2019). Therefore, net-zero industrial initiatives are gradually pursuing cost-effective emission reductions through the utilisation of shared infrastructure, resources, and overall energy efficiency measures, also supported by knowledge exchange (Rattle & Taylor, 2025). RHIC has been recognised as a benchmarking case study on cross-sectoral cooperation and a model that promotes sustainable supply chains particularly due to its international outlook and its structural dynamics, including infrastructural advantages (WEF, 2024). The port is characterised as a "forerunner cluster", demonstrating high geographical concentration, access to shared infrastructure, and well-established inter-firm linkages that have been actively supported by the PoR Authority (Rattle & Taylor, 2025). However, despite its forerunner status, support through both National and regional climate strategies and schemes has been gradually less prioritised (Lenhart et al., 2015).

4.2.3 Clustering and prior Industrial Symbiosis (IS) developments in RHIC

RHIC has been recognised as an example of implementation of Industrial Symbiosis in Europe (Cerceau et al., 2014). Thanks to its strategic geographical position, mix of industries, and scale of operation, PoR has potential for becoming a circular hub, as recognised in the recent report *Rotterdam towards a circular port - a deep dive into Waste-to-Value opportunities*' (Circle Economy, 2019). The chemical and other sectors have engaged for decades in exploring opportunities to use waste flows as inputs. Some recent projects have investigated the transformation of non-recyclable waste into valuable resources, including the production of sustainable alternative fuels, transport fuels and other base chemicals. The table below captures some of the existing exchanging in the area.

Table 2. Current waste energy, fuel, and material flows in RHIC. Source: authors' elaborated building on multiple sources

Opportunity	Status	Main Resource Converted	Estimated Benefit
CO_2 Capture & Utilisation (CCU)	Operational/Scaling	CO_2 → feedstock	Reduced CO_2 emissions; emerging industrial markets
Heat Energy Exchange	Pilot/Demonstration	Heat → power	Energy savings 20–30% in industrial processes
Brine Treatment (Zero Brine)	Pilot	Brine → water, NaCl, $Mg(OH)_2$	Produces tonnes/day of valuable outputs
Material Flow Exchange	Operational	Solid/liquid waste → raw inputs	Up to 80% waste recycling (mostly downcycling)
Sorting & Recycling Clusters	Operational/Scaling	Mixed waste → sorted recyclables	+30–50% diverted from landfill/incineration
Inland Waterways Logistics	Emerging	Transport of waste via waterways	Transport emissions reduced 30–40%
Advanced Methanol Rotterdam (AMR)	Under Construction (2023–2025)	Non-recyclable waste → renewable methanol	90,000 tonnes renewable methanol/year; 350,000 tonnes CO_2 eq emissions avoided; CO_2 for greenhouses
Waste-to-Chemicals Project	Planned/Development	Non-recyclable waste → SAF and renewable products	Up to 80,000 tonnes renewable products/year (~75% SAF)
Transition to New Raw Materials and Fuels	Ongoing Strategic Initiative	Waste, CO_2, biomass → chemicals, fuels	Substitution of fossil feedstocks; promotes hydrogen, electricity, and synthetic fuels

Funded by the European Union

Supporting Sustainable Shipping Fuels	Operational/Expanding	Waste oils, residues → biofuels & methanol	Increased biofuel availability: methanol bunkering supports clean shipping
Waste-to-Energy Plant	Operational	Household waste → electricity	Electricity recovery from municipal waste stream

As noted above in the table many of the synergies are related to the petrochemical sector, with some of the companies acting as anchoring tenants in the network, as there are a large variety of by-products from the oil refineries that have been transformed into inputs for industries within and beyond the boundaries of RHIC. Some of these exchanges have been supported by purposefully built infrastructures including pipeline connections.

Designed to further stimulate environmental management and inspired by other industrial symbiosis (IS) developments (in Kalundborg, Denmark), the Industrial Ecosystem Programme, initiated in 1994 by the industrial association Deltalinqs in collaboration with Erasmus University Rotterdam and Delft University of Technology. The programme launched the first INES Project (1994-1997) generating 15 initial project ideas targeting mostly utility sharing within the Europoort and Botlek areas, yet only three projects proceeded based on feasibility studies: a) joint compressed air systems, b) wastewater circulation, and c) a biosludge reduction system. Although none of these projects resulted in immediate innovation technologies, mainly due to financial constraints, the INES project increased the awareness on efficiency improvements and eventually put forward the idea of resource sharing within the cluster (Baas & Korevaar, 2010).

Following an evaluation process of the first INES Project, Deltalinqs proceeded to a 4-year follow-up project, the INES Mainport Project (1999-2002), this time exploring several IS potential in CO_2/energy, utility sharing, waste products/management (including waste heat utilisation potential), soil, and logistics. The project was developed within the framework of the ROM-Rijnmond covenant, focusing on spatial planning and environment measures in Rijnmond, the greater PoR region (Baas & Korevaar, 2010). The second phase of the INES Mainport Project initiated a strategic decision-making platform, the Rotterdam Climate Initiative (RCI) in 2007 (Lenhart et al., 2015), involving a large multi-stakeholder consortium consisting of industrial, government, municipal, academic, and environmental stakeholders. The platform members included Deltalinqs, the Ministry of Economic Affairs, the Ministry of Housing, Spatial Planning and the Environment (VROM), the Zuid-Holland Province, the PoR Authority, the DCMR Environmental Protection Agency (a joint-municipality environmental agency), RWS Zuid-Holland regional water management agency, MFZH (an environmental advocacy organisation), and Erasmus University (Baas & Korevaar, 2010). This platform inaugurated the beginning of a continuous information exchange process between industry and government in the wider region, promoting energy efficiency and waste management, not only to counter environmental concerns (i.e., CO_2 emission reduction) but also to explore their cost-efficiency potential (Baas & Korevaar, 2010). In addition, from the government officials' perspective, this exchange process was seen as a possibility to drive new industry-led, regulatory mandates fostering further industrial ecology (Baas & Korevaar, 2010). It is also seen as an establishment of lasting relationships with key industrial actors in the wider area (Lenhart et al., 2015). For instance, an "Industrial Ecology in Chemistry" study, prepared as part of the second phase of INES Mainport Programme, analysed 43 existing chemical clusters identifying RHIC's spatial restrictions and scoping space saving measures (higher productivity per sqm) and the potential of transitioning to biomass chemistry (Baas & Korevaar, 2010).

The third phase of the INES Programme marked its inclusion in the Sustainable Rijnmond and Energy 2010 program, under the label of R3 Sustainable Enterprises demonstrating a clear shift towards regional sustainable strategies, involving more high-level industrial and governmental actors, academic agents, and NGOs (Baas, 2008). This time, the partners' main concerns focused on optimising existing pipelines, creating a shared resource database, and establishing infrastructure for resource and by-product exchanges (Baas & Korevaar, 2010).

During the above programme phases, several IS studies and demonstration attempts went through or inspired further developments. For example, during the first phase of the INES Project, the idea of a joint compressed air system, although originally rejected due to lack of funding and pipeline infrastructure, inspired other suppliers, not involved in the project, to invest in the necessary pipelines and gradually expand their partnership with a growing number of companies in the region and in other parts of Netherlands and Europe (Baas & Korevaar, 2010). Another sub-programme focusing on small scale projects for the co-utilisation of waste steam, CO_2, and waste heat between industrial firms, the residential sector, and the greenhouse horticulture sector, secured subsidy funding from the Dutch National Project office to test their technical, operational, and economic feasibility within RHIC. In this case, although a big share of those projects were eventually rejected, again for economic reasons, companies continued their involvement in the project due to pressure from the regional Water Authority (Baas, 2008). The experience and expertise gained from the INES programme also triggered the Rotterdam Energy Approach and Planning (REAP), an industrial-urban symbiosis programme facilitating urban resource synergies with the municipality of Rotterdam (Lenhart et al., 2015). REAP attempted to close resource waste cycles locally capturing and feeding waste energy and water flows from RHIC's industries into Rotterdam's district heating grid, eventually pushing the municipality to reconfigure its infrastructural network and creating direct links between the city and the port (Lenhart et al., 2015).

The INES Programme trajectory demonstrates the prior slow regulatory processes in RHIC resulting in delays, uncertainty, and rejections for financial support sharpening opposing views between government and industry and thus delayed such an expansion (Baas & Korevaar, 2010). At the same time, however, the programme helped diverse stakeholders within RHIC to build trust in each other under the common ground of industrial ecology and foster a culture of sharing knowledge.

4.2.4 Governance structure

RHIC's governance status quo is often described as rather flexible (Janipour et al., 2020), demonstrating the ability to adapt to challenges through privately-led synergies rather than isolated state directives. Studies on industrial cluster decarbonisation have often referred to the Netherlands—and specifically the PoR example—as a best-practice case study due to the proactive leadership of the PoR Authority (Bosman et al., 2018; Gianoli & Bravo, 2020; Samadi et al., 2016; Schneider et al., 2020) being at the centre of the port's governance structure and actively collaborating with all private actors (i.e., industries).

The cooperative mentality of PoR has been put in motion by the Dutch Administrative Act (WGR) as early as 1984 (Vroomans et al., 2022). The National Government transferred much of its direct control and funding responsibility to regional authorities during the 1990's (Lenhart et al., 2015), essentially enabling the establishment of cooperative public-private ventures tailored to local needs and priorities. More recently, the revised WGR Act in 2015 set out rules for structuring partnerships and managing planning in a way that enables even broader collaborations among municipalities, provinces, and water authorities with private entities.

The PoR Authority's role could be better described as a semi-public entity aiming to balance both the cluster's bottom-up initiatives with national top-down imperatives for low-carbon developments. As such, the Authority is responsible for the day-to-day management and smooth operation of the port, acting as an unlisted public limited company since 2004, with the City of Rotterdam holding a majority stake (70%), and the Dutch State holding the outstanding share (30%) (Rattle & Taylor, 2023). The Authority's revenues come from terminal rentals and port dues, primarily by storage and shipping companies, as well as chemical and energy producers. The funds collected are then used in public infrastructure investments, both for logistics and industrial operations (Bosman et al., 2018).

Specifically, the Authority is responsible for the development, construction, management, and operation of RHIC as well as the effective handling of shipping and offshore developments, aiming at the port's competitiveness and world-class performance (Bosman et al., 2018). Focusing on the low-carbon transition, the Authority oversees the development of critical infrastructure related to green hydrogen and carbon capture initiatives. For these expansion and investment activities, the Authority goes through many rounds of consultation with industry representatives and energy network operators, actively supporting the cluster's private entities and associations (Janipour et al., 2020). Operating under a coherent industrial ecosystem, the relationship between the Authority and firms and businesses can be viewed as "partners" and "collaborators" (PoR Authority, 2024).

However, the PoR Authority—despite having a longstanding tradition on the development of sustainability plans—had not yet established a fossil fuel phase-out strategy when the provisions of the Paris Agreement came into effect (2015) (Bosman et al., 2018). Consequently, despite its central role in the cluster's governance, it is the so-called "technology gatekeepers" that are driving the transition, through privately-led voluntary synergies and knowledge exchange, and not the other way around (Rattle & Taylor, 2023). Committed to this privately-led cooperative ethos of RHIC, the Authority's responsibilities mostly evolve around managerial interventions such as addressing omissions and contradicting practices to fundamental symbiosis values during industrial operations (Rattle & Taylor, 2023).

However, this does not imply that the PoR Authority is a powerless actor that is only guided by private multinationals. Contrary, the Authority has demonstrated a repositioning of its role within this governance structure in order to act as a transition manager in support of the Paris Agreement, proactively advocating for the port's inevitable low carbon future as a means to avoid potential carbon lock-ins (Bosman et al., 2018). Specifically, the Authority decided to develop a transition unit, namely the Transition Arena, persuading and supporting businesses to contribute to sustainable development initiatives, such as funding for start-up hubs and maker spaces (Bosman et al., 2018). For example, the follow-up Biobased Port Transition Arena created a transition agenda towards bio-based and circular innovation (Bosman et al., 2018). Despite these efforts, pressure from fossil fuel-based energy producers has often obstructed the Authority's ambitions (Bosman et al., 2018). Consequently, the Authority has often being placed in the middle of the green economy and the objectives of the fossil fuel-based regime, been reluctant to fully commit to supporting the former. As such, instead of pursuing the acceleration of coal phase-out, halting the construction or refurbishment of refineries, and repurposing existing infrastructure (Bosman et al., 2018), it has predominantly focused on initiatives compatible with the existing regime's operations, for example through the adoption of CCS (see below).

Overall, RHIC's governance regime has yet to prove its resilience against landscape pressures - including high carbon prices and import-related uncertainties within stronger industrial EU regulations and global transition pathway trends, given the cluster's energy-intensive industries (EIIs) high capital costs and long investment cycles that usually hinder coordinated policy efforts to trigger new financial incentives (Carmona-Martínez et al., 2024).

4.2.5 Research & Development

Considering that ports are usually dominated by multinational companies, R&D activities are relatively limited as R&D priorities of such actors are rarely regionally oriented. For example, the large petrochemical and energy production multinationals usually attempt to couple their investments and innovation assets with their international operations. At the same time, the petrochemicals capital- and infrastructure-intensiveness, accompanied by long depreciation periods and the large needs of maintenance, lead to risk-averse behaviour on their end (Bosman et al., 2018). In this context, the role of ports—and consequently PoR as well—focuses on the early application of new knowledge instead of its creation from scratch (Mendes Constante et al., 2023). In the case of PoR, R&D investments are lower than the National average (Bosman et al., 2018).

A the same time, the Dutch Government is significantly involved in sustainability developments in PoR, guiding the port's innovation system based on pressing concerns, such as waste re-use, or prescribing the sectoral focus of any new innovation development, through public investment allocations (Mendes Constante et al., 2023). Supporting this, the PoR Authority has successfully developed competent knowledge networks, establishing its polycentric governmental role in energy transition that also take place in the rest of the Netherlands (Hoppe & Miedema, 2020).

This creates an interesting dynamic within the port. On the one hand, private actors (e.g., businesses etc.) act as the core implementors and drivers of projects (see the previous section on Governance), with the Authority, and by extension the national government embracing a supporting role to these operations. On the other hand, the same businesses sometimes fail or are unwilling to support innovation through R&D, this time with the national government leading such initiatives. Systemically, this implies that there could be an inherent conflict between these two actors, with the government supporting innovations for the green transition that the businesses might not be willing to implement. In the end, the path the port will take depends on which of the two forces could shift or bridge transition priorities. It also however highlights a risk embedded with the green transition, since political priorities are much easier to shift than business objectives.

Focusing on specific actors with R&D activities, the Center for Future Energy Business at Erasmus University Rotterdam has conducted strategic analyses to optimise RHIC's technological and market integration (Hentschel et al., 2018). Erasmus University also conducts a Port Innovation Barometer (Mendes Constante et al., 2023). Additionally, the Delft University has contributed to the cluster's alternative technology testing (PoR Authority, 2024). For example, The Netherlands Enterprise Agency (RVO) has supported the development of Battolyser technology, a novel battery-electrolyser hybrid developed by Delft University combining battery storage and hydrogen production, allowing vessels to efficiently utilise surplus renewable energy, reducing their dependency on fossil fuels. Together, these two academic institutions have been significantly involved to the cluster's spatial planning and have engaged in environmental initiatives under the context of earlier collaborative industrial symbiosis projects (L. Baas & Korevaar, 2010).

The Netherlands Environmental Assessment Agency (PBL) and Netherlands Organisation for Applied Scientific Research (TNO) play a pivotal role in RHIC's scientific knowledge production, particularly in the decarbonisation of the Botlek/Pernis area, where most petrochemicals industries are concentrated. Their research is further facilitated by their collaboration with MIDDEN the Manufacturing Industry Decarbonisation Data Exchange Network (MIDDEN) (Haas & Dril, 2022). These institutions along with ECN (Energieonderzoek Centrum Nederland) are involved in research, demonstrations, and policy assessments. Public intermediaries like TKI (TopConsortium voor de Kennis en Innovatie) and ISTP (Institution for Sustainable Process Technology) have extensively worked towards promoting innovation and collaboration. Additionally, private research institutions outside the Netherlands, like Wuppertal Institute, have conducted research focusing on the decarbonisation pathways of PoR (Samadi et al., 2016).

Among the PoR Authority's initiatives that further promote an R&D-friendly environment are the Erasmus Smart Port Rotterdam and the sustainability- and innovation- oriented RDM Centre of Expertise (Rattle & Taylor, 2025). Smart Port, a joint venture between the PoR Authority, Deltalinqs, the Municipality of Rotterdam, TNO, Deltares, Erasmus University, and Delft University of Technology set up in 2014, specifically aims at industry oriented research with a portfolio of nearly 50 projects and a total funding of over €9M (Mendes Constante et al., 2023). The organisation functions as PoR's principal innovation hub, relying on both industry and academia involvement. PlantOne, provides a site within the port to allow companies to test their innovation activities, supplying them with the necessary utilities (i.e., steam, compressed air, nitrogen, water) and a smooth environmental permit process (Mendes Constante et al., 2023). Several start-up incubators have been established within the port, such as PortXL, providing pilot contracts within its international network and the Rotterdam Port Fund, an independent bank system where newcomer businesses can invest their venture capital (Mendes Constante et al., 2023). However, such entities do not exclude big multinationals, which often choose to engage in many research phase pilots (e.g., Shell's involvement in RAMLAB, a lab specialised in advanced repair and manufacturing of metal parts) (Mendes Constante et al., 2023).

In addition, RHIC is embedded within crucial international public-private agreements to strengthen its role as a regional and EU industrial leader. Beyond its regional initiatives, PoR adheres to International Responsible Business Conduct Agreement (IMVO), emphasising safety, security, as well as circular economy principles (PoR, 2024). Two other cross-border collaboration projects are of particular interest: the Smart Green Ports as Integrated Efficient multimodal hubs (MAGPIE) and the North Seas Energy Cooperation (NSEC) scheme. As part of the MAGPIE project, RHIC fosters green energy carriers, digitalisation, and automation collaborating closely with DeltaPort (Germany), HAROPA (France), and Sines (Portugal), to share knowledge and implement sustainable logistics practices across Europe. The MAGPIE project has been awarded nearly €25M by the EU targeting to advance sustainable and smart logistics in the port operations through pilot and demonstration projects. Focusing on green hydrogen, ammonia, bio-LNG, alongside electric transport solutions, PoR Authority lead the project's consortium consisting of 45 companies, research institutions, and other port Authorities. Such cross-border partnerships could prove crucial for PoR since emerging collaboration spillovers could further provide for long-term shared sustainability pathways that could eventually decrease uncertainty levels and release private investment flows. The lately formed North Seas Energy Cooperation (NSEC) aims to expand offshore renewable energy and infrastructure by promoting hybrid and cross-border projects integrating renewable energy sources and interconnecting grids and reducing costs. Interregional collaboration complies with the Green Deal and REPowerEU funding and regulatory provisions to overcome barriers in offshore energy developments. NSEC is currently targeting a 260GW offshore wind capacity by 2050, representing over 85% of the EU target of 300 GW. From the renewable energy produced in the North Sea, the State coalition is expected to competitively establish as an interregional energy distributor hot spot to cover hinterland needs.

4.2.6 Human capital

PoR is a vital and strategic actor in the regional and national economy. The region's employment status including direct and indirect employment reached over 384,500 people corresponding to 4.2% of total Dutch employment (Gianoli & Bravo, 2020). However, the Dutch labour regime is deeply entrenched in structural schemes of specialised labour markets and interdependent supply chains (Lankhuizen et al., 2023). Specifically, the rigidity of inter-industry labour mobility within the wider Zuid-Holland province is slowing the reallocation of workers to greener sectors (Lankhuizen et al., 2023). In particular, the existing strategic industrial operations and extensive network of logistics of PoR promote highly specialised labour, due to the regime's reliance and dependence on specific activities, such as petroleum refining (Gianoli & Bravo, 2020). For instance, Gunvor Energy Rotterdam employs a skilled 200-people-workforce qualified in producing LPG, naphtha, gasoil, and gasoline in a capacity of 75,000 barrels per day, distributing finished and intermediate products. Industry-specific skills in EIIs are usually accumulated through on-the-job learning and specialised training (Lankhuizen et al., 2023). Thus, brown industry workers are encountering challenges to transit to renewable energy industries or advanced electrical equipment manufacturing, while shortages in human capital are anticipated across all skill and education levels (Hendriks & Gooyert, 2023). Skill mismatches, reflecting discrepancies between labour demand and available expertise, could act as a bottleneck in re-allocating labour from declining high emission sectors to emerging greener ones, since transitioning to low-carbon economy could render workers' skills obsolete (Lankhuizen et al., 2023). In addition, in many cases the overall declining labour demand in such sectors (e.g., in refineries) coincides with labour shortages due to low interregional mobility (Lankhuizen et al., 2023).

Another challenge related to human capital that could potentially hinder the low carbon transition in RHIC is the historically powerful impact of national labour unions in highly industrialised regions. Labour unions, such as FNV and CNV, have historically shaped Dutch labour policies by representing industrial workforce in councils and corporate boards, while trying to align labour policies with workers' needs. The FNV, representing over 1 million workers nationally, has numerous active members in RHIC in petrochemicals, refining, shipping, logistics, construction, industrial work, and transportation, while the CNV works closely with industrial employers to balance social justice with economic objectives, advocating both for workers' rights and corporate social responsibility. From the mid-80's until recently, the transition to automated logistics has tested the unions' ability to safeguard the workforce it represents. FNV's attempt to create a non-bulk collective labour agreement framework in 1991 failed, due to declining cross-sector solidarity, but unions still indirectly influenced labour practices across companies. Traditionally, national trade unions, also active in RHIC, used strikes and vetoed organisational change and external challenges (Parker, 2022). However, what threatens the unions' positive contributions towards sustainability transition processes is the prevailing dilemma of "labour versus environment" (Healy & Barry, 2017).

In order to respond to both skill mismatches and union pressures, the PoR Authority's employment policy agenda turned to SMEs to endorse employment and economic growth since 2010 (L. Baas & Korevaar, 2010). An illustrative example of such shift is the Makers District, a specific area within the port that focuses on innovative manufacturing, developed by the Municipality of Rotterdam and the PoR Authority (Mendes Constante et al., 2023). In addition, various academic institutions have tailored their programmes to meet

PoR's sustainability-oriented skills. Such programmes include "Urban, Port and, Transport Economics", "Logistics Management", "Maritime Economics & Logistics" in Erasmus University Rotterdam and "Industrial Ecology", "Transport, Infrastructure and Logistics" and "Hydraulic Engineering" in Technical University Delft (Mendes Constante et al., 2023). Currently, the overall student annual flow in port-oriented master's Programmes is more than 250, 100 of whom are foreign students meaning that they may not engage in regional employment after their graduation. Yet, most of these academic programmes are actively involving regionally based industrial actors, usually expanding their "corporate networks" to the port business community (Mendes Constante et al., 2023). However, such efforts still fail to address the fundamental job loss risk of the existing workforce, crucially those that are difficult to transition to other domains (e.g., specialised and/or older workers).

4.2.7 Infrastructural capacity

Companies within RHIC are linked to an integrated infrastructure based on a shared grid for the supply and consumption of electricity, hydrogen, residual gases, steam, heat, CO_2 etc. (Baas & Korevaar, 2010). The cluster has access to a vast pipeline network interconnecting all major industrial and terminal zones with docks and warehouses (PoR Authority, 2024). Consequently, the existing pipeline infrastructure of over 1,500 km is one of the major assets of PoR (Rattle & Taylor, 2023).

This infrastructure capacity includes over 70 electricity generation units operated by major providers such as Eneco, E.ON, Intergen, Electrabel, Eurogen, Enecal, Essent, Nuon, and various co-generation units, while two of them still operate with coal (Engie & E.ON) (Samadi et al., 2018). The renewable energy pipeline network is still evolving, and new pipelines are being developed to support hydrogen, biofuels, and synthetic fuels, especially in the Maasvlakte area. A hydrogen pipeline is under development by Shell, expecting to be fully operated by 2025. That could include 1,200 km of new hydrogen pipelines connecting industrial sites to each other, to other countries in the European hinterland, as well as with import and storage sites (PoR Authority, 2024). The cluster's electricity grid is going to be further updated to support additional energy demand by the Power Grid Upgrade project, a collaboration between grid operators TenneT and Stedin focusing on offshore wind farms expansion. In addition, the HyTransport.RTM project aims to advance RHIC as a hydrogen hub by constructing open access hydrogen pipeline network, mainly intended for green hydrogen instead of blue that is currently led by PoR Authority and Gasunie NV.

Steam is delivered by E.ON, Eurogen, Enecal, Electrabel, AVR and water is sourced by Evides and AVR. Steam networks are actively creating regional interdependencies, since companies within RHIC are increasingly relying on shared steam infrastructure. For example, Shell Pernis Refinery (acting as a central node) with Hexion, Shin-Etsu Persin, and Shell Chemie depend on steam coming from Pergen VOF. In the Rozenburg area in Botlek, Air Products, Eurogen, and Enecal supply steam to several firms including Esso, Lyondell, and Huntsman. On top of that, there are sites like Olechemicals, fully dependent on these networks to sustain their processes, underscoring the RHIC's growing systemic reliance on integrated steam flows (Haas & Dril, 2022).

Natural gas is imported and supplied directly to industrial operations through a pipeline grid, while industrial gases are provided by Air Products, Air Liquide, and Linde. Storage, warehousing, and distribution are critical to the PoR that features a total bulk liquid storage capacity exceeding 30M cubic meters. Crude oil, refined petroleum (e.g., gasoline, diesel, kerosene, and naphtha), bulk liquid chemicals, and edible oils are managed by producers maintaining their own tank storage facilities and by third-party logistical service providers in bulk liquid storage. Specifically, Europoort is the starting point of major pipelines, extending to the Port's refineries and storage terminals, including internal connections to Botlek and Shell Pernis, serving both traditional fossil fuel refineries as well as cleaner industrial capacities like bio-methanol production (Carmona-Martínez et al., 2024).

Pipelines from Botlek and Europoort transport raw chemical materials, gases, and fertilisers, supporting the chemical companies. The cluster offers designated corridors for new pipelines and provides leasing options through MultiCore, a pipeline bundle jointly managed by Vopak and the PoR Authority. MultiCore is an underground pipeline system supporting the distribution of chemicals and gases, addressing the infrastructural needs of many industrial companies that were unlikely to be individually funded (Rattle & Taylor, 2025). This initiative demonstrates the Authority's commitment to implement shared infrastructure to support its industrial tenants (Rattle & Taylor, 2025). This flexibility allows companies to access the network without needing to establish their own infrstructure, enhancing PoR's role as a logistics facilitator. Additionally, specialised pipelines operated by DOW Propylene, Air Liquide for industrial gases, and OCAP for CO_2 transport provide dedicated routes for specific chemical intermediates and industrial gases. This extensive pipeline network connects PoR with the Netherlands hinterland as well as with other European industrial areas through Belgian and German nodes via the Central European Pipeline System (CEPS), Rotterdam-Antwerp Pipeline (RAPL), and Rhein Main Rohleitung (RMR).

The Authority along with the global quality assurance and risk management company Det Norske Veritas (DNV) based in Norway, has also scoped the development of a long term collaborative CO_2 pipeline network to facilitate CO_2 emissions transportation, storage, and reuse fed from different industry sites within the wider PoR region, including the Moerdijk area or the Zeeland chemical industrial cluster (Van Beek et al., 2024). The captured CO_2 would either be transported and stored offshore in the Dutch North Sea or be processed for reuse in industrial sites including heavy petrochemical emitters, hydrogen producers, and greenhouses, both of which require smaller CO_2 input and would therefore not rely upon offshore storage (Van Beek et al., 2024).

4.2.8 Key decarbonisation strategies in PoR

The infrastructural integration of PoR is mainly profited by the co-location of supply and demand (Rattle & Taylor, 2023). This advantage can potentially achieve lower energy costs and promote key sustainability innovation technologies like hydrogen and CCUS, on top of efforts towards electrification and circularity. However, substantial expansion of green hydrogen infrastructure will be needed (Gianoli & Bravo, 2020), adding to the already high costs of other implemented net-zero solutions (i.e., CCS).

A core caveat on this effort is the lack of a holistic and concrete policy framework to drive the path to sustainability other than the more targeted Rotterdam Climate Initiative (RCI) and Rotterdam Climate Proof (RCP) (Gianoli & Bravo, 2020). RCI was a joint initiative between the PoR Authority and the Municipality of Rotterdam initiated in 2007, targeting to cut down half of the region's CO_2 emissions (city and port), by 2025. In 2013 RCI presented its action plan focusing on five areas of development. These included the Deltaplan energy infrastructure to transport and reuse heat, steam, and CO_2, the setup of PlantOne, an expert centre for the port's energy efficiency, the use of liquified natural gas (LNG) in water and road transportation, the implementation of CCS to capture and store emissions from the two coal-fired power plants of the PoR, and finally the Bio Port Initiative for the production of first generation biofuels (Bosman et al., 2018). However, the RCI failed to meet the objectives set, mainly due to the cancellation of the initial plans for offshore CCS, as well as the significant delay of later efforts that are currently under construction (see below), raising emissions by 50% instead of decreasing them (Bosman et al., 2018).

Balancing industrial market leadership with public acceptance of decarbonisation projects and mitigating fear of carbon leakage are thus of major concerns of the wider PoR region (Rotterdam-Moerdijk, 2018). During the last two decades, the PoR Authority has expanded its efforts towards developing decarbonisation pathways with a diversity of technologies featured, including offshore wind, hydrogen networks both for green and blue operations, co-firing biomass (with coal), as well as boosting hybrid and electric vehicles (Bosman et al., 2018). Specifically, the current decarbonisation roadmap of PoR includes the steam-sharing network expansion of Botlek to contribute a 0.5Mt of CO_2 reduction by 2030. Also, the South Holland Heat Alliance industrial heat delivery systems, such as heat pumps and electric boilers, is expected to provide 2.1 Mt CO_2 savings per year supported by 3 GW of offshore wind. The CCS projects, Porthos and Aramis (elaborated below) are designed to capture and store 3.6 of CO_2 annually by 2030. Recycling and biomass initiatives focus on mechanical and chemical recycling of plastics, alongside biomass valorisation, further contributing to solid waste management and CO_2 reduction. Such efforts have engaged governmental and private entities such as the Dutch Ministry of Economic Affairs & Climate Policy, the City of Rotterdam, the Netherlands Environmental Assessment Agency (PBL), the Netherlands Organisation for Applied Scientific Research (TNO), the Regional Development Agency, the Province of Zuid-Holland, and the Innovation Quarter, a regional economic development agency, which has been actively involved in renewable energy and decarbonisation projects in PoR (Haas & Dril, 2022). The Rotterdam Cluster Energy Strategy, introduced in 2021, serves as a blueprint aimed at aligning local efforts to the National energy strategy that aspires to achieve both energy efficiency and deep GHG emission reductions (Hendriks & Gooyert, 2023). However, many concerns have been expressed over CCS dominating mega offshore installations and potentially crowding out other mitigation options based on the expected significant emissions reduction potential as seen in Figure 7, which however may not materialise in time (Perdana et al., 2023). Given the impact of similar project delays and cancellations in the past (e.g., RCI initiative) leading to the failure to reach the targets set, reliance on one technology may hamper the viability of the roadmap.

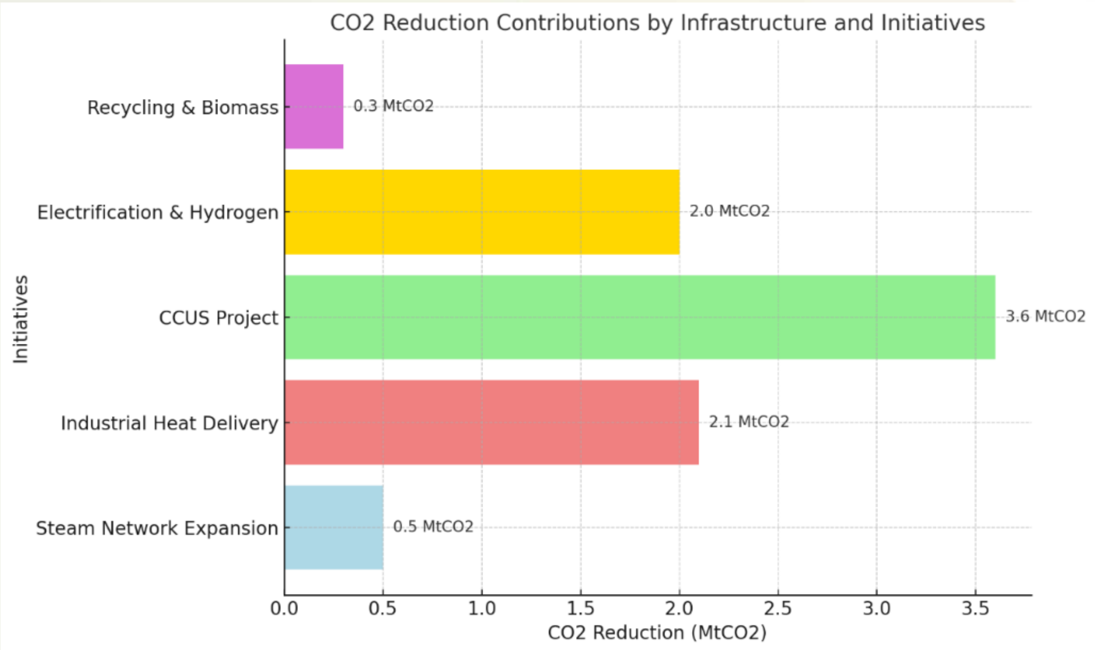

Figure 7. CO2 emissions reduction contribution by infrastructure and initiative until 2050.

Source: (Rotterdam-Moerdijk, 2018)

To prevent carbon leakage, PoR has mostly relied on national financial mechanisms such as the Stimulation of Sustainable Energy Production and Climate Transition (SDE++), a subsidy scheme aiming to cover the initial high adoption costs and advance the economic feasibility of green electricity projects. The SDE++ was introduced by the Dutch Government in 2020, building on an earlier version (SDE+ 2008) to support renewable energy and CO_2 reduction projects, intended to reduce the financial barriers to newcomers wanting to enter the Dutch energy sustainability market (Gianoli & Bravo, 2020). Since 2020, several industrial decarbonisation technologies have been included such as heat pumps, electrical boilers, hydrogen production through electrolysis (Van de Sande et al., 2024). At the same time however, such initiatives are often met with suspicion by incumbent stakeholders, who often express the fear that stronger regulatory mechanisms could hinder the cluster's operational flexibility and adaptability (Gianoli & Bravo, 2020).

4.2.8.1 Spatial limitations

The continued dependence on fossil fuels of the refinery and chemical industries in RHIC requires a major feedstock transition, from crude to renewable inputs, like biomass, used cooking oils, and waste on top of mitigation efforts based on hydrogen and CCUS. However, this feedstock transition raises a major bottleneck related to space availability, given that the PoR has already proceeded in expansions to cope with increasing industrial and logistics demand. This challenge has been recently highlighted by the Institute for Sustainable Process Technology (ISPT), in Utrecht, claiming that the energy transition will be strongly affected by the Port's spatial limitations (ISPT, 2025). According to their recent report, previous studies have indicated that renewable feedstock processing might require 2 to 4 times more space for the same fossil-based productivity rates, depending on the decarbonisation mix that will be eventually followed in RHIC (ISPT, 2025). For example, the report forecasts the dominance of CCS over CCUS since the latter is found to be more space-inefficient that the former. Other low carbon options are also expected to be severely affected by limited space, such as the synfuel value-chain through Fischer-Tropsch synthesis (FTS), a process that converts carbon monoxide (CO) and hydrogen (H2), known as syngas, into a variety of hydrocarbon fuels and waxes, or waste gasification for the production of methanol as well as a stronger reliance on plastic waste pyrolysis instead of bio-naphtha (ISPT, 2025). The spatial challenge can thus be of critical importance to the technology mix pathway that the RHIC will eventually rely on, despite other enabler factors that could potentially promote the application of other, spatially intensive low-carbon options.

4.3 Landscape

Both energy efficiency and GHG emissions reduction have been core objectives of the Dutch Government: a National Energy Agreement signed in 2013, was signed by more than 40 societal organisations targeting a total of 100PJ of industrial energy savings by 2020 (Janipour et al., 2020). In addition, a National Climate Agreement passed in 2019, originally targeting a 49% reduction of GHG emissions by 2030, and a 95% reduction by 2050, compared to 1990 levels and proposing measures for several sectors including industrial business (Janipour et al., 2020). The Climate Agreement identified the country's five main industrial regions, namely Rotterdam/Moerdijk, Zeeland (Terneuzen and surrounding areas), the North Sea Canal Area, the Northern Netherlands (Eemshaven-Delfzijl), and the Randstad region, prioritising them as the "acceleration chambers" for the implementation of low-carbon technologies, including green hydrogen and CCUS (Rattle & Taylor, 2025). Despite the ambition of these targets, many Dutch stakeholders are claiming that there is a level of discrepancy between deep emissions reduction and the level of energy efficiency policy measures, since emission reductions based on electrification might require further efficiency efforts (Janipour et al., 2020). Limited resources and time constraints could potentially create a trade-off between the two priorities (Janipour et al., 2020). At the same time, incumbent firms operating in RHIC actively seek EU-wide regulatory commitments to ensure long-term policy predictability for energy transition investments (Gianoli & Bravo, 2020). The European Climate Law and Carbon Border Adjustment Mechanism (CBAM) are considered crucial for ensuring long-term competitiveness by setting clear decarbonisation targets and regulating carbon-intensive imports (Gianoli & Bravo, 2020) and therefore responding to the cluster's growing uncertainty levels.

Changes connected to the PoR's fossil energy regime are expected to be significantly affected by current geopolitical uncertainties affecting the supply chain and the prices of energy, such as the Russian war, a shift towards shale gas production in the USA, conflicts in the Middle East, as well as environmental concerns and opposition over fossil-based industrial operations (Bosman et al., 2018). The uncertainty levels caused by new world configurations related to the evolving energy transition are a major concern for RHIC stakeholders. To respond to these uncertainties, coordinated policy making as well as cross-border cooperation are imperative.

Key global institutions, such as the World Economic Forum (WEF) and the United Nations Industrial Development Organisation (UNIDO) have strongly supported the potential of industrial clusters to materialise deep decarbonisation prospects, identifying high carbon prices, low-carbon infrastructure, and road map planning as the key elements in facilitating this objective (Schneider et al., 2020). Similarly, the significance of "adequately ambitious, stable, and predictable" climate mitigation policy at the EU and at the member-state level remains crucial for the successful operation of such prospects (Samadi et al., 2016). The WEF has consistently emphasised the significance of RHIC as a signatory member of global industrial decarbonisation initiatives, as a part of a broader network of industrial clusters actively pursuing low carbon technologies, such as CCUS and hydrogen infrastructure, to reduce emissions (WEF, 2024). Similarly, UNIDO indicates RHIC among other clusters as pioneers in sustainable industrial development, emphasising its role in emphasising their role in fostering job creation (UNIDO, 2024). The Paris Agreement and the International Maritime Organization (IMO) have regulated maritime and industrial emission reductions mandates, supporting the low-carbon transition in RHIC.

RHIC's international exposure, has driven the National Government to subsidise the difference between the generation costs of renewable energy and its fossil-based market price, actively supporting solar, wind, geothermal, and biomass energy as well as CCUS and hydrogen production (Gianoli & Bravo, 2020). Specifically, the Netherlands is home to the most advanced and the world's larger offshore CCS cluster projects (see below). To enhance CCS technologies, the Netherlands adopted subsidies and have created new cost-sharing mechanisms to promote their development, fulfilling their promise of increased adoption by 2035.

Additionally, following the European Council's approval of a gas and hydrogen market package launched in 2024, the Dutch Authorities are currently promoting an early coal phase-out in electricity generation as well as policies to scale up renewable energy sources by 2030.

Over the past 30 years, the Netherlands has demonstrated a growing offshore wind market, starting from a 6% share in all European offshore wind activities in 2002, to 14% in 2020, currently employing nearly 12,000 individuals (70 people over 100,000 of its population) (Van Der Loos et al., 2021). The country's geographic location in the North Sea, as well as previous experience from domestic offshore oil and gas production incentivised a period of heavily subsidised small demonstration farms during the 1990's (Van Der Loos et al., 2021). The two oil shocks in 2008 and 2014 raised expectations over renewable wind energy developments, leading to the construction of a large-scale wind farm in 2006 after receiving more financial and political governmental support. Eventually, the government decided to give out permissions for offshore wind, extending the Dutch North Sea allocated area for such developments that eventually did not follow due to tremendously high costs. However, the Dutch government promoted R&D specific to wind technology bearing these costs from private companies, tripling the number of Dutch stakeholders within Europe and promoting business networking and lobbying organisations, enabling the construction of the world's largest offshore wind farm, Gemini Park, in 2017 (Van Der Loos et al., 2021). The PoR Offshore Wind Coalition formed under the above context of steady political support for offshore wind, operating mostly outside the Dutch market and instead focusing in industry formation regardless of the market's location (Van Der Loos et al., 2021). At the same time, the Windmaster project, initiated in 2018 by the Dutch gas and electricity transmission grid operators TenneT (TNT) and Gasunie (GAS), the regional distribution system operator Stedin (STD), together with the PoR Authority, Siemens, Deltalinqs, the Institute for Sustainable Process Technology (ISPT), the Province of South Holland, and Delft University of Technology (Van Der Loos et al., 2021).

While offshore wind is expanding rapidly, especially in the Dutch, Belgian, Danish, and German parts of the North Sea, anticipated to reach 65GW by 2030 and 150GW by 2050, EU is pushing for a much higher operation level targeting 300GW by 2050 (P. Baas & Verzijlbergh, 2022). At the same time, the Dutch Offshore Wind Roadmap for 2030 doubled its target for approximately 20GW installed capacity, now reaching no more than 4GW (P. Baas & Verzijlbergh, 2022). The National Government is currently scheduling tenders for wind farm permits in designated seafloor areas to facilitate offshore developments, the biggest of which is the IJmuiden Ver Wind Farm Zone, 62km from the Dutch coast, expected to operate by 2030 with a 4GW capacity, covering 14% of the country's electricity demand (Eady et al., 2023).

The current dominant EU strategy to support the industrial low-carbon transition is mandating for higher CO_2 emission prices through the EU-ETS mechanism. However, a mixed-incentive approach is often proclaimed as most appropriate to EIIs to invest in low-carbon technologies while also eliminating fears of carbon leakage (Gianoli & Bravo, 2020). However, investment leakage, the quite opposite result of what carbon leakage policies aim for, is also a risk. The absence of funding to reduce GHG is currently undermining the effectiveness of the EU ETS, which has failed to reduce emissions since 2012 and expected to do so until 2030 (Gianoli & Bravo, 2020). However, RHIC industrial stakeholders are relying on long-term EU-wide commitments, like CBAM, to be reassured for their investment decisions, while they seem reluctant of over-regulation trends fearing this would hinder the cluster's flexibility (Gianoli & Bravo, 2020). To respond to the uncertainty level currently hindering the industrial low-carbon transition, the recently launched Clean Industrial Deal (2025) is expected to mobilise over €100 billion targeting EIIs like steel, metals, and chemicals, emphasising clean technologies and circular processes.

At the same time, cross-border cooperation is often hampered by legal and administrative obstacles. The EU Parliament put pressure on the European Commission to further prioritise cross-border contact points, with the Netherlands-Flanders cross-border contact point being expected to become fully operational within 2025, deepening integration prospects among all regions bordering Benelux. For the period 2021-2027, the Commission presented the CEF Energy Cross-Border Renewables program to encourage collaborative renewable energy infrastructure initiatives regionally. PoR was included in the project as an EU distribution hot spot in the EU's renewable hydrogen value chain. The European fund will invest €11.6M in CICERONE-Ammonia to prepare European ports for ammonia imports and cracking into hydrogen from Spanish renewable sources. To support a European green energy value chain, the project includes the construction of a 120MW green ammonia plant in Puertollano, Spain, powered by 400MW of renewable photovoltaics

(PV). PoR joined the project CICERONEGreenNH3stud, led by Iberdrola with €3.4M funding. The project is managed by the Netherlands Enterprise Agency (RVO).

4.4 Technological Innovation Systems

4.4.1 Hydrogen TIS

The regime structure of RHIC is appealing to hydrogen-related investments due to the accumulation of supply and demand–consisting of standard industrial applications, infrastructure has already been set in place to accommodate existing hydrogen industrial demand, including expansion plans (Schneider, 2022). Importing hydrogen for EIIs in Northwest Europe is a daunting issue due to the long-anticipated advancements in the respective regional pipeline networks. In response, the PoR Authority in collaboration with Gasunie NV, the state-owned grid operator proceeded in constructing a new hydrogen pipeline network connecting internal industrial company sites with the port's import and storage sites as well as to other countries in the European hinterland. The cluster is projected to supply Northwestern Europe with 4.6 Mtonnes of hydrogen annually by 2030, contributing to a reduction of 46 million tonnes of CO_2. The HyTransPort Project, led by PoR Authority and Gasunie, is central to the realisation of a hydrogen hub in the RHIC. In addition, Semi-public National electricity grid operators like TenneT, are increasingly involved in the expansion of hydrogen infrastructure (Samadi et al., 2016).

4.4.1.1 Entrepreneurial activities

Gunvor's decision to stop coal trading coincided with its shifted focus on sustainable fuels. Collaborating with Air Products, Gunvor established a green hydrogen import terminal in RHIC introducing green ammonia as a hydrogen carrier. The Maasvlakte ammonia terminal aims to achieve net zero emissions and minimal nitrogen oxides, demonstrating a scalable and sustainable approach to hydrogen conversion. The project seeks Important Project for Common European Interest (IPCEI status to ensure financial support, addressing the local production shortfall as well as the pioneering shift towards low-carbon alternatives by facilitating large-scale green hydrogen imports. The Gunvor refinery at Europoort is of strategic European importance for green ammonia imports from global production sites. Green ammonia is converted to hydrogen and distributed across the ARRRA region. Gunvor, a major operator within RHIC, has committed to reduce Scope 1 and 2 emissions by 40% by 2025 hoping to adopt sustainability-linked funding.

The strategic shift of dominant industrial players within the RHIC away from fossil-fuels portrays their decisions to maintain their key operations proceeding with alternative low-carbon energy inputs. Following Gunvor's shift, the Global Energy Storage (GES) acquired a Stargate Terminal part from Gunvor Group, to develop a 20-hectare site dedicated to storage solutions for biofuels, renewables, gas-to-chemicals, and hydrogen (green and blue). Thus, low-carbon innovations are being diffused as spillovers of larger sustainable developments within the cluster. Such innovation spillovers, especially related to green ammonia, have been endorsed by the PoR Authority's initiative to develop the ACE Terminal along with major industrial players such as Gasunie, Vopak, and HES International, scheduled to be fully operational by 2026. The new terminal of Maasvlakte II, designed to accommodate vessels from all over the world, is suitable to discharge green ammonia, since it accommodates cracking facilities that enable large-scale conversion of ammonia into hydrogen for distribution. It is estimated that €260-425M will be provided in indirect economic benefits to the Dutch economy, along with the creation of thousands of jobs over the next several years. However, its initial phase will only handle blue ammonia, further highlighting potential risks should CCS fail to materialise on time. Recently, OCI, a significant ammonia player, decided to triple its ammonia storage capacity, possibly operating within 2026.

Green ammonia is the only hydrogen carrier that can achieve carbon neutrality and thus is central for the decarbonisation of chemicals (Samadi et al., 2018). Green ammonia, produced by reacting green hydrogen with nitrogen, enables the large-scale transportation and storage of hydrogen efficiently. Ammonia can later be stored and converted back into hydrogen or used as CO_2-free fuel for shipping or as a feedstock for fertilisers. The PoR Authority has acknowledged that the upcoming ACE Terminal, a green ammonia terminal in Maasvlakte II will serve as a major import hub for green ammonia, which will either be reconverted into hydrogen or be directly used as a low-carbon fuel across Europe. This import hub is expected to significantly boost Europe's hydrogen capacity since imported ammonia will also be converted to hydrogen for regional use transported through pipelines to other European clusters. The joint venture of market players like Vopak and the German hydrogen company Hydrogenious, introduced a benzyltoluene-based (CO_2-containing) hydrogen, and a carrier system which is expected to connect to Gasunie's National hydrogen network, supplying the North-West European market. The hydrogen generated in RHIC will thus not be fully sustainable. However, the joint venture signals the market's financial commitments towards the commercialisation of storage, transport, and supply of hydrogen in the coming decades involving 18 industry partners (Air Liquide, Aramco, bp, Essent/E.ON, ExxonMobil, Gasunie, GES, HES international, Koole Terminals, Linde, OCI, RWE, Shell, Sasol, Uniper, Vopak, and VTTI). Even though it plays a pivotal role in the emerging European hydrogen infrastructure and market, it still does not thoroughly respond to the growing global demand for sustainable energy. LOHC technology, a novel process of binding hydrogen to a stable liquid carrier developed by Hydrogenious aims to make hydrogen's transportation more practical, revolutionising hydrogen logistics. Vopak will cooperate with Hydrogenious for the development of this hydrogen carrier of benzyltoluene which carbon-neutral potential when fed with renewable hydrogen (Distel et al., 2025). As a result of this cooperation, a 'LOHC' plant has been proposed to commercialise its application planning to initially decouple 1.5 tonnes of hydrogen per day. This initiative expands RHIC hydrogen production and market capacity while facilitating the broader integration of LOHC into hydrogen supply chains. The operations led by Vopak and Hydrogenious consists of another RHIC collaboration focusing on liquid organic hydrogen carriers LOHC-based hydrogen storage system, the sustainability of which will heavily depend on the hydrogen as well as the energy inputs throughout its cycle[23].

Investments in the already existing refinery infrastructure are important too; refining capacities provide RHIC's operational efficiency and market competitiveness (Samadi et al., 2016). Reinvestments oriented to accommodate alternative energy uptakes are necessary to allow for technical flexibility to process alternative feedstocks, such as biomass-derived Fisher-Tropsch products (Samadi et al., 2016). Importing electricity from the South of Europe or hydrogen from MENA countries to meet regional demand are among the offered solutions (Samadi et al., 2016). At the same time, BP, Nouryon and PoR Authority, are collaboratively shifting existing industrial practices towards hydrogen. However, the production and operational aspects of green hydrogen produced in Botlek using renewable electricity are dominated by Nouryon, with expertise in sustainable electrochemistry aiming to establish new value chains for low-carbon fuels. Nouryon leads the construction and the operation of Europe's largest 250MW water electrolysis

[23] https://www.portofrotterdam.com/en/news-and-press-releases/vopak-focuses-on-hydrogen-imports-in-rotterdam-with-german-company

facility, expected to supply up to 45,000 tons of green hydrogen annually to BP's refinery, potentially resulting into a CO_2 reduction emission up to 0.35 Mtons per year by replacing hydrocarbon-based hydrogen with green hydrogen.

Progressively, the PoR Authority also proceeds into international agreements to promote the leverage of sustainable fuels, such as the Green and Digital Shipping Corridor in partnership with the Maritime and Port Authority of Singapore, aiming to cut international shipping emissions by 20-30% by 2030, using green methanol, ammonia, and LNG. Additionally, a Hydrogen Coalition initiative was put forward, involving shippers and inland shipping cooperatives PTC and NPRC.

RHIC's petrochemical cluster will need to undergo a fundamental transformation through electrification of hydrogen production and industrial heating and cooling that could reduce overall GHG emissions by 70% (Cuppen et al., 2021) until 2030. The expansion of offshore wind renewable electricity production in the North Sea may prove crucial in this endeavour, with annual capacity additions expected to reach a 5GW per year (Cuppen et al., 2021). At the same time, given the highly industrialised levels of Noth-West Europe, RHIC's energy demands are unlikely to be met solely by domestic offshore renewable production, meaning that the cluster will continue to rely on imports (Rattle & Taylor, 2023). In addition, the existing electricity infrastructure (transmission and distribution networks) is not enough to support the influx of additional electricity. If expanded, as part of the proposed national hydrogen backbone strategy, it will significantly enhance the country's further integration with the German and Belgian industrial clusters and specifically the Antwerp, Rotterdam, Rhine-Ruhr (ARRRA) chemical supercluster (Rattle & Taylor, 2025). However, while its expansion is currently hindered by high investment costs and limited space (in the North Sea), with the lack of progress impacting industrial demand, resulting in a "wait and see" approach among relevant stakeholders (Cuppen et al., 2021)

4.4.1.2 Knowledge development/Knowledge diffusion through networks

Hydrogen production firstly appeared as a crucial decarbonisation technology in the Rotterdam Climate Agreement (2009) (Bakhuis et al., 2023). Today's key PoR business actors such as Shell, BP, TotalEnergies, Eneco, Vattenfall, Equinor, RWE, Uniper, Engie, Orsted, HYGEN Energy, Alliander, GreenMax, and Fluxys are active nation-wide in developing hydrogen projects. For example, Shell aims to replace grey hydrogen and GreenPlanet operates a hydrogen refueling station. Start-ups like H2Storage and HySilabs engage in innovative hydrogen technologies like storage tanks, new fuel cells and electrolysers. Such industrial players are actively cooperating with consultancies (e.g. PwC) or engineering firms to support knowledge developments and pilot projects. Due to the influence of research and policy evolution around hydrogen, Shell proceeded to the construction of the REFHYNE 10 MW hydrogen electrolysis plant at the Shell Rheinland refinery in 2018 in North Rhine Westphalia, Germany (Bakhuis et al., 2023). This investment fuelled the competition among refinery players in the two countries.

The high technology readiness level of hydrogen-related technologies has pushed the European Commission and many heavily industrialised member states to prioritise hydrogen R&D (Bakhuis et al., 2023). However, the Dutch industrial regime is currently supporting small scale hydrogen pilot projects through national subsidies and other EU innovation programmes despite its ambitious yet non-binding hydrogen market development targets (Broekstra, 2023).

Since 2005, the Energy Research Centre of the Netherlands in collaboration with TUDelft have initiated R&D activities in partnership with Shell, BP, Nuon, Eon, Ecofys, and Cgen regarding the implementation of hydrogen reactors (Bakhuis et al., 2023). The road towards the development of a Dutch hydrogen "backbone" strategy for industrial sustainability was further enhanced by EU hydrogen prioritisation in order to tackle both the lack of hydrogen supply and demand and hence organise the allocation/construction of hydrogen-related infrastructural requirements, on due course (Bakhuis et al., 2023). Eventually, the H-vision feasibility study began in 2018 within the context of European Research Project Stepwise (Bakhuis et al., 2023). The H-Vision project focused on producing blue hydrogen through steam-reforming natural gas and storing the resulting CO_2 under the North Sea. Initiated by PBL, in collaboration with Shell, BP, and ExxonMobil, the project's goal was to provide hydrogen as a low-carbon energy carrier for industrial processes and pave the way for future green hydrogen integration (Nikolopoulou & Koert, 2020). The H-Vision project has been integrated into the wider port planning configurations since developing accurate projections of future hydrogen demand will further reinforce PoR's status as a key European hydrogen hub.

The PoR Authority along with BP, Joulz, TNO, and Uniper developed a Power-2-Gas-2-Refineries project to test the technical and economic feasibility use of hydrogen and scope the construction of a 20MW electrolysis plant (Bakhuis et al., 2023). RHIC has activated its technological knowledge potential by integrating expertise from multiple stakeholders to regionally evaluate innovations. These include research collaboration teams, like the Wuppertal Institute, PBL, and TNO, that have been providing the Authority with decarbonisation roadmaps and scenario studies. NPRC, Europe's largest inland shipping cooperative, along with Nouryon, and Lenten Scheepvaart, conducted joint studies investigating zero-emission inland vessel developments using 100% green hydrogen. Similarly, BP, Nouryon, and the PoR Authority, accompanied by a memorandum of understanding, engaged in studying the feasibility of green hydrogen facilities and explore the opportunity of producing green hydrogen via water electrolysis for BP's refinery in Europoort.

Another factor affecting the diffusion of hydrogen technology depends on R&D progress is renewable electricity (Schneider, 2022). Green hydrogen production relies on renewable electricity, usually through electrolysis, which is directly affecting its scalability and cost-effectiveness. High renewable electricity prices and availability constraints can hinder the widespread adoption of green hydrogen developments. Thus, R&D processes targeting hydrogen should also focus on cost reductions, grid integration and efficiency improvements to bring out the potentials for cheap and abundant renewable electricity (Schneider, 2022).

In addition, the established network related to green hydrogen as shipping fuel indicates not only that the technology is available, but mostly that the RHIC regime is rather receptive to the change towards green hydrogen. Hydrogen developments in inland vessels are currently endorsed as "a sustainable win-win". The intention of this hydrogen innovation is to use hydrogen-derived fuels for the transportation of salt used in the manufacturing of chlorine and caustic soda. NPRC coordinates the logistics operations while Lentern Scheepvaart serves as an operational partner, providing vessels for testing a 100%-based hydrogen fuel replacement, while the National government participates as an external actor. This level of diffusion of green hydrogen technology indicates that further technological progress may decrease hydrogen prices, which is currently more expensive than other fuels. Even though water transport is traditionally considered as the less impactful form of cargo transportation, zero-emission shipping has been a thorny aspect for PoR (D. Baas, 2019). The Port Vision 2030 is now imposing stricter emission controls on inland ships, requiring ship-owners to invest in low-carbon technologies. Lately, the Dutch shipping company Future Proof Shipping (FPS) started to utilise hydrogen as a fuel for inland waterway shipping. Apart from hydrogen, bunkering involves vessels fuelled with green methanol as a viable alternative. Samskip Seahuttle is another cooperative initiative towards hydrogen-powered short-sea shipping, with plans to launch these vessels by 2026 In addition, RHIC highly depends on shore power developments to provide docked ships with access to the electrical grid minimising emissions of CO_2, nitrogen oxides etc. (Baas, 2019). Besides biofuels and shore power, recycling batteries and electronic waste, and CCS are also important carbon-reducing shipping practices strongly embraced by the RHIC regime (see Battolyser technology) (Baas, 2019). Through the ZES project, RHIC will invest in the development of 75 new battery containers units for maritime use, the installation of 14 different charging dock stations, as well as the electrification of 45 inland vessels, providing quiet and sustainable shipping solutions (Baas, 2019).

At the same time, biofuels, as a rival technology to hydrogen, also seek to replace natural gas inputs (Xavier & Oliveira, 2021). Although hydrogen shipping can make a huge breakthrough in the energy transition of maritime operations, the NPRC, in collaboration with maritime and shipping actors, is also investigating other alternative options towards sustainable shipping, such as biofuels, clean combustion engines, and electrification of ships (PoR Authority, 2024).

4.4.1.3 Guidance of the search/Market formation

The European Commission develops EU-level energy, industry, and mobility regulations & directives to set the overarching framework for hydrogen developments. The EC relaxed the rules requiring companies to prove the use of renewable energy for green hydrogen production at an hourly level to a monthly level. This encouraged hydrogen's market growth by making it easier and more attractive to invest in the technology and set the foundations for the launch of the Dutch National Climate Agreement (2019). The policy identified several hydrogen-based potential applications for carbon-free feedstocks as well as carbon-free energy carriers for high-temperature heat, controllable energy capacity and energy storage, and heating applications (Dutch Government, 2019). To promote further green hydrogen applications, the ambitious electrolyser target laid out in the Agreement aims to achieve 3-4GW of electrolyser capacity by 2030. Since 2022, the EU has targeted the rapid implementation of a hydrogen economy mandating the quadrupling hydrogen production and imports – from 5.6Mt to 20Mt – beyond the Fit for 55 targets and aligned with the REPowerEU framework towards increasing its energy independence and reducing reliance on fossil fuels.

The International Energy Agency's (IEA) Future of Hydrogen Report identifies clusters as "gateways" for hydrogen clean deployment reducing investments risks and ensuring a stable demand base scaling production (IEA, 2022). This is mainly because hydrogen production remains an applicable solution in decarbonising steel and chemicals production against large-scale energy imports (Merten et al., 2020; Schneider, 2022). However, as far as the North-West States like the Netherlands, Germany, and Belgium are concerned, the balance of green hydrogen imports and internal production is predicted to play a significant role due to their large-scale steel and chemical sectors as well as transportation applications (Samadi et al., 2016, 2018). However, hydrogen derived from electrolysis is currently challenging local hydrogen capacity since the RHIC alone is estimated to require up to 141TWh of electricity, a demand that if met would strain local energy infrastructures (Merten et al., 2020). Steel companies are central in diffusing successful hydrogen adoption through management practices (Schneider, 2022). Renewable energy providers deliver the required electricity for the production of low-carbon hydrogen, which can be used as an energy buffer, by converting electricity to hydrogen when there is overproduction and converting it back to electricity when there is shortage (Schneider, 2022). Storage distributors are the ones driving the hydrogen economy forward by investing in infrastructure including pipelines and storage facilities.

Due to heavily relying on substantial capital investments and infrastructural assets, offshore wind energy projects are critical for RHIC supplying renewable electricity to hydrogen electrolysis processes. Offshore wind energy capacity is projected to reach 11GW by 2030, supporting large-scale hydrogen production.

Accordingly, achieving long-term transition goals requires continuous investment in expanding renewable capacity and developing grid infrastructure to accommodate increased electrification demands. Offshore wind energy has been selected as the primary renewable power source for electrolysis to create low-carbon hydrogen production cycle. The regional infrastructure strategy implemented by industrial stakeholders of RHIC plays a decisive role towards the diffusion of hydrogen (Schneider, 2022). Shell's decision to install a 10MW electrolyser in the Cologne refinery to produce green hydrogen, increased competition within the context of the overall ARRRA region in 2018 (Bakhuis et al., 2023). Overall, the PoR Authority's commitment to large-scale electrolysers and offshore wind farms signals the long-term integration of green hydrogen in the RHIC.

4.4.1.4 Resources mobilisation/Creation of legitimacy

Hydrogen enjoys broad support, but debates persist over the balance between blue and green hydrogen (Nikolopoulou & Koert, 2020). However, non-profit organization like Greenpeace, Milieu Defensie (Friends of the Earth Netherlands), Natuur & Milieu (Nature & Environment), New Energy Coalition (NGO), and FME Metal (trade union) have strongly advocated for green hydrogen adoption.

Stakeholder dynamics introduced by oil and gas corporations, including Shell and ExxonMobil, have substantial influence over policy direction and technological adoption, especially for CCS which strongly relates to oil refining industries. PoR Authority acts as a strategic enabler by exploring options to create a blue and green hydrogen economy by facilitating necessary hydrogen infrastructure and distribution network in regionally. By supporting large-scale electrolyser developments and proceeding with the construction of offshore wind farms it strengthens the port's position as a frontrunner in the energy transition. Specifically, having approved the final investment decision since 2022, Nouryon will lead the construction and operation of a 250MW water electrolysis facility, the largest of its kind in Europe to supply up to 45,000 tons of green hydrogen annually in the premises of the old BP's refinery in Botlek. These mega investments could potentially achieve up to 350,000 tons of CO_2 emissions reduction per year by replacing blue hydrogen with green.

4.4.2 CCS TIS

4.4.2.1 Entrepreneurial activities/Knowledge development

The national target to reduce industrial emissions to 29.1Mtons by 2030 is based on the assumption that the implementation of CCS is expected to reduce emissions by half, through two large-scale national projects, the Port of Rotterdam CO_2 Transport Hub and Offshore Storage (Porthos) and the Aramis—cross-border CO_2 transport and storage project—as well as other transnational projects (Van de Sande et al., 2024). Although initiated by government actors, those projects aim to operate within a business-to-business market with competition between transport and storage facilities (Van de Sande et al., 2024).

While full scale CCS projects are relatively new in the Netherlands, the experience gained from previous CO_2 capture and use in greenhouses for crop fertilisation within PoR region (see industrial symbiosis above) gave government actors the confidence to proceed with major offshore CCS developments around 2010 (Van de Sande et al., 2024). Onshore CCS has been avoided since 2007, when Shell's first pilot project to permanently store CO_2 in a depleted gas field in Barendrecht (a town close to Rotterdam) was not given permission due to major public opposition (Roggenkamp, 2025). By then, the Dutch Government joined the North Sea Basin Task Force, established in 2005 by Norway and the UK, initiating inaugurating international collaboration on CCS (Van de Sande et al., 2024). The National Government taking advantage of the launch of EU-ETS (2005), aimed at heightening CO_2 prices, and of the European Economic Recovery Programme (EERP) following the financial crisis of 2008, to secure funding for its first CCS demonstrator, named the Rotterdam storage and capture demonstrator (ROAD) in 2013 but eventually cancelled in 2017 (Rattle & Taylor, 2023). ROAD aimed at capturing the flue gases of the two coal fired power plants, that were being constructed at that time and store them offshore. However, prevailing low carbon prices as well as public resistance over the continuation of coal-fired power generation, the project was eventually withdrawn (Van de Sande et al., 2024). This second failure shifted the government's attention from power generation towards EIIs, reflected in the Vision for CCUS, a national roadmap that highlighted relevant sectors and boundary conditions for CCS while also re-introducing CCU. Both the national Vision for CCUS and an equivalent statement by the international Task Force, the European Commission accepted CO_2 infrastructure developments as eligible for Projects of Common Interest (PCI) status (Van de Sande et al., 2024).

Following these major yet failed attempts described above, Porthos was initiated in 2017 by a joint venture led by three state-owned entities: the PoR Authority, Gasunie NV, a gas network operator, and EBN, an upstream hydrocarbons company. The project, aimed at capturing CO_2 emissions from the port's highest emitting industrial companies and store them in the North Sea, establishing an open access joint CO_2 transportation and storage infrastructure (Rattle & Taylor, 2025). Considered an important stakeholder in the national debate on decarbonisation targets, the PoR Authority was able to build support for Porthos, after a court case filed by the environmental group Mobilisation for the Environment, concerned by the environmental impacts of nitrogen emissions during its construction phase that was legally dismissed, although leading to the project's significant delay (Rattle & Taylor, 2025). Porthos set up expression of interest in 2019 attracting giants Air Liquide, Air Products, ExxonMobil, and Shell that committed to the project that same year, through signing Joint Development Agreements and after gaining access to SDE++ grants (Van de Sande et al., 2024). After gaining its PCE status in 2022, and thus securing financial support for the first 15 years of its market induction, construction eventually began in 2024 with its estimated commercial use expected to start after 2026, making it the world's most advanced industrial cluster decarbonisation project (Rattle & Taylor, 2025). The Porthos total infrastructure consists of approximately 30km of gathering pipelines within the PoR area, connected to a compressor station, and then to a 22km main pipeline leading gathered CO_2 to an existing offshore gas production facility to be refurbished to CO_2 storage installation, from where CO_2 will finally be injected under the sea (Roggenkamp, 2025).

Porthos is the EU's most advanced industrial CCS project enabled by sufficiently high carbon prices, support for market introduction, green investment support, roadmaps and infrastructure planning (Samadi et al., 2018). Porthos has thus been perceived as the outcome of an "adequately ambitious, stable, and predictable" mitigation policy both at National and EU level (Rattle & Taylor, 2025). Similarly, the Aramis CCS project, led by Gasunie NV, EBN, TotalEnergies, and Shell, under the same share (25% each), is awaiting investment decision by 2026, claiming financial support under Connecting Europe Facility (CEF), a European financial support mechanism for the development of cross-border CO_2 transport networks (Roggenkamp, 2025).

4.4.2.2 Knowledge diffusion through networks (Workshops/Conferences, network intensity)

CCS is perceived as a complementary technology to biofuel innovations (Samadi et al., 2016, 2018), and a critical option for the decarbonisation of certain petrochemical and refining industrial processes, that even maximum capacity hydrogen operations could not potentially meet (Janipour et al., 2022). CCS-dependent biofuels are currently feeding power plants in the Netherlands (Samadi et al., 2018). However, even though these Dutch biogas plants have established themselves in Europe since the late 1970s and continued in the mid-1980s, fluctuating prices, manure regulations, unsuccessful learning processes, and technical failures chronically provoked their fluctuated market demand and development (Geels & Raven, 2006). Synthetic fuel production entails large-scale sustainable biomass sourcing requiring massive infrastructural investments and CCS applications (Samadi et al., 2016). Many petrochemical processes like the Fischer-Tropsch method converting syngas—the steam cracking process producing ethylene and propylene—and the methanol-to-olefins (MtO) require CCS to produce minimum emissions and are depended on clustering (ISPT, 2025). Although not fully sustainable, pyrolysis and gasification could also be supported by CCS to reach zero emissions, in case of fossil feedstocks being used (ISPT, 2025). Additionally, applying CCS to steam-methane reforming (SMR) could extend its application for an additional 10-20 years, legitimising its use as a complementary technology to hydrogen applications (Janipour et al., 2021).

4.4.2.3 Market formation/Resources mobilisation

To promote CCS adoption, RHIC players leverage the cluster's robust infrastructure and strategic partnerships, as it is believed that a strong CCS network could enhance the industrial ecosystem (Janipour et al., 2021). Regional stakeholder's perception over CCS seen as a "temporary and intermediate solution" may suggest a positive effect on RHIC employment rates linked to carbon capture technologies, with the potential to mitigate the social impact of transitioning away from fossil fuels (Janipour et al., 2021). The application of CCS could potentially prevent job losses in fossil fuel-based industries exploiting the highly skilled workers in place (Janipour et al., 2021), as its large-scale implantations may possible shallow or deep carbon lock-in effects (Janipour et al., 2021). Considering the investments in CCS as well as the funding required to retrofit the power plant energy inputs to biomass, the adoption of such a technology mix could potentially result into lower cumulative CO_2 emissions (420 Mt) (Samadi et al., 2016, 2018; Schneider et al., 2020).

The Dutch government has been supporting the growing CCS market formation through subsidies, such as the SDE++ subsidy scheme, other tax incentives, and guaranteed funding. The EU has similarly strongly supported CCS deployment. In fact, the EU-ETS has a strong effect into shaping an environment that is appealing to CCS investments by setting a cap on total GHG emissions, requiring companies to obtain allowances for their emissions shaped under regulatory adjustments depending on European market conditions (Samadi et al., 2016). However, the effectiveness of this mechanism in driving CCS adoption is heavily influenced by allowance prices. In some cases, companies choose to purchase additional allowances rather than invest in CCS infrastructure, since the high capital and operational costs associated with CCS make it financially unappealing unless emission allowance prices were high enough to justify the investment. That is why companies often opt for lower-cost alternatives, such as energy efficiency improvements or switching to lower-carbon fuels, rather than committing to CCS projects (Samadi et al., 2016, 2018; Schneider, 2022). Additional measures have proven necessary to ease the CCS market induction. These mostly include EU level instruments intended to promote socio-economic developments such as the Just Transition Fund, or Recovery and Resilience Facility, innovation, i.e., Innovation Fund, or cross border cooperation i.e., Connecting Europe Facility (CEF) or trans-European infrastructure developments, i.e., Trans-European Energy Networks scheme (TEN-E) (Roggenkamp, 2025).

4.4.2.4 Creation of legitimacy/Guidance of the search

The rapid CCS deployment reflects the current PoR regime's dependency on fossil-based infrastructure. By implementing CCS, the regime is essentially extending the life of existing power plants run with coal and natural gas and locking in to a carbon-based infrastructure, delaying a broader shift to sustainable alternatives (Janipour et al., 2021). While a small part of incumbent industrial players perceives CCS as a temporary measure and a transitional technology, the majority considers it as the primary technology option that could guarantee large-scale negative emissions (Broekstra, 2023; Janipour et al., 2021). However, the legitimacy levels of CCS within the RHIC could also raise hopes for the future expansion of CCU developments.

Recent European policy initiatives on CCS, like the Net Zero Industry Act 2023, have designated CCUS as a "strategic net zero technology" targeting at a 50Mtpa of CO_2 storage capacity by 2030, highlighting the European prioritisation of CCS clusters or hubs instead of individual applications (Rattle & Taylor, 2025). However, CCS is generally perceived as a technology that legitimises the fossil fuel-based industry, an "easier" option offered to heavy emitting companies that need to proceed with GHG emission reductions (Janipour et al., 2021). Additionally, CCS is seen as potentially capable of "crowding-out" other low-carbon technologies, especially electrification, reflecting potential trade-offs between technologies driven by massive implementation costs (Janipour et al., 2021). The main counterargument to the above, is that CCS should be seen as an "intermediary option" towards electrification, envisioning operations based on blue hydrogen as transitionary (Janipour et al., 2021).

Strong reliance on and anticipation of large-scale CCS and blue hydrogen developments indicate RHIC's resistance to procced with radical transitions while keeping incumbent's investment interest alive (Rattle & Taylor, 2023). However, if climate policies demand cuts beyond 90%, relying on fossil-based CCS may not be viable, since reaching a full decarbonisation target may be technologically difficult due to fugitive emissions in the capturing process(Samadi et al., 2016). Nevertheless, CCS is essential for industrial sectors like cement and steel manufacturing, where process-related CO_2 emissions cannot be easily abated otherwise (Merten et al., 2020). In addition, by 2050, the ARRRA region would require to capture and store 32 Mt of CO_2 annually in order to reach decarbonisation targets (Merten et al., 2020), rendering CCS technology an indisputable part of PoR Authority's decarbonisation strategy. CCS has been prioritised in RHIC since the early 20's to meet medium-term GHG reduction targets while sustaining the operation of the two coal fired power units. Without CCS, these units would likely have to shut down or face regulatory pressures as they would not align with recent climate mandates. CCS deployment has met with rising expectations among the Dutch industrial world since many firms are involved with CCS demonstrations and experiments. At the same time however, CCS has been received with expressed reluctance by the Dutch public opinion, who mostly perceive CCS technology as a perpetuated carbon lock-in (Janipour et al., 2021).

Despite the institutional support for hydrogen innovations and less funding options for CCS, the technology has fiercely entered RHIC as a competitive option against other low-carbon solutions (Janipour et al., 2021). However, offshore CO_2 storage developments, estimated to exceed 158Mt, led by the PoR Authority, are a key driver for CCS-related investments from existing industrial players. Nevertheless, even the Porthos development has been affected by resistance barriers stemming from the existing policy and regulatory framework in the Netherlands. However, these barriers could also suggest a window of opportunity for the co-application of technologies, such as joint carbon capture and hydrogen initiatives (Janipour et al., 2021; Samadi et al., 2018). Many argue that a potential industrial carbon lock-in in the Netherlands from pursuing further CCS operations, could enhance the entire system's – supply chains, regulations, and market dynamics – resistance to the diffusion of other sustainable options (i.e., biomethane and other biofuels (L. Baas & Korevaar, 2010; Janipour et al., 2021; Wesseling & Van Der Vooren, 2017).

The probability of crowding out other low-carbon technologies within RHIC is under question given the divergence currently expressed in funding allocations and political aspirations. In any case, this competitive environment in terms of technology options is decreasing the urgency to create and deploy alternatives (Janipour et al., 2021; Kieft et al., 2021). Specifically, CCS could weaken the pressure to transition into renewables or delay their advancement, cost efficiency, and entrance to the market, affecting negatively investors decisions (Janipour et al., 2021; Kieft et al., 2021). On the other hand, increased investments in CCS may lead to increased legitimacy of fossil industries, incentivising further investments in fossil production processes and thus further increasing their reliance to CCS (Janipour et al., 2021).

The possibility that CCS could be leading to an “unavoidable” technological lock-in trap is mainly related to the already established CO_2 network infrastructure. Existing pipeline networks currently facilitate CO_2 emissions of steel and iron industries that are based in the ARRRA region to offshore storage sites in the North Sea (Janipour et al., 2021; Schneider, 2022). However, at the same time, a potentially strict dominance of CCS is hindered by the concept of a bio-based industrial transition, closely examined by the PoR Authority (commissioning studies by Samadi et al., 2016, 2018), scoping circularity flows and biofuels supply chains for power generation as well as alternative chemical and refining feedstocks.

4.4.3 Circular Economy TIS

4.4.3.1 Entrepreneurial activities/Market formation

PoR Authority envisions a shift towards functional CE involving substituting fossil fuels with biofuels (Nikolopoulou & Koert, 2020). The RHIC oil refineries account for around 90% of the total Dutch refining capacity and could partially utilise sustainable feedstocks after modifications. Steam cracking facilities, now limited within the PoR but available in adjacent industrial areas, will need to at least double to enable the cluster’s sustainable feedstock transition (ISPT, 2025). Replacing crude oil with biomass and waste as primary feedstocks in several industrial processes in RHIC could potentially reach RHIC’s decarbonisation targets. This would entail a Fischer-Tropsch synthesis and oil residue gasification producing raw materials such as naphtha and gas oil feeding steam crackers for the production of petrochemicals (Samadi et al., 2018). In addition, PoR is currently hosting a facility to host 2 Mt of sustainable aviation fuel made from used cooking oil in collaboration with Neste. The fraction of the refined used cooking oil is also sent to a cracker (not in the Port) to make precursors of plastics. This would account for a far bigger investment compared to the waste plastic pyrolysis invested by Shell.

The Dutch Ministry of Economic Affairs & Climate Policy supports the bio-methanol production as a sustainable fuel and has agreed to develop mechanisms and regulations that help bring this new technology to full scale. The cluster’s authority aims for 20% of internal fuel and chemicals to be produced with circular processes by 2030. Main tools of these efforts comprise the large-scale biofuel production as well as the integration of renewable raw materials, like biomass or waste instead of fossil fuel derivatives (PoR Authority, 2024). The chemical sector is expected to rely on hydrogen, biomass, and waste by 2030. Studies by Schneider et al., (2020), Samadi et al., (2018), Samadi et al., (2016) agree that RHIC’s decarbonisation could follow a strategy combining circular activities at maximum capacity for petrochemicals and biofuels as a main resource for refineries, while restricting CCS applications. However, a scenario heavily relied on biomass imports would currently require 9 million tons of (dry) biomass annually until 2050 and could only proceed as a net zero option if operating with CCS (Samadi et al., 2018). However, such an option is not realistic given the spatial constraints of PoR.

A waste-to-chemicals plant is planned to operate commercially in Botlek by company giants Air Liquide, Nouryon, Enerkem, and Shell, making it the first plant of its kind to produce valuable chemicals and biofuels out of non-recyclable waste materials in the EU. The facility will benefit from the state-of-the-art infrastructure available in the PoR while Enerkem will provide the technology expertise gained in another W2C plant in Edmonton, Canada. Air Liquide will supply the required oxygen and Nouryon will cover the hydrogen demand. The facility's sustainable methanol output is expected to be then purchased by Nouryon and Shell. A dedicated joint venture company has been set up in 2019 to manage necessary preparatory work, detailed engineering, and the permitting process. The plant uses syngas from unrecoverable plastics and other mixed waste streams with a capacity to convert up to 360,000 tons of waste into 270,000 liters of bio-methanol, corresponding to the total annual amount of domestic waste of the wider Rotterdam region and a 300 tons of CO_2 emissions cut-off (Haas & Dril, 2022; Tönjes et al., 2020). Although an industry-led initiative, the planned facility has been openly supported by the Dutch Ministry of Economic Affairs & Climate Policy as well as the City of Rotterdam, the Province of Zuid-Holland, and InnovationQuarter, the regional development agency, assuring for technology-relevant mechanisms and regulation.

4.4.3.2 Guidance of the search/Knowledge development

Circularity in RHIC is often characterised as under-developed since existing initiatives mainly focus on lower-order strategies (e.g., recycling and energy recovery) due to lack of financial maturity and external funding (Hendriks & Gooyert, 2023). Reusing residual heat and water, promoting industrial symbiosis, and allocating land for circularity projects are not perceived as adequate measures towards exploiting material flows and industrial value chains to achieve full circularity by 2050 (Hendriks & Gooyert, 2023). RHIC has shifted to embrace circular economy practices and the global sustainability agenda as core elements of its transition. Building upon industrial symbiosis principles, RHIC is focusing on efforts to minimise waste, enhance resource efficiency, and reduce environmental impact. The PoR Authority as a legal entity, is a competitive market player which desires to engage in global trade of (bio)fuels storage and handling, allowing efficient management and advancing in both raw material imports and finished biofuel exports (Rotterdam-Moerdijk, 2018). Circular economy principles are fostered by such mixed model, supporting the sustainable feedstock transition (Rotterdam-Moerdijk, 2018).

While fuel switching to low-carbon sources, such as hydrogen and biofuels, in tandem with CCS integration, is deemed necessary to meet stringent emission reductions and maintain global competitiveness, circular economy (CE) principles praised by RHIC stakeholders and the diffusion of already established IS practices could eventually reduce the cluster's reliance on fossil fuels while sustaining its global industrial leadership (Haas & Dril, 2022). Since 2005, RHIC utilises captured CO_2 in greenhouse horticulture and waste heat networks and since 2010 it has facilitated steam sharing and district heating integration (Rotterdam-Moerdijk, 2018). Currently, the RHIC system is directed towards an integrated broader mix of sustainable raw materials/feedstocks into production processes (Rotterdam-Moerdijk, 2018).

In addition, in 2022, the EU funded Hubs for Circularity Europe (H4C) project, establishing a community of practice in the RHIC that connects various stakeholders to promote industrial symbiosis and circular value chains. Its Circular Economy Action Plan has been adopted as a core strategy of the EC to advance learning development and diffusion processes to other member-states. PoR Authority actively engaged in this knowledge exchange process.

4.4.3.3 Resources mobilisation/Creation of legitimacy

The two most dominant pathways for the Dutch chemical industries consist of transitioning either towards renewable electricity (for electrification and electricity-based hydrogen) and/or biomass (for high temperature heat and alternative feedstocks) (Janipour et al., 2020). The PoR Authority committed to a 3.5Mt reduction of CO_2 emissions by 2030 emphasising additional savings from heat and CO_2 reuse for industrial and greenhouse applications (Rotterdam-Moerdijk, 2018). Alternative materials like biomass are also predicted to enter the alternative feedstock mix, while there are aspirations to establish an international recycling hub by 2050 (Rotterdam-Moerdijk, 2018). The Dutch electricity system shifts observed from 1960 to 2004, involving changes in regulations and social networks over time, along with the landscape-level events like the oil crisis created development and diffusion opportunities for biomass to gain traction within the electricity production regime (Verbong & Geels, 2007). Hence, RHIC gradually adapted its industrial strategies to proceed with biomass integration. However, the cost as well as uncertainty over the availability of renewable electricity, heat, and feedstock (biomass or waste) (Haas & Dril, 2022) suggest an unknown future for the decarbonisation of the chemical sector, making it hard for companies to predict investment risks and payback time (Janipour et al., 2020). According to the Dutch Chemical Industry Association (VNCI) the cost of renewable feedstocks and fuels for will be at least 50% higher than the fossil-based ones (Janipour et al., 2020).

The Antwerp-Rotterdam-Rhine-Rhur Area (ARRRA) based in the Netherlands, Belgium, and the German state of North Rhine-Westphalia consists of an established network, infrastructurally interconnected and a knowledge exchange hub. Vital for European trade, this industrial conglomeration includes crucial manufacturing and chemical processes, connected to seaports, and dependent on energy and material imports. Considering that chemical production is one of main ARRRA industrial activities, making it a chemical supercluster that uses carbon as a raw material, this area could potentially drive a coordinated organic chemical value chain with the application of a closed-carbon cycle, involving the collection, recycling, and purification of carbon-containing products (Haas & Dril, 2022). Technologies such as heat co-generation and power-to-hydrogen (P2H) conversion belong to circular industrial processes that could ensure efficient energy distribution and benefit the cluster's energy flows (Samadi et al., 2018).

Waste is thought as an option to enable a closed carbon cycle within the petrochemical cluster with the potential to achieve a carbon-neutral cluster by 2050 without relying on CCS. This option would entail waste gasification to create syngas as a chemical feedstock. Recycled carbon would then be combined with renewable hydrogen (via electrolysis) to produce synthetic fuels and chemicals (Samadi et al., 2018). Minimising new carbon inputs or storage would therefore suggest heavy reliance on RES (for hydrogen).

Around 1980s, anaerobic digesters, manure and co-digestion processes entered the Dutch industrial regime for the first time (Geels & Raven, 2006). Currently there are four waste processing companies carrying out such waste treatment in the Port(?) (Rotterdam-Moerdijk, 2018). The Dutch waste management sector is characterised by robust and growing profitability, potentially exerting a significant, albeit passive, influence on industry development. With the revenue from the waste treatment and disposal industry projected to reach approximately \$2.43 billion by 2025[24], with contributions from waste collection amounting to about

[24] https://www.statista.com/forecasts/904717/waste-treatment-and-disposal-revenue-in-the-netherlands

$27 billion, and wholesale of waste and scrap $7.83 billion by 2025, the sector demonstrates considerable financial strength. These figures are further enhanced by the waste collection turnover increase of 3.82% in 2025. This may potentially attract businesses and investments towards waste management activities within clusters, shaping their specialisation and focus without necessitating active regional directives. As a result, the waste management sector could be seen as indirectly influencing RHIC's circularity towards the use of waste streams as feedstocks. Approximately 40,000 tonnes of plastic waste of RHIC would account for the maximum capacity expected to be converted into 30,000 tonnes of pyrolysis oil annually, serving as a raw material for the chemical industry, by Pryme operating in Botlek. Botlek is intended to house the first of its kind waste to chemicals (W2C) facility in Europe, with an estimated capacity to recycle a total annual waste of more than 700,000 households saving CO_2 emissions about 300,000 tons more than the fossil fuel-based production of methanol (PoR Authority, 2024).

Another prominent industrial symbiosis development could be related to the reuse of industrial waste stream. Botlek accommodates the main steam network, including the production of naphtha, manufacturing of intermediary products for plastics, and steam left over from nuclear process (fatal steam), except for steam from waste and waste wood. Shell maintains a steam cracker in Moerdijk, outside PoR, apart from its Pernis facility which recently underwent a major maintenance procedure, including a residual heat utilisation system currently operating, a biofuel plant under construction, and a new hydrogen pipeline connected to Shell's Maasvlakte electrolyser (ISPT, 2025). However, there is capacity of expanding the steam pipes network among other company sites for the exchange of larger quantities of steam, offering a potential reduction in emissions by 0.5 Mt of CO_2 per year by 2030" (Rotterdam-Moerdijk, 2018).

4.5 Discussion

PoR, one of the world's largest ports, plays a significant role in international trade and distribution, connecting major European and international markets and adding strategic value to local and peripheral industrial facilities in Northwestern Europe. The port's established connections to the European hinterland is one of RHIC's most prominent assets, along with its high level of cluster integration and infrastructure. RHIC's major EIIs feature oil refining and petrochemicals, operated by major multinational companies that have long been dependent on fossil fuels but are currently engaging in incremental sustainability developments, including the switch to alternative fuels and energy efficiency measures. However, recent emission reduction trends driven by such efforts will not easily meet EU regulatory targets, since PoR does not feature a shared vision over decarbonisation operations while the existing regime is resisting radical transition developments, also influencing the postponing of the coal phase-out.

However, PoR also features enablers for the transition, mainly based on a highly specialised workforce to support maritime and logistics sustainability efforts and a culture that actively promotes world-leading private investment decarbonisation initiatives. For example, the cluster hosts or is expected to host prominent innovation applications, including the largest bioethanol plant, the largest water electrolysis facility, the most advanced offshore CCS project in Europe, and the world's first large scale waste-to-chemicals plant. These major developments have been actively supported by the PoR Authority and the Dutch Government. Specifically, the proactive leadership of PoR Authority has been viewed as crucial towards fostering a consistent privately led cooperative ethos, that also engages with developed knowledge networks with local academia, leading to several demonstration/pilot initiatives.

We highlight that RHIC is currently facing a highly uncertain landscape context, driven by challenges and strong dependence on external, geopolitical developments subject to fluctuating directions of global

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transition pathways (i.e., shifting international energy markets, geopolitical conflicts, and inconsistent EU-level regulatory signals impacting decarbonisation investments). The growing uncertainty and international exposure, EU pressure for stricter decarbonisation targets, the high capital costs and long investment cycles faced by the local EIIs, as well as major spatial constraints, create challenges on the cluster's efforts to foster a stable and predictable investment-oriented environment. Infrastructure developments projected to accommodate crucial decarbonisation operations, such as offshore wind, offshore CCS, and hydrogen have been subjected to delays or cancellation. On the one hand the civil society and the public have consistently advocated for emission-free technologies and processes (e.g., green hydrogen). On the other hand, an apparent "technology gatekeeping" attitude of RHIC's multinational players have resisted such prospects, showing a preference for low-carbon processes dependent on CCS or blue hydrogen.

At the same time, RHIC stakeholders have embraced CE practices, including IS that features great potential for transforming the cluster. Prior experience and expertise gained through several CE developments, including IWH and residual CO_2 re-utilisation in industrial and urban locations, are now starting to materialise in practice, legitimising new cross-sectoral cooperation initiatives. These include substituting fossil fuels with biofuels using biomass and waste as primary feedstocks and undergoing developments focusing on waste pyrolysis and bio-menthanol production prioritising (petro-)chemicals decarbonisation and resource efficiency.

Although all these options represent important steps towards RHIC's overall sustainability efforts, large-scale infrastructure implementation is essential to respond to the cluster's decarbonisation targets, with potential technological frictions. This is crucially the case for major offshore CCS developments which are pushed for by incumbent actors as dominant technologies, but that could potentially crowd-out other deep decarbonisation options (i.e., hydrogen, or renewable energy), exposing the cluster to a lock-in trap, and a no-materialisation risk based on experiences from past cancellations.

5 The Basque Country case study

5.1 Background

The Autonomous Community of the Basque Country (ACBC), one of 17 Autonomous Communities in Spain, is situated in the northern part of the country and comprises the three provinces of Alava, Biscay, and Gipuzkoa, sharing borders with southwest France. These provinces, along with the region of Navarre, are the only jurisdictions that benefit from a decentralised fiscal regime within Spain (OECD, 2011). The Basque region is predominantly urban, with more than 80% of the population living in the metropolitan areas around the capitals of the three provinces namely the cities of Bilbao (Biscay), Donostia-San Sebastian (Gipuzkoa), and Vitoria-Gasteiz (Alava) (European Commission - Joint Research Centre, 2021). The total population of the region is approximately 2.2 million covering a surface area of 7,234 km² (1.4% of Spain),

The region is significantly contributing to the Spanish economy. It hosts two commercial ports in both maritime provinces Biscay and Gipuzkoa, while 55% of its surface is covered by pine forests (Barañano et al., 2022). The three provinces of ACBC exhibit some socio-economic asymmetries: Biscay, including Bilbao, hosts over half the region's population and economy; Alava, home to the capital Vitoria-Gasteiz, is smaller but with higher GDP per capita and productivity; Gipuzkoa hosts roughly a third of the region's population and economy, and has a strong cooperative presence (OECD, 2011). Responsibility over forest conservation, management, and policy lies with the Provincial Councils, while industrial development lies with the Basque Government (Barañano et al., 2022).

ACBC has been historically highly industrialised, experiencing a remarkable growth since the 1980s, with the GDP per capita being 9% points above the EU average (Mosquera & Larrea, 2025). The Basque Country recovered from de-industrialisation and political instability to become a leading European region, featuring exceptional industrial resilience in the midst of consequent crises (oil & gas during 1990s, and financial crises of 2008), and an economy growing faster than the Spanish and European averages, despite the relevant dominance of the service sector in terms of GDP and employment (Valdaliso et al., 2011). The so called "Basque competitive paradox" (OECD, 2011) is attributed mainly to major R&D investments (reaching 2% of GDP in 2019) and export shares (36.4% of GDP) (Aranguren Querejeta et al., 2021). However, ACBC has recently been exposed to strong demographic pressure, with high ageing population rates negatively affecting production rates (Mosquera & Larrea, 2025), high energy dependency reaching 90.3% in 2023 (Eustat, 2024), and high exposure to climate change impacts (mainly floods, wildfires, and droughts) (European Commission. Joint Research Centre., 2021).

Due to its small size and mountainous geography, industrial activities have been organised in several clusters. These are mostly dominated by regional SMEs, with manufacturing being the core activity that represents 85% of the regional industrial Gross Value Added (GVA) (Susur et al., 2018). Despite its relatively small size, the region is the third-largest machine tool producer in Europe with the sector accounting for 53% of all industrial production and 2% of total employment (Mosquera & Larrea, 2025). Contrary clusters related to metals, automotive, and machinery production dominate exports (Valdaliso et al., 2011). However, the iron and steel industry, and pulp and paper industry, together account for more than half of total energy use (AlShaaibi, 2014).

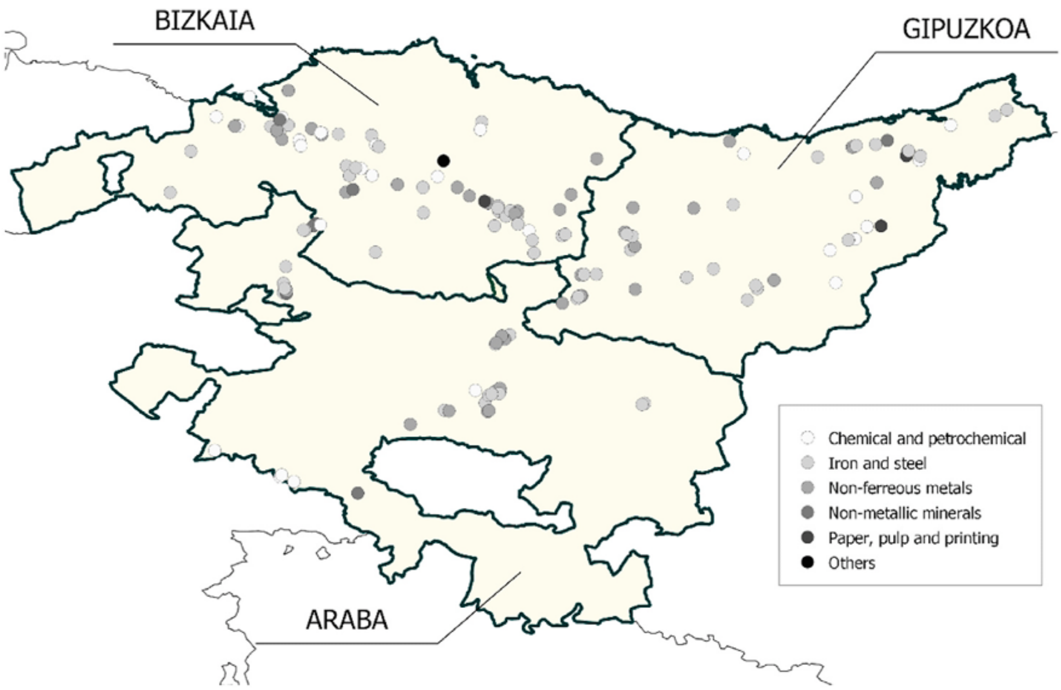

Figure 8. Distribution of industrial companies (studied by the authors) in the three Basque Provinces.

Source (Larrinaga et al., 2021)

Energy demand in the Basque Country has been dominated by fossil fuel imports, particularly oil and natural gas, which together accounted for over 70% of total energy consumption until the early 00's. Specifically, industry alone accounted for 39% of total energy demand, primarily for natural gas (41.7%), and electricity (36.9%), with a regional self-supply rate of only 5.8% (among the lowest in the EU) (AlShaaibi, 2014). Renewable energy contributes no more than 8.7% of the region's total energy demand (EVE, 2023).

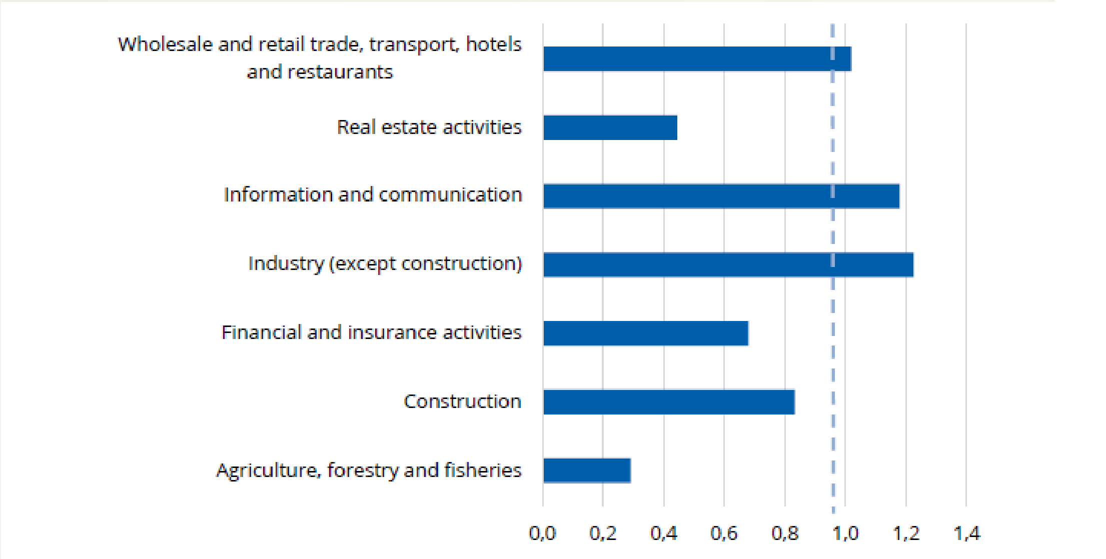

Figure 9. Sectoral specialisation ration of the Basque economy.

Source: (Mosquera & Larrea, 2025)

In terms of GHG emissions, ACBC presents a rate 20% lower than the EU average (Morandeira-Arca et al., 2024). However, the region faces strong GHG emission reduction pressure due to nationally binding EU net-zero target for 2050. Spain is the fifth largest emitter in the EU after Germany, France, Italy and Poland (Sun et al., 2021), and although industrial CO_2 emissions fell by 42% between 2005 and 2017, this was mainly attributed to post-crisis contraction—rather than structural change (Gerres et al., 2019)—followed by a gradual rebound. The national decarbonisation strategy targets are aligned with the EU net-zero vision, and thus Spain plans to reach climate neutrality by 2050, according to Law 7/2021 (MITECO, 2025). Besides, ACBC approved the Basque Law 1/2024 (IHOBE, 2025) that establishes the legal framework to achieve climate neutrality by 2050, with a goal to potentially advance this to 2045.

Spain is ranked as the largest ecological reserve in Europe featuring a high diversity of biodiversity placed in the vast protected areas and a remarkable climate variety—with humid Atlantic conditions, semi-arid areas, and cold alpine climates (Rodrigo et al., 2023). At the same time, it is arguably among the most vulnerable European countries in terms of climate change impacts being within the Mediterranean climate change hotspot (Cos et al., 2022), with an average temperature rise of 1.7 °C higher than the average (between 1850 and 1900), an alarming see level rise since 1990's, and an estimated surface of 74% in risk of desertification, while more recently the country has been severely affected by wildfires (Rodrigo et al., 2023). Consequently, the country featured the fifth highest economic loss by climate change-related events (Rodrigo et al., 2023). The ACBC stands out as a hotspot of biodiversity, hosting over 700 species of vertebrates, 1,780 invertebrates, and around 7,600 plants, despite its relatively small size. However, this rich natural heritage faces increasing pressures: 46 vertebrate species are endangered, 21 at risk of extinction, and 125 species of flora are also endangered, with 54 at risk of extinction. Climate change is intensifying these threats, with projections indicating rising temperatures (mostly in winter and summer), a drop in rainfall by almost 20% by the end of the century, and a notable increase in sea temperatures by 2–3 Celsius. These changes are expected to cause the "mediterraneisation" of forest ecosystems, favour invasive species, and threaten the survival of local plant and animal communities, while rising sea levels and more frequent extreme weather events place coastal habitats and populations at risk. In response, the ACBC has implemented a robust Biodiversity Strategy 2030 with a significant amount of nature-based solutions, aiming to protect and restore ecosystems, enhance resilience, and preserve its unique natural legacy for future generations (Basque Government, 2016).

5.2 Regime

5.2.1 Historical evolution of the cluster's structure

The evolution of industrial policy in the Basque Country since the 1980s was defined by the creation of a new regional administration amid a profound economic and industrial crisis (Ahedo, 2004). The State intervened significantly, as the business system inherited from the Franco era remained highly concentrated, monopolistic, and dependent on public institutions (Ahedo, 2004). During this early period, traditional heavy industry sectors such as shipbuilding, iron and steel, and cement dominated the economy, while developments in the forestry sector, particularly the expansion of eucalyptus and pine plantations, were initially profitable, but eventually faded out due to falling prices and growing environmental concerns (Barañano et al., 2022). Similarly, the cement industry, which historically had underpinned regional industrialisation since the 19th century, demonstrated major decline following the Spanish Civil War and was displaced by artificial cement production from Portland (Varas et al., 2007). The restructuring effort entailed high public expenditure to rescue major industrial firms, in a context where industrial and business associations were weakly developing (Ahedo, 2004).

The 1990s marked a shift toward a new industrial strategy, which was focused on competitiveness through cluster development. In 1991, the Porter report, commissioned by the Basque Government, proposed a methodology of cluster working groups aimed at generating sectoral Action Plans (Ahedo, 2004). This laid the foundation for the 1991–1995 Industrial Policy Framework and the broader Competitiveness Programme (Ahedo, 2004). The introduction of cluster policy was a pioneering initiative within the EU context and was widely recognised for improving R&D, innovation, and business competitiveness (Valdaliso et al., 2011). At the same time, the Basque industrial structure underwent major transformation developments since traditional heavy industries were progressively replaced by more diversified sectors including automotive, machine tools, electronics, and household appliances production (Ahedo, 2004).

Between 1995 and 2008, the region experienced a modest shift, with construction increasing its share in the gross value added while agriculture, manufacturing, and services slightly declined (OECD, 2011). The steel sector continued to play a major part of the regional economy, contributing 5.9% of GDP and 2.5% of employment. From 1990 to 2005, it achieved further expansions while at the same time reducing total GHG emissions by over 70%. This was mostly attributed to the closure of integrated plants and the shift to electric arc furnaces (EAF) (González-Eguino et al., 2012). However, despite significant economic and policy transformation, the Basque Country faced major political tensions, persistent demands for greater autonomy, and terrorist events, constraining its attractiveness to external investors. In response, Basque nationalist parties have often favoured endogenous development strategies, particularly by supporting SMEs (Ahedo, 2004).

5.2.2 The Smart Specialisation Strategy

Since the early 1980s, the Basque Country has implemented a distinctive industrial development model, grounded in technological modernisation, institutional coordination, and strong regional leadership (OECD, 2011). In response to the collapse of traditional industries and within a context of high unemployment rates and political instability, the Basque Government developed a strategic innovation-led industrial policy, driving the so-called "first great transformation" (OECD, 2011). Ever since, the Basque Government consistently prioritised industrial competitiveness, with technology-oriented funding accounting for a large part of the community budget, five times more than the science-oriented one (OECD, 2011). However, the financial crisis of 2008 marked the beginning of a new strategic phase (2008–2020), in which the Basque Country demonstrated a higher degree of resilience than most Spanish regions (OECD, 2011). A key feature of this phase was the explicit adoption of a Smart Specialisation Strategy, which provided a framework for prioritising strategic sectors and mobilising collective action by firms, universities, technology centres, and policy institutions (Aranguren Querejeta et al., 2021).

The Smart Specialisation Strategy targeted three groups of actors: intermediary organisations (especially cluster associations), innovation actors, and companies. Intermediary organisations have proven to be crucial to the Basque Government's engagement with industry. Specifically, the gradual expansion of cluster policies, including setting up new organisations, imposing more stringent public funding criteria in 2016, prompted institutional consolidation through mergers and alliances (Aranguren Querejeta et al., 2021). Inter-cluster collaboration was encouraged through the Smart Specialisation Strategy working groups and events such as the annual Observatory on the Industrial Environment and the Basque Cluster Day. This period also saw the continued consolidation and influence of public–private institutions including Ikerbasque, Innobasque, and Orkestra. By 2022, the region featured 22 cluster associations covering a wide range of sectors, such as automotive, machine-tools, telecommunications, energy, construction, and audiovisual industries among others (Barañano et al., 2022). These aimed at enhancing the competitiveness of Basque firms through cooperation on strategic challenges that could not have been addressed individually (Borowik, 2014). These cluster organisations are composed of private firms enabling coordinated action upon each sector. Innovation remains a central focus, with joint projects directed at exploring new low-carbon technologies and frequently supported by European funding programmes. At the same time, cluster associations operate as exclusive business memberships, and their governance is fully controlled by the private sector (Borowik, 2014). The Basque model is also characterised by strong regional and international cooperation, enabled by the region's autonomy in shaping its own economic policies (Borowik, 2014).

In parallel, efforts were made to increase the involvement of Basque companies in key policy institutions, such as the Basque Council on Science, Technology and Innovation and the steering groups of the Smart Specialisation Strategy. This approach was partly driven by concerns over the weakening of traditional business groups due to mergers and foreign capital investment flows (Aranguren Querejeta et al., 2021). In response, the Basque Government established the Basque Trade and Investment Agency to support a more proactive internationalisation strategy, contributing to an increase in export shares from 34.3% of GDP in 2008 to 36.4% in 2019. At the same time, the Smart Specialisation Strategy aimed to address the competitiveness challenges faced by SMEs (Aranguren Querejeta et al., 2021).

The Basque Country has supported its Science, Technology, and Innovation (STI) system through both institutional re-organisation and stakeholder engagement. One major development has been the establishment of the Basque Research and Technology Alliance led by the Basque Government, aiming to align R&D developments with industrial needs. Specifically, policy efforts have strengthened links between universities, the business sector, and knowledge-intensive business services targeting SMEs by introducing integrated vocational training centres (Aranguren Querejeta et al., 2021). The Smart Specialisation Strategy was also responsible for changes in the governance structures. A restructured Science and Technology Council now includes actors from business, technological centres, and academia, with the Basque Government leading the policy design, while implementation falls under the influence of private firms, clusters, and technology centres. Universities remain underrepresented in decision-making, while the involvement of the civil society and trade unions is limited, or even largely absent. These raises concerns over a potential institutional lock-in (Magro et al., 2017).

Overall, the long-term strategy combined proactive industrial policies, investment in technological capabilities, and robust regional governance. These factors enabled the region's resilience against economic shocks, while facilitating the renewal of its industrial base, with the region emerging as one of Europe's top performers in GDP per capita, social cohesion, and innovation capacity (Aranguren Querejeta et al., 2021).

5.2.3 Industrial sectors in ACBC and associations

The Basque Country currently features a high concentration of energy- and emission-intensive industries, including large firms active in utilities, steel, petrochemicals, and materials production (Wang et al., 2025). Over the past 25 years, three distinct socio-business communities have shaped the region's industrial structure, each characterised by different patterns of ownership, organisation, and institutional embeddedness (Ahedo, 2004). The community of large capital firms with historical roots in Bilbao's port trading houses, are closely connected to major financial institutions and energy companies like Iberdrola and had significant influence in the region's industrial diversification (Ahedo, 2004). Their interests are represented through elite networks like the Círculo de Empresarios Vascos (Basque Business Circle), bringing together around 60 large and mid-sized enterprises (Ahedo, 2004).

A second community is built around the cooperative model, most prominently the Mondragon Cooperative Corporation (MCC) (Ahedo, 2004). Emerging during the 1960s and expanding significantly in the following decades—especially in Gipuzkoa—MCC facilitates synergies across around 100 cooperatives operating in sectors such as machine tools, household appliances, and automotive components (Ahedo, 2004). It is organised through the Federation of Basque Cooperatives (comprising 440 cooperatives) and ASLE, the Basque Association of Employee-owned Companies (representing around 300 firms and 16% of the similar enterprises in Spain).

The third and most diverse community is composed of SMEs, which make up approximately 97% of the private firms in the region (Ahedo, 2004). Though traditionally fragmented and less formally represented, SMEs have gained increasing strength through provincial and sectoral business associations and through participation in cluster organisations supported by regional policies (Ahedo, 2004). Their growing prominence is also reflected in recent industrial strategies that pay greater attention to the specific needs and challenges of SMEs (Ahedo, 2004). Despite their importance, these three socio-business communities have historically remained institutionally separate, with no organisational platform linking them together (Ahedo, 2004). The EIIs of ACBC are solely represented by large capital firms and SMEs.

The Muskiz refinery operated by Petronor is a major asset of the Basque oil and gas sector. Spanning 220 hectares and connected to the Bilbao port via an eight-line pipeline, it has a distillation capacity of 12 million tonnes per year. Though the refinery maintains its own brand and operational identity, it is fully integrated into the larger Spanish international oil company Repsol (85.980% ownership in 2025). Its recent strategy combines efforts to enhance refinery efficiency with expansion into electric mobility, distributed energy resources, green hydrogen, and decarbonisation services, positioning the company as a key actor in the Basque energy transition (Wang et al., 2025).

The Basque chemical sector includes 123 companies, organised under the Aveq-Kimika association, encompassing the full chemical value chain, from basic and industrial chemical to pharmaceuticals and plastics. However, its dependence on foreign decision-making centres and the underutilisation of bio-based feedstocks for green chemistry applications are hindering its decarbonisation prospects. The sector employs approximately 6,838 people (Aveq-Kimika, 2025).

The Basque Country hosts a large share of iron and steel production in Europe, accounting for nearly 50% of Spain's steel output and 10% of all European EAF-based steel production (Gerres et al., 2019). Notably, all steel in the region is produced using the EAF route of production, making it one of the least CO_2-intensive steel production regions globally. Plants operated by multinationals ArcelorMittal and Sidenor, responsible for approximately 80% of total steel output (González-Eguino et al., 2012). Despite better GHG emission performance, the potential for additional technological improvements within the current technological base is limited, raising concerns over the potential relocation of production under current climate policies (Gerres et al., 2019). Such risks may be associated with medium-to-high levels of materialisation, due to the high degree of integration and limited efficiency gains (González-Eguino et al., 2012). Additionally, the dominance of secondary steel production implies that the steel and metal industries are heavily reliant on electricity, along with the growing electricity-intensive aluminium production (Gerres et al., 2019).

Heidelberg Materials operates two cement plants in the Basque Country—in Añorga (San Sebastian) and Arrigorriaga (Bilbao)—along with several ready-mixed concrete sites. The multinational firm has been viewed as a regional lead actor, especially since the acquisition of the Italcementi Group and FYM. (Wang et al., 2025). Besides, Cementos Lemona, located in Lemoa (Biscay), is the third cement plant in the ACBC, and it was bought by the Irish group CRH in 2013.

The pulp and paper sector is a historic pillar of the Basque industrial economy, currently representing 4.0% of industrial GDP (2022) and employing over 5.6% of the industrial workforce (Panorama de la Industria Vasca, 2024). Most firms are in Gipuzkoa, especially along the Oria and Urumea rivers.

5.2.4 The ACBC institutional structure

ACBC stands out as a politically and fiscally autonomous region. Since the creation of its government in 1980, it has held an unparalleled degree of self-governance, collecting most taxes and setting its own fiscal and industrial policies (Elgorriaga Kunze & Quintana San Miguel, 2018). This autonomy has been a key enabler of long-term regional strategies, particularly in industrial development, where the Department of Industry has played a central role (Navarro et al., 2014). Over time, the Basque Government has built an extensive institutional infrastructure. The institutional context of the Basque Government has benefited from a highly professional and stable civil service, exhibiting a clear division between political leadership and administrative execution, which has contributed to policy continuity (Aranguren Querejeta et al., 2021). Yet coordination remains a challenge: while regional Governmental entities exist to align with the Spanish and EU policy context, the Basque innovation policy, driven by technology centres, clusters, and other innovation organisations often operate independently, with limited cross-provincial or interregional cooperation (Magro et al., 2017). Nevertheless, over the decades, a consolidated policy community has emerged, connecting public agencies, cluster associations, businesses, and research institutions, working under a shared vision (Aranguren Querejeta et al., 2021). This policy community has been institutionalised through organisations such as Innobasque and Orkestra, which have facilitated training, policy dialogue, and analytical capacity (Aranguren Querejeta et al., 2021). However, this institutional density has also created some unintended consequences. The strong presence of public funding and government-led cooperation has formulated a dependency culture, with innovation mostly being pursued in low-risk, publicly subsidised areas (Gurrutxaga Abad, 2011).

Among the key agencies that have recently been instrumental in expanding the scope of industrial and environmental policy the Economic Development, Sustainability and Environment Department of the Basque Government (SPRI) established in 1981 stands out. The agency has consistently received financial support to manage innovation and business development programmes and coordinate efforts across regional and provincial governments (Ahedo, 2004). IHOBE, the environmental management agency, has developed life cycle-based expertise to promote sustainability throughout the product and production chain (Elgorriaga Kunze & Quintana San Miguel, 2018). The Basque Energy Agency (EVE) actively involved in these strategies, has supported sustainable investments, subsidies, and participation in demonstration projects. It has also contributed to the development of companies specialised in renewable energy and smart grid technologies (Mosquera & Larrea, 2025). Through the EnergiBasque strategy and the 3E-2030 roadmap, the Basque Government has prioritised electrictrification, identifying strategic areas such as wind, solar thermal, wave energy, energy storage, and grid modernisation (Mosquera & Larrea, 2025).

Overall, the Basque Country is renowned for its strong industrial culture and elements of economic democracy. However, direct worker participation through labour unions remains rare, only indirectly represented through cooperative enterprises and industrial clusters.

Overall, these structures have contributed to the resilience and competitiveness of the Basque industry following the 2008 crisis in a more effective manner than most other Spanish regions (Köhler, 2019).

5.2.5 Key policies towards sustainability

Since the beginning of the 21st century, ACBC has pursued major environmental policies, with a framing of green growth. This orientation was institutionalised by the Basque Environmental Strategy for Sustainable Development 2002–2020 framing environmental protection as a strategic objective for competitiveness and innovation (Elgorriaga Kunze & Quintana San Miguel, 2018).

One of the structural factors enabling this approach is the region's high degree of fiscal autonomy as previously discussed. This fiscal autonomy extends to environmental and energy policy, allowing the Basque Country to align with national climate goals while retaining the ability to pursue its own strategies—e.g., through targeted taxes, regulations, or industrial policies—to meet those objectives (González & Dellink, 2005). However, Spain's decentralised system has also created complications between the central government and Autonomous Communities, resulting in fragmented taxation schemes and conflicting legislation, undermining market unity (Sáenz De Miera & Muñoz Rodríguez, 2015). Moreover, the regional environmental taxation has often lacked true ecological rationale, reflecting a revenue-driven logic, according to which operating facilities are taxed regardless of their GHG emissions (Sáenz De Miera & Muñoz Rodríguez, 2015). The absence of CO_2-specific taxes and the limited use of tax benefits for pollution-reducing technologies highlight a broader structural divergence between fiscal tools and environmental objectives (Sáenz De Miera & Muñoz Rodríguez, 2015).

To address this gap, ACBC implemented a tax incentive framework aimed at promoting environmental investments, beginning in the 1990s with a 15% corporate tax deduction for green investments, expanding it in 2004 through the creation of the Basque Clean Technology List (BCTL). Being in this List offers a 30% deduction for companies investing in certified clean technologies (Elgorriaga Kunze & Quintana San Miguel, 2018). Managed by IHOBE, in coordination with SPRI and EVE, the scheme is particularly targeting SMEs, illustrating how regional fiscal tools can be directed towards sustainability objectives (Elgorriaga Kunze & Quintana San Miguel, 2018).

Another sustainability incentive mechanism has been the green public procurements. According to IHOBE, entities participating in the Basque Green Procurement and Contracting Programme achieved double sustainability rates compared to the rest of the public sector, nearing the 50% target set for 2020. Of the 5,829 tenders issued in 2019, collectively worth €2 billion, 1,407 (worth €449 million) incorporated environmental criteria, reflecting the ACBC's strong positioning in public procurement processes among other European regions (Barañano et al., 2022).

5.2.6 The evolution of the Basque regional innovation

However, the most impactful ACBC policy towards sustainable growth has been systematically targeted R&D innovation development.

In response to industrial decline and the need to strengthen its innovation system, the Basque Government developed successive Science, Technology and Innovation (STI) plans from the 90s onward. These plans prioritised knowledge development. However, cooperation levels among strategic actors remained limited (OECD, 2011). Gradually, new institutions, including cooperative research and technology centres, aimed at fostering further cooperation and alignment with technology demand. At this stage, funding remained concentrated in the Department of Industry, whose budget grew significantly (OECD, 2011). The last version of the Science, Technology and Innovation plan (2007–2010) responded to the ambition of a "second great transformation" by promoting high-technology sectors such as biosciences, nanosciences, and renewables, and by launching new support for institutions, including Innobasque and the Basque Council for Science, Technology and Innovation (OECD, 2011). In 2011, about €170 million was allocated to innovation support (Borowik, 2014). The government prioritised the role of regional research and technology organisations, using them as intermediaries to channel public R&D funding into private industry (Alcalde-Heras et al., 2023). From 2013 to 2020, the Basque innovation strategy entered the Smart Specialisation phase focused on combining demand-driven and technology-driven research (Alcalde-Heras et al., 2023).

Throughout this period, the Basque Science, Technology and Innovation Network was restructured to address inefficiencies, promote coordination, and clarify roles among its many agents (Aranguren Querejeta et al., 2021). The resulting system included technology parks, research centres, and specialised firms and contributed to significant gains in R&D intensity and research employment (Aranguren Querejeta et al., 2021). Business R&D has historically accounted for a high share of total R&D in the Basque Country (reaching 76% in 2009), though this share decreases when excluding privately managed but publicly funded entities (Aranguren Querejeta et al., 2021). Basque private firms receive considerable public support for innovation—estimated at 0.47% of GDP and accounting for 56% of total R&D funding (81% when including public-private arrangements), while SMEs innovation performance rates remain limited (OECD, 2011). While this strategy has admittedly strengthened practical R&D and innovation, the system has suffered from underinvestment in basic research, a consequence also expressed in the region's young university context and the scarcity of national research centres (Bilbao-Ubillos & Camino-Beldarrain, 2011). Since the 2000s, however, targeted support for universities and public research centres has aimed to respond to this imbalance (Bilbao-Ubillos & Camino-Beldarrain, 2011).

5.2.6.1 Technology and Research centres

Technology parks in the region serve as organisational platforms hosting a range of institutions engaged in technological development. Although privately managed, they are substantially funded by public sources, with the Basque Government covering approximately 50% of their operating budgets (Bilbao-Ubillos & Camino-Beldarrain, 2011). This public-private collaboration is justified by SMEs limited access to research. The establishment of the Bizkaia Technology Park in 1985, which was hailed as a pioneering initiative within Spain, and was later followed by parks in Araba and Donostia-San Sebastian during the 1990s and the Garaia Innovation Centre in 2005. These parks continue to expand, with ongoing activities (Bilbao-Ubillos & Camino-Beldarrain, 2011).

Technology centres are recognised for their effectiveness in securing competitive funding at national and European levels. In response to international competitive pressures and the need for cost rationalisation, the region consolidated two major alliances: Tecnalia and IK4. This restructuring aimed to increase international visibility and efficiency by reducing duplication and promoting specialisation (Bilbao-Ubillos & Camino-Beldarrain, 2011). The Tecnalia Foundation was formed through the merger of eight organisations and became Spain's largest private R&D centre by 2011, with over 1,500 staff and international operations in 22 locations. Tecnalia is particularly active in EU Framework Programmes and operates across a range of fields, including sustainable construction, energy, transport, ICT, and health. Its Energy and Environment Division conducts applied research in areas such as renewable energy, energy efficiency, smart cities, and ecodesign (Bilbao-Ubillos & Camino-Beldarrain, 2011). In parallel, the IK4 Alliance brought together seven centres under a coordinated platform, specialising in interdisciplinary research. IK4 employs around 1,250 professionals and generates approximately €80 million in annual revenue (Bilbao-Ubillos & Camino-Beldarrain, 2011).

The Basque Science, Technology and Innovation Network (RVCTI) constitutes the core of the region's scientific and technological capacity. In 2018, this capacity was further consolidated with the creation of the Basque Research and Technology Alliance (BRTA), a public consortium formed through a partnership between the Basque Government, the SPRI Group, the three Provincial Councils, and 17 technology centres. The BRTA seeks to promote strategic cooperation to address technological and industrial challenges and enhance international positioning (Barañano et al., 2022). Technology Knowledge-Intensive Business Services (TKIBS) contribute to the innovation ecosystem by facilitating knowledge transfer to the private sector. These services, often provided by private firms and technology centres, support business modernisation and help regional firms adapt to global production challenges (Borowik, 2014).

The Basque university system comprises four main institutions: the University of the Basque Country (UPV/EHU), Universidad de Deusto, Mondragon Unibertsitatea, and the University of Navarra (Tecnun). Despite progress, research activities at these institutions remain somewhat limited compared to other European institutions (Bilbao-Ubillos & Camino-Beldarrain, 2011). Still, UPV/EHU plays a leading role in experimental sciences and health-related research, receiving government support that led to a 62% increase in its research output in experimental sciences between 2002 and 2008 (Bilbao-Ubillos & Camino-Beldarrain, 2011).

Cooperative Research Centres constitute a core element of the Basque innovation infrastructure, acting as interdisciplinary platforms that bridge scientific research and industrial application (Borowik, 2014). These centres are designed to foster collaboration among universities, research institutes, technology centres, companies, and the broader society, with the aim of advancing both basic and applied research in emerging strategic sectors such as micro-technologies, biotechnology, nanotechnology, and energy. They support knowledge transfer into industry through mechanisms such as spin-offs, patents, and licenses, and promote participation in international research initiatives. Their role includes attracting global research talent and forming project-specific alliances (Borowik, 2014). Complementing the role of technology centres, funding arrangements in the Basque innovation system facilitate interdepartmental collaboration. For instance, universities and the Basque Excellence Research Centres (BERCs), managed by the Department of Education, are also eligible to receive funding. This arrangement supports greater integration between educational and industrial research efforts (OECD, 2011).

The Basque vocational training system was a leader in Spain, demonstrating high levels of population uptake and industry linkage. Since 2009, approximately 50% of vocational training courses in ACBC were related to industrial sectors, compared with 30% at the national level (Aranguren Querejeta et al., 2021). A key institution in this domain is Tknika, the Innovation Centre for Vocational Training, which leads numerous projects in technology, training, and management (Barañano et al., 2022).

5.2.6.2 Ecodesign

ACBC's commitment to ecodesign has evolved through a series of public initiatives, institutional frameworks, and strategic collaborations. Building on early pilot actions that began with a 1998 collaboration between IHOBE and Delft Technical University, a Programme for the Promotion of Ecodesign was formally launched in 2004 (O'Rafferty, 2012). It aimed to involve forty firms by 2006 and two hundred by 2012, reflecting the broader goals of the Basque Environmental Sustainability Strategy 2002–2020. However, the lack of market differentiation for ecodesign products limited its initial success (O'Rafferty, 2012). Nevertheless, its implementation coincided with the EU Ecodesign Directive (2005), which generated demand for guidance, particularly from the electrical and capital goods sectors. IHOBE responded by producing numerous methodological guides to support the directive's adoption (O'Rafferty, 2012). This also led the Basque Government to reassess its ecodesign strategy towards international partnerships that eventually led to the foundation of the Basque Ecodesign Center in 2011—a public-private partnership including IHOBE, SPRI, and major industrial firms, a combined turnover of €36 billion, and over 10,000 suppliers (O'Rafferty, 2012).

5.2.6.3 Industry 4.0

The strategic orientation towards R&D has been accompanied by targeted investments in infrastructure. Although these have declined after the 2008 financial crisis, despite a recovery around 2014-2015, the Basque Country has diverged from national trends by investing less in traditional physical infrastructure and more in digital infrastructure aligned with Industry 4.0 priorities (Aranguren Querejeta et al., 2021). Key examples include the establishment of the Basque Cybersecurity Centre (BCSC) and the Industrial Cyber Security Centre-Gipuzkoa (ZIUR), with both initiatives aiming at supporting digital transformation and industrial security (Aranguren Querejeta et al., 2021). These technologies could prove game-changers for the industrial sector by enabling the development of interconnected, intelligent, and self-regulating systems, characterised by both horizontal integration across company functions and vertical integration along the value chain. In the Basque context, 54% of SMEs are already engaged in Industry 4.0 implementation processes (Estensoro et al., 2022).

5.2.6.4 Electricity grids

The development of electricity grids in the Basque Country plays a pivotal role in enabling the region's industrial and energy transition, particularly as energy-intensive sectors seek reliable, low-carbon electricity sources. Although the capacity of the Basque Government in energy production is limited, its involvement in planning, authorisation, and promotion of infrastructure projects has supported regional engagement in grid development (Mosquera & Larrea, 2025). The Energy Cluster of the Basque Country dominates this specialisation, with over 200 companies and entities active in grid-related technologies. In 2022, the sector generated €15.7 billion in revenue and invested €266 million in R&D, reflecting the importance of the grid to regional competitiveness (Mosquera & Larrea, 2025). Investments in electricity infrastructure have broad benefits, including cost reductions for key industrial sectors and their decarbonisation. Without adequate progress, however, electricity grids may become a structural bottleneck to decarbonisation (Mosquera & Larrea, 2025). Public institutions are now focusing on instruments to mobilise private investment in decarbonisation, particularly for grid expansion and smart infrastructure (EERA, 2025).

5.3 Landscape

5.3.1 National Policies

According to Gerres et al (2019), national policies regarding environmental protection and overall sustainability have consistently been characterised as ineffective. Most national policies targeted energy efficiency improvements in the energy and EIIs sectors, fearing that higher energy prices could jeopardise industrial competitiveness (Gerres et al., 2019). However, since 2020, the country's compliance to EU obligations has driven several national initiatives, including both mitigation and adaptation measures, as expressed in the adopted National Energy and Climate Plan (NECP) (PNIEC in Spanish) (2021-2030) and the National Plan for Adaptation to Climate Change (NPACC) (Rodrigo et al., 2023). The long-term objective of the Plans is to achieve net-zero by 2050, with an electricity system solely based on renewable sources. Adaptation measures have received the joint agreement of Autonomous Communities. The Climate Change and Energy Transition Law was eventually passed in 2021, targeting the reduction of GHG emissions by at least 20% compared to 1990 levels, increase renewable energy by at least 35% of final energy consumption—accounting 70% for electricity—and improve energy efficiency by reducing primary energy consumption by at least 35% compared to EU baseline, by 2030 (Rodrigo et al., 2023). Compliance with EU and other international laws fall under the responsibility of the National Government. Any national commitment deriving from these laws (e.g., EU Treaties) become part of the Spanish Law and are binding for Autonomous Communities, besides the rest of the Spanish constituency (Rodrigo et al., 2023). In October 2024, the new version of the PNIEC (2023-2030) with updated targets was released. Such document includes to reach: 32% reduction in greenhouse gas emissions compared to 1990; 48% renewables in final energy consumption; 43% improvement in energy efficiency in terms of final energy; 81% renewable energy in electricity generation; and Reduction of energy dependence to 50%.

5.3.2 National-Regional coordination and frictions

Although decentralisation in Spain has been successful, there have been calls for greater federalisation, mainly expressed by the Autonomous Communities, also in relation to climate policies (Rodrigo et al., 2023). Autonomous Communities enjoy an established autonomy in policy experimentation, however, their binding compliance to national targets has been causing frictions, mostly due to the diversity of climate challenges faced by different Spanish regions (Rodrigo et al., 2023). In addition, Autonomous Communities have no formal influence over the nationally binding environmental policies, hence they cannot proceed in setting up their implementation to suit the individual characteristics of their constituencies (Rodrigo et al., 2023). The non-existence of federal entities to discuss and align the interests of the autonomous communities is a problem that persists in Spain. The "Conference of Presidents" is the most similar mechanism, a high-level meeting between the Prime Minister (in Spanish it is preferred the tag "President of the (Spanish) Government") and the presidents of the autonomous communities. In this meeting, the presidents discuss on topics concerned by each of them but in practice it is a claim for more budget since most of the taxes are state level (with the exception of the Basque Country and Navarre, since they preserve fiscal autonomy from centuries ago). For specific agendas, the Sectoral Conferences are meetings between the Ministers and the regional responsible, but those meetings are unidirectional and top-down.

At the same time however, over the past decade all Autonomous Communities have adopted regional strategic frameworks, action plans, and/or programmes both for mitigating and adapting to climate change. However, this has also triggered competition among them especially when attempting to receive EU funding for regional developments (Rodrigo et al., 2023). This competitive environment also suggests a relative resemblance of each Community's main objectives and scopes (Rodrigo et al., 2023).

5.3.3 Compliance with EU targets

One crucial concern that affects both the Autonomous Communities and the national Government is compliance with EU benchmarks and targets, formulated outside not just from the influence of the Basque cluster actors, but usually national actors as well (Gerres et al., 2019). Spanish sustainability stakeholders have pointed out that progress made in other industrialised European Member States, in terms of long-term industrial strategies and national funding schemes, do not reflect the reality of most industrial regions in Spain. Indeed, Spain has faced prolonged stagnation in new industrial developments while the dominance of multinationals implies that most investment decisions are mainly driven by locational factors, cultivating a persistent fear in the region of potential relocation of established facilities out of Spain. Uncertainty over volatile energy and CO_2 emission prices as well as reduction of industrial production, particularly in the automotive sector, further hinders alliance with other European competitors (Gerres et al., 2019).

5.3.4 Crises and the impact on societal acceptance of decarbonisation efforts

Within the Spanish landscape, public discussions orient over the perceived unfairness of EU CO_2 emission reduction targets, causing significant frictions. Specifically, the net-zero target for 2050 has been the same for all EU member states, benchmarking the transition against national emission intensity in 1990. However, Spanish per capita emissions that year were highly reduced, only to rise again during the following two decades, due to the financial crises and a following economic restart in the 90s and the early 00s (Gerres et al., 2019). This trend is also observed in the country's absolute emissions (UNFCCC, 2025), peaking at 2005 after a roughly more than 50% increase from 1990 to 2005 in terms of GHG emissions without LULUCF (Figure 10).

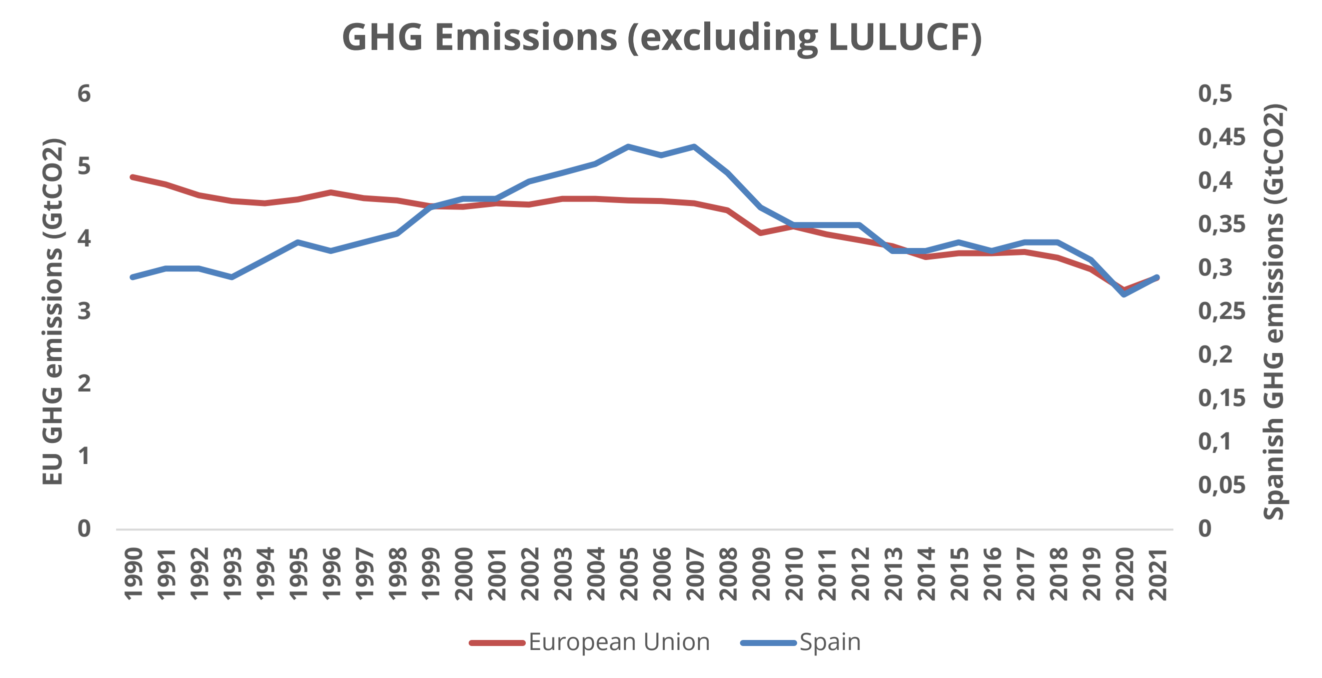

Figure 10. GHG emissions (excluding LULUCF) in Spain and the European Union between 1990-2021.

Based on conceptualisation by (World Bank 2019; Gerres et al., 2019) and UNFCCC data

This discrepancy has triggered questions over the Spanish industrial sustainability goals, as to whether the country should endanger its competitiveness levels over radical emission reductions (Gerres et al., 2019). In parallel, although implementation of renewable energy commitments has initially led to important savings in the energy system by reducing electricity market prices, the evolution of renewable regulatory costs after 2010 have not compensated these savings, leading to social costs imposed on consumers (Espinosa & Pizarro-Irizar, 2018). Given this major transition deficit, as well as lagging behind the EU in terms of the readiness levels of niche innovation technologies, the alignment EU net-zero pathway with the Spanish socio-economic objectives has risked been destabilised and depreciated as a one-size-fits-all approach

(Gerres et al., 2019). Therefore, a large share of the society considers that the CO_2 reduction measures imposed by the EU have been justified in Spain only until 2011, meaning that ever since the net-zero regulatory costs have been increasingly shadowing Spain's compensation prospects (Espinosa & Pizarro-Irizar, 2018).

The recent environmental, economic, and geopolitical events cause further distraction, especially for oil and gas companies facing costly transition challenges and, at the same time, uncertainty over the global role of natural gas and oil in the future (Menéndez-Sánchez et al., 2023). This suggests that the energy transition needs to proceed following parallel, multi-energy transition pathways. Hence, oil and gas companies have both proceeded in low-carbon and renewable investments but, at the same time, have not quickly adapted their business models (Menéndez-Sánchez et al., 2023). However, due to mounting pressure towards sustainability benchmarks, many companies take up leading roles in major clean energy technologies, Petronor, the only large-scale refinery in ACBC, being an illustrative example (see below).

5.4 Niches

5.4.1 Renewable Energy Technologies

5.4.1.1 Current status of established technologies and entrepreneurial activities on new opportunities

According to the National Renewable Energy Action Plan, there were expectations that the country's share of renewables in the annual average electricity demand could come close to 40% by 2020 (Stamatakis et al., 2022), a target largely met (Red Eléctrica, 2020). Out of the gross total electricity generation, wind energy (onshore and offshore) represents the biggest share (52%) while both hydro and solar photovoltaic energy follow at a high distance (8.3% and 7.4 respectively) (Stamatakis et al., 2022). At the same time, the Territorial Sector Plan for Spain, linked to the European Green Deal, has proposed the installation of 2,500 MW of solar, 1,100 MW of onshore wind, and 2,450 MW of other technologies, including biomass, geothermal, aerothermal, solar thermal, oceanic and mini-hydro, hoping that they would cover around 30% of final energy consumption (including the current 10% renewable energy generation capacity) (Mosquera & Larrea, 2025). Yet, these plans would not suffice in terms of the overall EU target emissions targets set for 2030, making it difficult for Spain to meet net zero by 2050 (Mosquera & Larrea, 2025).

The ACBC features low levels of solar radiation as well as low onshore wind potential (due to high population density, its mountainous terrain limiting suitable locations for large-scale wind farms, and public resistance to wind farm developments) and low expectations over significant developments on mini hydro, despite many existing plant installations (Mosquera & Larrea, 2025). However, since 2023 many private firms, supported by the Basque Government, have been increasingly investing in large-scale wind and solar developments within the framework of the Basque Research and Innovation Strategy for Smart Specialisation (RIS3 Strategy). For example, the Labraza and Azazeta onshore wind farms in Álava have been promoted by Haizeindar, while offshore wind farms secured €1 million by Initiative Three of the RIS3 Strategy for advanced manufacturing (Mosquera & Larrea, 2025). In addition, the Biscay Marine Energy Platform (BIMEP), and Initiative Four of the RIS3 Strategy have set a budget of €33.1 million on solar energy, promoting solar plants by Indarberri, a joint venture between Solaria and the Basque Energy Agency (EVE), and Ekinea, a private equity fund management company (Mosquera & Larrea, 2025).

At the same time, the use of residual forest biomass for energy production is considered particularly relevant to the ACBC since it has been the most widely used source of renewable energy, at least until the first two decades of 00's (Mateos et al., 2016). The Basque government's Strategy 3E-2020 had set the goal of forest biomass representing 85% of the region's renewable contribution to final energy consumption (6.8%) by 2020 (Mateos et al., 2016). Given that a large share of ACBC's land is already used for forestry, the benefits of forest biomass use are highlighted, including high energy self-sufficiency potential, employment opportunities in rural communities, and an important reduction of forest fires (Mateos et al., 2016). However, the amount of biomass residues has been estimated to be low compared to the region's annual forest growth (Mateos et al., 2016).

5.4.1.2 RES promotion through R&D projects, investments, and networking

ACBC's business and R&D sector features a high specialisation in electricity grids (Mosquera & Larrea, 2025). Smart grids, introduce a bi-directional energy flow that can address power system flexibility combining a variety of niche innovation technologies, such as storage devices, vehicle-to-grid systems, and energy management systems (Mosquera & Larrea, 2025). Obviously, digital technologies play a crucial role in smart grid developments since they can support operation and integration efficiency aspects while increasing energy system security, which according to IEA has been an urgent European priority, especially in Spain. Europe and specifically the ACBC has emerged as a centre of specialisation in smart grid technology (IEA, 2024). Although R&D expenditure has been clearly directed towards industrial production and technologies (by 45% in 2021), and less towards energy (12.8%), different research projects are currently ongoing in the field within the ACBC Energy Cluster, a business collaboration network set up in 1996 (Mosquera & Larrea, 2025). For example, Tecnalia in collaboration with the School of Engineering of the University of Navarra (Tecnun) are involved in the LIFE IP Urban Klima 2050 project, assessing the impact of climate change in electricity grids in ACBC (Mosquera & Larrea, 2025). Such projects are usually performed in collaboration with private industrial companies, subsidised by the Basque Government and/or Horizon Europe programmes. For instance, Iberdrola has developed the Global Smartgrid Innovation Hub, a global centre of innovation and knowledge in smart grids, located in Bilbao, specialising students and professionals under related R&D activities. Overall, smart grids can have a potentially disruptive nature within the context of renewable energy developments in the area.

In terms of bioeconomy, the Department of Economic Development, Sustainability, and Environment of the Basque Government's plans to provide economic support for private actors willing to proceed with biomass pilot and demonstration projects have emerged mainly since 2018 with a budget of more than €28 million, provided by European and national calls, and privately led contracts (Barañano et al., 2022). A Basque Alliance for Bioeconomy was created in 2019 to generate a network of private actors that specialise in primary and food sectors as well as sustainable development to promote collaboration with technological centres and public entities (Barañano et al., 2022). However, despite this seemingly intensive research landscape, no sufficient technology transfer to actual production has been established (Barañano et al., 2022).

The Transitioning Industrial Clusters towards Net Zero initiative by World Economic Forum (WEF) has been actively supporting cluster development and collaboration mechanisms mostly in the form of joint workshops and roundtables, facilitating cluster initiation through ongoing net-zero strategy implementation (WEF, 2023). The Net Zero Basque Industrial Super Cluster, led by SPRI and energy companies Petronor-Repsol, and Iberdrola, falls under this WEF initiative. The Super Cluster initiative aims to accelerate energy supply decarbonisation and industrial energy efficiency, creating market opportunities for niche innovation technologies working closely with the Basque Energy Cluster Association (WEF, 2023).

5.4.1.3 Creation of legitimacy and concerns

The Territorial Sectoral Plan for Renewable Energies (TSP-RE) of ACBC was one of the first plans in Spain to promote medium to large-size renewable energy projects mostly in rural land with limited development prospects, also providing a delimitation plan for environmentally protected areas (Urkidi Azkarraga & Gurrutxaga, 2024). The TSP-RE assess the feasibility of developing new renewable developments excluding protected natural spaces, cultural heritage areas, scenic landmarks, as well as areas in proximity to urban centres. However, the Basque TSP-RE has been met with skepticism by regional stakeholders, particularly environmental organisations and some provincial institutions, since it does not include offshore wind energy or large hydroelectric plants (although no new projects are currently underway). In addition, it does not provide estimations on small-scale generation facilities. Instead, stakeholders propose the prioritisation of urban, peri-urban or industrial locations as an alternative to large-scale projects (Urkidi Azkarraga & Gurrutxaga, 2024). Resistance over large-scale renewable energy developments tend to evolve around the defense of rural space arguing for a political misrecognition of rural populations and identity. In addition, legitimacy concerns are ultimately expressed by municipalities who have currently no decision-making power over such developments, although they might be in favour of renewable energy overall (Urkidi Azkarraga & Gurrutxaga, 2024).

Social opposition is also expressed against the development of energy grids, immersed within the overall refusal of excavating natural resources and installing large-scale energy infrastructures by more than half of the Spanish population. Examples include the rejection of Solaria's project for three solar parks and the two associated high voltage energy grids in Álava, as well as opposition against the electricity interconnection between Spain and France through the Bay of Biscay from both countries. These highlight a prevailing sentiment from citizen’s that renewable energy projects do not generate benefits for their communities (Mosquera & Larrea, 2025). At the same time, it is also perceived that renewable energies continue to be deployed away from demand locations, hence constituting energy grid developments indispensable for electricity distribution towards hinterland (Mosquera & Larrea, 2025).

5.4.1.4 Cooperatives for renewable energy (RESCOOPs)

Spain has a strong tradition in energy cooperatives since the beginning of the twentieth century, mainly found in rural areas not connected to the national electricity grid (Sciullo et al., 2022). Since 2010, retailing of renewable electricity was handled by non-governmental energy cooperative organisations motivated by environmental and social concerns in the midst of anti-nuclear energy movements (Sciullo et al., 2022). The cooperatives’ decision-making autonomy and freedom of membership have pushed the Spanish oligopolistic energy model—controlled by multinational entities—towards a more decentralised, citizen-owned sustainable model, especially after the liberalization of the electricity market in 1997 (Morandeira-Arca et al., 2024). The Basque Country is renowned for the Mondragon Group’s cooperatives (MCC), the world’s largest worker’s cooperative movement as well as two other cooperative groups, the BARRIZAR Cooperative Energy Services Company set up in 2013 and the GOIENER Renewable Energy Cooperative. Both groups are linked to the REAS Network of Social and Solidarity Economy in Spain and REScoop.eu, a federation that brings together initiatives related to the production, marketing, assessment, distribution and/or supply of renewable energy in line with the principles of the International Cooperative Alliance (ICA). (Morandeira-Arca et al., 2024). The BARRIZAR group is not an electricity retailer but an organisation that provides citizens with renewable energy generation installations (mainly for solar, biomass, and combined heat and power (CHP) energy generation) promoting energy efficiency measures at a supra-municipal level and in cooperation with public and private entities. Its focus has recently shifted towards electricity self-consumption installations that dominates its member's interest. However, the group actively supports cooperative retailer GOINER. One important feature of the two groups is that they are not only engaged in renewable energy contracting and retailing but are also involved in public awareness activities in collaboration with other social cooperative associations, taking a clear position in favour of reducing energy dependency (Morandeira-Arca et al., 2024).

5.4.2 Hydrogen

5.4.2.1 Current state and existing plans/activities

Hydrogen technologies in Spain are widely recognised and accepted for decarbonising the energy and transport sectors. However, the country has focused its strategy on renewable hydrogen, prioritising it over other forms of decarbonised hydrogen production. Specifically, hydrogen is thought of for energy generation through biomass pyrolysis, biogas and biofuel generation, and as a storage technology for surplus renewable energy generation, to be used in several applications (i.e., chemical industry) or delivered to the gas network (Stamatakis et al., 2022). Therefore, hydrogen is considered crucial for the biogas, wind, and power sectors. The main policies that define the Spanish hydrogen strategy are the Hydrogen Roadmap published in 2020, the National Integrated Energy and Climate Plan (PNIEC) 2023–2030, the Climate Change and Energy Transition Law approved in 2021, the 2050 Long-Term Decarbonisation Strategy, the Just Transition Strategy, and the Energy Storage Strategy (Urbasos & Escribano, 2024). Few exceptions focus on blue hydrogen production in refineries, in projects usually led by private companies. However, the country's lack of significant oil and gas extraction has mainly excluded blue hydrogen from the national Roadmap (Urbasos & Escribano, 2024). Instead, given the fact that Spain consumes approximately 500,000 tons of hydrogen exclusively in industrial uses, refining and fertiliser sectors are expected to lead the transition to green hydrogen as raw material, followed by methanol, synthetic fuel, and steel sectors (Urbasos & Escribano, 2024).

One important aspect in green hydrogen adoption in Spain is that its Hydrogen Roadmap preceded the country's R&D capacity, and thus hydrogen pilot and demonstration projects were initiated by the private sector (Urbasos & Escribano, 2024) (see the role of Petronor in hydrogen R&D below). This led to outsourcing costly hydrogen technology from Western European multinationals, particularly for electrolyser installations. Gradually, cheaper Chinese-manufactured alkaline electrolysers have managed to enter the Spanish hydrogen market sparking the interest of Spanish developers (mainly involved in power electronics) (Urbasos & Escribano, 2024). Expectations over the emergence of an electrolyser assembly industry on the national level might facilitate domestic hydrogen demand but such a development would not necessarily rely upon the innovation capacity of regional players (Urbasos & Escribano, 2024).

At the same time, the Spanish Alliance for Energy Research and Innovation (ALINNE) has insisted on hydrogen's potential in fuel cell niche innovations, predicting hydrogen scale up in the next decade. However, the high cost of niche hydrogen and fuel cell technologies, as well as under-financing of related R&D initiatives during the last decade hinder and may delay their application (Stamatakis et al., 2022). Other national associations around hydrogen applications, active inter alia in the Basque Country, include the Spanish Hydrogen Association (AeH2), the National Hydrogen Centre (CNH2), the Spanish Hydrogen and

Fuel Cell Platform (PTEHPC), and the Spanish Fuel Cell Association (APPICE) (Stamatakis et al., 2022).

The Spanish refining sector aims to pioneer in the production and use of renewable hydrogen by 2030, expecting to decarbonise all hydrogen consumption. As a net exporter of refined products, reaching €29 billion of combined value in 2022, Spain has endorsed hydrogen applications in the sector, while major refining companies, including the Basque Country-based Petronor, have eagerly initiated ambitious decarbonisation strategies (Urbasos & Escribano, 2024). However, hydrogen is currently thought of as a transition technology, mainly used in established refining applications (hydrogenation and hydrocracking) and subsequently on the production of synthetic fuels (Urbasos & Escribano, 2024). Green hydrogen adoption in the refining sector is backed up by high natural gas prices, the end of free EU-ETS allowances by 2034, and the proven renewable development progress made by refining operators (Urbasos & Escribano, 2024).

5.4.2.2 R&D and prospective initiatives

Petronor, the Spanish oil and gas company (owned by multinational Repsol by 85.98%) operating its biggest refinery in Muskiz, Biscay, is strategically positioned towards several low-carbon innovation projects. The company aims to create a low-carbon innovation and decarbonisation hub within its assets in the Port of Bilbao. This hub will engage in wind energy, CCS, green hydrogen production via large electrolyser facilities, biogas, and synthetic fuels. The hub will also host an Energy Intelligence Center, a business/research institution aiming to foster public-private synergies (Menéndez-Sánchez et al., 2023). Petronor's ambitious plans involve the development of technological cooperation with other leading foreign oil companies, yet at the same time the company aims to financially support regional energy communities as well as decarbonisation solutions for the industry, commercial, and residential sectors. The company also aims towards circularity activities mainly engaging in car battery recycling and urban waste recycling to biogas (via pyrolysis) (Menéndez-Sánchez et al., 2023).

Hydrogen applications demonstrate a strong pillar for Petronor's sustainability plans since 2021, involving electrolysis and biogas production, combined with CCS, mainly targeting the mobility sector. The company is currently a leading participant in two major hydrogen and decarbonisation R&D initiatives, involving a large number of projects: the Basque H2 Valley and the government-led SPRI. Specifically, the Basque Net Zero Industrial Super Cluster initiative, led by Basque Government's Business Development Agency (SPRI), aims to achieve the full decarbonization of the EIIs in the Basque Country. The initiative extends its collaboration with 16 Basque industrial associations representing oil refining, iron and steel, foundry, cement, and pulp and paper industries responsible for 65% of the Basque industry's CO_2 emissions.

These initiatives bring many Basque companies engaged in industrial decarbonisation under the same roof and with active collaboration with Basque energy institutions, such as the Basque Government's Energy Agency and the Basque Energy Cluster. This has further encouraged hydrogen-related cooperation activities, initiating the Basque Hydrogen Sectorial Forum, aiming to support the implementation of regional hydrogen innovation strategies (Menéndez-Sánchez et al., 2023). In addition, both initiatives are involved in the Basque Hydrogen Corridor (BH2C) project, also led by Petronor. BH2C is a long-term regional innovation and industrial development public-private partnership among 80 regional entities—including private firms, technology centres, universities, and public institutions—aiming to develop a competitive hydrogen value-chain in ACBC, based on the company's current low-carbon technology projects (Menéndez-Sánchez et al., 2023). Obviously, Petronor's innovation strategy is deployed around several simultaneous dimensions involving a wide range of regional and international actors, strengthened by specialised subsidiaries, empowering the local innovation ecosystem (Menéndez-Sánchez et al., 2023).

5.4.2.3 Geopolitical developments

Green hydrogen has been embraced by the Spanish Government, publishing the Hydrogen Roadmap during the economic and social crises caused by COVID (2020) but especially after the Russian invasion to Ukraine, that marked the urgent imperative to support industrial development and diversification, as expressed within REPowerEU (Urbasos & Escribano, 2024). These two major challenges have shifted Spain's focus on exports and infrastructure development. Specifically, the "young" Spanish Hydrogen strategy was suggested as a driver of re-industrialisation as opposed to the country's energy export model (Urbasos & Escribano, 2024). This major shift was also caused by the fear that existing constraints in electricity interconnections with other EU markets would be replicated for hydrogen (Urbasos & Escribano, 2024). However, Spain still employs a so called "hydrogen diplomacy" with key European allies, such as France, the Netherlands, Germany, Portugal, and Italy as well as with other Mediterranean energy cooperation schemes and Latin American investment developments (Urbasos & Escribano, 2024).

Measures for energy security were particularly manifested through bilateral hydrogen cooperation agreements with Italy in 2020, and Portugal in 2021. Traditionally, Spain has prioritised energy interconnections with Europe, aiming for a green hydrogen corridor towards central European markets as well as with North African states, already established to some extent for electricity and gas trade (Urbasos & Escribano, 2024). However, France has consistently obstructed these plans by not agreeing in the construction of natural gas and electricity grids in the past. Therefore, Spain's competitive advantage over its abundant renewable resources has faced great export uncertainty (Urbasos & Escribano, 2024). The announcement of the construction of the H2Med offshore pipeline in 2022 connecting Spain with France, was an unexpected improvement of the two country relations, although these are still perceived as fragile. However, this major infrastructure development is expected to define hydrogen's future in the Iberian Peninsula or also mark an alternative orientation towards non-European players (Urbasos & Escribano, 2024). At the Basque level, the Basque Hydrogen Strategy (EVE, 2021) has served to establish concrete goals and actions at regional level.

5.4.2.4 Revamping of hydrogen's role: Financial opportunities and challenges

Following the developments described above, the Spanish National Energy and Climate Plan's (PNIEC in Spanish) revised the national electrolyser capacity target for 2030, raising it from 4 to 12 GW (MITECO, 2024), also increasing the renewable hydrogen quota in conventional industrial uses from 25 to 74% by 2030. (Urbasos & Escribano, 2024). The potential of generating cheap green hydrogen has been suggested as an opportunity to attract investment in the decarbonisation of the metallurgical, chemical, and petrochemical sectors, where hydrogen feedstock represents an important part of the final costs. Additionally, renewable hydrogen is seen as a backup storage option for the country's energy system, given the wide-spread expectation of renewable energy generation surpluses thanks to increasing renewable applications (Urbasos & Escribano, 2024). In 2022, four Spanish hydrogen projects gained the status of Important Projects of Common European Interest (IPCEI), securing €5.4 billion for investments towards increasing internationalisation, while 20% of the IPCEI call targeting industrial decarbonisation and infrastructure were obtained by Spanish companies (Urbasos & Escribano, 2024). In addition, NextGenerationEU Funds were also used to further drive green hydrogen technologies in Spain via the Strategic Projects for Economic Recovery and Transformation (PERTE) programme, reaching up to €450 million of funding, mainly provided for the transformation of large-scale fossil-based industrial facilities (Urbasos & Escribano, 2024).

Despite securing abundant financial resources for green hydrogen technologies, Spain is still facing two major challenges: the lack of skilled human capital and the inability of SMEs to benefit for these generous funds. Both challenges affect project development, causing delays in hydrogen expansion. However, it is expected that skilled labour will be available in the long run, considering the emergence of targeted policies for re-skilling and vocational training via the Recovery Fund hydrogen package (Urbasos & Escribano, 2024). At the same time, renewable energy developments are not expected to create many job-related opportunities whereas the implementation of hydrogen applications can offer greater growth potential. This could imply more social support for hydrogen in contrast to observed public opposition trends for large-scale renewable infrastructure developments (see above) (Urbasos & Escribano, 2024). However, these opposition movements have already targeted the H2Med pipeline (Urbasos & Escribano, 2024).

5.4.3 Carbon Capture, Utilisation, and Storage (CCUS)

5.4.3.1 Past initiatives

As the fifth-largest CO_2 emitter in the EU, Spain is considering the high decarbonisation potential of CCS, as also revealed by national assessments for CO_2 storage capacity (Sun et al., 2021). During late 00's three pilot projects kicked off, but further implementation was ceased by the financial crisis of 2008 (Sun et al., 2021). The first national law for geological storage was eventually signed in 2010, incorporating EU directives into the Spanish geological, industrial, and energy characteristics, although causing several conflicts on behalf of different Spanish constituencies (Sun et al., 2021). No other major CCS developments have been currently planned.

5.4.3.2 CCS potential in the literature

A study by (Sun et al., 2021) identified 15 CO_2 emission hot spots and industrial clusters as potential sites for future CCS development across Spain, mainly distributed in coastal areas, including the Basque Country as seen in Figure 11 (Sun et al., 2021). These hubs or clusters represent around 20% of total GHG emissions in 2018, mainly deriving from thermal power plants, oil refineries, iron and steel, cement, and pulp and paper production facilities (Sun et al., 2021).

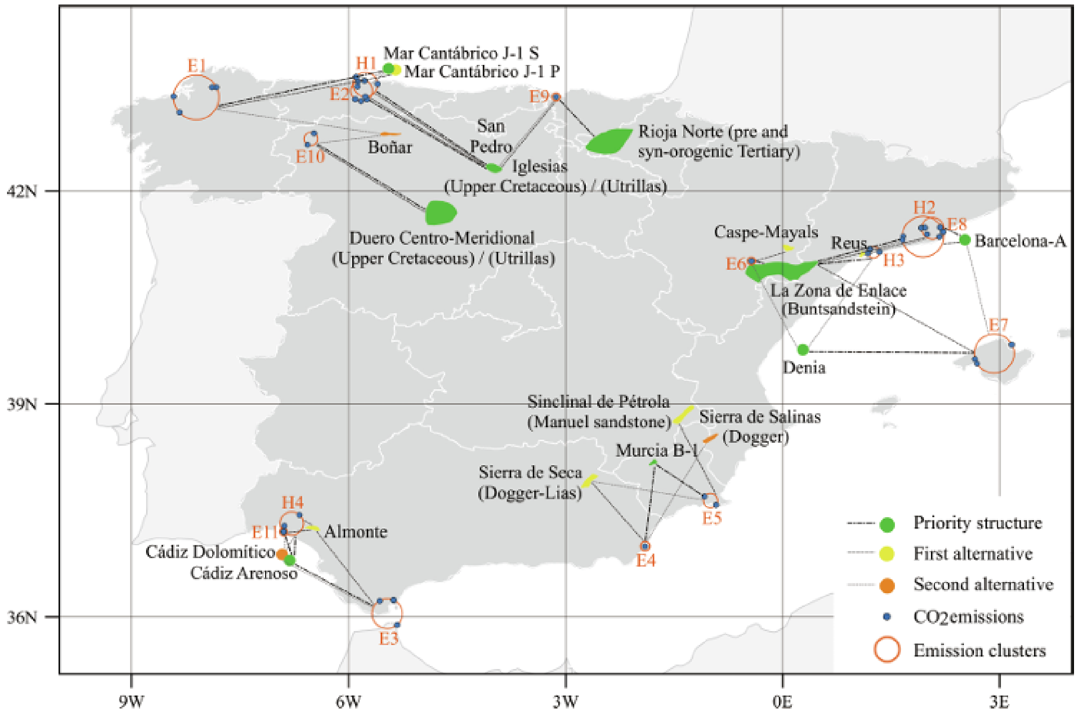

Figure 11. The priority source-to-sink clusters and their alternative storage structures.

Source: (Sun et al., 2021)

CCS applications are expected to become cost-effective after renewable energy developments are established, hinting at the large costs related to CCS (Sun et al., 2021). EIIs are primarily in need of such CO_2 storage applications due to their emissions-intensive processes concentrated in large-scale plants and the limited availability of other decarbonisation options (Sun et al., 2021).

Another EU study, the GeoCapacity project (2006-2009) revealed a potential of 14Gt total storage capacity in Spain, ranking it the fourth largest (theoretical) resource in Europe after Norway, Germany, and the UK. The Spanish Geological and Mining Survey (IGME) conducted the ALGECO2 project (2009–2010) proceeded in more detailed characterization of such potential while the COMET project (2010–2013) assessed the most cost-effective CO_2 transport and storage infrastructure able to serve the West Mediterranean area, namely Portugal, Spain and Morocco. The study suggested the implementation of joint large-scale transnational infrastructures to achieve better financial performance (Sun et al., 2021). Although CCS has been suggested as a realistic option for emission reduction in Spain, and approved by the Spanish Parliament, the Spanish Government's explicit support has been limited to the creation of the CIUDEN Foundation, a public sector research institute also addressing CCS prospects (Sun et al., 2021).

5.4.3.3 Potential applications

ACBC's CO_2 storage potential combined with forest-based biomass availability makes Bioenergy with Carbon Capture and Storage (BECCS) could also suggest a realistic option to meet future emission targets, as well as deal with just transition concerns, expressed by rural areas in the region, although entailing the creation of a specialised labour force.

Indeed, the potential of commercial-scale CCS projects in Spain and the Basque Country, could involve a transnational integration approach, involving multiple CO_2 pipelines connecting sources and storage sites.

The possibility of an integrated European CO_2 pipeline network would rather favour most coastal CO_2 hot spots, identified above, already featuring established pipeline networks for natural gas (Sun et al., 2021). Similarly, the Western Mediterranean (i.e., Portugal, Morocco) could benefit from Spain's potential CO_2 storage capacity via pipeline interconnection (Sun et al., 2021). Such prospects could be driven via European funding schemes such as the Connecting Europe Facility for Energy (CEF Energy) under the IPCEI programme (Sun et al., 2021).

5.4.4 Circular economy

5.4.4.1 Policies and efforts towards research and knowledge development

In 2020, a Pact for a Circular Economy was approved by the Spanish Government representing the adoption of the EU directive. A Spanish Strategy for Circular Economy (SSCE) Action Plan was set up in 2022, counting on Next Generation EU Funds for financial support (Pablo-Romero et al., 2024). The Plan includes CE developments for decarbonisation processes, mostly focusing on waste recovery from blades of the wind turbines, photovoltaic solar panels, and batteries as well as the promotion of CE in enterprises (Pablo-Romero et al., 2024). Although basic environmental legislation falls under the responsibility of the National Government, the Autonomous Communities can publish their own CE laws (Pablo-Romero et al., 2024).

The Basque Country produces 5.5 million tons of waste yearly, including 58% of non-hazardous industrial waste, 20% of municipal solid waste, 16% of construction and demolition waste (Elgorriaga Kunze & Quintana San Miguel, 2018). According to IHOBE, the value of these waste materials estimated at €44 million a year, including €12 million of potential value per year in secondary plastics and €7 million in ferrous metals (Elgorriaga Kunze & Quintana San Miguel, 2018). Hence, the Basque Government introduced a Circular Economy Demonstration Projects call in 2015 to support pre-industrial and industrial tests to confirm the environmental, economic, and technical feasibility of alternative technologies to recover secondary materials, or components of manufacturing products (i.e., metal, construction, automotive, electric/electronic, and plastics). Projects that went forward under this call included recovering steel mill dust in blast furnaces, recycling of solar photovoltaic modules, and the use of steel aggregates to produce concrete prefabs. However, it was widely accepted that such CE applications would require public-private partnerships to enter the market (Elgorriaga Kunze & Quintana San Miguel, 2018).

The Basque Government has strategically supported education for sustainable development (ESD) within its 2030 agenda, in coordination with United Nations's Global Action Programme (Minguez et al., 2021). Since 2002, the University of the Basque Country (UPV/EHU) has supported several teaching experiences related to Life Cycle Thinking or Ecodesign, inaugurating an Ecodesign Learning Center at the faculty of Engineering. Within this framework a master's degree named "Circular Economy: Business Application" was introduced in 2019, attracting students from various disciplines (e.g., manufacturing engineering, environmental engineering, economics) (Minguez et al., 2021). This initiative has obviously established alliances with the Basque Ecodesign Center and IHOBE and has since motivated cooperation with other European universities (Minguez et al., 2021). Specifically, IHOBE created a Basque Circular Hub, a centre for advanced circular economy services in collaboration with ACBC's academic institutions (such as the University of the Basque Country, the University of Deusto, the University of Mondragón), the Council of the City of Bilbao, and two vocational foundations, Tknika and Novia Salcedo Foundation (Barañano et al., 2022). The Hub has advanced the experience accumulated by previous initiatives (i.e., Basque Ecodesign Hub) to support the development of circular economy projects by Basque companies and the creation of a Circular Economy Observatory for the Basque Country besides the master's training programme mentioned above (Barañano et al., 2022). In addition, a network of Applied Bioeconomy in Vocational Training has been promoted by the same university, aiming to support skills in the generation of competitive bio-based products and services (Barañano et al., 2022).

In recent years, the Basque Government has actively prioritised the development of a forest-based bioeconomy, recognising forest biomass as the region's most abundant biological resource and thus central to the Circular Economy and Bioeconomy Plan 2024 (Barañano et al., 2022). The plan initially focused on this sector considering ACBC's extensive forest coverage and longstanding administrative support. To extend this support through regional and international collaboration, the Basque Country joined the Bioregions Facility of the European Forest Institute, with the aim of advancing a sustainable and productive forest-based bioeconomy (Barañano et al., 2022). Traditionally centred on timber, pulp and paper, the sector is now diversifying into bioenergy, biochemicals, textiles, lignocellulosic bioplastics and packaging, thereby moving towards higher-value CE activities (Barañano et al., 2022). As mentioned above, while forest management and policy remain under the authority of Provincial Councils, industrial development and research fall within the remit of the Basque Government. Thus, ACBC's institutional commitment since 2017 has been marked by several key milestones, including the 2018 "Bioeconomy in the Basque Country" conference, the 2019 Circular Forest Bioeconomy Roadmap, and the Basque Alliance for Bioeconomy (Barañano et al., 2022).

5.4.4.2 Perceptions of CE's impact

According to a study conducted by (Ormazabal et al., 2016) in 2016, most Basque industrial companies did not perceive any benefit from circular economy (CE), claiming that environmental management would have no impact on their market development (Ormazabal et al., 2016).

However, according to IHOBE, the Environmental Management Agency of the Basque Country, up to 7% of industrial process costs could be saved with low-cost CE measures (Gerres et al., 2019). Still, CE measures have been greatly perceived in relation to the recycling industry, involving mainly the recycling of organic waste streams, or household appliances (Gerres et al., 2019). The Basque Government has launched a strategic CE vision— aligned with the CE action plan set by the European Commission—along with companies and academic institutions mainly focusing on helping companies to assess and test CE business models in the textile and recycling clusters (Rincón-Moreno et al., 2022). However, the deployment of CE practices within the regional industrial context, dominated by SMEs, hinders stakeholder participation. In 2022, less than 2% of ACBC's GDP accounted to CE activities (Rincón-Moreno et al., 2022).

However, ACBC exhibits potential for the use of recovered industrial waste heat (IWH) towards greater industrial energy efficiency mainly due to its high industrialisation, being the second most industrialised county in Spain. Assessments have been published during the early 00's scoping this potential, considering high spatial resolution, suggesting that relevant activities could be transferred to other regions as well (Miró et al., 2016). Specifically, industrial waste heat could be recovered and reused in industrial processes (to preheat incoming water or combustion air, preheating furnace loads, etc.), or transformed to electricity, cold, or other types of heat, possibly serving residential areas. In the case of ACBC, studies assessed eight different IWH potential applications in nine industrial sectors, including steel, pulp and paper, metal, cement, and chemicals, although using different methodologies and thus deriving to contrasting results.

Nevertheless, the Basque province Bizkaia has been assessed as having the greatest IWH potential in comparison to the other Basque provinces, due to its concentration of industrial activities applicable to IWH

(Larrinaga et al., 2021). Specifically, the iron and steel sector would be the most appropriate to develop IWH according to the sector's viable investments and payback period expected to be below five years (Larrinaga et al., 2021). The chemical and petrochemical sectors are also relevant with similar investment payback period, although only for high temperatures, while the cement sector features low quality IWH potential due to very low temperatures (Larrinaga et al., 2021).

5.4.4.3 Prospective initiatives: The case of the Basque Industrial Hub for Circularity

In 2024, the Basque Industrial Hub for Circularity (BIH4C) was launched, led by Tecnalia and supported by the Energy Cluster, the Consorcio de Aguas Bilbao Bizkaia as well as private companies Calcinor (lime extraction), Sidenor (steel manufacturing), SBS Process (waste treatment), Lointek (petrochemical), Petronor (refinery), Smurfit Kappa (paper packaging), and Nortegas (gas distribution). The hub is part of the European IS2H4C project subsidised by the European Commission through the Horizon Europe Programme, including other Hubs in the Netherlands, Germany, and Turkey. The Basque H4C is also part of the Net-Zero Basque Industrial Supercluster initiative (Mosquera & Larrea, 2025).

The hub for circularity (H4C) is an emerging concept that extends the traditional boundaries of industrial symbiosis (IS) networks by facilitating resource exchanges, within an industrial cluster and surrounding urban and rural areas. The concept involves cross-company coordination, assessing waste or raw materials availability, renewable energy generation, and market prices of IS practices towards transforming traditional supply chains (Wang et al., 2025). Its main objective is to transform conventional industrial zones into collaborative, resource-sharing, and environmentally sustainable hubs, stemming from industrial cluster particular characteristics (Wang et al., 2025).

As the largest hub within the IS2H4C project, ACBC H4C involves steel, cement and lime, oil refining, and pulp and paper industries, and their facilities. The Basque Hub particularly focuses on captured CO_2 due to the emission intensiveness of its industrial processes, including CO_2 utilisation in lime and cement production, in hydrogen generation via electrolysis for both e-fuel and steel production. Waste from the pulp and paper industry is also employed in biofuel production, while steel slag, a by-product of steel manufacturing is utilised in the cement industry for carbonation. In terms of industrial-urban-rural symbiosis, the Hub involves biogas and bio-coke production from the pyrolysis of urban waste, replacing natural gas and substituting coal-based coke in cement, lime, and steel industries. Wastewater is repurposed to produce bio-gas biogas and e-fuels (Wang et al., 2025). Resource exchanges are demonstrated in Figure 12.

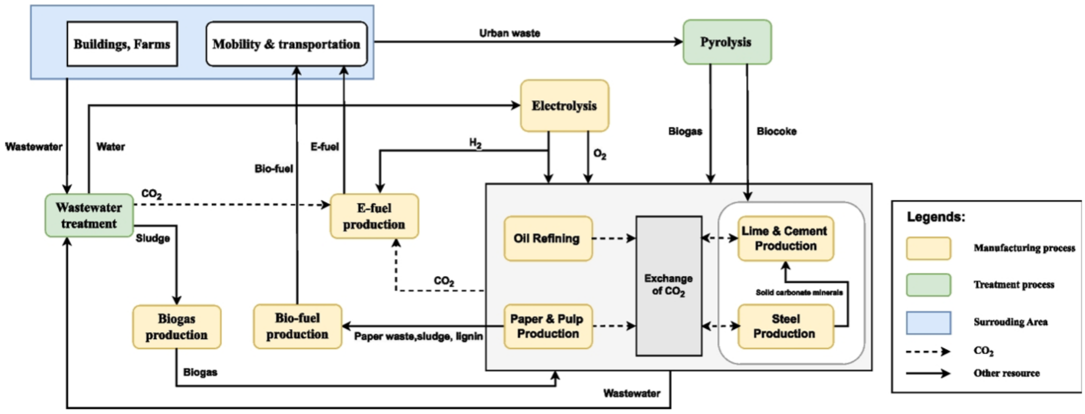

Figure 12. Illustration of the Basque H4C.

Source: (Wang et al., 2025)

Although several uncertainties prevail in the successful implementation of such cross-sectoral resource exchanges (e.g., uncertainty for biogas/biocoke availability due to fluctuations of urban/rural waste generation), the project is expected to drive a sequence of IS spillovers as soon as the economic profitability of such practices has been widely recognised.

5.5 Discussion

ACBC is a highly industrialised region with a thriving economy compared to Spanish and European averages. Despite its relatively small size, the cluster's impressive resilience against consequent oil and financial crises has often been recognised as a success story, mainly thanks to the region's strong state-led cooperative composition. ACBC has been heavily dependent on fossil fuels, particularly oil and natural gas, but has taken remarkable steps forward, leading major renewable energy developments (mainly wind, solar, and hydro). The cluster features a low emission-intensity compared to the European average yet is currently facing strong mitigation pressure due to nationally binding commitments—often viewed as unfair by the public due to the low baseline year used in the calculations. However, the regulatory autonomy has enabled a series of privately led, yet state- and EU-financed, low carbon initiatives towards meeting these targets. Nevertheless, ACBC has been exposed to pertinent demographic pressure that might hinder the transition, given its currently low skilled workforce dynamic.

State interventions have followed a coherent Smart Specialisation Strategy grounded in technological modernisation and robust institutional collaboration among universities, technology centres, policy institutions, vis-à-vis a diverse energy-intensive industrial ecosystem hosting big industrial players and SME's, represented by integrated cluster associations. Public/private partnerships do not, however, actively involve civil society and trade unions. ACBC EII sectors include iron and steel, dominated by EAF-based secondary steel production, petrochemicals, a major refinery run by multinational Petronor, pulp and paper, and cement industries. Green initiatives have been prioritised as drivers for the cluster's competitiveness and hence, major funding is being allocated towards consensus-framed decarbonisation technologies, along with tax and public procurement incentives. Yet, ACBC's most prominent efforts have been oriented towards strategically targeted, industry-led R&D developments, making it a leading knowledge hub that specialises in machinery, industry 4.0, and eco-design.

ACBC is embedded within a highly uncertain global trade environment that is currently driving parallel multi-energy transition pathways. The Basque government promotes extensive coastal and offshore wind and solar operations, although subjected to the growing geopolitical uncertainty fuelling bigger private companies' scepticism over their next steps. ACBC also scopes the potential of forest-based biomass, planning to financially support it. Hydrogen has been pursued inter alia by initiatives from Petronor as a viable energy carrier and storage medium, promoting large scale electrolyser capacity and biogas and fuel cell technology, thus restricting its use in refinery-related applications, targeting the mobility sector. At the same time however, the announcement of H2Med offshore pipeline connecting Spain to France has currently incentivised more hydrogen-based industrial processes, also attracting foreign investments. Both large scale wind, solar, and electricity grid developments are expected to face opposition by the public, advocating for small-scale generation facilities, inspired by the powerful regional cooperativism movement. Additionally, prior failed attempts to implement CCS, due to financial constraints, have delayed the diffusion of this decarbonisation option, with the current infrastructural state being essentially non-existent, despite being extensively researched. ACBC is also scoped as a H4C hub and for its IWH potential, involving most of its energy-intensive industrial processes.

6 Bringing It All Together: Concluding Synthesis

During the analysis of the three empirical case studies, common elements as well as notable differences have been identified, which can be crucial when attempting to understand the decarbonisation of European industry from a holistic perspective. Understanding the impact of solutions that might work on numerous different contexts, while also respecting the particularities of each region, will be an important aspect of efficient sustainability planning.

In the following sections, we summarise these insights and offer initial reflections on how these results—along with information elicited with and from stakeholders during the engagement process of the project—can potentially inform industrial transition modelling, including influencing and/or accompanying quantitative model-based pathways.

6.1 Cross-cutting themes and differences across regions

6.1.1 Activities of the clusters and infrastructure opportunities/challenges

Rhine-Ruhr can be viewed as essentially two clusters merged into one, namely one focusing on chemicals/refineries (Rhineland) and one on primary steel production cycles (Ruhr). Although these report to different regional planning authorities, they are holistically coordinated under the umbrella of the NRW state. On one hand, the Ruhr is dominated by a few multinational companies, currently undergoing reorientation from the traditional coal-imported BF-BOF processes towards the adoption of H-DRI, and growing EAF-based secondary production routes. On the other hand, Rhineland—still hosting open cast lignite sites expected to gradually phase out—presents a diverse (petro-)chemical portfolio producing high-value chemicals. Activities are led by both multinational firms and SMEs, featuring excellent network integration regionally as well as internationally within the ARRRA chemical supercluster. Existing infrastructure expansion needs will depend on the feasibility to retrofit natural gas grid lines, and a particularly complex transportation and distribution network run by several operators.

However, Rhine-Ruhr's lack of a CO_2 pipeline grid suggests coordinated cross-border action to accommodate joint chemical CCUS pathways. This can be particularly the case with RHIC, where a series of specialised terminals and excellent internal and cross-border integration networks through underground pipeline grids for oil, natural gas, electricity, hydrogen, and CO_2 are already established and managed by a few private operators. The existence of a local hydrogen grid in both cases is viewed as an enabling factor for further hydrogen infrastructure promotion. In addition, active EU support for cross-border infrastructure collaboration could potentially facilitate closed carbon cycles for the chemical sectors in both regions.

As a frontrunning cluster, also part of the ARRRA supercluster, RHIC is particularly favoured by these minimal transportation costs. RHIC is dominated by refinery and petrochemical industries operated by big multinational firms and is also dependent on coal imports—which it also distributes to the Ruhr via the PoR—and natural gas. The region nonetheless is attempting an active reorientation towards alternative fuel and feedstock, which is hindered by severe spatial constraints. The PoR has already been expanded to accommodate sustainable processes, and thus any new technological developments need to be consistent with such limitations.

The Basque case study has also evolved into a highly specialised clustered industrial ecosystem, hosting the most diverse portfolio of EIIs, including EAF-based secondary steel production, one refinery, chemicals, cement, and pulp and paper. These processes are operated by both big capital firms and SMEs, governed by their equivalent cluster associations that are fully controlled by the private sector. The cluster has neither CO_2 nor hydrogen infrastructure in place, but it is currently developing a smart electricity grid, given the large scale solar, wind, and hydro developments.

6.1.2 Public-Private cooperation

The three regions feature established cooperation networks among regional policy institutions, academia, and industrial companies. However, these cooperation networks are not always driven by shared decarbonisation visions. For example, in PoR such cooperation activities are mostly oriented towards privately led synergies, only managed by the local Authority that does not impose clear technological pathways. At the same time, these synergies are carefully monitored by the Dutch Government, pushing for its national environmental targets as well as guiding technological substitution through targeted funding allocations.

Contrary, in Rhine-Ruhr prior cross-sectoral collaborations (Carbon2Chem) have driven the consolidation of a stakeholder-inclusive and state-led platform (IN4Climate.NRW), which involved several less energy-intensive sectors (cement, paper, glass, aluminium), thereby enabling a rather holistic decarbonisation perspective (i.e., including both the private and public sector), creating an environment that is more appealing to the cultivation of new niche innovation. However, political transitions and instability have often affected the successful implementation of regional or state strategies/roadmaps.

In the case of ACBC, a shared and coherent strategy is consolidated, while a stable civil service as well as an established policy community, enabled by the Basque Government's fiscal and policy autonomy, ensures the minimisation of directional shifts. However, in this case, these strategies are mostly driven by the needs of private companies.

6.1.3 R&D

ACBC is the most distinctive case in terms of its R&D capacity compared to the other two regions. The regional government has considered such capacity as a driver towards safeguarding the cluster's resilience and competitiveness, actively pursuing a "second" wave of major reorientation—the first being sectoral clustering—towards innovation-led and technology-focused growth. Although local R&D capacity is privately led, the government is promoting the allocation of regional and EU funding towards strategically targeted industry needs—yet, without always including SMEs in the process.

In contrast, RHIC features much lower levels of R&D activity, as its industrial outlook is dominated by multinational companies whose global technological priorities might not necessarily fit well with regional needs. As mentioned above, the national policy context is actively supporting certain technologies such as RES, which may often lead to less attention and reluctant R&D support for other options necessary for the industrial transition. This often creates an inherent conflict between policymaking and businesses, with the PoR Authority often acting as a middleman between diverging priorities. Good practice examples may still emerge, nonetheless, such as improvements in the port's highly digitalised and electrified maritime and logistics sector.

Rhine-Ruhr stands somewhere in between the other two regions, featuring a well-established knowledge technological foundation—led by many leading academic and technology institutions—that, nevertheless, do not follow a coherent pathway but are experimenting with several niche-innovations.

6.1.4 Landscape externalities

Geopolitical uncertainty is currently affecting all three regions, especially after the Russian invasion of Ukraine, which saw an increase in natural gas prices as well as global trade insecurity and broader implications for critical raw materials supply chains. However, each case study's resilience to external shocks as well as its access or readiness to generate clean energy or feedstocks—also subject to international competition—varies.

Specifically, Rhine-Ruhr faces the biggest energy challenge due to the perceived spatial limitations in terms of access to renewable energy (e.g., onshore wind) and lack of carbon storage. In contrast, the region might become severely dependent on offshore wind farms and large-scale CO_2 storage operations in the North Sea, outside the jurisdiction of the cluster or Germany. And still, even such large-scale developments may be insufficient for the increasing green energy demands of major Northwester European industrial clusters, including the RHIC and the Rhine-Ruhr. Therefore, EU regulatory incentives (e.g., increasing carbon taxes) could have in the case of Rhine-Ruhr smaller impact (the lack of infrastructure may render substitution harder), whereas in the case of PoR they are eagerly anticipated to drive green investments. Undoubtedly, a relatively ambitious, stable, and predictable EU framework is going to work in favour of all three case studies, albeit with different impacts, and might potentially require cross-border cooperation to support clean infrastructure on the European hinterland.

6.1.5 Reflections on key industrial decarbonisation technologies

6.1.5.1 Hydrogen adoption

NRW is embracing the prospect of a hydrogen economy, counting on all different processing routes (green, blue etc.) to promote the technology's quickest ramp-up. The State is working towards establishing a regional Hydrogen Valley, covering the entire hydrogen value chain—both to feed recent H-DRI steel developments and as a chemical feedstock. Yet, these plans are not backed up by solid hydrogen generation capacity nor pipeline network. As such, NRW is scoping to retrofit the existing natural gas grid to accommodate hydrogen as well as to expand the existing internal grid with new pipelines. Given that Germany has secured major IPCEI funding for green hydrogen, public investments in infrastructure are expected to follow. However, it is feared that a quick hydrogen ramp-up may lead to higher emissions, especially in the case of grey hydrogen.

Contrary, in the case of ACBC, electrolysis and biogas production combined with CCS has been initiated since 2021, mainly targeting the mobility sector as well as regional and cross-border hydrogen infrastructure projects (i.e., BH2C, and H2Med respectively) that promote green hydrogen applications. The region already faces heightened hydrogen demand to support several industrial processes, including the refinery, fertiliser, and mobility sectors, indicating a more mature market formation. However, a similar risk to NRW remains over a potential increase in emissions, if production is unable to cope with demand, and there is a switch to less clean forms of hydrogen production.

In the case of RHIC, offshore wind installations are expanding rapidly—with the Dutch Government doubling its targets—facilitating hydrogen water electrolysis, while dedicated port terminals have been specified for green hydrogen imports. The region is expecting to host the largest water-electrolysis capacity in Europe, mainly to replace hydrocarbon-based hydrogen in refinery and petrochemical industries. However, rising competition with Germany, given Shell's refinery retrofit to biofuel production in Cologne, might also drive

RHIC's adoption of more green hydrogen operations.

6.1.5.2 CCS

RHIC is leading CCS technology adoption through the mega offshore project Porthos, after several failed attempts but now boosted with national subsidy schemes. However, CCS is perceived as a complementary or even transition technology to other deep decarbonisation technologies, mainly due to rising public opposition.

Although CCS is excluded from German pathways, the country's renewed targets to reach net-zero sooner by 2045 will probably see the role of CCS re-emerging, despite high opposition by the German public opinion. Still CCU in chemical operations is considered a more socially legitimised option. CCS is currently absent from planning in the ACBC, although the region has been considered potentially very relevant due to its geospatial attributes and could prospectively complement biomass-based operations.

6.1.5.3 Circular Economy/Industrial Symbiosis

Both RHIC and ACBC have prior experience with IS activities, while they are also scoped from a H4C perspective. RHIC is also leading a feedstock transition mostly based on biomass and waste re-utilisation to produce sustainable fuels and chemicals, although handling biomass imports may be challenging within the port's limited space. In contrast, ACBC features many unexploited waste streams with high economic value, such as industrial, demolition, and municipal waste. At the same time, however, the cluster has been extensively assessed for IWH re-utilisation and forest-based biomass while it presents a clear CE vision backed up by an emerging R&D academic orientation towards CE-focused innovation technologies that has recently established alliances with local industrial players. Rhine-Ruhr CE activities mainly involve prior synergies between the steel and chemical sectors (Carbon2Chem) and emerging chemical recycling based on plastic waste and biomass streams.

6.2 Entry points for modelling

The empirical findings based on the secondary sources collected and analysed through a socio-technical lens can be combined with primary data collected through stakeholder engagement in the workshops organised by the project as part of WP2 activities. This collective knowledge can then be used to influence model development and use, by providing the necessary socio-technically informed parametisation and/or the creation of socially desirable scenario narratives. Additionally, the qualitative elements identified in this report can be combined with quantitative model results to create holistic storylines for the industrial transition.

Although the modelling process in the TRANSIENCE project will be a long endeavour, also influenced by additional stakeholder engagement activities in the next Phases, in the following sections we have already attempted to identify entry points for our findings in the modelling process. We acknowledge, however, that full integration between socio-technical frameworks and integrated assessment models is generally not considered feasible (Geels et al., 2016).

6.2.1 Technology diffusion

On cooperation and R&D, we essentially observe three different levels of cooperation and power dynamics between the public and the private sector. These are bound to impact both investments, with an efficient private-public cooperation possibly finding it easier to raise funds, and potential uptake of policies, targets, and overall transition direction, with a strong private sector—coupled with a weaker public one—potentially decelerating any transformation pathway. Although such political aspects and R&D investments are usually outside the scope of mitigation modelling frameworks, including MIC3, the diffusion rate of technologies that are not yet commercially available at-scale and which would require private-public R&D support could be influenced by these insights to create more realistic assumptions on their uptake (Koasidis et al., 2023).

This is of particular interest to CCS diffusion assumptions, as our analysis highlighted numerous hindering factors, including public opposition, delayed or cancelled projects, and overall reduced political support. Although the level of diffusion of CCS in mitigation pathways has been challenged (Grant et al., 2022), the role of the technology has always been viewed as a viable and often necessary solution in the industrial sector (Muratori et al., 2017). On top of the perceived risks of delay of CCS that are established in literature (Perdana et al., 2023), our results indicate that even in the industrial sectors some constraints may apply, with the technology appearing as more appropriate for specific applications. These could offer critical insights on the limitations that should be imposed on modelled pathways.

Additionally, we observe different speeds in terms of hydrogen generation with the Basque Country and the Port of Rotterdam already having clear plans for infrastructure expansion that could support a hydrogen economy. In the case of the Basque Country, this also includes successful pilot operations, while in the Port of Rotterdam ambitious investment plans. Still, all regions have ambitious plans and initiatives, hinting at potential competition that could further drive technology costs down as well as improve penetration speeds. All these assumptions could be potentially considered in the TRANSIENCE project's scenario exercises.

6.2.2 Carbon prices

We observed that the impact of carbon taxes to drive the uptake of clean energy technologies may vary across regions. Carbon prices (CPs) are usually an essential driver of most modelling frameworks, but their real-life relevance is often challenged (Sognnaes et al., 2021). Our results can accompany pathways driven by CPs to create narratives on the impact of the mechanism. Also, dedicated European industrial pathways developed by MIC3 could inform the sociotechnical analyses here, to shed light on how to pursue cross-border cooperation, which appears as an essential solution to spatial limitation challenges.

6.2.3 Upscaling of best practices

In both the Port of Rotterdam and the Basque country, we have identified interesting pilot applications of CE practices with a potential to contribute both to emissions reductions and economic gains (e.g., in the form of exploiting waste materials). Modelling the impact of upscaling such practices to the national and European level within MIC3 could offer insights into the true mitigation potential of such options and hence support further implementations of such activities.

6.2.4 Provision of narratives

Based on the collective analysis and the findings of the synthesis, it is evident that the industrial transition needs a diversity of approaches and regional considerations, as one-size-fits-all solutions fail to capture the dynamics, prospects, advantages, and limitations of the regions.

For example, we observed that the Rhine-Ruhr region features a wider range of industrial activities than the other regions and is also faced with strong limitations on accessing cheap renewable energy, as well as CO_2

storage. At the same time, the Port of Rotterdam has much cheaper access to these resources but lacks the R&D initiatives to ramp up innovation diffusion, which are prevalent in the Basque Country, especially in the chemical sector. These observations can accompany model-based pathways to offer qualitative descriptions, as well as provide a first validation of the prescribed technology mixes.

6.3 Concluding Remark

In this report, we aimed to provide a socio-technical lens to the industrial transition of three key industrial clusters, namely the Rhine-Ruhr, the Port of Rotterdam, and the Basque Country. We facilitated three empirical analyses on each cluster, employing combinations of sociotechnical analytical approaches and eliciting second-hand resources with an extensive literature review, to shed light on trends and system dynamics within these clusters, as well as examine the potential for innovation diffusion. While the clusters share some common challenges and potentially synergistic solutions, distinct characteristics seemingly require place-based approaches to shape the direction of the transition and efficiently foster innovations.

There are inherent dynamics that might not be captured in our analysis, either from the selection of these three regions (although they are among the strongest/most prominent clusters in the EU) or from the focus on English literature (considering some useful reports may be in each cluster's language). Still, efforts have been made to ensure that the results can be meaningfully used to inform decision- and policy-making in the three regions of interest to this report, as well as to provide reflections that may be transferable to different contexts. Within TRANSIENCE, the insights gained can be used within the modelling process (see previous section) to provide a more holistic lens to industrial sustainability transitions.

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