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INDUSTRIAL ENERGY TRANSFORMATION AND MULTI-LEVEL GOVERNANCE: EVIDENCE FROM GERMANY

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This paper investigates the energy sector transformation in the German federal state of North Rhine-Westphalia as a process of systemic industrial restructuring within one of Europe's historically most carbon-intensive production regions. Drawing on an integrated analytical framework that combines legislative analysis with comparative empirical case studies, the study examines how climate-neutral transformation ambitions are operationalised in practice at the regional level. The analysis situates contemporary decarbonisation strategies within the long-term economic-historical pathway of the Ruhr industrial complex, characterised by strong path dependencies in fossil-fuel-based infrastructures, spatial industrial clustering, and high energy intensity. The findings demonstrate that energy transition in advanced manufacturing regions unfolds as a multidimensional reconfiguration of technological systems, infrastructure networks and governance arrangements, rather than as a linear substitution of energy carriers. The empirical analysis is based on six industrial transition case studies – Thyssenkrupp Steel tkH_2Steel, Carbon2Chem, STEAG / Iqony HydrOxy Hub Walsum, HyCologne regional hydrogen initiative, LyondellBasell MoReTec, and the Dortmund district heating modernisation – complemented by one municipal modernisation example, namely the renewable electricity procurement and public building decarbonisation strategy of the City of Cologne; together, these cases demonstrate how industrial hydrogen projects, carbon-utilisation initiatives, circular-economy investments, urban heat-system transformation, and public-sector renewable procurement constitute diverse yet interrelated transition pathways addressing heterogeneous emission sources within a regional industrial economy. Industrial process transformation emerges as a central driver of decarbonisation dynamics, yet its feasibility is shown to depend critically on the parallel development of low-carbon energy infrastructures and coordinated regional planning mechanisms. A key contribution of the article lies in highlighting the decisive role of multi-level governance in shaping regional transition trajectories. Federal climate legislation establishes binding regulatory frameworks and market incentives, but their practical implementation is mediated through state-level strategic coordination and municipal investment capacities. North Rhine-Westphalia thus functions as an analytically revealing case in which the effectiveness of vertically integrated climate governance can be assessed under conditions of strong industrial path dependency. Thus, the study contributes to contemporary debates on climate-neutral industrial transformation by demonstrating that decarbonisation in legacy manufacturing regions requires the synchronisation of technological innovation and institutional adaptation as well as socio-economic restructuring. The regional experience analysed here suggests that the long-term success of European energy transition strategies will depend on the capacity to reconcile ambitious emission-reduction targets with industrial competitiveness and labour-market stability. In this sense, North Rhine-Westphalia represents not merely a regional case but a strategic test environment for the future of climate-neutral industrial modernisation in advanced economies. *Key words:* industrial decarbonization, energy transition, climate governance, hydrogen infrastructure, regional energy policy, socio-technical transitions, North Rhine-Westphalia, Germany

Промислова енергетична трансформація та багаторівневе врядування: досвід Німеччини. Білоконь А.О., Алексєєва А.О.

У статті досліджено трансформацію енергетичного сектору німецької федеральної землі Північний Рейн-Вестфалія як процес системної індустріальної реструктуризації в одному з найбільш індустріальних регіонів Європи, де історично підприємства зосереджені на переробці вуглецевої сировини. Спираючись на теоретичну основу, що поєднує законодавчий аналіз і емпіричні кейси, у статті проаналізовано, яким чином на регіональному рівні відбувається перехід до кліматичної нейтральності. Розглянуто сучасні стратегії декарбонізації в довгостроковій економіко-історичній перспективі розвитку індустріального комплексу Рурського регіону, що характеризується розвинутою викопно-паливною інфраструктурою, кластеризацією промисловості та високою енергоємністю.

Отримані результати свідчать, що енергетичний перехід у розвинених індустріальних регіонах відбувається не як лінійна заміна енергоносіїв, а як багатовимірна реконфігурація технологічних систем, інфраструктурних мереж, а також механізмів управління. Емпіричну основу становлять шість кейсів індустріальної трансформації – Thyssenkrupp Steel tkH_2Steel, Carbon2Chem, STEAG / Iqony HydrOxy Hub Walsum, регіональна воднева ініціатива HyCologne, LyondellBasell MoReTec та модернізація систем централізованого теплопостачання у м. Дортмунд – доповнені муніципальним прикладом модернізації, а саме стратегією закупівлі відновлюваної електроенергії та декарбонізації громадських будівель міста Кельн. У сукупності

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ці кейси демонструють, як індустріальні водневі проєкти, ініціативи утилізації вуглецю, інвестиції у циркулярну економіку, трансформація міських теплових систем і публічні закупівлі відновлюваної енергії формують різноманітні, але взаємопов'язані напрямки переходу, спрямовані на різнорідні джерела викидів у межах регіональної промислової економіки.

Трансформація промислових процесів постає ключовим рушієм динаміки декарбонізації, однак її здійсненність критично залежить від паралельного розвитку низьковуглецевої енергетичної інфраструктури та скоординованих механізмів регіонального планування. Важливий внесок статті полягає у висвітленні визначальної ролі багаторівневого врядування у формуванні регіональних напрямків переходу. Федеральне кліматичне законодавство встановлює обов'язкові регуляторні рамки та ринкові стимули, проте їх практична імплементація опосередковується стратегічною координацією на рівні федеральних земель і інвестиційними спроможностями муніципалітетів. У цьому сенсі Північний Рейн-Вестфалія виступає аналітично показовим кейсом, що дозволяє оцінити ефективність вертикально інтегрованого кліматичного врядування в умовах сильної індустріальної залежності від попереднього розвитку.

Дослідження робить внесок у сучасні наукові дискусії щодо кліматично нейтральної індустріальної трансформації, демонструючи, що декарбонізація у регіонах зі «спадковою» промисловою структурою потребує синхронізації технологічних інновацій, інституційної адаптації та соціально-економічної реструктуризації. Проаналізований регіональний досвід свідчить, що довгостроковий успіх європейських стратегій енергетичного переходу залежатиме від здатності поєднати амбітні цілі скорочення викидів із забезпеченням промислової конкурентоспроможності, інфраструктурної стійкості та стабільності ринку праці. У цьому контексті Північний Рейн-Вестфалія постає не лише як регіональний приклад, а як стратегічне «тестове середовище» для майбутнього кліматично нейтральної індустріальної модернізації в розвинених економіках. *Ключові слова:* індустріальна декарбонізація, енергетичний перехід, адаптація до зміни клімату, воднева інфраструктура, регіональна енергетична політика, соціотехнічні трансформації, Північний Рейн-Вестфалія, Німеччина.

Introduction and historical background. North Rhine-Westphalia (NRW) represents the historical core of Germany's fossil-fuel-based industrialisation and continues to constitute one of the most analytically significant regions for examining the structural dynamics of energy transformation in advanced industrial economies. From the late nineteenth century onwards, the Ruhr area evolved into a major integrated coal-and-steel production complex. The geographical concentration of hard-coal resources, the expansion of inland waterway transport along the Rhine and Ruhr rivers, and the rapid development of railway infrastructure enabled the formation of dense, vertically integrated industrial clusters linking mining, metallurgy, heavy engineering, and thermal power generation. This historically embedded industrialization generated persistently high levels of energy intensity and created long-term capital lock-ins in carbon-based infrastructures that continue to shape contemporary development pathways.

Despite several decades of structural adjustment, North Rhine-Westphalia retains a macroeconomically dominant position within the German federal system in terms of both demographic weight [1] and economic output [2]. The regional economy remains strongly influenced by the presence of large-scale manufacturing activities and energy-intensive basic industries. Industrial production therefore continues to play a structurally significant role in regional value creation, reflecting the enduring importance of sectors such as steelmaking, chemicals, machinery production, and associated supply chains.

Energy consumption patterns further illustrate the industrial character of the region. The concentration of process-heat-intensive industries contributes to comparatively high levels of industrial energy demand and reinforces the systemic interdependence between production technologies, infrastructure networks, and regional energy systems. Labour-market structures likewise demonstrate the continued socio-economic relevance of manufacturing, as industrial employment remains an important pillar of regional economic stability and social cohesion.

The long transition from coal-based industrial expansion to a lower-carbon economic structure has therefore not resulted in a fully post-industrial economy but rather in a hybrid industrial system combining advanced manufacturing capabilities with persistent fossil-fuel dependencies. The formal end of hard-coal mining in Germany marked a symbolic turning point in this transformation process; however, the continued operation of carbon-intensive production routes and fossil-based power generation illustrates the structural inertia of legacy energy systems.

From an economic-historical and socio-technical perspective, North Rhine-Westphalia thus represents a paradigmatic case of path-dependent industrial decarbonisation. Long-term capital investments in fossil infrastructures have led to institutional, technological, and labour-market lock-ins that constrain the pace and direction of transformation. Simultaneously, dense industrial clustering, advanced research capacities, and highly developed logistics networks create favourable conditions for innovation-driven restructuring. The energy transition in NRW must therefore be understood as a process of systemic industrial reconfiguration rather than a linear substitution of energy carriers.

In analytical terms, developments in this region extend far beyond the German national context. The capacity of North Rhine-Westphalia to reconcile ambitious climate mitigation targets with the preservation of industrial competitiveness and employment stability will constitute a decisive test case for the broader feasibility of climate-neutral transformation strategies in Europe's traditional manufacturing heartlands.

State of the Art. Recent scholarship has increasingly emphasised that industrial decarbonisation constitutes one of the most complex dimensions of contemporary energy transition processes, requiring the simultaneous transformation of technological systems, market structures, and governance frameworks. New research (Kim, 2024) highlights that achieving climate neutrality in energy-intensive sectors depends not only on fuel switching and electrification but also on systemic innovation across energy, material, and resource-efficiency strategies [3]. Such perspectives move beyond earlier technology-centric approaches by conceptualising industrial transition as a socio-technical restructuring process embedded in specific regional economic contexts. At the same time, the governance literature (Lockwood et al., 2025) has shifted towards analysing policy-mix dynamics and institutional coordination challenges associated with industrial decarbonisation pathways. Recent empirical studies demonstrate that fragmented regulatory frameworks and sequencing problems in climate policy instruments can significantly affect the implementation of decarbonisation investments, particularly in advanced industrial economies [4]. These findings underscore the importance of analysing transition processes through a multi-level governance lens that considers both top-down regulatory coherence and bottom-up regional implementation capacity. Another emerging research strand focuses on spatial and regional dimensions of industrial transition. Contemporary studies (Norris, 2024) emphasise that decarbonisation trajectories are strongly shaped by place-based socio-economic conditions, including industrial heritage, labour-market dependencies, and regional innovation ecosystems [5]. This territorial perspective has gained further prominence as scholars increasingly investigate the role of industrial clusters and dispersed production sites in shaping decarbonisation feasibility and policy design (Rattle, 2024) [6]. More broadly, interdisciplinary research highlights the need to integrate energy-system modelling with industrial transition analysis in order to understand the mutual impacts of electrification and hydrogen deployment as well as infrastructure investment planning. Recent modelling studies (Raillard-Cazanove et al., 2024) indicate that industrial decarbonisation is likely to generate substantial increases in electricity and hydrogen demand, thereby reshaping regional energy markets and investment priorities [7]. These insights reinforce the argument that industrial transformation should be analysed as a systemic process involving technological substitution, infrastructural expansion, and institutional adaptation.

Research Gap. Despite this growing body of scholarship, significant research gaps remain. First, much of the existing literature addresses energy transition either at the macro-policy level or through sector-specific technological studies, while comparatively fewer contributions provide integrated analyses that combine legislative frameworks with detailed empirical investigation of industrial transformation projects. Second, while hydrogen-based decarbonisation and circular-economy innovations have received increasing attention in conceptual debates, there is still limited regionally grounded research examining how these pathways are implemented in historically carbon-intensive industrial territories. Third, the interaction between industrial decarbonisation initiatives and municipal energy governance structures remains insufficiently explored, particularly in large metropolitan manufacturing regions characterised by dense infrastructural interdependencies.

This paper seeks to address these gaps by developing a combined institutional-empirical analytical framework applied to North Rhine-Westphalia, one of Germany's largest industrial federal states. By examining both the legislative architecture of energy transition and a set of strategically selected industrial and urban case studies, the study contributes to a more differentiated understanding of how climate neutrality objectives are operationalised within complex regional production systems. In doing so, it provides new insights into the governance and socio-economic dynamics shaping the feasibility of climate-neutral industrial transformation in advanced economies.

Methodology. This article adopts a qualitative multi-level analytical design in order to examine how energy transition processes are operationalised within a historically carbon-intensive industrial region. The research combines institutional policy analysis with empirically grounded case-study investigation, thereby allowing for the assessment of both regulatory frameworks and their practical implementation in technological and investment decisions. Such an approach is particularly appropriate for the study of energy transition in North Rhine-Westphalia, where structural transformation unfolds through the interaction of federal climate policy and municipal energy governance.

Methodologically, the study proceeds through two complementary steps. First, it undertakes a systematic examination of legislative and policy frameworks at federal, state, and municipal levels. This institutional analysis serves to identify the regulatory incentives, planning instruments, and governance mechanisms that shape the strategic environment for decarbonisation. By analysing binding targets, market-support mechanisms, infrastructure planning obligations, and sector-specific regulatory measures, the study situates regional transformation processes within the broader architecture of Germany's multi-level energy governance system. The legislative context is therefore treated not as descriptive background, but as an analytical dimension that conditions technological trajectories and investment feasibility.

Second, the research employs a comparative qualitative case-study approach in order to explore how these institutional frameworks are translated into concrete transition practices. Case selection followed four criteria: (1) demonstrable technological or policy innovation relevant to decarbonisation, (2) availability of reliable public documentation from industrial, governmental, or research sources, (3) geographical location within North Rhine-Westphalia, and (4) potential analytical transferability to other industrial regions undergoing energy tran-

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sition. On this basis, six principal cases were selected representing key transition domains, including industrial process transformation, hydrogen infrastructure development, circular-economy innovation, urban heat-system restructuring, and municipal energy procurement strategies.

Each case is analysed as a self-contained empirical unit to ensure methodological transparency and facilitate cross-case comparison. The analytical framework applied to all cases includes examination of technological configuration, stakeholder constellations, financing structures, measurable performance indicators, implementation timelines, and risk factors. Particular attention is given to the interaction between industrial investment strategies and regulatory conditions at different governance levels. This structured comparative design enables the identification of recurring patterns and systemic constraints shaping regional decarbonisation trajectories.

The qualitative design prioritises analytical depth and contextual interpretation over statistical generalisation. The selected cases therefore illustrate structurally significant transition pathways rather than providing an exhaustive representation of all decarbonisation initiatives in the region. Moreover, many projects analysed remain in development or early operational phases, meaning that technological performance, cost structures, and emission-reduction impacts may evolve over time. The findings should consequently be understood as a process-oriented assessment of industrial transformation dynamics within a multi-level governance framework.

On this methodological basis, the analysis proceeds first to the examination of the legislative and policy context structuring the institutional environment of the energy transition in North Rhine-Westphalia, and subsequently to the empirical investigation of selected transition projects that demonstrate how regulatory frameworks are translated into practical implementation pathways.

Theoretical and analytical contributions. Building on the identified research gaps, this article makes the following contributions to the literature on industrial energy transformation:

− Conceptualises energy transformation in legacy industrial regions as a process of systemic production restructuring, rather than as a linear substitution of energy technologies, thereby integrating perspectives from socio-technical transition theory and regional political economy.

− Demonstrates empirically how multi-level climate governance frameworks shape industrial decarbonisation pathways, showing that regulatory targets and market instruments are mediated through regionally specific institutional capacities and infrastructural constraints.

− Develops a comparative analytical framework that links legislative policy analysis with project-level empirical evidence, contributing methodological insight into how technological transformation processes can be studied across governance scales.

− Provides new regionally grounded evidence on the interaction between hydrogen innovation, circular material strategies, urban energy systems, and public-sector demand formation, thereby advancing understanding of diversified transition pathways in advanced manufacturing economies.

Legislative and Policy Context

The energy sector transformation in North Rhine-Westphalia unfolds within a dense and multi-layered regulatory environment shaped by federal climate legislation, state-level strategic planning, and municipal implementation instruments. Understanding this institutional configuration is essential for interpreting regional decarbonisation dynamics, as investment decisions in industrial transformation, energy infrastructure, and urban energy systems are strongly conditioned by binding emission targets, market-support mechanisms, and spatial planning obligations. This chapter therefore examines the key legislative frameworks and policy strategies that define the operational parameters of the transition process. By analysing how federal regulatory instruments interact with state-level implementation strategies and local governance practices, the section establishes the institutional context within which the subsequent empirical case studies are situated.

Federal level: binding regulatory frameworks. The institutional architecture of Germany's energy transition is primarily defined at the federal level through a set of interrelated statutory instruments that establish binding targets, market incentives, and planning obligations. These laws collectively structure investment conditions and determine the regulatory environment within which regional and local transition processes unfold.

A central pillar of the regulatory framework is the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG), which governs the expansion of renewable electricity generation through auction systems, grid priority rules, and long-term remuneration mechanisms. Amendments adopted in 2023 significantly strengthened expansion targets for wind and solar energy as part of Germany's strategy to achieve climate neutrality [8]. The Energy Industry Act (Energiewirtschaftsgesetz, EnWG) provides the legal framework for the operation and regulation of electricity and gas networks, including provisions for grid access, infrastructure planning, and market integration of new energy carriers such as hydrogen. Recent legislative reforms have aimed at accelerating grid expansion and facilitating system integration of renewable energy sources [9]. Climate governance is further anchored in the Federal Climate Change Act (Bundes-Klimaschutzgesetz, KSG), which establishes legally binding national greenhouse-gas reduction targets and sectoral emission budgets. The reform adopted in 2024 strengthened long-term climate neutrality targets and adjusted governance mechanisms for monitoring sectoral compliance [10]. In the buildings sector, the Building Energy Act (Gebäudeenergiegesetz, GEG) sets minimum efficiency standards and defines requirements for the gradual integration of renewable heating technologies in new installations and system replacements. The law constitutes a key regulatory instrument for reducing emissions in the residential and public building stock [11]. A major recent addition to the regulatory landscape is the Heat Planning Act (Wärmeplanungsgesetz, WPG) adopted in 2023. This legislation introduces mandatory municipal heat planning obligations, requiring local authorities to assess future heat demand structures and designate preferred supply solutions such as district heating networks or decentralised heat pump systems. By establishing statutory deadlines and planning responsibilities, the law directly influences local investment strategies in heat infrastructure [12]. Complementing these measures, the Combined Heat and Power Act (Kraft-Wärme-Kopplungsgesetz, KWKG) provides targeted financial support for high-efficiency cogeneration installations. CHP technologies are considered an important transitional instrument for improving energy efficiency and reducing emissions in both industrial and urban heat supply systems [13]. Finally, federal spatial planning instruments for renewable deployment have been strengthened through the Wind Energy Area Requirements Act (Windenergie flächenbedarfsgesetz, WindBG). This legislation obliges federal states to allocate legally defined land shares for onshore wind energy development, thereby accelerating permitting procedures and reducing planning uncertainty [14]. Taken together, these federal laws establish a comprehensive regulatory envelope that combines climate targets, market-based support mechanisms, infrastructure planning rules, and sector-specific obligations.

State level: policy adaptation and strategic coordination in North Rhine-Westphalia. Within this federal framework, the Länder play a crucial role in translating national objectives into regionally adapted implementation strategies. North Rhine-Westphalia has articulated its policy approach in the Energy and Heat Strategy NRW (Energie- und Wärmestrategie Nordrhein-Westfalen, 2024), which defines sectoral priorities including renewable expansion, hydrogen deployment, industrial decarbonisation, and district heating modernisation [15]. In addition, the state has introduced legislative initiatives aimed at strengthening social acceptance of renewable infrastructure. The NRW Citizen Energy Act (Bürgerenergiegesetz NRW) seeks to promote financial participation of local communities in wind energy projects, thereby addressing distributional conflicts frequently associated with spatial planning for renewable generation [16]. Parallel strategic initiatives include the development of a regional hydrogen roadmap and import strategy designed to secure long-term supply for energy-intensive industries. These policy instruments reflect the specific structural conditions of NRW as Germany's largest industrial state and aim to align decarbonisation pathways with regional economic resilience objectives.

Municipal level: implementation and investment decisions. At the municipal scale, energy transition policies become operational through spatial planning, procurement strategies, and infrastructure investment decisions. Under the federal Heat Planning Act, municipalities are now legally required to prepare binding local heat plans (Kommunale Wärmeplanung) that define future heat supply pathways and guide public and private investment [17]. In practice, many cities complement statutory planning obligations with broader climate action programmes, including the procurement of renewable electricity for public buildings, the expansion of district heating networks, and incentives for rooftop photovoltaic deployment. These local instruments play a decisive role in translating regulatory frameworks into concrete decarbonisation outcomes.

Findings

The interaction between federal legislation, state-level strategic coordination, and municipal implementation produces a governance system that is legally coherent yet institutionally complex. Successful energy transition projects depend on effective vertical policy alignment, clearly defined financing responsibilities, and sufficient administrative capacity at the local level.

The institutional configuration of the German energy transformation becomes particularly visible in North Rhine-Westphalia because the region concentrates structural conditions that require intensive coordination across governance levels. As Germany's largest industrial Land and a major centre of energy-intensive production, NRW is simultaneously subject to binding federal climate targets, dependent on state-level strategic steering, and reliant on municipal implementation capacities for the practical realisation of infrastructure projects. Federal legislation defines the regulatory envelope through sectoral emission budgets, renewable expansion frameworks, and planning obligations, yet the spatial and economic implications of these rules are negotiated and operationalised at the regional and local scale. In NRW, where industrial decarbonisation, grid expansion, hydrogen deployment, and heat transformation intersect within densely populated metropolitan areas, policy implementation inevitably involves vertical integration of competencies and financial instruments.

This multi-level governance dynamic is further intensified by the region's historical path dependency. The legacy of coal-based industrialisation has produced entrenched infrastructures and socio-economic interests that cannot be transformed solely through national policy directives. Instead, transition processes depend on coordinated action between federal ministries, state governments, municipal utilities, industrial actors, and financial institutions. North Rhine-Westphalia therefore functions as a particularly revealing empirical setting in which the effectiveness of Germany's layered governance architecture can be assessed. The region illustrates how energy transition in advanced industrial economies unfolds as a negotiated restructuring of territorial production systems rather than as a purely technocratic policy exercise.

The examined legislative instruments and policy strategies reveal that the energy transition in North Rhine-Westphalia is embedded in a vertically integrated governance framework that combines binding federal climate targets with regionally differentiated implementation pathways. While national regulations establish long-term decarbonisation objectives and market incentives, their practical realisation depends on state-level strategic coordination and municipal planning capacities. This multi-level institutional configuration creates both opportunities and constraints for industrial and urban transformation processes. In order to assess how these regulatory conditions shape concrete technological choices, investment dynamics, and infrastructural developments, the analysis now turns to a set of empirically grounded case studies from key sectors of the regional economy.

Empirical Case Studies of Industrial and Urban Energy Transformation in North Rhine-Westphalia

The following part presents a series of empirically grounded case studies that illustrate how energy transition policies are operationalised within the industrial and urban context of North Rhine-Westphalia. Each case is structured as a self-contained analytical subsection in order to ensure methodological transparency and facilitate cross-case comparison. The analysis begins with a concise summary of the project's strategic relevance, followed by a systematic examination of its technological configuration, stakeholder constellation, financing arrangements, measurable performance indicators, and implementation trajectory. Particular attention is given to publicly available quantitative evidence on capacity development, emission-reduction potential, and investment scale. The subsections further assess key risk factors and mitigation strategies before concluding with short reflections on policy relevance and the potential transferability of the observed transition pathway to other industrial regions.

Case 1. Thyssenkrupp Steel: tkH_2Steel (Hydrogen-based Direct Reduction Transformation, Duisburg). The tkH_2Steel programme represents one of Europe's most advanced large-scale industrial decarbonisation initiatives, aiming to replace carbon-intensive blast-furnace steel production with hydrogen-based direct-reduction technology integrated with renewable electricity supply chains [18].

A. Context and technical description. Thyssenkrupp Steel Europe is pursuing a phased transformation of its Duisburg production complex centred on the gradual substitution of blast-furnace routes with hydrogen-based direct-reduction (DR) processes. The technological concept involves the production of direct-reduced iron (DRI) using hydrogen as a reducing agent, followed by melting in electrically powered furnaces. This approach is intended to substantially reduce process-related carbon emissions inherent in conventional coke-based steelmaking.

The transformation programme combines three interdependent components. First, the construction of pilot and subsequently commercial-scale direct-reduction plants constitutes the technological core of the transition. Second, the company has initiated procurement procedures for large volumes of low-carbon hydrogen, including a public tender seeking supply contracts of up to approximately 151,000 tonnes annually. Third, the electrification of production processes requires long-term access to renewable electricity, secured in part through power-purchase agreements. In this context, Thyssenkrupp concluded a ten-year electricity supply agreement with RWE covering approximately 112 GWh per year for the first DR installation [19].

B. Stakeholder constellation. The project is led by Thyssenkrupp Steel Europe as owner-operator and strategic investor. Hydrogen supply is expected to be provided through a combination of industrial electrolysis projects in the region and third-party producers participating in long-term supply tenders. Renewable electricity suppliers, notably RWE in the initial phase, constitute a further critical stakeholder group through contractual power-purchase arrangements.

Public authorities at federal and state levels play an enabling role through subsidy programmes, regulatory approvals, and infrastructure planning support. Hydrogen network development initiatives, including regional coordination platforms such as HyCologne, contribute to long-term system integration [20]. Local municipalities and labour representatives are also directly involved, given the project's implications for regional employment structures and urban industrial development trajectories.

C. Financing structure and business model. Financing structure and business model. Public information indicates that the transformation is supported by substantial state aid. There are some challenges German industry faces in meeting emissions targets while staying competitive in a sector that suffers from high energy costs and cheaper products from Asian rivals. Media reporting suggests that federal support commitments may reach several billion euros, although detailed capital structures and financing mixes remain undisclosed [21].

From a commercial perspective, the business model combines long-term electricity procurement contracts, hydrogen supply agreements, and anticipated carbon-cost savings associated with EU emissions trading. However, the company has publicly emphasised that economic viability remains contingent on the availability of competitively priced hydrogen, indicating residual financing risk and the continued relevance of public risk-sharing mechanisms.

D. Measurable outputs and performance indicators. Publicly available project documentation provides several indicative quantitative benchmarks. As of 2024, requirement for 143,000 metric tons of hydrogen is to be covered, signalling the scale of demand [19]. The renewable electricity supply agreement for the first DR facility corresponds to roughly 112 GWh annually. In terms of emissions performance, company statements and independent assessments suggest that full operation with renewable hydrogen could significantly reduce direct process emissions compared with conventional blast-furnace production [22]. Precise lifecycle emission reductions will ultimately depend on the carbon intensity of hydrogen supply and electricity sourcing.

E. Permitting trajectory and implementation milestones. The hydrogen procurement process entered the public tender phase in early 2024. Parallel planning steps include contractual arrangements for electricity supply and the preparation of investment decisions for pilot direct-reduction units. Project timelines remain dependent on regulatory approvals, grid connection procedures, and confirmation of hydrogen supply contracts. Industrial decarbonisation projects of this scale typically involve multi-year permitting processes linked to environmental impact assessments and infrastructure integration requirements.

F. Risk factors and mitigation strategies. The most significant structural risk concerns hydrogen availability and price volatility. Public statements by company leadership indicate that sustained high hydrogen costs could undermine investment feasibility. Mitigation strategies include long-term offtake contracts, participation in European funding programmes such as Important Projects of Common European Interest (IPCEI), and potential regulatory support for electrolysis electricity pricing.

Additional risks relate to delays in hydrogen pipeline deployment and electricity grid expansion. Regional coordination initiatives and phased investment strategies are intended to reduce infrastructure timing mismatches. Social acceptance risks are addressed through engagement with municipal stakeholders and labour representatives, given the project's importance for employment continuity in the Ruhr industrial cluster.

G. Policy relevance and transferability. The tkH_2Steel programme demonstrates that large-scale industrial decarbonisation requires synchronised development of production technologies, renewable electricity supply, hydrogen infrastructure, and public financing instruments. The case illustrates both the opportunities and systemic vulnerabilities associated with first-mover investments in hydrogen-based industrial transformation. For policymakers, the project underscores the importance of coordinated infrastructure planning, stable regulatory frameworks, and targeted subsidy mechanisms to support early industrial adopters while avoiding long-term stranded-asset risks.

Case 2. Carbon2Chem: Industrial Carbon Capture and Utilisation in Integrated Steel Production (Duisburg Region). Carbon2Chem represents one of Europe's most advanced research-to-demonstration programmes exploring the conversion of metallurgical process gases into chemical feedstocks, thereby linking industrial decarbonisation strategies with circular carbon utilisation pathways [23].

A. Context and technical description. The Carbon2Chem initiative was launched as a multi-actor innovation programme aimed at reducing industrial greenhouse-gas emissions through the utilisation of process gases generated in steel production. Integrated steelmaking releases significant volumes of carbon-rich off-gases containing carbon monoxide, carbon dioxide, and hydrogen. Traditionally, these gases are combusted for internal energy recovery. Carbon2Chem explores an alternative technological pathway in which such streams are captured, purified, and converted into chemical intermediates such as methanol or ammonia.

The technological concept combines gas cleaning, catalytic synthesis, and the integration of renewable hydrogen into chemical conversion processes. By transforming emissions into industrial feedstocks, the project seeks to establish circular material loops linking the steel and chemical industries. The programme has evolved through several phases, progressing from laboratory experimentation to pilot-scale demonstration facilities and regional system-integration testing [24].

B. Stakeholder constellation. Carbon2Chem operates as a collaborative research and innovation network coordinated by Thyssenkrupp Steel and involving multiple industrial and scientific partners. Key participants include research institutions such as Fraunhofer UMSICHT and Forschungszentrum Jülich, which contribute expertise in catalysis, process engineering, and systems integration. Chemical industry actors participate as potential off-takers of synthetic feedstocks, while federal research funding bodies provide financial support for pilot development and experimental infrastructure. This multi-actor configuration reflects the systemic character of industrial decarbonisation challenges, which require cross-sectoral cooperation beyond single-firm investment strategies.

C. Financing structure and business model. Publicly available information indicates that the programme is financed through a combination of industrial co-funding and government research grants, particularly from German federal innovation funding schemes. Detailed capital expenditure figures for potential commercial-scale deployment are not publicly disclosed. The emerging business model centres on the valorisation of previously under-utilised industrial gas streams. By producing synthetic chemical feedstocks, the technology could create new revenue streams while simultaneously reducing compliance costs associated with carbon pricing mechanisms. However, commercial viability depends on several uncertain variables, including hydrogen input costs, product market prices, and future regulatory incentives for low-carbon materials.

D. Measurable outputs and performance indicators. Demonstration activities have resulted in pilot installations capable of producing limited quantities of

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synthetic methanol from metallurgical gases, illustrating the technical feasibility of the conversion pathway. Published project materials indicate production at experimental scales ranging from laboratory outputs to small demonstration volumes, with ongoing research focused on scaling potential and process stability [24]. Quantified emission-reduction potentials depend on the extent to which captured gases replace fossil-based chemical feedstocks and on the carbon intensity of supplementary hydrogen supply. Consequently, lifecycle assessments remain project-specific and are still under development.

E. Permitting trajectory and implementation milestones. As a research-driven innovation programme, Carbon2Chem has progressed through staged development phases. Early phases focused on laboratory validation, followed by pilot-scale installations integrated into existing industrial sites. Current project phases concentrate on industrial demonstration and system optimisation. Full commercial deployment would require standard industrial permitting procedures for chemical synthesis facilities, including environmental impact assessments and integration into regional infrastructure systems.

F. Risk factors and mitigation strategies. Key technical risks relate to process scalability and the management of fluctuating gas compositions in metallurgical operations. Mitigation strategies include modular pilot deployment, advanced gas-conditioning technologies, and continuous process monitoring. Economic risks arise from uncertain demand for low-carbon chemical products and volatile hydrogen input costs. These uncertainties may be addressed through long-term offtake agreements, certification schemes for low-carbon materials, and targeted industrial policy support. Regulatory risks concern the evolving classification of carbon-capture-and-utilisation technologies within European climate policy frameworks. Clear standards for lifecycle accounting and product labelling are likely to be critical for large-scale market adoption.

G. Policy relevance and transferability. Carbon2Chem demonstrates the strategic importance of integrating carbon-management solutions into industrial decarbonisation portfolios. Unlike fuel-switching strategies alone, utilisation pathways offer the possibility of maintaining industrial value creation while reducing net emissions. The case illustrates how research-industry consortia can function as innovation incubators for systemic transition technologies. For policymakers, the project highlights the need for sustained public support for pilot infrastructures, cross-sectoral coordination mechanisms, and regulatory clarity regarding the climate benefits of carbon utilisation. The approach may be transferable to other industrial clusters characterised by concentrated emissions sources and proximity to chemical production networks.

Case 3. STEAG / Iqony HydrOxy Hub Walsum: Large-Scale Electrolysis Infrastructure for Industrial Hydrogen Supply (Duisburg-Walsum). The HydrOxy Hub Walsum project represents a strategic attempt to establish large-scale electrolysis capacity within an existing industrial brownfield site, thereby creating regional hydrogen supply infrastructure for energy-intensive industries in the Ruhr area [25].

A. Context and technical description. The planned electrolysis facility at the former Walsum power-generation site reflects a broader shift from fossil-fuel-based energy supply towards integrated hydrogen infrastructures tailored to industrial demand. The project concept envisages the installation of electrolysis units with a potential capacity of up to approximately 500 MW, enabling the production of renewable hydrogen for nearby industrial consumers, including steel and chemical facilities. Technically, the project combines water electrolysis technologies, high-voltage grid connections, hydrogen compression and storage systems, and potential pipeline interfaces linking production sites with industrial offtakers. The reuse of an existing industrial site with established energy infrastructure is intended to reduce permitting complexity and accelerate implementation timelines [26].

B. Stakeholder constellation. The initiative is jointly advanced by energy infrastructure developer Iqony (formerly STEAG Power GmbH) and industrial partners, including Thyssenkrupp Steel as a prospective anchor hydrogen consumer. Technology providers specialising in large-scale electrolysis systems are expected to supply core process components, while transmission system operators and regional network planners are involved in grid integration and potential hydrogen transport solutions. Public authorities at both federal and state levels participate through funding programmes and regulatory oversight, particularly in the context of European Important Projects of Common European Interest (IPCEI) frameworks for hydrogen infrastructure development [27].

C. Financing structure and business model. Publicly available information suggests that the project has sought recognition within European hydrogen funding schemes designed to reduce investment risk for first-of-a-kind infrastructure. While detailed capital expenditure estimates have not been formally disclosed, large-scale electrolysis installations of this magnitude typically involve substantial upfront investment in process equipment, grid connections, and auxiliary systems. The underlying business model is based on long-term hydrogen supply contracts with industrial customers combined with potential revenue streams linked to renewable energy market participation and carbon-pricing incentives. Financial viability therefore depends on stable regulatory frameworks governing hydrogen certification, electricity pricing for electrolysis, and infrastructure cost allocation.

D. Measurable outputs and performance indicators. The projected electrolysis capacity of up to 500 MW would place the Walsum facility among the largest planned hydrogen production sites in Germany. Depending on operational load factors and technological efficiency, such capacity could enable annual hydrogen production in the range of several tens of thousands of tonnes. Precise emission-reduction impacts will depend on the extent to which the hydrogen produced substitutes fossil-based energy carriers in industrial processes and on the carbon intensity of electricity supply used for electrolysis. As the project remains in planning and early development stages, verified operational performance data are not yet available.

E. Permitting trajectory and implementation milestones. Initial feasibility studies and cooperation agreements were publicly announced in the early 2020s. Progression to construction phases is contingent upon successful funding approvals, grid-connection planning, environmental permitting procedures, and confirmation of long-term hydrogen demand commitments. Projects of comparable scale typically require multi-year planning horizons, reflecting the complexity of integrating new energy infrastructures into existing industrial systems.

F. Risk factors and mitigation strategies. A primary risk concerns the availability of competitively priced renewable electricity, which constitutes the dominant operational cost component of hydrogen production. Potential mitigation strategies include long-term power-purchase agreements and policy instruments aimed at reducing electricity levies for electrolysis. Infrastructure synchronisation risks are also significant. Delays in hydrogen transport network deployment could constrain the effective utilisation of production capacity. Regional coordination initiatives and phased capacity expansion strategies are therefore critical to reducing systemic bottlenecks. Regulatory uncertainty regarding hydrogen market design, certification standards, and state-aid frameworks represents an additional challenge for investment planning.

G. Policy relevance and transferability. The Walsum electrolysis hub illustrates the infrastructural dimension of industrial decarbonisation, demonstrating that technological transformation within production processes must be accompanied by parallel development of low-carbon energy supply systems. The project highlights the importance of spatial clustering between hydrogen production and industrial demand as a strategy for reducing transport costs and accelerating market formation. From a policy perspective, the case underscores the need for coordinated planning of electricity grids, hydrogen pipelines, and industrial investment incentives. Similar brownfield-based hydrogen hub concepts may be transferable to other legacy industrial regions seeking to combine decarbonisation objectives with economic restructuring.

Case 4. HyCologne: Regional Hydrogen Cluster and Infrastructure Coordination in the Rhineland. HyCologne represents a regional coordination platform designed to aggregate industrial hydrogen demand, facilitate infrastructure planning, and support the phased development of a metropolitan hydrogen economy in the Cologne–Rhineland industrial corridor [28].

A. Context and technical description. The HyCologne initiative (Wasserstoff Region Rheinland e.V.) was established as a multi-stakeholder association aiming to accelerate hydrogen deployment in one of Germany's most industrialised metropolitan regions. The project operates primarily at the level of strategic system integration rather than technological demonstration. Its core objective is to align hydrogen production projects, transport infrastructure planning, industrial demand aggregation, and municipal energy strategies within a coherent regional framework. Feasibility studies undertaken within the initiative, ncluding the Hydrogen Rhineland (H2R) concept, have mapped potential pipeline corridors, identified industrial demand centres, and proposed phased infrastructure expansion scenarios. These planning exercises are intended to reduce coordination failures that could otherwise arise from fragmented project development across administrative and corporate boundaries [28].

B. Stakeholder constellation. HyCologne functions as a network organisation bringing together industrial firms, municipal authorities, energy utilities, infrastructure operators, and research institutions. Member organisations include major industrial energy consumers, regional utilities, transport providers, and local governments seeking to integrate hydrogen solutions into climate action strategies. This governance structure reflects the recognition that hydrogen market formation requires collective action mechanisms beyond individual investment decisions. The initiative therefore acts as a platform for information exchange, joint project development, and coordinated funding applications within national and European support programmes.

C. Financing structure and business model. As a coordination and planning initiative, HyCologne does not itself operate hydrogen production assets. Instead, its activities are financed through a combination of membership contributions, public funding for regional development projects, and participation in feasibility studies supported by federal and EU innovation programmes. The underlying economic rationale is to reduce transaction costs for infrastructure deployment by creating predictable demand signals and shared planning frameworks. By aggregating industrial consumption forecasts and aligning project timelines, the initiative aims to enhance investment security for private developers of hydrogen production and transport infrastructure.

D. Measurable outputs and performance indicators. HyCologne's outputs are primarily strategic and organisational rather than technological. These include stakeholder network expansion, the development of regional hydrogen roadmaps, and the identification of priority infrastructure corridors. Public documentation indicates that the initiative has compiled a portfolio of numerous proposed hydrogen-related projects across

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the Rhineland region, reflecting growing industrial engagement with hydrogen transition pathways [29]. Quantitative emission-reduction impacts depend on the implementation of individual infrastructure and industrial projects facilitated by the coordination platform.

E. Permitting trajectory and implementation milestones. Since its establishment, HyCologne has focused on preparatory activities including feasibility analyses, stakeholder consultations, and strategic concept development. The transition from planning to implementation is contingent upon funding approvals, regulatory clarity regarding hydrogen network operation, and investment decisions by participating firms. Infrastructure deployment timelines will therefore vary according to project-specific permitting procedures and market conditions.

F. Risk factors and mitigation strategies. A principal risk associated with regional hydrogen initiatives concerns coordination complexity. Divergent investment timelines among industrial actors and infrastructure developers may lead to mismatches between supply availability and demand uptake. HyCologne addresses this risk through continuous stakeholder engagement and the development of shared planning scenarios. Regulatory uncertainty regarding hydrogen transport regulation and market design also represents a constraint. Active engagement with federal policy processes and participation in funding consortia are intended to improve institutional predictability.

G. Policy relevance and transferability. HyCologne demonstrates the importance of governance innovation in energy transition processes. While technological solutions such as electrolysis or hydrogen-based production routes attract significant attention, their large-scale deployment depends equally on regional coordination mechanisms capable of aligning infrastructure development with industrial restructuring strategies. The initiative offers a transferable model for other metropolitan industrial regions seeking to organise hydrogen transition pathways through collaborative planning platforms. It highlights that decarbonisation in complex industrial territories is not solely a matter of technological substitution but also of institutional capacity-building and spatial governance integration.

Case 5. LyondellBasell MoReTec: Industrial-Scale Chemical Recycling and Circular Feedstock Integration (Wesseling). The MoReTec project represents one of the first industrial-scale advanced chemical recycling investments in Germany, aiming to convert mixed plastic waste into secondary petrochemical feedstocks and thereby reduce lifecycle emissions in polymer production [30].

A. Context and technical description. The Wesseling facility forms part of LyondellBasell's broader strategy to integrate circular-economy technologies into existing petrochemical value chains. The MoReTec process is based on catalytic pyrolysis techniques that thermochemically convert mixed plastic waste streams into hydrocarbon feedstocks suitable for further processing in steam crackers and polymer production units.

This technological pathway differs from mechanical recycling approaches by enabling the treatment of contaminated or heterogeneous waste fractions that are otherwise difficult to recycle. By reinserting recovered feedstock into primary production processes, the project seeks to reduce dependence on virgin fossil raw materials and contribute to emissions reductions along the lifecycle of plastic products. The plant is being constructed within an established chemical cluster, allowing direct integration into existing industrial infrastructure and logistics systems [31].

B. Stakeholder constellation. LyondellBasell acts as project developer, investor, and future operator of the facility. Local and regional authorities are involved through permitting procedures and site-development coordination. Waste-management companies constitute important upstream partners by supplying plastic feedstock streams, while downstream integration occurs within the company's own polymer production networks and potentially through external chemical industry customers. The project also reflects broader policy interactions with European circular-economy legislation and regulatory pressures concerning recycled content quotas in packaging markets.

C. Financing structure and business model. Public disclosures describe the facility as a strategic industrial investment; however, detailed capital expenditure figures have not been formally published. The business model is based on the production of chemically recycled feedstock that can be marketed as lower-carbon or circular input material within polymer value chains. Revenue prospects are therefore linked to regulatory drivers such as recycled-content mandates, consumer demand for sustainable materials, and potential price advantages associated with carbon-pricing mechanisms. Integration within an existing petrochemical site reduces marginal infrastructure costs and improves logistical efficiency.

D. Measurable outputs and performance indicators. According to company statements, the Wesseling plant is designed for a processing capacity of approximately 50,000 tonnes of plastic waste per year, positioning it among the largest advanced recycling facilities currently under development in Europe [30]. Lifecycle emission-reduction potential depends on the degree to which recycled feedstock substitutes fossil inputs and on energy consumption within the pyrolysis process. Quantified emission savings are therefore contingent on detailed lifecycle assessments that remain under evaluation.

E. Permitting trajectory and implementation milestones. The project entered the construction phase following the laying of the foundation stone in September 2024. Commissioning is anticipated around the mid-2020s, subject to completion of construction works, technical integration into existing production systems, and regulatory compliance verification. Industrial chemical recycling installations are typically subject to stringent environmental permitting procedures, including emissions monitoring requirements and safety assessments.

F. Risk factors and mitigation strategies. A central operational risk concerns the availability and quality consistency of plastic waste feedstock. Long-term supply agreements with waste-management partners and improvements in sorting technologies constitute important mitigation measures. Regulatory and societal scrutiny regarding the environmental performance of chemical recycling technologies represents another challenge. Transparent lifecycle assessments, compliance with emissions standards, and credible certification schemes are therefore essential for maintaining public legitimacy and market acceptance.

Market risks are linked to price volatility in petrochemical feedstocks and uncertain demand for circular materials, particularly during early stages of market formation.

G. Policy relevance and transferability. The MoReTec project illustrates how circular-economy strategies can complement energy-focused decarbonisation policies by addressing emissions embedded in material production cycles. It demonstrates the potential for integrating waste management and petrochemical industries within regional industrial transition frameworks. For policymakers, the case highlights the importance of regulatory clarity regarding the classification and certification of chemically recycled products, as well as the role of innovation funding in enabling industrial deployment of emerging circular technologies. Similar investments may be transferable to other petrochemical clusters seeking to reduce carbon intensity while maintaining production capacity.

Case 6. Dortmund District Heating Transformation: Industrial Waste-Heat Integration and Urban Heat Network Modernisation. The Dortmund district heating modernisation project illustrates how surplus industrial process heat can be integrated into municipal heat supply systems, thereby reducing fossil fuel consumption and contributing to urban decarbonisation [32].

A. Context and technical description. The transformation of the district heating system in Dortmund represents a systemic intervention at the interface between industrial production and urban energy provision. The project centred on the utilisation of surplus process heat generated by industrial operations at the carbon black manufacturer KG Deutsche Gasrußwerke (DGW). Technically, the initiative involved the installation of condensers and heat-exchange infrastructure capable of capturing previously unused thermal energy from industrial exhaust streams. The recovered heat was then integrated into a modernised hot-water district heating network operated by the municipal utility DEW21. This transition from a steam-based system to a lower-temperature hot-water network improved overall energy efficiency and enabled the substitution of natural gas previously used for heat generation [32].

B. Stakeholder constellation. The project was implemented through cooperation between the industrial heat supplier DGW, the municipal energy utility DEW21, and the City of Dortmund as planning authority. Financial support was provided through programmes administered by the German development bank KfW, reflecting the role of public financing institutions in facilitating energy-efficiency investments. This stakeholder configuration demonstrates the importance of cross-sectoral collaboration in urban energy transition processes, particularly where industrial infrastructure can be leveraged for municipal decarbonisation objectives.

C. Financing structure and business model. Public information indicates that the industrial partner invested approximately €5.3 million in the installation of condensers and related integration technologies. A portion of these investments was supported through KfW funding schemes designed to promote energy efficiency and climate mitigation projects [32]. From a business perspective, the project enables the monetisation of surplus industrial heat that would otherwise be dissipated. The municipal utility benefits from reduced fuel procurement costs and improved system efficiency, while industrial partners gain additional revenue streams and enhanced environmental performance.

D. Measurable outputs and performance indicators. Project documentation reports an estimated annual reduction of approximately 45,000 tonnes of CO_2 emissions associated with the modernised district heating system. These reductions result primarily from decreased reliance on fossil gas for urban heat generation [32]. Additional performance improvements include enhanced network efficiency and the long-term stabilisation of heat supply costs for connected buildings.

E. Permitting trajectory and implementation milestones. The modernisation process involved phased planning and infrastructure upgrades over several years, including industrial-site modifications, network retrofitting, and customer-side adaptations. Environmental permitting procedures were required for the installation of heat-recovery equipment and network conversion measures.. Such urban heat transformation projects typically proceed incrementally in order to maintain supply reliability and manage capital expenditure constraints.

F. Risk factors and mitigation strategies. Operational risks include dependence on the continuity of industrial heat supply. Contractual arrangements and the maintenance of auxiliary heat-generation capacity provide safeguards against potential disruptions. Technical integration challenges arise from the conversion of legacy steam networks to modern hot-water systems, necessitating coordinated engineering solutions and stakeholder communication strategies.

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Financial risks are mitigated through public funding instruments and the long-term cost savings associated with improved system efficiency.

G. Policy relevance and transferability. The Dortmund case demonstrates the strategic importance of integrating industrial waste heat into urban energy planning frameworks. Such approaches offer comparatively cost-effective decarbonisation opportunities, particularly in regions characterised by dense industrial-urban spatial interdependencies. For policymakers, the project underscores the need for supportive regulatory frameworks that facilitate heat-network modernisation, as well as targeted financial instruments to overcome initial investment barriers. Similar models may be transferable to other industrial cities where surplus process heat remains underutilised.

Municipal Example. City of Cologne: Renewable Electricity Procurement and Public Building Decarbonisation. The City of Cologne's large-scale procurement of renewable electricity for municipal buildings illustrates how public-sector purchasing strategies can deliver immediate operational emission reductions while supporting the expansion of renewable energy markets [33].

A. Context and technical description. Municipal governments in Germany play an important role in climate policy implementation through the management of public infrastructure portfolios, including administrative buildings, schools, cultural institutions, and social facilities. The City of Cologne has pursued a procurement strategy aimed at sourcing renewable electricity for a substantial share of its municipal property stock. The supply contract concluded with the energy provider LichtBlick covers approximately 120 million kilowatt-hours of electricity annually, delivered to around 2,800 municipal buildings. This measure complements broader local climate action initiatives, including building energy-efficiency retrofits and the deployment of rooftop photovoltaic installations [33].

B. Stakeholder constellation. The procurement initiative is led by the municipal administration as contracting authority. The renewable electricity supplier assumes responsibility for energy delivery and certification, while municipal facility managers oversee implementation within individual buildings. Additional stakeholders include the municipal utility RheinEnergie and local climate governance bodies involved in coordinating long-term decarbonisation strategies. The initiative thus reflects the interaction between public procurement practices and broader urban energy planning processes.

C. Financing structure and business model. Financial details of the electricity supply contract have not been publicly disclosed. However, long-term procurement arrangements are typically designed to provide price stability for municipal budgets while enabling suppliers to secure predictable demand for renewable generation assets. The economic rationale is therefore twofold: reducing operational emissions associated with electricity consumption and mitigating exposure to volatility in wholesale electricity markets.

D. Measurable outputs and performance indicators. The annual supply volume of approximately 120 GWh corresponds to a significant share of municipal electricity demand. By substituting conventional grid electricity with certified renewable sources, the city effectively reduces scope-2 emissions linked to public building operations. The precise magnitude of emission reductions depends on the carbon intensity of the displaced electricity mix and certification methodologies applied.

E. Permitting trajectory and implementation milestones. The procurement strategy was implemented through standard municipal contracting procedures rather than infrastructure permitting processes. Supply arrangements commenced in the early 2020s and form part of Cologne's longer-term climate mitigation planning framework. Future milestones include potential contract extensions, expansion of on-site renewable generation capacity, and continued building-modernisation programmes.

F. Risk factors and mitigation strategies. Potential risks relate to supplier continuity and market-price fluctuations over the contract duration. These risks are typically mitigated through multi-year contractual frameworks and diversification of procurement strategies. Debates concerning the additionality of renewable electricity sourcing also represent a reputational consideration for municipal authorities. Transparent certification mechanisms and the integration of procurement with local generation projects can enhance policy credibility.

G. Policy relevance and transferability. The Cologne example demonstrates that municipalities can act as influential market actors in the energy transition by leveraging their purchasing power to stimulate demand for renewable electricity. Such procurement strategies offer comparatively rapid emission-reduction opportunities, particularly when combined with building-efficiency improvements and decentralised generation initiatives. From a policy perspective, the case highlights the importance of aligning public-sector procurement rules with climate objectives and supporting local administrative capacity to manage complex energy contracts. The approach is readily transferable to other cities seeking cost-effective pathways to reduce operational emissions.

Findings

The six empirical cases analysed in this study reveal that the energy sector transformation in North Rhine-Westphalia does not follow a single technological trajectory but rather unfolds as a multi-dimensional restructuring of an historically carbon-intensive industrial system. The cases demonstrate that decarbonisation processes in advanced manufacturing regions are characterised by the simultaneous transformation of production technologies, energy supply infrastructures, material cycles, urban energy systems, and governance mechanisms.

A first cross-cutting observation concerns the centrality of industrial process transformation as a driver of regional transition dynamics. Projects such as tkH_2Steel indicate that deep emission reductions in heavy industry require fundamental changes in production routes rather than incremental efficiency improvements. The shift towards hydrogen-based direct reduction exemplifies a systemic technological substitution that affects not only plant-level operations but also upstream energy supply chains and regional infrastructure planning. At the same time, the Carbon2Chem initiative demonstrates that decarbonisation strategies increasingly extend beyond fuel substitution to include carbon-management approaches, integrating capture and utilisation pathways into industrial value creation processes. This diversification of technological options reflects the structural complexity of emissions sources in integrated industrial clusters.

A second pattern emerging from the comparative analysis relates to the infrastructural preconditions of industrial decarbonisation. The planned electrolysis hub at Duisburg-Walsum highlights that low-carbon industrial production is contingent upon the development of new energy supply systems, particularly hydrogen generation capacity and associated transport networks. In parallel, the HyCologne initiative illustrates that infrastructure deployment requires institutional coordination mechanisms capable of aligning investment decisions across multiple actors and administrative jurisdictions. These cases underscore that technological feasibility alone is insufficient; the timing and spatial configuration of infrastructure development constitute critical determinants of transition success.

Third, the cases reveal the growing importance of material-efficiency and circular-economy strategies within regional decarbonisation portfolios. The MoReTec chemical recycling project demonstrates that emission reductions in industrial regions are not limited to energy systems but also involve the restructuring of raw-material cycles. By integrating waste streams into petrochemical production processes, such initiatives address lifecycle emissions embedded in industrial consumption patterns. This suggests that energy transition policies increasingly intersect with broader industrial transformation agendas encompassing resource efficiency, product regulation, and innovation policy.

A fourth analytical dimension concerns the interaction between industrial production and urban energy systems. The Dortmund district heating project illustrates how surplus industrial heat can be mobilised as a strategic asset for municipal decarbonisation. This case exemplifies the spatial interdependence of industrial and urban infrastructures in legacy manufacturing regions. Rather than treating cities and industrial sites as separate transition arenas, the evidence indicates that effective emission reduction strategies often rely on cross-sectoral integration and cooperative governance arrangements.

Finally, the municipal procurement strategy of the City of Cologne highlights the role of public-sector demand aggregation as a catalyst for market transformation. While technologically less complex than industrial conversion projects, such measures can generate immediate emission reductions and provide stable demand signals for renewable energy expansion. This demonstrates that energy transition processes operate simultaneously at multiple scales, from high-capital industrial investments to comparatively low-cost administrative interventions.

Taken together, the cases suggest that the energy sector transformation in North Rhine-Westphalia is best conceptualised as a systemic reconfiguration of an industrial energy regime shaped by historical path dependencies. The coexistence of hydrogen innovation, circular material strategies, infrastructure coordination platforms, and municipal policy instruments reflects the need for diversified transition pathways capable of addressing heterogeneous emission sources.

From a governance perspective, the comparative evidence confirms that successful decarbonisation in industrialised regions depends on vertical policy alignment and horizontal actor coordination. Federal regulatory frameworks establish long-term climate targets and market incentives, but their practical implementation is mediated through regional industrial structures and municipal investment capacities. The NRW cases therefore illustrate the operational realities of multi-level energy governance in a context where economic competitiveness and climate mitigation objectives must be pursued simultaneously.

The findings contribute to ongoing debates on the feasibility of climate-neutral industrial transformation in Europe's traditional manufacturing heartlands. The regional experience suggests that decarbonisation is not a linear process of technological substitution, but rather a broader restructuring of production systems that involves infrastructural investment, institutional change, and socio-economic adaptation.

Conclusion. This study has examined the energy sector transformation in North Rhine-Westphalia as a process of structural transformation unfolding within one of Europe's most historically carbon-intensive industrial regions. By combining institutional policy analysis with empirically grounded case studies, the article has demonstrated that decarbonisation in advanced manufacturing territories cannot be understood as a simple technological substitution of energy carriers. Rather, it represents a complex and negotiated reconfiguration of production systems shaped by long-term industrial path dependencies, infrastructural lock-ins, and multi-level governance arrangements.

The legislative analysis shows that Germany's energy transition is structured through a dense regulatory architecture that establishes binding climate targets, market incentives, and spatial planning obligations. Yet the empirical evidence from North Rhine-Westphalia indi-

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cates that the practical effectiveness of these frameworks depends on their translation into regionally adapted implementation strategies. Industrial decarbonisation initiatives such as hydrogen-based steel production, carbon-utilisation technologies, and large-scale electrolysis infrastructure reveal the scale of investment and coordination required to transform energy-intensive production clusters. At the same time, circular-economy innovation, urban heat-network modernisation, and municipal renewable procurement strategies demonstrate that systemic transition processes extend beyond industrial core sectors into broader territorial energy systems.

A key contribution of the article lies in highlighting the interdependence between technological innovation and institutional capacity. The analysed cases show that the success of industrial transformation pathways is contingent not only on engineering feasibility but also on the synchronisation of infrastructure development, regulatory stability, financing instruments, and stakeholder cooperation across governance levels. North Rhine-Westphalia therefore provides an analytically revealing setting in which the operational realities of multi-level climate governance become visible. The region illustrates how federal policy objectives are mediated through state-level strategic coordination and implementation at the municipal level, producing differentiated transition trajectories within a common regulatory framework.

From a wider European perspective, the findings underscore the strategic importance of regional industrial policy in achieving climate neutrality. Traditional manufacturing heartlands across the continent face similar challenges related to capital-intensive production assets, workforce transition, and spatial concentration of emissions. The experience of North Rhine-Westphalia suggests that effective decarbonisation strategies must combine long-term public support for first-mover investments with mechanisms that maintain industrial competitiveness and social stability. Energy sector transformation in such contexts is therefore best conceptualised as a socio-economic restructuring process rather than solely an environmental policy agenda.

At the same time, the analysis points to several unresolved uncertainties. The economic viability of hydrogen-based industrial production, the scalability of carbon-utilisation technologies, and the long-term performance of circular material strategies remain contingent on evolving market conditions and regulatory developments. Moreover, the success of municipal and regional transition initiatives depends on administrative capacity and financial resources that may vary significantly across territories. These dynamics highlight the need for continued empirical monitoring and comparative research on industrial decarbonisation pathways.

Future research could therefore extend the analytical framework developed in this study by examining cross-regional learning processes within the European Union, assessing the distributional implications of industrial climate policies, and investigating the interaction between technological innovation and labour-market restructuring. Such perspectives are essential for understanding how climate neutrality can be reconciled with economic resilience in industrialised societies.

The North Rhine-Westphalia emerges from this analysis not merely as a regional case study but as a critical testing ground for the broader feasibility of climate-neutral industrial transformation in advanced economies. The region's experience demonstrates that the energy sector transformation is ultimately a question of systemic governance, coordinated investment, and institutional adaptability, factors that will determine whether ambitious climate targets can be translated into durable socio-economic transformation.

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