Industrial Symbiosis² Hubs 4 Circularity

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Author(s):	**KPMG** (Céu Carvalho, Olívia Rocha, Vasco Barros, Inês Gomes)
Reviewer(s):	**UT** (Devrim Yazan and Elif Erdinc-Arca), **TEC** (José Ignacio Barbero), **ZLC** (Alicia Martínez, Beatriz Royo and Sara Sánchez), **TUDO** (Michael Kohlgrüber and Mathias Cuypers), **HUB Leaders** (Bram Reinders (**ALMELO**), Stijn Stoffels (**SOLENCO**), Danny van den Heuvel (**H2HT**), Thomas Bayer (**IH**), Furkan Ergenç (**TUPRAS**), İpek Harmanlı (**TUPRAS**), Betül Sena Süzen (**TUPRAS**), Juan Pedrero Alegria (**TEC**))
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Abstract

The Deliverable *D6.1 - Report on HUB Starting Lines* lays the groundwork for transforming selected industrial zones into HUBs for Circularity (H4C) as part of the **IS2H4C** project. By applying principles of industrial symbiosis (IS) and deploying innovative technologies, the project aims to improve resource efficiency, boost the uptake of renewable energy, and minimise waste generation, while promoting integration with surrounding urban and rural ecosystems.

This report presents comprehensive baseline assessments for the four key HUBs of the project, located in Turkey, Spain, the Netherlands, and Germany. Each HUB is defined by its distinct industrial profile, existing infrastructure, and strategic initiatives aligned with circular economy principles. In Turkey, the Izmir-Manisa HUB is focused on producing e-methanol and non-isocyanate polyurethane (NIPU) using green Hydrogen (H_2) and captured Carbon Dioxide (CO_2) from oil refining processes. The Basque HUB in Spain targets decarbonisation of key sectors—steel, cement, lime, oil refining, and pulp and paper—through synergies involving H_2 and CO_2 utilisation. The Dutch HUB prioritises decentralised H_2 production and energy storage to establish a positive energy district. Meanwhile, Germany's Industriepark Höchst HUB seeks to demonstrate integrated CO_2 capture and utilisation technologies alongside circular energy systems.

The report details each HUB's starting points, technological pathways, including energy consumption and emissions data. It also outlines specific requirements for technology deployment, success metrics for evaluation, and anticipated challenges. A preliminary framework for evaluating the success of the project has been developed, with a particular emphasis on technological uptake, strategic sustainability, and operational feasibility. This framework applies predefined metrics to assess the performance of implemented solutions and their alignment with overarching project objectives. Key risks—such as data reliability, financial viability, market maturity, and stakeholder engagement—have been identified, and proactive mitigation strategies are embedded to address them effectively. The anticipated outcomes include enhanced environmental performance, increased cost efficiency, job creation, and strengthened collaboration across the industrial value chain. Scalability and transferability considerations are also integrated, paving the way for broader replication and uptake of successful solutions in other regions.

To support this analysis, the report is structured across six chapters. **Chapter 1 – Introduction** provides the background, objectives of Work Package (WP) 6, and outlines the scope of the deliverable. **Chapter 2 – Methodology** details the data collection process, the framework for defining techno-economic parameters, and the criteria for evaluating success. **Chapter 3 – Overview of HUBs for Circularity** introduces the H4C concept, emphasising industrial symbiosis and circularity through global examples. **Chapter 4 – Strategic Overview of IS2H4C HUBs** presents the current state of the four HUBs, including technological routes and visual flow diagrams. **Chapter 5 – Validation of Success and Impact** focuses on the assessment framework, associated risks, and the expected environmental, economic, and social benefits. Finally, **Chapter 6 – Conclusions** synthesises the key findings and proposes strategic recommendations and next steps to facilitate circular transformation, scalability, and continuous improvement throughout the **IS2H4C** project.

The report outlines the initial conditions of each HUB, which differ significantly in terms of technology adoption, energy consumption, and emission profiles—providing a robust baseline for defining the current state-of-the-art and validating the progress and impact of each project HUB.

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List of Abbreviations

ACM	Authority for Consumers and Markets
CC	Carbon Capture
CCU	Carbon Capture and Utilisation
CEAP	Circular Economy Action Plan
CFD	Computational Fluid Dynamics
CH_4	Methane
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CoP	Community of Practice
D	Deliverable
DoA	Description of Action
EAF	Electric Arc Furnace
EMS	Energy Management System
GA	Grant Agreement
GHG	Greenhouse Gas
H_2	Hydrogen
H4C	HUBs for Circularity
HAZID	Hazard Identification
HAZOP	Hazard and Operability
IoT	Internet of Things
IS	Industrial Symbiosis
IS2H4C	From Industrial Symbiosis to HUBs for Circularity
IURS	Industrial-Urban-Rural Symbiosis
KPI	Key Performance Indicator
NIPU	Non-Isocyanate Polyurethane
O_2	Oxygen
PCP	Public-Civil Society Partnerships
PPP	Public-Private Partnerships
PtC	Power-to-Chemicals
PtG	Power-to-Gas
PtL	Power-to-Liquid
PtX	Power-to-X
PV	Photovoltaic
SME	Small and Medium-Sized Enterprise
SNG	Synthetic Natural Gas
tCO_2-eq	Tons of Carbon dioxide equivalent
Tpd	Tons per day
TRL	Technology Readiness Level
WP	Work Package

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1. Introduction

1.1. Background and Context

The "From Industrial Symbiosis to HUBs for Circularity: **IS2H4C**" project is a transformative initiative aimed at fostering sustainable regional development through the creation of H4C. These HUBs are designed to address the challenges of resource efficiency, renewable energy adoption, and waste minimisation within industrial zones while ensuring the integration of surrounding urban and rural ecosystems. By leveraging innovative sustainable technologies, **IS2H4C** promotes the reuse and recycling of waste streams and introduces systemic infrastructure enhancements to achieve a net-zero circular economy. Crucially, the project emphasises societal engagement, ensuring transparency, inclusion, and trust among citizens while respecting planetary health boundaries.

The project employs a holistic methodology encompassing four interconnected phases: **technology development, sustainability assessment, deployment**, and **outreach**. Demonstrating its principles in HUBs across Turkey, Spain, the Netherlands, and Germany, **IS2H4C** integrates cutting-edge solutions such as green H_2 production, carbon capture (CC), and waste heat recovery. A pivotal component is the digital collaboration platform "DigitalH4C", which facilitates resource monitoring, matchmaking for symbiosis opportunities, and secure information exchange. These initiatives are supported by tailored financial models and societal innovation strategies to ensure broad acceptance and long-term viability.

IS2H4C's relevance today lies in its alignment with the EU Green Deal and global sustainability goals, addressing critical environmental challenges such as climate change and resource scarcity. By transforming IS into scalable and replicable H4C models, the project paves the way for a resilient, circular economy that balances economic growth, environmental stewardship, and social wellbeing.

1.2. Objectives of the Work Package

This document is part of **Work Package (WP) 6 - Integration and Demonstration in HUBs**, which is focused on the practical deployment and integration of the pre-selected technologies within the designated industrial HUBs. The primary objective of WP6 is to transform these industrial zones into H4C by applying the technologies in real-world operational environments. This transformation will be guided by the principles of circularity and IS, ensuring that both existing and new infrastructures are effectively integrated. WP6 plays a crucial role in the overall project, as it is where the **real-world impact of the project's efforts will be observed and measured**.

The deliverable is aligned with Task 6.1, which is dedicated to **defining the current state-of-the-art and validating success**. Since each of the four HUBs involved in the project has unique starting points for their transformation into H4C, it is essential to establish a clear techno-economic baseline. This baseline will serve as a benchmark for all subsequent efforts to achieve the project's targets. Task 6.1 is divided into three key components: 1) an executive summary outlining the HUBs' initial conditions in terms of technology, CO_2 emissions, and energy consumption, which will serve as a foundation for upcoming tasks; 2) a definition of the industrial plants' requirements for technology implementation, based on the initial report; and 3) an outlook on the success of each implemented measure, providing the present dissemination report with defined success criteria for all tasks.

1.3. Scope of the Report

This deliverable focuses on addressing the objectives outlined in Task 6.1, emphasising the integration and demonstration of circularity principles and IS within industrial HUBs. By providing a comprehensive assessment of the current state-of-the-art and defining the technological baseline, the report establishes the foundation for the transformation of these HUBs into H4C. It highlights the unique starting conditions of the participating HUBs, evaluates their existing infrastructures, and identifies specific requirements for implementing selected technologies. The report also sets forth criteria for evaluating the success of these measures, ensuring alignment with the overarching goals of WP6 and the broader project.

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2. Methodology

The methodology adopted in this report ensures a systematic and structured approach to evaluating the current state of industrial HUBs and their transformation into HUBs for Circularity. By combining qualitative and quantitative methods, the analysis captures the unique characteristics of each HUB, identifies the potential for implementing circularity and IS principles, and assesses the feasibility and impact of proposed interventions.

The following sections outline the core components of the methodology: data collection and analysis, the framework for baseline techno-economic parameters, and the definition of success criteria.

2.1. Data Collection and Analysis

A structured data collection process was implemented to establish a comprehensive understanding of the baseline conditions at each HUB. Primary data was gathered through one-on-one meetings with HUB leaders and direct observations during consortium meetings, while secondary data was sourced from technical reports, operational records, and existing literature.

The one-to-one meetings with HUB leaders followed a semi-structured approach. No predefined script was used; instead, the conversations began with a general prompt such as: *"To start off, could you briefly explain how your HUB operates?"* From there, the discussions evolved organically, with follow-up questions tailored to the specific context and responses of each HUB. This flexible method allowed the team to preliminarily assess whether the data required for the deliverable could be obtained and to identify relevant operational and contextual details. Detailed notes were taken during each session to capture key insights and relevant information.

To streamline the process, an Excel template (Appendix 1) was developed and shared with the HUB leaders, to facilitate the collection of core information, particularly on energy consumption and emission profiles for each HUB. The collected data focused on key parameters such as energy consumption disaggregated by source (e.g. natural gas, diesel, renewable and non-renewable electricity), Greenhouse gas (GHG) emissions (including CO_2, CH_4, and CO), emissions to water, including total nitrogen and phosphorus, Water usage, including water withdrawn, discharged, and consumed, and waste generation and diversion, including quantities recycled or reused. The template requested annual data from 2019 to 2024, enabling both longitudinal analysis and cross-HUB benchmarking. A dedicated comments section allowed HUB representatives to clarify assumptions or provide contextual explanations for anomalies in the data.

Additionally, insights into key technologies and their feasibility were drawn from Deliverable D2.1 (*Technology map with key technologies, technical and economic feasibility and contribution to synergies, including an assessment of their scalability*), which provided an overview of relevant technologies, their scalability, and potential synergies. Deliverable D3.1 (*Map of Stakeholders and their Interests/Needs*), further enriched the analysis by identifying stakeholder needs and socio-economic factors. Moreover, Deliverable D3.2 (*Methodology for assessment of non-technological issues*) was also taken into account, providing a structured approach to evaluate regulatory, societal, and market-related barriers and enablers that may influence the deployment of these technologies.

The collected data was systematically analysed to identify technological capabilities, trace material and energy flows, and extract key performance indicators, allowing for the detection of patterns, gaps, and opportunities for intervention.

2.2. Framework for Techno-Economic Parameters

This report establishes a structured framework to define the baseline techno-economic parameters for each HUB, creating a reference point for assessing progress throughout the project. Rather than conducting a detailed techno-economic analysis at this stage, the focus is on identifying essential references that reflect each HUB's initial conditions.

To ensure consistency with the broader implementation strategy, the framework adopts four core dimensions—technical, infrastructural, resource-related, and regulatory—as the organising structure for defining HUB requirements. These dimensions capture the key enablers and constraints influencing the adoption of circular and low-carbon technologies across industrial contexts. They also serve as a foundation for future performance evaluations, providing a coherent structure for comparing progress over time.

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The methodology considers the technological readiness, existing infrastructure, and contextual feasibility of integrating circular economy principles. It is designed to remain flexible, allowing for updates as technologies evolve and new data becomes available. The framework also incorporates input from stakeholders, ensuring that identified parameters reflect practical conditions and operational realities.

This approach aligns with Tasks T6.2 and T6.3, which focus on implementation and monitoring. As new technologies are deployed and optimised, the framework will be iteratively refined to improve the robustness of techno-economic assessments and track the impact of interventions in a structured, comparable way.

2.3. Success Criteria Definition

The transformation of HUBs into H4Cs requires a structured, multidimensional evaluation framework that reflects the strategic goals of the project and provides a robust basis for decision-making. This framework has been developed with the support of Zaragoza Logistics Center (ZLC) and is designed to be dynamic and iterative, enabling continuous refinement as new data and insights emerge through implementation and monitoring activities (T6.2 and T6.3), in coordination with WP4, WP6 and WP7.

The success evaluation methodology is structured around three integrated layers:

- **Technology adoption and operational performance**, measured through HUB-specific KPIs and milestone-based assessments (e.g. post-commissioning, post-500 hours).
- **Strategic sustainability success**, assessed using environmental, economic, and social indicators aligned with project-wide objectives.
- **Scalability and transferability**, evaluated through stakeholder engagement, replication potential, and alignment with regulatory and policy frameworks.

Each HUB has actively contributed to the definition of tailored success metrics for its specific use case, **ensuring local relevance while maintaining alignment with the overarching project vision**. These metrics cover diverse dimensions of success and allow for comparability across different industrial and regional contexts.

The framework integrates four core success domains:

- **Technological success**, evaluated based on the performance, efficiency, and reliability of the demonstrated solutions.
- **Economic success**, assessed through cost-effectiveness, operational savings, and financial viability.
- **Environmental success**, measured by reductions in CO_2 emissions, energy consumption, waste generation, and improvements in circular resource use.
- **Social success**, captured through indicators such as stakeholder involvement, job creation, knowledge transfer, and regional development impact.

These domains are reflected in the common KPIs defined for WP6, enabling a project-wide evaluation of sustainability impact, IS, and circular economy achievements.

The evaluation process is supported by a baseline assessment conducted prior to implementation, followed by regular monitoring and milestone reviews. Each HUB's success metrics are harmonised with the overall evaluation framework to enable both individual and systemic impact assessments.

Finally, the framework incorporates a strong focus on operational feasibility, long-term viability, and potential for replication. Through a structured process of stakeholder mapping, workshops, and targeted surveys—developed in collaboration with the Community of Practice (CoP)—each HUB assesses the enablers and barriers for scaling and transferring its solutions. Insights from these activities are used to refine technology roadmaps, inform policy recommendations, and support future investment in circular and low-carbon industrial ecosystems.

Relationship Between Techno-Economic Parameters and Success Criteria

While both the techno-economic parameters and success criteria serve as foundational elements for the evaluation of HUB development, they address different aspects of the project's lifecycle. The

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techno-economic parameters represent a set of *initial requirements and conditions*, identified by each HUB, that need to be in place to reach the targeted technological maturity. These parameters capture the enabling factors—technical, infrastructural, regulatory, and resource-related—that define what each HUB needs in order to deliver its intended transformation.

In contrast, the **success criteria** provide a set of *measurable indicators* used to evaluate whether each HUB is making effective progress towards its goals throughout the project. These include KPIs related to technology adoption, sustainability impact, and scalability potential.

Both frameworks are grounded in data collected during the early phases of the project. Baseline assessments, stakeholder consultations, and contextual analyses have informed the definition of both the techno-economic parameters and the success criteria, ensuring they reflect practical realities and are tailored to each HUB's specific context. As the project evolves, ongoing data collection and monitoring will continue to refine both sets of metrics, ensuring alignment between what is needed and what is achieved.

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3. Overview of HUBs for Circularity (H4C)

3.1. Conceptual Foundation

3.1.1. Definition and Objectives of H4C

H4C are integrated, cross-sectoral regional ecosystems designed to accelerate the transition towards a circular economy. They do so by establishing **systemic and collaborative value chains** that prioritise resource efficiency, waste minimisation, and the continuous reuse of materials. HUBs act as **dynamic platforms for innovation and cooperation**, where diverse actors (industries, businesses, local governments, research institutions, and civil society) co-develop and implement **scalable circular solutions tailored to local needs.**

Their core objective is to **maximise resource productivity** through IS and systemic innovation, reducing emissions and environmental pressures via **closed-loops material and energy systems**.

In contrast to traditional IS, which typically focuses on linear, bilateral exchange of by-products or resources between companies[1,2], H4Cs operate at a **strategic, territorial scale**. They promote **urban-IS**, leveraging **geo-based clustering**, especially in regions with high density, to enable multi-sectoral, long-term cooperation across infrastructures and value chains[1].

Moreover, H4Cs are engines of innovation, fostering **circular business models**, sustainable product design, and shared service platforms. Their **resilience and scalability** are reinforced by Public-Private Partnerships (PPPs) and Public-Civil Society Partnerships (PCPs), which involve structured collaborations between public authorities (such as governments or municipalities) and civil society organisations (CSOs) like energy communities, to jointly tackle social, environmental, or community challenges. By leveraging **shared infrastructure and inclusive governance models**, H4Cs unlock new market opportunities while empowering industries and communities to co-create long-term social, environmental, and economic value.

They also function as **matchmaking and coordination platforms** for symbiotic resource exchanges, expanding both the temporal and geographical scope of IS interactions. By embedding digital technologies, H4Cs can monitor, adapt, and optimise resource flows in real-time and are thus overcoming the limitation of conventional IS networks and enabling a more responsive, data-driven circular economy.

3.1.2. Industrial Symbiosis as a Pillar of Circular Economy

IS is a **fundamental enabler of circular economy**, allowing waste and by-products from one entity to become valuable inputs for another. This systemic approach enhances the efficiency of resource use, reduces dependency on virgin materials, and contributes to climate mitigation and supply chain resilience[2].

One of IS's most important strength lies in its ability to **implement material loops**, thereby reducing resource scarcity risks and price volatility while enhancing economic viability and environmental performance[3]. For instance, waste heat from manufacturing plants can be repurposed for district heating, while wastewater can be treated and reused within industrial processes, reducing reliance on freshwater sources and energy inputs.

IS actively supports the shift from linear to circular models by embedding **sustainability into the operational core of industrial systems**. It not only prevents resource depletion but also enables a **systemic reconfiguration of value chains,** making them more resilient, efficient, and environmentally sounds.

3.1.3. Key Mechanisms of Industrial Symbiosis

IS functions through several mechanisms that enhance circularity and systemic efficiency. These include:

[1] Mendez Alva F., et al. 2021. "HUBs for Circularity: Geo-Based Industrial Clustering towards Urban Symbiosis in Europe". *Sustainability*.
[2] Castellet-Viciano L., et al. 2022. "Industrial Symbiosis: A Mechanism to Guarantee the Implementation of Circular Economy Practices". *Sustainability*.
[3] Domenech T., et al. 2019. "Mapping industrial symbiosis development in Europe: Typologies of networks, characteristics, performance and contribution to the circular economy". *Resources, Conservation and Recycling*.

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- **Material exchanges**, where by-products and residues from one process serve as feedstocks for another, reducing both input costs and landfill disposal.
- **Energy Sharing,** wherein surplus heat or renewable energy can be redistributed within or beyond the industrial cluster, cutting overall energy demand and associated emissions.
- **Water reuse**, through which treated process water is reintegrated into industrial operations, conserving natural water sources, and improving operational sustainability.

Beyond these physical exchanges, IS depends on several key enablers:

- **Institutional capacity-building**, which facilitates cooperation between businesses, public authorities, and innovation actors, ensuring knowledge sharing, stakeholder engagement, and the mobilisation of resources to initiate and maintain symbiotic relationships[4].
- **The formation of IS networks**, which vary in scale and complexity depending on the types of materials involved, transportation logistics, and market value of by-products. These networks support the shared use of infrastructure, joint service models, and coordinated waste valorisation strategies[Error! Bookmark not defined.,5].
- **Supportive regulatory and economic frameworks**, which are crucial to overcome barriers such as high initial investment costs, regulatory misalignments, and market failures. Well-designed incentives and governance structures can stimulate innovation, derisk collaboration, and unlock finance for symbiotic infrastructure[6].

Digitalisation is a game changer for IS. AI-driven tools help detect new resource flows, blockchain enables **transparent and traceable exchanges**, and IoT combined with big data analytics supports **real-time** optimisation of material, water, and energy streams. These technologies significantly enhance the responsiveness, adaptability, and overall performance of IS systems.

Ultimately, IS is not only about **waste reduction**—it is about designing **smarter, collaborative, and regenerative production systems** that can underpin the circular economy at scale.

3.1.4. Structural Components of H4C

The effective operation of H4Cs relies on **four key components**:

- **Physical infrastructure**, such as shared processing facilities, decentralised recycling centres, and energy recovery systems. These enable efficient material and energy flows and support circular operations across sectors.
- **Stakeholder networks,** which connect businesses, governmental bodies, public institutions, academia, and communities to co-design and implement circular initiatives, ensuring strong multi-actor collaboration.
- **Geo-spatial clustering and planning**, guided by regional industrial and urban dynamics, helps identify high-potential sites for H4C deployment, optimising logistics and proximity-based synergies[1], thereby improving both environmental outcomes and economic feasibility.
- Policy and technology enablers, including financial incentives, regulatory frameworks, and cutting-edge digital tools such as AI, blockchain, and smart logistics systems. These tools enable traceability, real-time monitoring, and strategic planning across value chains.

Together, these components form the **backbone of high-impact H4Cs**, linking innovation, governance, and territorial development for a **systemic shift to circularity**[7].

[4] Abreu M.C.S. & Ceglia D. 2018. "On the implementation of a circular economy: The role of institutional capacity-building through industrial symbiosis". Resources, Conservation and Recycling.
[5] Florencio de Souza F., et al. 2020. "Temporal Comparative Analysis of Industrial Symbiosis in a Business Network: Opportunities of Circular Economy". Sustainability.
[6] Corsini F., et al. 2023. "Industrial symbiosis as a business strategy for the circular economy: identifying regional firms' profiles and barriers to their adoption". Journal of Environmental Planning and Management.
[7] Yu Y., et al. 2023. "Circularity information platform for the built environment". Automation in Construction.

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3.1.5. Governance and Collaboration

Robust governance is essential to the long-term **success, scalability, and legitimacy** of H4Cs. These ecosystems thrive on inclusive coordination models that align diverse stakeholders around **shared circular economy goals**.

PPPs are central to ensuring both financial sustainability and joint ownership of H4C initiatives. They facilitate co-investment in shared infrastructure, promote innovation, and foster accountability. Alongside PPPs, **PCPs** also play a vital role, enabling civil society organizations—such as energy communities—to actively contribute to governance, co-financing, and the social relevance of H4C projects.

Multi-stakeholder governance further supports H4Cs by integrating the perspectives of industry, academia, civil society, and local governments. This enhances knowledge flows and enables the co-creation of best practices and adaptive strategies.

Regulatory coherence is also critical. H4Cs benefit from frameworks that promote sustainable waste management, incentivise resource sharing, and encourage innovation. At the same time, H4Cs adopt **flexible governance models** that can adapt to **local needs and institutional realities**, blending top-down policy coordination with **bottom-up engagement**[1].

By establishing permanent **coordination units, innovation clusters**, or "living labs," H4Cs promote continuity, coherence, and **ongoing stakeholder alignment**. This includes integration of local knowledge, co-design processes, and community engagement, which together enhance **social inclusivity** and **place-based impact**[8].

3.1.6. Economic and Environmental Benefits of H4C

H4Cs bring substantial **economic, social, and environmental benefits**. Economically, they foster **job creation** in green industries, such as circular manufacturing, waste valorisation, and clean technology. They also deliver cost savings through resource and energy efficiency, while opening up **new market opportunities** for circular products and services.

Environmentally, H4Cs reduce greenhouse gas emissions, prevent waste generation, and conserve natural resources by promoting **material circularity and regenerative land use**. They also enable urban renewal by revitalising underutilised industrial sites and integrating them into greener, more sustainable urban fabrics.

Socially, H4Cs **create value for local communities** by increasing participation in decision-making, promoting green skills, and raising awareness of circular lifestyles. **Makerspaces and innovation HUBs** within H4Cs empower local entrepreneurs and innovators to test and scale solutions aligned with circular principles[8].

By shortening supply chains and **optimising material flows** within regions, H4Cs also reduce emissions associated with transport and logistics, enhancing local resilience to **supply disruptions and climate risks**[9].

Aligned with the EU Green Deal, the Circular Economy Action Plan, and the SDGs, H4Cs represent **strategic enablers of Europe's green transition**. Their systems-based approach and cross-sector coordination make them **powerful levers for industrial transformation and sustainability-led growth**[1].

3.2. Enabling Environment

3.2.1. Policy and Regulatory Frameworks Supporting Circularity

As nations increasingly adopt circular economy principles, IS emerges as a linchpin for **decoupling economic growth from environmental harm**. By fostering collaborative networks among industries, governments, and communities, this strategy ensures a future where economic and environmental priorities align for the benefit of all stakeholders.

Effective policy and regulatory frameworks are essential to enable, expand, and scale up both IS and H4Cs. These frameworks should not only provide high-level guidance but also include concrete

[8] Premyanov N., et al. 2024. "Circular Entrepreneurship via Makerspaces Towards Fostering Sustainable Cities: A Mixed-Method Approach with Case Studies". Journal of Circular Economy.

[9] Yang X., et al. 2023. "Integrating bottom-up building stock model with logistics networks to support the site selection of circular construction HUB". Journal of Cleaner Production.

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mechanisms such as regional circular economy laws, targeted fiscal instruments, and harmonised sustainability criteria to support implementation[10].

The European Union's Circular Economy Action Plan (CEAP)[11] promotes extended producer responsibility and resource efficiency, encouraging industries to adopt circular economy models. In addition, national sustainability strategies increasingly integrate IS through legal mandates, green procurement guidelines, and support for regional circular innovation ecosystems[12,13].

However, legal, and regulatory fragmentation remains a barrier for the implementation of HUBs for Circularity, as most policies focus on sectoral or product-specific circularity without addressing cross-sectoral industrial ecosystems[10].

In the context of global sustainability ambitions, IS and H4Cs are central to achieving the **EU's Green Deal** targets and the SDGs. They drive the shift towards regenerative, near-zero wastes economies by maximising resource circularity. To operationalise this transition, performance measurement systems that track resource flows, emissions, and symbiosis opportunities are increasingly being adopted to support transparent and data-driven governance[14,15]. Advanced performance measurement frameworks are increasingly required to integrate environmental, economic, and social indicators to support circular decision-making at regional and industrial scales[13]. For example, initiatives within the EU4Environment framework[16] highlight how integrating IS can enhance the functionality and sustainability of eco-industrial parks, demonstrating improved resource efficiency and economic competitiveness. Digital platforms and geospatial data systems are increasingly used to map resource flows and identify synergies across industrial sectors, enabling more targeted and efficient implementation of IS strategies.

Despite these advances, several barriers persist. Regulatory inconsistencies across sectors, lack of long-term funding instruments, and high upfront costs for shared infrastructure often inhibit the formation of robust IS networks. To overcome these challenges, multi-level policy coordination is required, involving regional, national, and EU-level actors.

Governments play a crucial role in facilitating IS by offering subsidies, tax incentives, and grants that support the transition to circular production systems. However, existing financial incentives are often not tailored to the collaborative and cross-sectoral nature of IS, calling for more adaptive and context-specific funding schemes[14]. Additionally, regional policies promoting eco-industrial parks and circular economy HUBs create an enabling environment for industries to engage in symbiotic exchanges, especially when combined with institutional capacity-building programmes that train local authorities, businesses, and innovation actors to identify and implement symbiotic opportunities.

3.2.2. Education, Skills, and Capacity Building

The successful deployment and scaling of IS and H4Cs hinge not only on regulatory support, but also on the availability of skilled professionals and institutional capacity. Education and training systems must evolve to equip current and future workers with the technical, managerial, and systemic skills required to implement and sustain circular practices. This includes competencies in material flow analysis, process optimisation, life cycle thinking, and collaborative innovation[17].

Cross-sectoral knowledge-sharing platforms, vocational upskilling programmes, and interdisciplinary curricula at higher education institutions are essential to close the circular skills gap. Furthermore, capacity-building initiatives targeting public authorities, SMEs, and industrial associations can accelerate local uptake of symbiotic models by enhancing the ability to identify, design, and manage cross-sectoral collaborations. As part of this enabling environment, peer-learning networks and regional

[10] Cagno E., et al. 2023. "One framework to rule them all: An integrated, multi-level and scalable performance measurement framework of sustainability, circular economy and industrial symbiosis". Sustainable Production and Consumption.
[11] European Commission. 2020. "Circular economy action plan".
[12] Laatsit M. & Johansson G. 2025. "Fostering industrial symbiosis in process industries: An innovation policy perspective". Environmental Technology & Innovation.
[13] Babkin A., et al. 2023. "Framework for assessing the sustainability of ESG performance in industrial cluster ecosystems in a circular economy". Journal of Open Innovation: Technology, Market, and Complexity.
[14] Harris S., et al. 2021. "Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy". *Sustainable Production and Consumption*.
[15] Franco N.G., et al. 2021. "A strategic measurement framework to monitor and evaluate circularity performance in organizations from a transition perspective". *Sustainable Production and Consumption*.
[16] EU4Environment. s.d. "EU4Environment: Action for the environment in the Eastern Partnership".
[17] Beducci E., et al. 2024. "Unleashing the role of skills and job profiles in circular manufacturing". *Journal of Cleaner Production*.

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circular economy accelerators play a vital role in fostering experimentation, replication, and trust-building among diverse stakeholders[18].

3.2.3. Data Availability and Digital Tools

Digitalisation is a cornerstone of modern circular economy strategies, serving as both an enabler and a driver of IS. High-quality, interoperable data on material and energy flows, emissions, and production processes is essential for identifying potential synergies and managing resource exchanges efficiently.

Emerging digital tools—including digital twins, blockchain traceability systems, geospatial mapping platforms, and AI-powered matchmaking engines—are increasingly used to visualise industrial ecosystems and uncover symbiotic opportunities in real time[19,20]. These platforms also enhance transparency and foster trust among participants by ensuring secure, auditable, and anonymised data sharing[21].

However, data fragmentation, lack of common standards, and insufficient digital maturity across sectors remain major barriers. To address these, H4Cs must be supported by robust digital infrastructures and data governance frameworks that encourage interoperability and the ethical use of shared data. Public–private partnerships and EU-level platforms such as the Digital Product Passport and the European Circular Economy Stakeholder Platform provide promising pathways for improving digital readiness and integration[22].

3.2.4. Monitoring, Metrics, and Standards

Operationalising circularity in industrial ecosystems requires clear, consistent, and measurable indicators that reflect both environmental and socio-economic performance. Standardised metrics are critical for assessing the effectiveness of symbiotic exchanges, benchmarking progress, and ensuring alignment with EU and global sustainability targets[23].

Performance monitoring systems must go beyond material efficiency and emissions reduction to include broader indicators such as resource productivity, social equity, job creation, and regional resilience. Frameworks such as the ISO 14009 standard, the EU Taxonomy for Sustainable Activities, and the Circular Economy Monitoring Framework offer foundational tools for evaluating circular transitions. Readiness checklists and circularity indices are increasingly used to assess the preparedness of organisations for circular transitions, while ESG (Environmental, Social, Governance) frameworks provide a broader view of sustainability performance[24].

To be truly effective, these metrics must be embedded into governance structures and planning processes at H4C level. Regular monitoring and reporting, combined with feedback loops for adaptive management, can help identify systemic bottlenecks, inform investment decisions, and validate the added value of IS initiatives. The development and adoption of harmonised KPIs will also facilitate cross-border comparisons, enable access to green finance, and support policy alignment.

3.3. Examples of Existent HUBs at a Global Level

Across the globe, several pioneering initiatives have successfully implemented the principles of circularity and IS at scale, providing valuable lessons and replicable models for the development of future H4Cs. These initiatives demonstrate how integrated approaches—combining resource efficiency, technological innovation, and multi-stakeholder collaboration—can lead to substantial environmental and economic gains.

Among the most prominent examples are **Kalundborg Symbiosis** in Denmark and the **Port of Rotterdam Circular HUB** in the Netherlands. These sites offer concrete evidence that circular industrial ecosystems are not only feasible but also resilient and adaptable to diverse regional contexts. The following subsections explore these cases in more detail, highlighting their governance models,

[18] Oluleye B. I., et al. 2023. "Modeling the principal success factors for attaining systemic circularity in the building construction industry: An international survey of circular economy experts". *Sustainable Production and Consumption*.
[19] Calabretta, G., et al. 2022. Circular business models in the digital age: An overview of digital technologies for the circular economy. *Business Strategy and the Environment.*
[20] Baldassarre, B., Calabretta, G. Why Circular Business Models Fail And What To Do About It: A Preliminary Framework And Lessons Learned From A Case In The European Union (Eu). *Circ.Econ.Sust.*
[21] Chen Q., et al. 2022. "Revamping construction supply chain processes with circular economy strategies: A systematic literature review". *Journal of Cleaner Production*.
[22] European Environment Agency (EEA). 2022. *Digitalisation and the environment: Opportunities and risks of the digital transition*.
[23] Ramírez-Rodríguez L. C., et al. 2024. "Mapping sustainability assessment methods through the industrial symbiosis life cycle for a circular economy". *Sustainable Production and Consumption*.
[24] Cagno E., et al. 2023. "One framework to rule them all: An integrated, multi-level and scalable performance measurement framework of sustainability, circular economy and industrial symbiosis". *Sustainable Production and Consumption*.

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technical innovations, and measurable impacts.

3.3.1. Kalundborg Symbiosis (Denmark)

Kalundborg Symbiosis is widely recognised as the world's first and leading example of IS[25,26]. Established in the 1960s and continually evolving over decades, it stands as a pioneering model of how industrial collaboration can drive sustainability, economic resilience, and environmental efficiency. Located in Kalundborg, Denmark, the initiative unites a diverse network of public and private stakeholders in a circular system where industrial by-products, energy, water, and materials are exchanged to maximise resource efficiency and reduce environmental impacts. At its core, lies the principle that *"one company's waste becomes another's resource"*.

Shared Resource Flows in Kalundborg Symbiosis

Kalundborg's network operates as a cooperative ecosystem, rather than as isolated industrial units, reducing emissions, cutting operational costs, and optimising the use of natural resources. The illustration below (Figure 1) categorises shared flows into three main domains[26], with reference numbers corresponding to specific exchanges (indicated in parentheses for reference):

- **Energy**: Includes redistributed waste heat and energy streams to maximise efficiency, including steam (1), electric power (2), hot condensate (3), heat for district heating (4), and natural gas (5).
- **Water**: Covers reuse of water streams in various forms, including wastewater (6), clean wastewater (7), surface water (8), used cooling water (9), deionised water (10), and clean surface water (11).
- **Materials**: Involves the exchange of industrial by-products and residual materials, such as residue (12), sulphide (13), yeast sludge (14), sand (15), sludge (16), NovoGro (17), ethanol residue (18), biomass (19), and fertilisers (20).

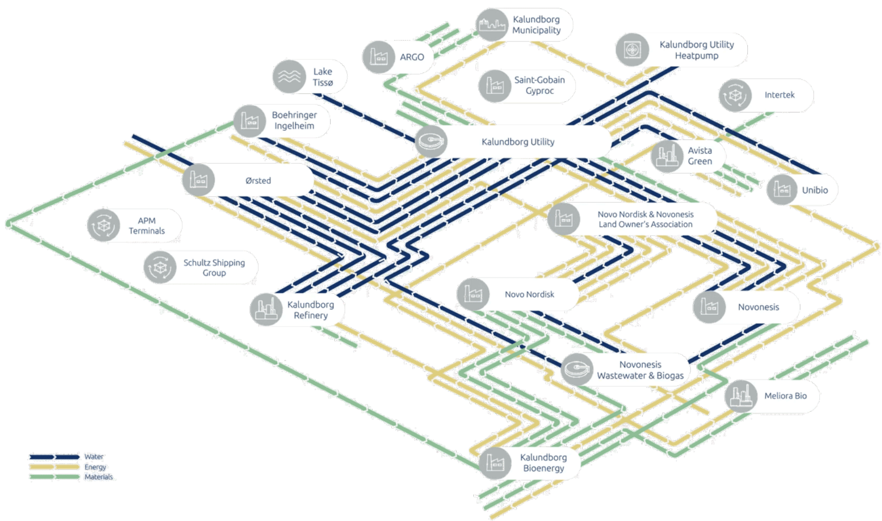

Figure 1: Kalundborg Symbiosis[26].

Environmental and Economic Benefits

The long-term impact of Kalundborg Symbiosis is remarkable. Since 2020, following the Asnæs Power Plant's conversion to carbon-neutral biomass (wood chips), the symbiosis has enabled an annual reduction of approximately 635,000 tons of CO_2 emissions. The initiative has also reduced dependency on virgin raw materials, enhanced water reuse, and generated significant cost savings for participating industries. Key success stories include[26]:

- **District Heating Expansion:** Surplus heat from the Asnæs Power Plant is redirected to warm approximately **20,000 homes**, reducing reliance on conventional heating methods, and cutting energy costs for residents.

[25] Ehrenfeld J. & Gertler N. 1997. "Industrial Ecology in Practice: The Evolution of Interdependence at Kalundborg". Journal of Industrial Ecology.

[26] Kalundborg Symbiosis. n.d. "Official Website".

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- **Agricultural Circularity:** By-products from **Novo Nordisk's** pharmaceutical production are repurposed into high-quality fertilisers, reducing waste while supporting sustainable farming practices[27].
- **Water Reuse Innovations:** Treated municipal wastewater is redirected to industrial operations, significantly **reducing freshwater withdrawals,** and ensuring sustainable water management in the region.

A Scalable and Replicable Model for the Future

Kalundborg Symbiosis proves that IS is not only viable but also scalable and adaptable worldwide[28,29]. It serves as a benchmark for circular industrial development and a blueprint for establishing future H4Cs. Its success has been supported by a robust governance model characterised by:

- **Long-standing partnerships** between industries, municipalities, and academic and research institutions.
- **Supportive policies and incentives** that foster sustainable investment.
- A **culture of innovation and adaptability**, allowing the symbiosis to evolve with new technologies and shifting sustainability priorities.

By showcasing the tangible benefits of circular collaboration, Kalundborg has inspired similar initiatives across Europe, North America, and Asia—demonstrating that IS can deliver environmental sustainability and economic competitiveness hand in hand.

3.3.2. Port of Rotterdam Circular HUB (The Netherlands)

The Port of Rotterdam, Europe's largest seaport, is spearheading a bold transition into a major circular economy HUB, redefining the way industrial ecosystems operate sustainably[30]. As a global nexus for trade, logistics, and heavy industry, the port is uniquely positioned to enable IS, connecting chemical manufacturers, waste processors, logistics providers, and emerging cleantech firms. This transformation aims to **reduce reliance on virgin resources**, **optimise energy and material flows, and drive carbon neutrality** across sectors. By leveraging its strategic location and vast infrastructure, the Port of Rotterdam is becoming a global reference point for large-scale circular industrial development-integrating material reuse, energy recovery, and cutting-edge technologies to build a highly efficient and sustainable industrial landscape.

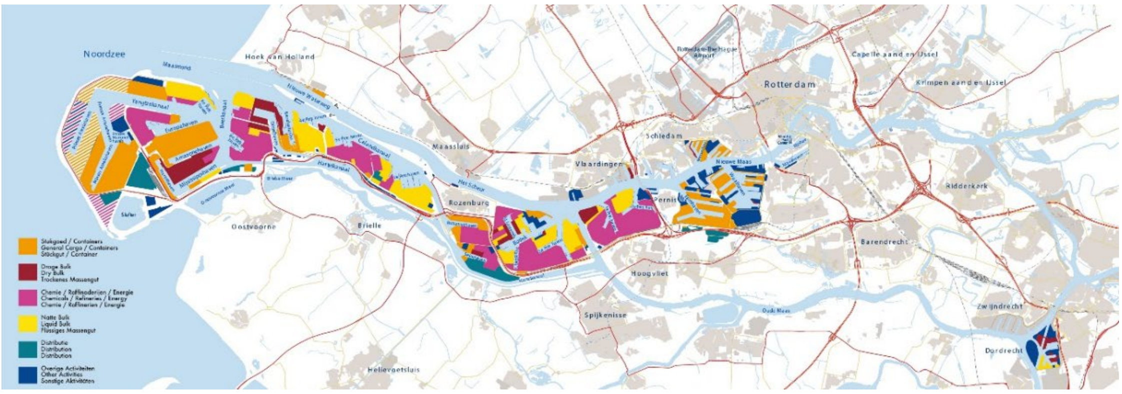

Figure 2: Port of Rotterdam (Source: [30]).

Key Circular Economy Initiatives

The Port of Rotterdam Circular HUB is home to a range of pioneering initiatives that promote circularity, lower emissions, and enhance resilience:

- **Advanced Plastic Recycling and Upcycling**: The port hosts state-of-the-art recycling plants that convert plastic waste into high-quality secondary raw materials. Innovative companies, such as

[27] Novo Nordisk. n.d. "Sustainability: Circular solutions in production"
[28] Jacobsen N.B. 2006. "Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects". Journal of Industrial Ecology.
[29] Chertow M.R. 2007. "'Uncovering' Industrial Symbiosis". Journal of Industrial Ecology.
[30] Port of Rotterdam Authority. n.d. "Energy Transition".

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BRIGHTLANDS Circular Space[31] and Ioniqa Technologies[32], are advancing chemical recycling, breaking plastics down to their monomers and enabling superior recyclability.

- **Biofuel Production from Organic Waste**: Organic streams—from agricultural residues to industrial biomass—are transformed into biofuels and biochemicals. This supports the decarbonisation of maritime transport and heavy industry, in line with EU climate targets[33]. Industry leaders like Neste[34] and Shell Renewable Solutions are scaling up production.

- **Industrial Energy Recovery and Carbon Utilisation**: Waste heat is captured and redistributed via district heating networks to power homes, greenhouses, and nearby industries. Carbon capture and utilisation (CCU) technologies repurpose CO_2 into synthetic fuels, construction materials, and even algae-based food. A flagship project, Porthos[35], aims to store 2.5 million tonnes of CO_2 annually beneath the North Sea—substantially cutting industrial emissions.

- **Smart Logistics and Digital Circularity Solutions**: Blockchain technology ensures transparent tracking of materials in circular supply chains, while AI-powered platforms optimise the flow of resources, reducing waste and inefficiencies. The port is also advancing autonomous and electric freight transport, cutting emissions from logistics operations.

Collaboration-Driven Innovation

The Port of Rotterdam's success is rooted in a multi-stakeholder approach, bringing together industry, government, academia, and startups to co-develop and implement circular innovations. Key partnerships include:

- **Startups and Innovation HUBs:** The port works with cleantech incubators such as **YES!Delft[36]** and **Plant One Rotterdam[37]** to scale up innovative solutions in waste-to-resource conversion, biorefining, and sustainable chemicals.

- **Academic and Research Institutions:** Universities such as **TU Delft** contribute research on circular business models, material sciences, and CC technologies.

- **Public-Private Partnerships:** Collaboration with **Port Authority Rotterdam, the Dutch government, and EU policy initiatives** ensures regulatory alignment and financial incentives for circular economy projects.

Impact and Global Leadership

Through these **bold initiatives**, the Port of Rotterdam is reinforcing its position as **one of the world's most advanced IS HUBs**, demonstrating that large-scale circularity is not only feasible but economically viable[38].

- It has significantly **reduced dependency on virgin raw materials**, cutting costs and emissions.

- **Industrial CO_2 emissions are decreasing**, aligning with national and EU-wide **climate action goals**.

- The port's **digital innovations are creating new economic opportunities**, fostering sustainability-focused business models.

By integrating **policy support, technological innovation, and cross-sector collaboration**, the Port of Rotterdam is setting a global benchmark for industrial HUBs transitioning to circular economies. It exemplifies how large-scale industries can achieve economic growth while advancing environmental sustainability—proving that circularity is the future of industrial development.

[31] Brightlands Circular Space. (n.d.). *Circular plastics*.
[32] Ioniqa Technologies. (n.d.). Company.
[33] European Commission. (n.d.). *Renewable Energy Directive: Targets and rules*.
[34] Neste. (n.d.). *Sustainability*.
[35] Porthos. (n.d.). *CO_2 transport and storage in Rotterdam*.
[36] YES!Delft. (n.d.). *Tech incubator for startups*.
[37] Plant One Rotterdam. (n.d.). *Test and demonstration location for sustainable process technology*.
[38] Port of Rotterdam Authority. (n.d.). *Sustainable port*.

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4. Strategic Overview of IS2H4C HUBs

The four H4C, situated in **Turkey**, **Spain**, the **Netherlands**, and **Germany**, represent strategic nodes for embedding innovative technologies into existing industrial frameworks. These HUBs are instrumental in advancing the objectives of the EU Green Deal by facilitating the transition towards circular and climate-neutral economies. Each HUB is distinguished by a unique industrial profile—ranging from energy-intensive manufacturing to renewable energy ecosystems and urban-industrial integration—as illustrated in Figure 3.

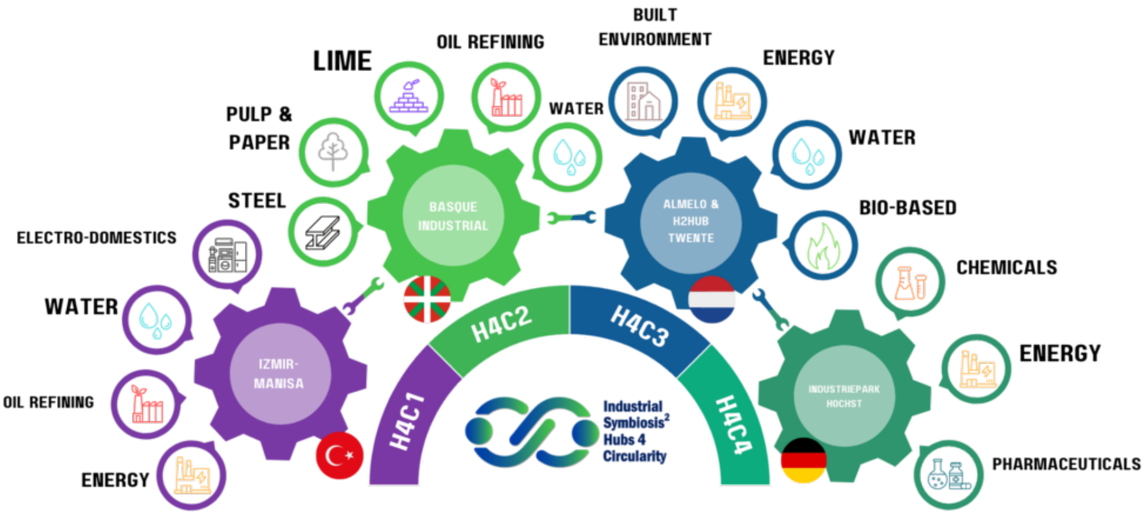

*Figure 3: **IS2H4C** overall concept and HUB presentation.*

- The **Izmir-Manisa HUB** in Turkey integrates refinery waste recovery with appliance manufacturing to generate value by transforming waste into products. Priorities include producing e-methanol using electrolytic H_2, exploring pathways for utilising oxygen (O_2) from electrolysis, and capturing CO_2 to produce e-methanol and NIPU (without isocyanate), an alternative to conventional polyurethane (with isocyanate) used in refrigerators.
- The **Basque Industrial HUB** for Circularity (BIH4C) is located in the Basque Country, northern Spain, a region known for its strong industrial base and innovation clusters. It focuses on decarbonising sectors such as steel, cement, lime, oil refining, and pulp and paper. Key initiatives include integrating electrolytic O_2 and H_2 into steel production, capturing CO_2 from lime and cement kilns, valorising steel slags in construction, and converting urban waste into biocoke and biogas through pyrolysis.
- The **Dutch HUB** based in **Almelo**, in the eastern Netherlands, hosts a decentralised H_2 ecosystem coordinated by Almelo Energy and H2HUB Twente, in close collaboration with subcontractor (Distribution Systems Operator) COGAS. The H2HUB Twente ecosystem brings together around 20 industrial companies committed to advancing regional H_2 innovation and deployment. Near the H2HUB Twente, in the village of Aadorp, this project will demonstrate the replacement of natural gas with green H_2 from solar and wind energy for residential heating. The initiative explores energy storage solutions to stabilise the renewable energy supply, research the feasibility of transporting H_2 to local crematoria as a natural gas substitute, and integrating O_2 from electrolysis into wastewater treatment processes, and in turn use their process water for purification to production water for the electrolyser.
- The **Industriepark Höchst HUB** is located in Frankfurt / Main, Germany, and hosts around 90 companies in the pharmaceutical, chemical, biotechnology, and services sectors. The HUB aims for achieving carbon neutrality by employing CCU, upgrading waste heat recovery for district heating, producing H_2 and implementing microwave-assisted hydrothermal carbonisation of biogenic wastes to produce H_2.

The **IS2H4C** project promotes the integration of mature and emerging technologies (across various Technology Readiness Levels (TRLs)) to enhance energy and resource efficiency, while fostering Industrial-Urban-Rural Symbiosis (IURS). Key technological synergies identified include **17**

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demonstrated within the project scope with an additional **24 earmarked for future exploration and HUB expansion**.

The next section outlines the specific starting points and technological pathways for each HUB, accompanied by corresponding flow diagrams.

4.1. HUBs' Starting Points

The following sub-chapters provide a concise overview and a corresponding flow diagram for each HUB, illustrating the existing processes (**BLUE COLOR**), the synergies to be demonstrated within this project (**GREEN COLOR**), and the processes or synergies planned for exploration as part of the HUBs' expansion strategies (**PURPLE COLOR**).

The identification of relevant actors, as well as potential leverage points for enhancing circularity and industrial symbiosis in each HUB, can be found in *Deliverable 3.1*, where diagrams and descriptions lay the foundation for assessing the maturity level of each HUB, identifying opportunities for innovation, and aligning future interventions with regional strengths and ambitions. This structured overview serves as a reference point for the demonstration activities and supports the strategic planning of each HUB's transition towards a fully integrated and circular system.

4.1.1. Turkish HUB

The Turkish HUB is strategically located in the highly industrialised Izmir-Manisa port region on Turkey's Aegean coast. This area serves as a major industrial corridor, hosting key national and international players in sectors such as oil and gas refining—exemplified by TÜPRAŞ, Turkey's largest refinery—and advanced manufacturing, including Arçelik, a global leader in household appliances. Its proximity to maritime infrastructure, free trade zones, and logistics centres reinforces its role as a gateway for industrial production, innovation, and export. **IS2H4C** will capitalise on existing infrastructure—oil refineries, refrigerator production facilities, and green H_2 production via electrolysis powered by renewable energy sources (as shown in Figure 4)—to demonstrate innovative circular technologies.

This integration involves a tightly coupled system that captures CO_2 from refinery tail gases and produces high-purity green H_2 via a PEM electrolyser powered by renewable energy. The captured CO_2 and H_2 are then combined to synthesise e-methanol, which feeds into downstream processes for producing carbamates and, ultimately, NIPUs. This closed-loop process demonstrates the value of carbon reuse in industrial contexts.

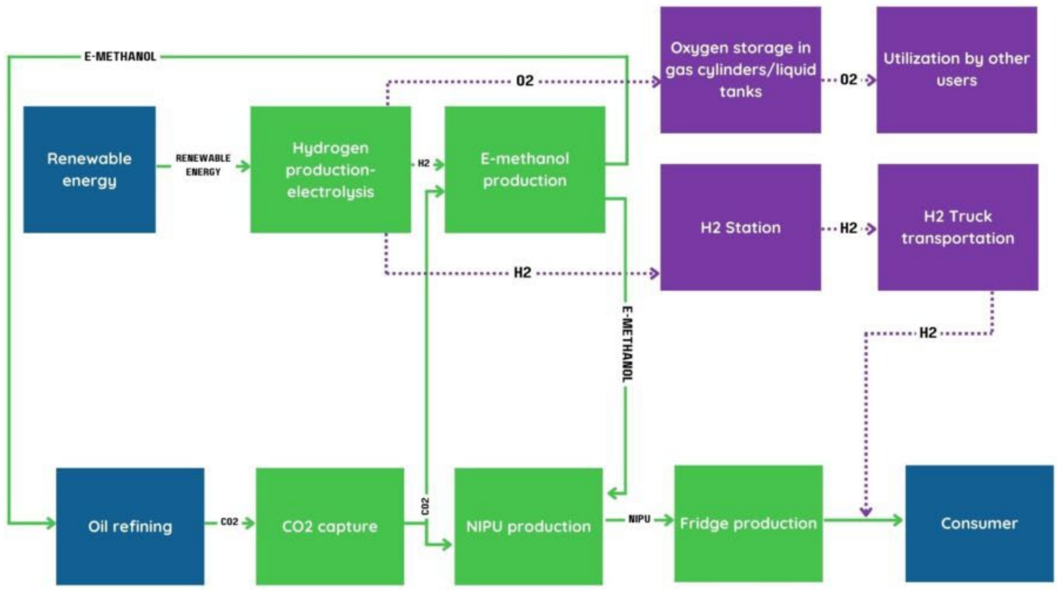

Figure 4: Turkish HUB Flow Diagram.

Demonstration activities will include the production of **e-methanol** using green H_2 (produced via electrolysis powered by renewable electricity) and captured CO_2. This e-methanol will replace conventional methanol in refining processes. Furthermore, captured CO_2 will also be utilised in the production of **NIPU**, a more sustainable alternative to traditional polyurethane used in refrigerator

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insulation.

Originally, the project planned to reuse the MOF4AIR CC unit previously installed at the Izmit refinery. However, due to its limited CO_2 purity for methanol synthesis, a new cryogenic CC unit with improved performance will be installed at the Izmir refinery. This unit will compress and separate PSA tail gases—containing around 42.8% CO_2 and 30.1% H_2—achieving a CO_2 purity of 99.9%, essential for high-efficiency methanol production. Additionally, while the initial project proposal included plans for a large-capacity electrolyser investment, this has been delayed. To maintain alignment with the project timeline, a small-scale electrolyser will instead be procured and deployed at the refinery site, dedicated to the e-methanol (e-MeOH) unit.

Expansion strategies for the Turkish HUB encompass multiple value-added synergies:

- Exploring options for storing O_2 generated during electrolysis in other sectors such as chemicals, pharmaceuticals, and pulp and paper industries.
- Exploring options for supplying green H_2 to consumers via refuelling stations and H_2 transport trucks, supporting decarbonisation beyond the HUB boundaries.
- Leveraging stored O_2 in gas cylinders for medical applications, including use in hospitals and therapeutic care.
- Scaling up CC technologies to support increased production of e-methanol, NIPU, and potentially other CO_2-derived materials such as ethylene and acetic acid.

The H_2 required for this process will be produced using a PEM electrolyser, operating at around 35 bar, to generate high-purity H_2. After pre-heating, the H_2 and CO_2 mixture is fed into a methanol reactor operating at 220–250°C and 50–100 bar. The resulting methanol-rich stream is cooled, separated, and distilled, aiming at a production capacity of ~2 kg/day.

As CC technology is deployed, expanding CC capacity will lead to increased production of e-methanol and polymers, which could attract a wider range of companies from different sectors. Other materials, such as ethylene and acetic acid, could also be produced from captured carbon, similar to the approach in the German HUB. Increased NIPU production will allow Arçelik to extend its use across other facilities, and higher e-methanol output will enable Tüpraş to achieve significant cost savings on traditional methanol purchases.

Tüpraş is a key actor in this transition. As part of its strategic roadmap, Tüpraş plans to install a 20 MW electrolyser between 2028-2030, marking the beginning of large-scale green H_2 production. By 2030, the company aims to expand its installed capacity to 128 MW. In parallel, Tüpraş is actively evaluating the integration of green H_2 into Sustainable Aviation Fuel (SAF) production processes. Looking ahead, the total green H_2 production capacity is targeted to reach 350 MW by 2035. Additionally, the company plans to initiate third-party sales of green H_2 starting in the same year. The company is also developing renewable energy investments, such as solar power plants, to meet the clean energy needs for green H_2 production up to 2050. Tüpraş operates four refineries (İzmir, İzmit, Batman, and Kırıkkale), which already house high-purity H_2 production and consumption units. Three of them (Kırıkkale, İzmir, and İzmit) utilise **Steam Methane Reforming** (SMR)—99.99 vol.%—and H_2-rich gas—~91 vol.%—for internal processes.

In March 2025, a HAZID (Hazard Identification) study was conducted on-site at the İzmir refinery, followed by basic engineering preparation and revisions. A HAZOP (Hazard and Operability) study is scheduled for June 2025. Installation preparations and the production of units, including the CC unit, electrolyser, and methanol synthesis reactor, is planned to begin in September 2025.

Within the project, a TRL9 water electrolysis will be implemented to supply H_2 for e-methanol synthesis. E-methanol will also serve as a feedstock for NIPU production, which will be demonstrated under refinery conditions, while advancing Fraunhofer's current NIPU production process from TRL3 to TRL7.

Tüpraş is also working closely with Fraunhofer and Arçelik to define process standards and technical requirements for upscaling NIPU production. Sample exchanges and lab-scale synthesis have begun, laying the groundwork for real-world demonstration under refinery operating conditions.

To establish the baseline for the Izmir-Manisa HUB, an initial assessment of energy consumption, emissions, water use, and waste management has been conducted. This evaluation highlights the current technological landscape, existing synergies, and areas for further optimisation.

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Table 2: Baseline assessment of the Turkish HUB's energy consumption, emissions, and technological capabilities.

Data Collected	Currently, the Turkish HUB is still under development on the field for basic pre-operation needs and physical infrastructure and basic engineering studies for demonstration activities. Therefore, no baseline data is yet available for the energy consumption, emissions or resource flows that will be included in the entire HUB circularity corridor. Once the basic engineering studies are completed; methanol will be produced with the CO_2 captured in the flue gas, which is the waste of refinery processes, and high purity H_2 produced by electrolysis, and this methanol and captured CO_2 will be used for NIPU. The final product of the HUB, the Refrigerator (NIPU as its insulation material), will also be included in the circularity corridor and will be included in the mentioned data according to the final design. Within the scope of the HUB, studies are ongoing to meticulously maximise environmental performance, innovation uptake and impact delivery throughout the implementation of **IS2H4C** by designing and monitoring the progress of the HUB from its inception and evaluating unique modification opportunities for industrial needs.
Current Technologies	• Refrigerator Production • H_2 Production • Oil refining (Existing high-purity H_2 production units, consumer units, and purge systems at refineries)
HUB Synergies	The Izmir-Manisa region, situated near an industrialised port on the Aegean coast, is home to petrochemical and household appliance companies. The planned synergies include: • (i-ii) Using green H_2 produced through renewable-powered electrolysis combined with CO_2 captured from oil refining activities via CC adsorption technology, for e-methanol production. • (iii-iv) Utilising captured CO_2 in the production of NIPU as a substitute for traditional polyurethane in refrigerator manufacturing.
Other Opportunities for HUB Optimisation	1 Development of sector-coupled energy systems, integrating industrial waste heat into regional heating, or using dynamic pricing and AI-based load balancing to shift demand to green supply. 2 Deployment of advanced CO_2 valorisation pathways, such as microbial or electrochemical conversion into high-value chemicals (beyond e-methanol). 3 Use of treated wastewater in electrolysis to reduce freshwater demand; AI-driven water monitoring to improve leak detection and reuse. 4 Creation of a digital material passport for industrial by-products to enable secondary markets. Explore bioconversion of organic waste into biochar, enzymes, or fibres. 5 Blockchain-based traceability of CO_2 and H_2 flows, enabling carbon accounting and market transparency. Use of high-temperature heat pumps for SMR replacement.

*Data has been normalised to preserve confidentiality and to address constraints associated with data aggregation.

**Total Energy = Total Electricity Consumption (Renewable + Non-renewable electricity usage) + Total Direct fuel energy consumption (energy from combustion or use of the fuel itself)

The Turkish HUB exemplifies how industrial decarbonisation and circular economy strategies can be integrated at scale by leveraging existing refinery and manufacturing infrastructures. Through the demonstration of green H_2 production, high-purity CO_2 capture, and the synthesis of e-methanol and NIPU, the HUB creates a closed-loop system with strong potential for replication. While challenges remain—particularly in energy dependency, waste valorisation, and water recovery—the HUB's

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ambitious expansion plans and engagement of key industrial actors like Tüpraş and Arçelik position it as a frontrunner in Turkey's transition towards climate neutrality and industrial circularity.

4.1.2. Basque HUB

The Basque Industrial HUB for Circularity (BIH4C), located in northern Spain, builds upon a strong regional foundation that includes regional initiatives, such as the **Net-Zero Basque Industrial SuperCluster (NZBISC)** and the **Basque Hydrogen Corridor**. The Basque Country, recognised as a strong innovation region, hosts a dense concentration of energy- and emission-intensive industries and has already demonstrated success in establishing cross-sectoral synergies that contribute to measurable reductions in emissions, resource use, and material consumption.

Coordinated by TECNALIA, the HUB brings together a broad alliance of industrial stakeholders—including leading companies such as SIDENOR, and PETRONOR—alongside technology centres and public authorities notably SPRI, and EVE, all of whom are identified as relevant stakeholders in *Deliverable 3.1 – Map of Stakeholders and their Interests/Needs*. Its mission is to accelerate the decarbonisation and circular transformation of the regional industrial fabric through collaborative innovation and the deployment of sustainable technologies.

The BIH4C is strategically aligned with key regional and European policy frameworks, including the Basque Green Deal, the EU Green Deal, the EU Industrial Strategy, and the Circular Economy Action Plan. It is also well-positioned to contribute to broader initiatives such as the Net-Zero Industry Act and the Clean Transition Dialogues, reinforcing its role as a key player in Europe's industrial transformation.

The HUB encompasses a diversified industrial ecosystem comprising the steel, cement, lime, oil refining, and pulp & paper sectors. It also incorporates existing infrastructures and technologies for wastewater treatment, waste pyrolysis, electrolysis, and e-fuel production for transportation (as shown in Figure 55). **IS2H4C** will demonstrate and expand a series of circular synergies across these sectors.

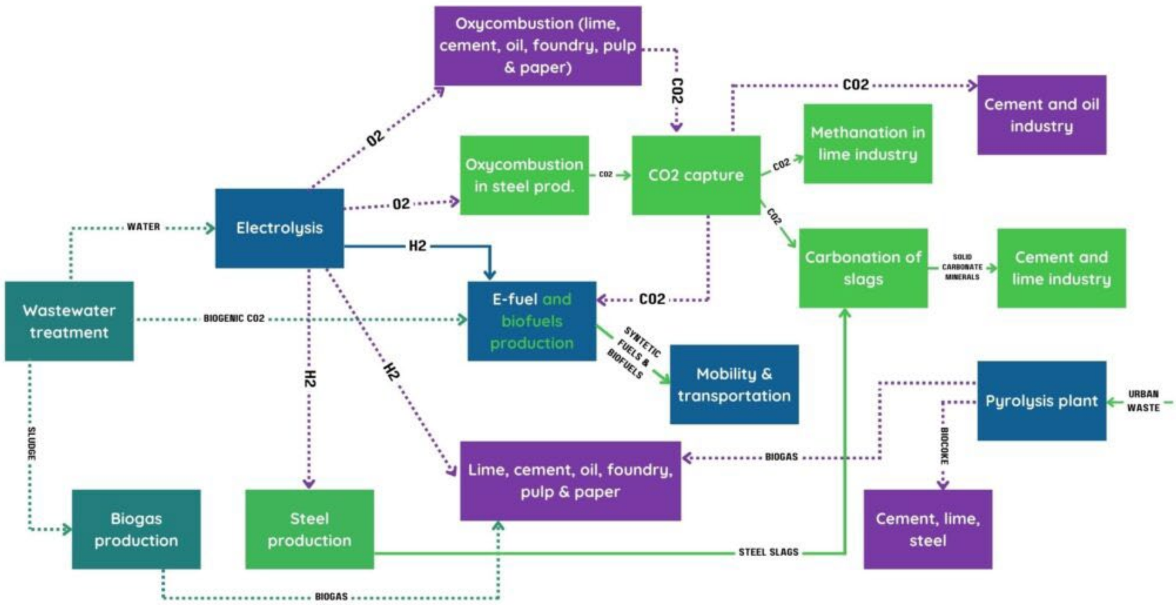

Figure 5: Basque HUB Flow Diagram.

As part of the core demonstration, three key technologies are being validated under industrial conditions:

- **Carbon Capture and Utilisation (CCU):** At CALCINOR, a CO_2 capture and purification system has been implemented based on a flue gas cleaning setup using particle filters, silica gel moisture removal, and a PSA system with zeolite 13X. The system targets over 95% CO_2 purity for subsequent methanation. A pilot methanation reactor using a Ni-based catalyst aims to produce synthetic methane (CH_4) with >90% CH_4 content at 300°C and 10 bar, achieving 95% CO_2 conversion and 100% selectivity in a single stage.
- **Oxy-fuel Combustion:** SIDENOR has installed a new oxy-combustion burner for ladle heating,

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aiming to reduce natural gas consumption and CO_2 emissions while maintaining optimal refractory temperatures. Thermocouples and Computational Fluid Dynamics (CFD) simulations by TECNALIA have been used to define and optimise the heating curve, with upcoming efforts focused on improving energy efficiency and refractory longevity.

- **Carbonation of Steel Slags:** SIDENOR's electric arc furnace (EAF) and ladle furnace slags have been characterised and tested for their CO_2 sequestration potential. Batch tests in a spouted bed reactor with optimised slag grain sizes (0–2 mm) showed up to 76 g CO_2/kg uptake, demonstrating the importance of conditioning and slag type. This process valorises industrial residues while contributing to permanent CO_2 storage in building materials.

In parallel, O_2 and H_2 produced via electrolysis will support low-carbon combustion processes, especially in steelmaking. O_2 generated through electrolysis will be used for oxy-combustion in steel production, with potential applications in other sectors being explored as part of the HUB's expansion plan. This O_2, along with H_2—particularly from electrolysis infrastructure connected to the oil refining sector—will enable significant reductions in carbon emissions across high-temperature processes. Captured CO_2 from lime production will be utilised in carbonation reactions with steel slags to produce construction materials for the cement industry, thereby transforming industrial residues into valuable secondary raw materials. This synergy is already being demonstrated under real operating conditions and represents a critical pathway to close the carbon loop. Additionally, the potential use of captured CO_2 to produce synthetic CH_4 and support e-fuel production in the oil refining sector is currently under assessment, further reinforcing the integrated and circular approach of the HUB.

Exemplifying this collaborative approach, pilot activities at SIDENOR's steel plant will demonstrate the use of oxy-combustion and H_2 burners, supported by infrastructure provided by PETRONOR (oil refining) and NORTEGAS (gas distribution). These partnerships facilitate the sharing of circular by-products and enable cross-sector resource optimisation.

In terms of HUB expansion, **IS2H4C** will explore the integration of **biocoke and biogas**—derived from urban waste pyrolysis— substitutes for fossil-based fuels in the cement, lime, and steel industries, as well as in other energy-intensive sectors such as pulp & paper and oil refining. In particular, biocoke will be assessed as a replacement for coal-based coke, while biogas will be evaluated as an alternative to natural gas. The **deployment of H_2** in these industries is also under consideration to support low-carbon industrial processes. Additionally, the feasibility of expanding oxy-combustion technologies—currently demonstrated in the steel sector—to other industries will be assessed.

The HUB will further investigate the role of wastewater treatment in supporting green H_2 production through electrolysis, creating synergies between water management and energy systems. In parallel, an expansion study will assess the potential of producing biofuels using biogenic CO_2 obtained as a result of wastewater treatment, offering a new pathway to valorise unavoidable emissions and integrate bio-based circularity into the industrial ecosystem.

BIH4C begins at a systemic TRL 5, drawing on existing H_2 pipelines and electrolysers, and targets a systemic TRL of 7 by the project's end. The HUB also integrates innovative CO_2 capture and utilisation (CCU) technologies, including solutions developed through partnerships with actors such as SBS-Thermal Technologies, CALCINOR, and LOINTEK. These collaborations demonstrate advanced CCU applications under real industrial conditions (TRL7) and serve as a reference model for IS.

The supply and demand of by-products and gases will be dynamically managed based on industrial needs. For example, **O_2 and H_2 supplied by PETRONOR** will support processes in steel, foundry, cement, and lime sectors. Meanwhile, **CO_2 captured from lime and cement production** will be utilised in **PETRONOR's e-fuel production**, fostering a mutually beneficial and economically efficient ecosystem.

The development of these industrial synergies is actively supported by the DCARTECH Alliance, coordinated by the Basque Energy Cluster in cooperation with sectoral platforms such as ACLIMA, SIDEREX, and CLUSTERPAPEL. Through quarterly forums, the alliance brings together over 150 representatives from industries and research institutions to foster innovation, exchange knowledge, and co-develop viable decarbonisation pathways aligned with circular economy principles.

The table below presents a consolidated baseline of the Basque HUB's resource consumption, emissions profile, and technological developments. This assessment highlights both current industrial performance and emerging opportunities for decarbonisation, circularity, and cross-sector innovation.

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Table 3: Baseline assessment of the Basque HUB's energy consumption, emissions, and technological capabilities.

<table>
<tr><td rowspan="6">Data Collected*
(Average annual consumption)</td><td>Non-Renewable Electricity</td><td>Data not available</td></tr>
<tr><td>Renewable Electricity</td><td>Data not available</td></tr>
<tr><td>Total Electricity</td><td>Data not available</td></tr>
<tr><td>Total Energy**</td><td>5,485,117.20 MWh</td></tr>
<tr><td>Total GHG Emissions</td><td>2,504,208.07 tCO_2eq</td></tr>
<tr><td>Total Water</td><td>2,500,000.00 m³</td></tr>
<tr><td>Data limitations</td><td colspan="2">Accurately determining the share of renewable vs. non-renewable electricity in the HUB is challenging due to varied company-level practices, such as green electricity contracts and CHP systems feeding the grid. This obscures the true energy mix and limits assessment of decarbonisation progress. Additionally, emissions data lacks detail on specific pollutants beyond CO_2 equivalents, hindering comprehensive environmental management. Waste data is also incomplete, preventing evaluation of circularity and recycling performance. Improved data granularity is essential for aligning with EU climate and circular economy goals.</td></tr>
<tr><td>Critical Analysis</td><td colspan="2">Energy Consumption
• Strong Reliance on Fossil Fuels: The HUB shows a predominant dependence on fossil fuels, particularly natural gas, making it the primary energy source. Other non-renewable fuels such as fuel oil, diesel, and coke contribute further to the overall carbon-intensive energy mix.
Emissions Profile
• High GHG Emissions Consistent with Fossil Use: With 2,504,208.07 tCO_2eq reported, the HUB's emissions are in line with its heavy fossil fuel use. This level of emissions underscores the urgent need for systemic decarbonisation strategies, such as fuel switching, CC, and greater energy efficiency.
Water Use and Waste Management
• Significant Water Withdrawal Without Circular Practices Evident: The HUB records 2,500,000 m³ of total water consumption, but lacks data on water withdrawal versus discharge, as well as on water recycling or reuse. This gap hinders the assessment of the water circularity performance, especially relevant in the context of increasing water scarcity and industrial water efficiency targets.</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Current Technologies</td><td colspan="2">• CO_2 transport prototype from CALCINOR to LOINTEK.
• Membrane module connections checked.
• PSA system dimensioning and partial redesign (vent purge & heating/cooling).
• Thermal insulation and flue gas intake assessments.
• Industrial flue gas analysis.
• Slag selection and basic characterization (EAF, LF, mixed).
• Design of carbonation protocols and first carbonation trials.
• Installation of burner and purchase completed.
• CFD setup and steady-state simulation (NG/O_2 combustion).</td></tr>
</table>

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HUB Synergies	The HUB aims to establish key **demonstrated and planned synergies**: • (i) Oxy combustion using electrolytic O_2 and green H_2 in the steel sector, sourced from future electrolysis facilities in the oil refining sector. • (ii-iii) CO_2 captured from the lime industry will be used to **methanation** (produce CH_4) and, potentially, for future e-fuel synthesis in oil refining. • (iv) Steel slags will undergo carbonatation using captured CO_2 from lime production to create construction materials, aligning with circular construction strategies.
Other Opportunities for HUB Optimisation	1 Integration of decentralised energy clusters, such as community-based H_2 production and storage in industrial parks. Use of AI for predictive energy balancing. 2 Carbon-negative products from slag carbonation, positioned as certified construction materials. AI-driven emissions forecasting tools linked to production planning. 3 Valorisation of treated effluents for electrolyser feedwater or IS with agriculture via nutrient recovery. 4 Circular Procurement: Adopting procurement practices that prioritise reused, recycled, or modular products will foster market demand for circular solutions and reduce upstream impacts. 5 Create a regional industrial cloud for real-time optimisation of synergies, including dynamic gas exchange (H_2, CO_2, O_2) and water-energy-nutrient nexus. Deploy digital twins of pilot facilities for scenario modelling.

*Data has been normalised to preserve confidentiality and to address constraints associated with data aggregation.

**Total Energy = Total Electricity Consumption (Renewable + Non-renewable electricity usage) + Total Direct fuel energy consumption (energy from combustion or use of the fuel itself)

The Basque HUB exemplifies a mature and strategically aligned regional initiative with a strong foundation for advancing industrial decarbonisation and circularity. By leveraging existing infrastructure, multi-sectoral synergies, and robust stakeholder engagement, the HUB demonstrates a practical and scalable model for systemic transformation. As **IS2H4C** progresses, the BIH4C is expected to serve not only as a demonstration site but also as a replicable blueprint for other industrial regions across Europe, contributing meaningfully to the EU's climate neutrality and circular economy ambitions.

4.1.3. Dutch HUB

The Dutch HUB, centred around H2HUB Twente and Aadorp, serves as an experimental and collaborative environment where entrepreneurs, researchers, public institutions, and knowledge centres co-develop H_2-based technologies and circular energy solutions. Through research and infrastructure testing, knowledge and experience are cultivated to drive innovation in setting up (pilot) projects in key areas such as energy generation and storage, mobility, high-temperature combustion, industrial processes, and applications in the built environment. Located in the Twente region, this HUB champions localised energy transitions, with a strong focus on self-sufficiency, decentralisation, and the replacement of fossil fuels with renewable alternatives.

The HUB is anchored by H_2HUB Twente, Almelo Energie, University of Twente and SOLENCO, and benefits from strong support from the municipality of Almelo, the regional grid operator COGAS/Coteq, Waterschap Vechtstromen, and other local stakeholders. It brings together renewable energy generation, H_2 distribution, circular water management, and urban-industrial symbioses to form a model for integrated circular energy systems.

At the heart of the Dutch HUB is the ambition to transform Aadorp into one of the Netherlands' first **Positive Energy Districts**, fully eliminating natural gas use and reducing dependence on centralised energy distribution. Through demand-side flexibility, load shifting, and energy storage, the district aims to optimise local energy flows and enhance sustainability at neighbourhood scale. Almelo Energy, based in Twente, is leading this transition and serves as a regional pioneer in decentralised, net-positive

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neighbourhood energy systems. By enabling local energy balancing, peak shaving, load shifting through demand response, and increasing self-consumption at the district level, they provide a replicable model for clean, integrated energy systems. This approach not only showcases how decentralised systems can optimise resource use and enhance sustainability but also aligns directly with Twente's broader regional goals for decarbonisation.

Aadorp / Almelo Energie

The pilot programme in Aadorp will serve four local users: two homes, a small business, and a community centre, each transitioning from natural gas to green H_2 **(synergy iii)**. H_2 will be supplied by H2HUB Twente and injected into a dedicated local distribution network developed by COGAS **(synergy i)**. Preparations for infrastructure and regulatory approvals, particularly from the Dutch Authority for Consumers and Markets (ACM), are ongoing, with initial operations expected by autumn 2026. Public engagement and social co-creation activities are also being conducted to address safety, reliability, and affordability concerns, following principles from the Economy for the Common Good.

H_2Hub Twente

The H_2Hub (Figure 6) benefits from an established ecosystem that already includes solar-powered H_2 production infrastructure. The site hosts two major photovoltaic (PV) fields, with a combined installed capacity of 1MWp. Each PV field operates independently, connected to dedicated inverters that feed the converted DC energy into the site's local AC network. A 70-kW alkaline electrolyser is available on site, complete with the full balance of plant required to produce both Grade A and Grade B H_2, serving various applications such as fuel cell operation, combustion testing, and research activities. The H_2Hub Twente ecosystem includes strategic partners located on adjacent plots. One is the wastewater treatment facility managed by the regional waterboard, which treats municipal sewage into biologically clean water discharged back into Dutch waterways. Another key partner is Crematorium Twente, which operates four cremation centres across the region. Crematorium Twente is currently transitioning away from fossil fuels towards renewable energy, and H_2Hub Twente has been supporting this shift from the outset, with a specific focus on integrating H_2-based solutions. Once Crematorium Twente completes its technical preparations, H_2Hub Twente will supply H_2 to its eligible sites (**synergy v**). To complement PV generation and enhance renewable energy stability, wind turbines with a minimum combined capacity of 70 kW will be installed (**synergy ii**), together with an energy storage system of at least 1.4 MWh (**synergy iv**). These assets will be integrated with the electrolyser to enable continuous 24/7 green operation, reducing dependence on the public electricity grid. A certified green electricity contract will serve as a backup power source. Furthermore, smart control systems will be deployed to ensure advanced load management and participation in demand response schemes. Much of this functionality is already embedded within the energy management system (EMS) of the selected storage units; it will be further configured and optimised to maximise the overall performance and efficiency of the H_2Hub ecosystem once operational.

According to the overall and detailed implementation plan, H_2Hub Twente scheduled the project with the regional waterboard to commence in the second half of the project period. All necessary resources and infrastructure must be fully installed and commissioned before the supply of O_2 can begin. As the waterboard is a semi-public organisation, H_2Hub Twente maintains regular discussions with its representatives to ensure that key decision-makers are informed and prepared for the pilot to start according to the planned timeline. Prior to including this activity in the GA, H_2Hub Twente and the waterboard signed a project contract defining the terms for O_2 delivery and process water supply (see **synergy vi** and **synergy vii**).

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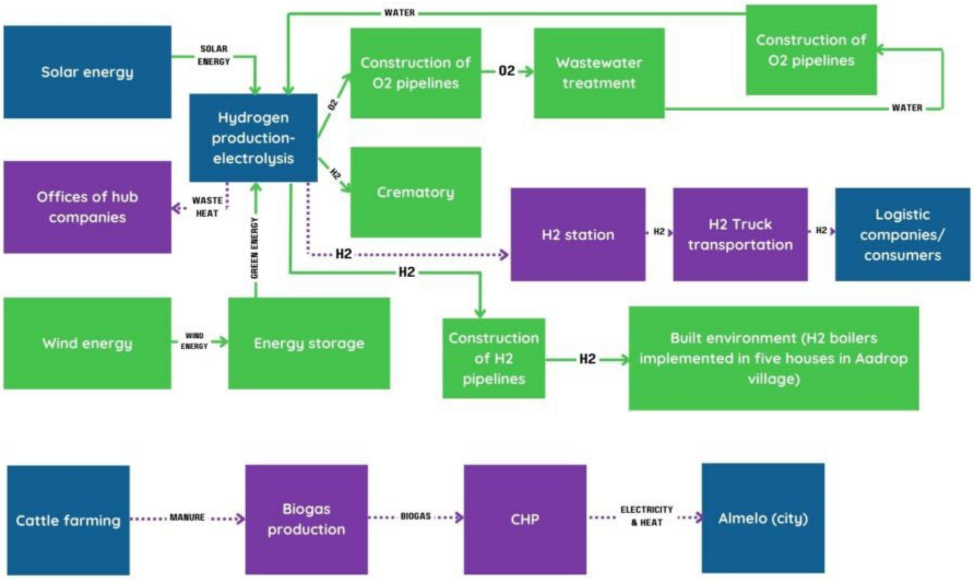

Figure 6: Dutch HUB Flow Diagram.

Under **IS2H4C**, several key synergies will be demonstrated:

(i) **D.P1:** H_2 pipelines will be constructed by Cogas (local grid operator) to inject green H_2 produced by H_2HUB Twente. The HUB's production is powered by 1MWp solar energy and 70 kW of wind capacity (to be implemented), connected to 70 kW alkaline electrolyser. The H_2 will be supplied to two residential houses, one community centre, and one small business located in Aadorp village, meeting their heating demand with green H_2.

(ii) **D.P2:** To complement existing solar generation, wind turbines with a minimum total capacity of 70 kW will be installed by H_2Hub Twente. This addition will provide a diversified renewable energy mix for the electrolyser system, ensuring stable H_2 production during periods of low solar irradiance.

(iii) **D.P3:** Two residential houses, one small business, and one community centre (four buildings in total) in Aadorp will be disconnected from the natural gas grid and supplied with green H_2 via repurposed and newly constructed pipelines. This initiative will be supported by Almelo Energy and Solenco and aims to demonstrate the feasibility of H_2-based heating systems in small-scale built environments. This configuration reflects a deliberate effort to mirror the diversity of real-world energy users and optimise the representativeness of the demonstration. By integrating a small enterprise and a large community centre alongside residential households, the pilot captures a broader range of demand profiles and consumption patterns, enhancing its technical relevance and scalability. Particularly, the inclusion of the community centre, an emblematic social facility, also enriches the project's engagement dimension, fostering stronger ties with local stakeholders and aligning with the Living Lab approach under WP3. Through this setup, the Dutch HUB promotes both technological demonstration and social co-creation, anchoring H_2 integration within the fabric of local communities.

(iv) **D.P4:** A 1.4 MWh energy storage system will be deployed by H_2Hub Twente to buffer intermittent solar and wind generation, stabilise H_2 production, and enable 24/7 operation of the electrolyser using locally produced renewable energy. This measure will enhance system reliability and overall resilience.

(v) **D.P5:** Green H_2 produced at H_2Hub Twente will be transported via H_2 trucks to supply a regional crematorium, where it will replace natural gas as the main fuel source for one of its high-temperature ovens. This substitution will significantly reduce CO_2 emissions and serve as a practical demonstration of H_2's potential in high-temperature industrial and service applications. The partnership with Crematorium Twente, which operates multiple facilities across the region, marks an important step in extending H_2 applications beyond the energy sector. One of the cremation ovens at the Enschede site is currently being converted from natural gas to H_2, with fuel supplied directly from H_2Hub Twente via tube trailers. This collaboration provides a unique

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testbed for validating H_2's performance, safety, and logistics in high-temperature processes, while contributing to the decarbonisation of essential public services. It also strengthens regional know-how on H_2 distribution and infrastructure compatibility, creating synergies between industrial innovation, environmental responsibility, and community value.

(vi) **D.P6:** The O_2 generated as a by-product of electrolysis will be supplied to the adjacent wastewater treatment facility, operated by the regional waterboard. The O_2 will be used to enhance biological purification processes, partially replacing externally sourced O_2, and thereby reducing energy demand for aeration. This integration creates a circular, resource-efficient link between green H_2 production and sustainable wastewater treatment, improving system efficiency and environmental performance.

(vii) **D.P7:** Treated water from the adjacent wastewater treatment facility will be recirculated into the electrolyser system, creating a closed-loop water cycle that conserves freshwater resources and eliminates the need for alternative water sources in a region prone to water scarcity. This activity will be jointly implemented by H_2Hub Twente and the waterboard.

The following table provides an overview of the Dutch Hub's synergies and their corresponding impacts, illustrating how the activities described above are interconnected within the H_2Hub Twente ecosystem.

Table 4: Overview of Dutch HUB synergies and their impact.

Synergy	Impact
DP1	Replaces natural gas with green H_2 for building heat demand, reducing approximately 32.82 tonnes of CO_2 emissions per year.
DP2	Avoids approximately 1,740 tonnes of CO_2 emissions annually and contributes to a 65% reduction in carbon footprint within the surrounding residential area.
DP3	Achieves an annual reduction of around 32.8 tonnes of CO_2 emissions through substitution of natural gas.
DP4	Stabilises H_2 production by buffering renewable energy intermittency, enabling 24/7 operation and improving overall system resilience.
DP5	Significantly reduces CO_2 emissions and showcases the practical application of H_2 in high-temperature industrial and service processes beyond the energy sector.
DP6&DP7	Avoids approximately 306 tonnes of CO_2 emissions per year through process integration. Saves energy required to treat about 400 million litres of wastewater annually. Enables the reuse of ~8,000 tonnes of O_2 by-product and treated water in electrolysis, reducing energy consumption by 18%. Additionally, the reuse of waste heat within office facilities avoids approximately 34% of energy losses.

Further exploration will include:

- **D.E.1:** Biogas will be produced using manure sourced from local cattle farms in the Twente region, contributing to regional renewable energy generation and circular resource utilisation.
- **D.E.2:** Biogas produced from local agricultural manure will be utilised to replace natural gas in a combined heat and power (CHP) system serving the city of Almelo. This initiative offers a dual environmental benefit: reducing agricultural nitrogen emissions while supporting decentralised renewable energy generation. It directly contributes to the Dutch Hub's ambition of establishing interconnected, circular energy systems that integrate H_2, biogas, and waste heat for sustainable regional development.
- **D.E.3:** Waste heat generated during the electrolysis process will be recovered and repurposed for space heating in office buildings, thereby reducing dependence on natural gas boilers and improving overall energy efficiency.
- **D.E.4:** H_2 distribution will be expanded to logistics companies and end-users through refuelling stations and tube trailers, providing a low-carbon alternative to diesel-based transport.
    - H_2 refuelling stations will have a capacity between 200–1,000 kg/day, achieving an estimated

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CO_2 reduction of ~19,274 tonnes, assuming a 70-kW electrolyser.

- A full-scale 5 MW electrolyser implementation could produce approximately 2 tonnes of H_2 per day, leading to an annual CO_2 reduction of around 20,000 tonnes, based on deployment across five stations.

- **D.E.5:** These developments will support the regional decarbonisation of the transport sector and facilitate the broader adoption of H_2 mobility, reinforcing the Dutch HUB's leadership in sustainable, circular, and interconnected energy systems.

These initiatives are part of a broader effort to increase the TRLs of key systems, which reflect the HUB's commitment to building a resilient and future-proof H_2 economy:

- **Waste Heat Recovery (TRL5 → TRL7):** Waste heat generated from the electrolysis process will be recovered and reused for space heating in nearby office buildings, reducing dependence on natural gas boilers and improving overall system efficiency.
- **Oxygen Utilisation in Wastewater Treatment (TRL8 → TRL9):** O_2, produced as a by-product of electrolysis, will be supplied to the neighbouring wastewater treatment plant located directly beside H_2Hub Twente. This synergy closes the loop between H_2 production and water treatment, demonstrating an advanced circular resource integration approach.
- **Water Reuse in Electrolysis (TRL6 → TRL8):** Treated effluent from the wastewater treatment facility will be recirculated into the electrolyser system, establishing a closed-loop water cycle that conserves freshwater resources and avoids the use of other water sources in a region prone to water scarcity. The reuse of treated effluent as process water for electrolysis will be scaled from TRL6 to TRL8, verifying long-term reliability, water quality control, and operational stability.
- **Regional Circular Economy and Industrial Integration**: The increased O_2 availability may attract regional industries that use O_2 as a key resource (e.g., wastewater treatment, chemical, and metallurgical sectors). The HUB also serves as a regional innovation and demonstration centre, offering infrastructure testing, consulting, and training for stakeholders interested in H_2 technology. Successful demonstration of H_2 in the built environment could lead to infrastructure investments for broader deployment. Located between the North Sea–Baltic and Rhine–Alpine transport corridors, the H_2 station's position could attract international logistics operators using H_2-powered vehicles.
- **Biogas Integration and District Heating:** A biogas digester using locally available cattle manure will produce renewable energy while simultaneously reducing nitrogen emissions from livestock farming—one of the major environmental challenges in the Netherlands. The biogas can replace natural gas in a CHP plant, supplying both electricity and heat to the district heating system in Almelo. This integration supports Dutch climate goals and demonstrates cross-sectoral synergies between agriculture, energy, and urban sustainability.

These advancements are supported by ongoing system integration efforts, such as co-locating energy assets to maximise spatial efficiency and combining waste heat recovery with heat pump systems for low-carbon heating solutions.

The core objective is to demonstrate the technical viability, regulatory compliance, and safety of H_2 distribution at the local level. Special focus is placed on adhering to strict safety standards and protecting consumers during all stages of design and implementation.

The planned pipeline route presents several technical and environmental challenges:

- Tree-Protected Zones: In areas where mature trees line the route, excavation is restricted to protect root systems and local biodiversity. These sections require horizontal directional drilling instead of open trenching.
- Congested Underground Infrastructure: Other segments pass through areas with dense networks of existing infrastructure, such as gas pipelines and electrical cables. Directional drilling is also required here to avoid damaging these assets.

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While directional drilling is a feasible alternative, it is significantly more expensive than traditional methods and will also increase future decommissioning costs due to the complexity of pipeline removal.

Although the Dutch HUB is still in its pre-operational phase, the emerging technologies and planned synergies already reflect a strong foundation for circular and decentralised energy systems. The overview below (Table 5) outlines the initial technological developments and strategic integration pathways that will be monitored as the HUB progresses toward full implementation.

Figure 7: Proposed pipeline route at Almelo

(Blue: Reuse of an existing gas pipeline (which still requires verification for hydrogen suitability), approximately 700 meters. | Yellow: New pipeline installation using standard excavation, approximately 1,500 meters. | Orange: New pipeline constructed through directional drilling (at six locations), totalling 900 meters.)

Table 5: Pre-operational overview of technological initiatives and planned synergies at the Dutch HUB.

Data Collected	At present, the Dutch HUB remains in a **pre-operational phase**. While the foundational concepts and stakeholder network are well-established, the physical infrastructure and demonstration activities are still under development. As such, **no baseline data for energy consumption, emissions, or resource flows is yet available**. However, this offers a unique opportunity to monitor the HUB's progress **from its inception**, allowing for rigorous tracking of environmental performance, innovation uptake, and impact delivery throughout the implementation of **IS2H4C**. In this sense, a preliminary benchmark data collection was made in two houses, one community centre and a small business in built environment in Aadorp: • Total natural gas consumption= 16,408.5 Nm^3 NG/year • Total GHG emissions= 32.82 tonnes CO_2/year
Critical Analysis	**Energy Consumption** Exact energy consumption data are currently unavailable, as individual units were not metered in the past. Between 2020 and 2021, the cooperative Coöperatie Waardemakers in Waterstof UA selected a former high-tech factory building in Almelo as the home of H_2Hub Twente. Originally constructed in the mid-20^{th} century, the site served for decades as a global production centre for sensor and electronics technologies, establishing a strong foundation of innovation and technical expertise. Today, that legacy is being redefined to drive forward the H_2 economy. While the building's history is rooted in advanced electronics manufacturing, its future lies in enabling sustainable energy solutions. Since historical energy data were not recorded for earlier operations, new performance baselines will be established as H_2Hub Twente evolves into a centre for clean-energy innovation. The following estimations are based on equipment in operation and staff interviews: • **Electrolyser and auxiliary equipment:** ±105 kW/h before relocation; estimated at 120 kW/h at the new site, including the 70-kW stack • **Office energy consumption:** ±20 kW/day based on heat pump specifications and staff occupancy.

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	• **EV charging station:** ±150 kW per week. • **Heat demand:** 164 MWh/year for two houses, one community centre, and a small business in Aadorp. **Emissions Profile** The site at Kolthofsingel 8, shared by H2Hub Twente and other tenants, was disconnected from the natural gas grid by the current owner in 2016. The location holds an A+++++ energy label issued by the competent Dutch authority. Electricity demand is fully met by on-site PV fields, with production exceeding the combined consumption of all tenants. In periods of low solar activity, the owner has secured a green electricity contract with the grid operator to ensure continuous renewable energy supply. As a result, the site's carbon emissions are effectively neutral, aligning with the objectives of H_2Hub Twente to demonstrate sustainable energy use within industrial and community settings. **Water Use and Waste Management** • The electrolyser is designed for continuous operation using deionized water, corresponding to an annual consumption of about 15 lit/hr. • Waste streams are fully separated. Everyday waste such as plastics, paper, and general materials is collected by a third-party operator for appropriate processing. • Chemical waste, including the electrolyte used in the electrolyser, is collected by a specialised company for recycling or safe disposal, depending on the material condition. • Treated water reuse within the process is being developed as an innovative and circular solution to minimise resource demand. • Future plans include establishing biogas production using manure and other circular resource streams, further enhancing the site's contribution to local circular economy initiatives.
Current Technologies	• 1 MWp of solar PV fields: Two independent PV fields are installed on site, each connected to its own inverter to feed the converted DC energy into the site-wide AC network. • Solar-powered electrolysis for green H_2 production: A 70 kW alkaline electrolyser stack, including the full balance of plant, is available on site to produce Grade A and Grade B hydrogen for various uses (fuel cells, combustion tests, and research experiments). • 1.4 MWh battery storage system: Integrated with an advanced energy management system, the battery provides grid balancing and optimises the use of locally generated renewable power. • On-site wastewater treatment facility: Located approximately 100 metres from the H_2 hub, the plant treats sewage water to biologically clean water, which is then safely discharged back into the Dutch waterways. • H_2-fuelled crematorium: A crematorium equipped with one oven has been adapted to operate using hydrogen instead of natural gas, demonstrating the potential for decarbonising heat-intensive processes. • Initial development of H_2 pipelines: Construction design has begun to enable the injection of green hydrogen into the local distribution network (e.g.

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	supplying households in Aadorp).
HUB Synergies	The Dutch HUB comprises a network of approximately 20 industry actors linked to H_2HUB Twente. The H_2 pipeline will connect four buildings contributing to the Positive Energy District of Aadorp. The planned synergies are aggregated as follows: • (i–ii–iii) Use of solar- and wind-powered green H_2 to supply two houses, one community centre and a small business in Aadorp through newly developed and repurposed H_2 pipelines. • (iv) Installation of energy storage systems to stabilise electricity supply and address intermittency in renewable energy generation. • (v) Feasibility study for delivery of H_2 to three crematoria in the Twente region via tube trailers, substituting natural gas. • (vi–vii) Direct utilisation of O_2 from electrolysis in wastewater treatment, with treated process water returned to the electrolyser, creating a closed-loop system for resource efficiency.
Other Opportunities for HUB Optimisation	1 Peer-to-peer energy trading using blockchain in Positive Energy Districts. Introduce hybrid PV–wind–biogas microgrids to balance fluctuations. 2 Real-time carbon footprint dashboards linked to district-level emissions pricing and offset mechanisms. 3 Use of bio-electrochemical systems to clean wastewater and produce low-grade H_2 for less critical applications. 4 Circularity by design: require industrial partners to pre-declare material recovery strategies for all pilot assets. 5 Gamification of household energy behaviour in Aadorp to align consumption with H_2 availability. Digital twins for dynamic H_2 grid management.

This configuration highlights the strong synergy between H_2HUB Twente and Almelo Energie, showcasing Twente's potential to become a frontrunner in developing an integrated, H_2-powered circular economy.

4.1.4. German HUB

The German HUB is anchored in Industriepark Höchst, one of Europe's most established industrial complexes, located in Frankfurt / Main. Founded in 1863, the park spans 4.6 km² and hosts approximately 90 companies across the chemical, pharmaceutical, and biotechnology sectors. It includes 120 production plants and over 980 buildings, employing more than 22,000 people. Operated by Infraserv Höchst, a dedicated industrial site manager, the park offers integrated services including energy supply, logistics, environmental management, and safety systems—providing a stable and innovation-ready environment for industry.

Industriepark Höchst is strategically positioned at the core of European transport and industrial corridors, with excellent multimodal connectivity (rail, road, air, and inland waterways), reinforcing its role as a logistics and manufacturing HUB.

The HUB builds on the existing Process4Sustainability cluster, which provides a coordinated framework for advancing industrial decarbonisation. The cluster focuses on key enabling technologies such as **Carbon Capture and Storage (CCS), Carbon Capture and Utilisation (CCU), H_2, heat pumps, and bio-based feedstocks**. These technologies support the deployment of **Power-to-X** (PtX) solutions—including **Power-to-Gas (PtG), Power-to-Liquids (PtL), and Power-to-Chemicals (PtC)**—positioning the site as a testing ground for carbon-neutral production pathways.

Carbon Capture (CC) is a central strategic pillar of the HUB. Given the site's annual methanol demand of approximately 300,000 tonnes, the local capture of CO_2 is of high interest—particularly from biogenic sources, which are considered climate-neutral. The sewage sludge incineration plant (SSIP) at

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Industriepark Höchst has been identified as a key asset for this purpose. Operating two lines with a total capacity of 225,000 tonnes per year, it processes a range of biogenic and non-biogenic waste streams. Initial studies confirmed that around 35% of the CO_2 in the flue gas is biogenic, making it highly suitable for climate-neutral methanol synthesis and other CCU applications.

A major strategic focus is the development of Sustainable Aviation Fuels (SAF), aligning with the EU's ReFuelEU Aviation Regulation, which sets binding SAF targets (2% by 2025, 70% by 2050). The park hosts the start-up companies CAPHENIA and INERATEC, which strive to produce SAF, by utilising captured CO_2 and renewable energy to synthesise low-carbon fuels, currently focusing on intermediary products such as synthesis gas (e.g. by Caphenia). These efforts are supported by CENA Hessen (Centre of Competence for Climate, Environment and Noise Protection in Aviation), an initiator for a sustainable future of aviation.

Complementing these activities, **IS2H4C** supports a comprehensive CC initiative using a pilot plant developed by GEA. Installed in 2025 with temporary authorisation, this facility extracts flue gas from the SSIP, separates CO_2 through amine-based absorption, and collects operational data on energy consumption, solvent stability, and CO_2 purity. Early results will guide optimisation of full-scale deployment, which could reach up to 50,000 tonnes of CO_2 captured annually.

The German HUB aligns closely with national and European strategies, including the EU Green Deal, the Circular Economy Action Plan, the Net-Zero Industry Act, and Germany's climate neutrality targets. Its multi-technology focus and strong industrial base make it a critical actor in Europe's clean transition, combining decarbonisation, circular economy principles, and industrial resilience.

The **IS2H4C** project will build on the park's extensive infrastructure—spanning chemical production, energy generation, wastewater treatment, and electrolysis—to demonstrate integrated IS solutions (Figure 7).

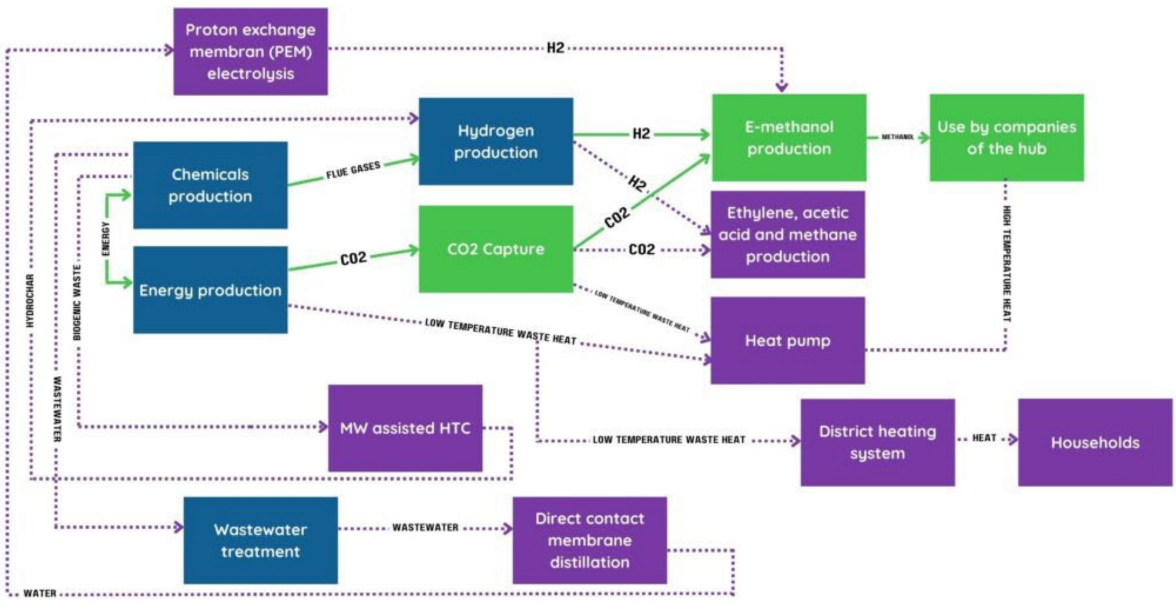

Figure 8: German HUB Flow Diagram.

The key synergy to be implemented is the **production of e-methanol from H_2 and captured CO_2**, which will substitute fossil-based methanol in chemical and pharmaceutical production processes. The H_2 will be sourced from the site's existing electrolysis units, which also recover industrial waste heat, while the CO_2 will be captured from an on-site incineration plant operated by Infraserv Höchst. Notably, this CO_2 stream contains a significant share of biogenic content, supporting truly climate-neutral synthesis. This closed-loop integration demonstrates a viable pathway towards decarbonised and circular industrial production.

In addition to the core demonstrations, **IS2H4C** will explore several **expansion opportunities**:

- The synthesis of ethylene, acetic acid, and CH_4 from the combination of captured CO_2 and green H_2, offering alternative low-carbon feedstocks for the chemical industry.

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- The deployment of Proton Exchange Membrane (PEM) electrolysis for enhanced e-methanol production efficiency and flexibility.
- The use of industrial waste heat for district heating through high-temperature heat pumps, supporting energy symbiosis between the park and surrounding urban areas.
- The recovery of excess industrial heat for use in residential heating systems.
- The conversion of biogenic waste from chemical production into carbon-rich materials for H_2 generation through microwave-assisted hydrothermal carbonisation (HTC).

Ongoing studies are also examining the integration of captured CO_2 into methanol-to-SAF conversion pathways. Preliminary discussions with partners such as Fraunhofer aim to establish a roadmap for scale-up.

These additional pathways vary in technological maturity, but are expected to advance significantly throughout the project, further strengthening the role of Industriepark Höchst as a key enabler of Europe's industrial decarbonisation and circular economy ambitions. While H_2 electrolysis is currently at Technology Readiness Level (TRL) 6, other processes—including CC, membrane distillation, and HTC—are progressing through various stages of demonstration and validation. The overall systemic TRL at the German HUB is **expected to advance from 5 to 7 by the end of the project**.

Industriepark Höchst is expected to play a catalytic role in accelerating the deployment of CC and H_2 technologies. The development of these solutions—alongside ethylene, acetic acid, and CH_4 synthesis—is anticipated to drive sustained investment in enabling infrastructure, including CC units, electrolysis systems, and heat integration technologies. These advancements, underpinned by the park's strategic focus on IS and circularity, are designed to align with viable long-term business models for sustainable industry. As the ecosystem evolves, it is likely to attract further infrastructure investments and incentivise broader participation in shared-cost initiatives among companies located within the HUB.

To support the development of circularity and decarbonisation strategies, the table below (Table 6) presents a consolidated baseline of Industriepark Höchst's resource consumption, emissions profile, and technological capabilities. This assessment highlights both the current performance and the opportunities for systemic improvement.

Table 6: Baseline assessment of the German HUB's energy consumption, emissions, and technological capabilities

Data Collected* *(Average annual consumption)*	Non-Renewable Electricity	1 307 490,00 MWh
	Renewable Electricity	296 010,00 MWh
	Total Electricity	1 603 500,00 MWh
	Total Energy**	5 569 030,00 MWh
	Total GHG Emissions	1 387 402,00 $tCO_{2\text{-eq}}$
	Total Water	3 500 000,00 m^3
Data limitations	Lack of Granular Data: The analysis is constrained by the availability of data from only one HUB company, while data from other participating entities of Industriepark Höchst is currently unavailable. Disaggregated data from all relevant stakeholders is essential to enhance the precision of the assessment and to develop tailored circularity strategies.	
Critical Analysis	The baseline data for the Industriepark Höchst HUB provides an essential snapshot of energy consumption, emissions, water use, and waste management from 2019 to 2022. **Energy Consumption** • <u>Heavy Reliance on Non-Renewable Sources</u>**:** The HUB remains largely dependent on non-renewable sources, with over 5,229,960 MWh from non-renewable electricity and extensive use of natural gas. This reliance is a critical barrier to sustainability, especially given the circularity goals of minimising environmental impact and resource depletion.	

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	• Underutilisation of Renewable Energy: Renewable electricity consumption shows a modest upward trend but remains at just 1,184,040 MWh over the period. Expanding renewable energy integration will be crucial for reducing emissions and achieving circular energy flows. • Waste-to-Energy Potential: Energy derived from waste contributes significantly to the energy mix, with 1,402,340 MWh in 2019. Although this figure has declined slightly over time, it reflects a foundation for resource recovery. However, optimisation and scaling of waste-to-energy systems could unlock greater circularity benefits. **Emissions Profile** • Declining GHG Emissions: The total GHG emissions have decreased steadily, from 1,537,481 $tCO_{2\text{-}eq}$ in 2019 to 1,442,508 $tCO_{2\text{-}eq}$ in 2023. This reduction aligns with efforts to improve energy efficiency and shift toward lower-carbon sources. However, the rate of decline is not sufficiently ambitious to meet climate targets or circularity goals. • Air Emissions Remain High: Emissions to air remain proportionally significant, driven by the reliance on fossil fuels. Investments in cleaner production technologies and emissions reduction measures, such as CC, will be necessary to accelerate decarbonisation. **Water Use and Management** • High Water Dependency with Specific Sources: The HUB withdraws approximately 69.5 million m³ of water annually, with 95.1% sourced from rivers, 4.5% from wells, and 0.4% from municipal drinking water. This indicates a heavy reliance on natural water bodies, particularly for cooling processes. • Efficient Water Discharge with Cooling Dominance: Of the 66 million m³ of discharged water, most river water is assumed to be used for cooling. While this implies low contamination risks, the practice highlights opportunities for integrating advanced cooling technologies, such as closed-loop cooling systems, to reduce freshwater dependency. • Stable Water Consumption: Total water consumption (3.5 million m³ annually) represents only a fraction of the withdrawn water, reflecting efficient cooling and minimal process water use. However, there is no evidence of water recovery or recycling systems, which limits the HUB's circular water management potential.
Current Technologies	• Chemicals Production: Established industrial base with 120 production plants supporting the pharmaceutical and chemical industries. Emerging focus on e-methanol, ethylene, acetic acid, and CH_4 production from captured CO_2 and H_2. • Energy Production: Significant industrial heat and power generation, including waste-to-energy systems, with ongoing investments in CC technologies to reduce emissions. • H_2 Production: Existing electrolysis facilities producing H_2, with plans to integrate industrial waste heat to improve efficiency and scale up production. H_2 from PEM electrolysis is currently at TRL6, with further advancements expected. • Wastewater Treatment: Well-developed wastewater management, with opportunities to use membrane distillation and electrolysis for H_2 production. Plans to optimise water recycling and closed-loop cooling for improved sustainability.

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HUB Synergies	Industriepark Höchst is anticipated to develop the following planned synergies: • (i-ii) CO_2 captured through a forthcoming CC technology in a waste incineration unit, along with H_2 produced from the existing electrolysis process, will be used in the pilot production of e-methanol, replacing traditional methanol in the chemical and pharmaceutical industries. • The production of large quantities of PtX is only possible once a H_2 network has been stabilised in Germany and sufficient quantities of H_2 are available at competitive prices. This is unlikely to be the case before 2035.
Other Opportunities for HUB Optimisation	1. Deploy Power-to-X with integrated AI forecasting to dynamically route energy flows. Test modular waste-to-fuel microplants within the park. 2. Certify biogenic CO_2 streams for green methanol export, traceable via blockchain. Introduce machine-learning-based anomaly detection in flue gas streams. 3. Heat-integrated membrane distillation units to recover water + heat simultaneously. Model water-energy interdependencies via digital twins. 4. Incorporate industrial waste into SAF (Sustainable Aviation Fuel) pathways, e.g. lignin-rich or carbonaceous feedstock via HTC. 5. Develop a circular economy innovation sandbox within Industriepark Höchst, combining regulatory waivers, digital regulation (e.g. “circular passports”), and experimental product streams.

*Data has been normalised to preserve confidentiality and to address constraints associated with data aggregation.

**Total Energy = Total Electricity Consumption (Renewable + Non-renewable electricity usage) + Total Direct fuel energy consumption (energy from combustion or use of the fuel itself)

The German HUB at Industriepark Höchst demonstrates the powerful role that long-established industrial ecosystems can play in driving Europe’s clean and circular transition. Leveraging its robust infrastructure, strategic location, and diverse industrial base, the HUB offers a compelling model for integrating CC, H_2 technologies, and Power-to-X solutions within a cohesive symbiotic framework. The planned production of e-methanol from captured CO_2 and green H_2 exemplifies a high-impact circular use case with strong replication potential. Despite challenges related to energy dependency, water use, and the need for deeper renewable integration, the HUB’s systemic approach and clear technological roadmap position it as a key enabler of decarbonised, circular industrial production in Europe.

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4.2. Definition of Requirements for Technology Implementation

Effective technology implementation within **IS2H4C** HUBs necessitates a structured approach to defining key prerequisites that ensure seamless adoption and integration. These requirements can be categorised into four fundamental dimensions: **technical, infrastructural (including integration with existing processes), resource-related, and regulatory** (Figure 9).

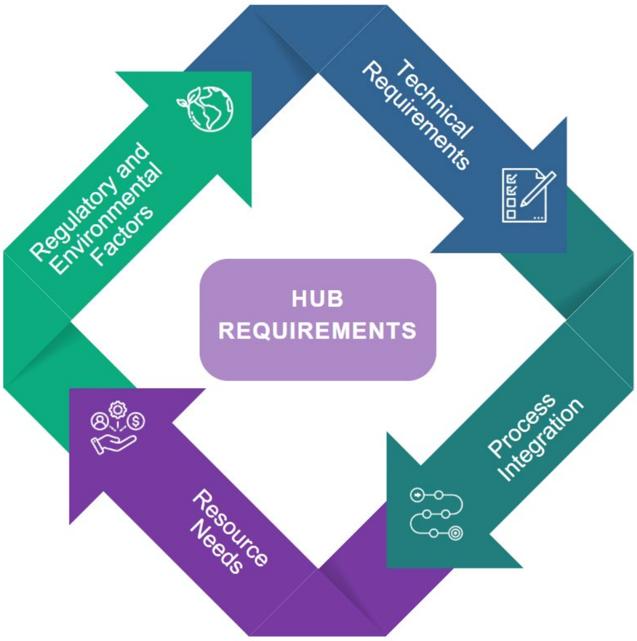

*Figure 9: Core dimensions of HUB requirements for effective technology implementation within the **IS2H4C** ecosystem.*

- **Technical requirements** encompass the modifications and advancements needed for successful technology deployment. This includes upgrading essential equipment, such as pipelines, reactors, and CO_2 compression systems, to accommodate new processes. Infrastructure must also be adapted to support transport and storage facilities, ensuring compatibility with energy supply sources, including H_2 and renewables. Establishing clear guidelines for hardware, software, data management, process integration, and interoperability is essential to ensuring scalability, security, and operational efficiency.

- **Process integration considerations** focus on ensuring that new technologies fit within existing industrial settings. This involves assessing operational adjustments required for technologies like CCS and evaluating their compatibility with other processes, such as slag carbonation or methanol synthesis. Seamless integration minimises disruptions and maximises efficiency across industrial operations.

- **Resource needs** cover the essential inputs required for technology implementation. A skilled workforce, adequate training programmes, and financial investment are critical to facilitating deployment. Material availability, including feedstock and essential raw materials, must also be ensured to support continuous operation and scalability.

- **Regulatory and environmental factors** define the external conditions that influence technology adoption. Compliance with permits, industry standards, and environmental regulations is vital to ensuring legal and operational feasibility. Policies related to emissions reduction and sustainability goals further shape implementation strategies, requiring alignment with national and international carbon targets. Considering these factors is essential for ensuring both compliance and long-term sustainability in operations.

Additionally, stakeholder engagement plays a crucial role in refining these requirements, addressing real-world challenges, and driving innovation within the **IS2H4C** ecosystem. In the following sub-chapters, the identified requirements for each HUB will be presented, outlining the essential conditions for the effective implementation of the methodologies.

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4.2.1. Turkish HUB

To successfully implement the planned technologies at the Turkish HUB, a structured approach is required to address key prerequisites across technical, process, resource, and regulatory dimensions. The deployment of renewable H_2 production, CCU, e-methanol production, and NIPU manufacturing necessitates a well-defined framework to ensure seamless integration into refinery operations. The main requirements include:

*Table 7: Key technical, infrastructural, resource-related, and regulatory requirements identified for the Turkish HUB, essential for the effective implementation and integration of its specific technologies within the **IS2H4C** framework.*

Technical requirements	**Renewable H_2 Production:** • Deployment of commercial **water electrolysis (TRL9)** for green H_2 generation requires **stable renewable electricity supply** and **optimisation of electrolysis efficiency** to ensure cost-effectiveness. • Electrolysis **byproduct O_2 utilisation** must be assessed for potential applications in **chemicals, pharmaceuticals, pulp & paper, and medical sectors**, requiring feasibility studies for **storage and delivery mechanisms at later stages of the project**. **Carbon Capture & Utilization (CCU):** • The proposal suggested that the TRL6 demo-scale CC unit from the İzmit refinery will be relocated to İzmir, requiring careful infrastructure adaptation and integration into refinery operations. Due to the challenges related to its location in another refinery field, the associated costs and efforts for transportation and integration, and the purity requirements not being met for methanol production, a new cryogenic CC unit will be implemented. • Further technological scaling is needed to **increase capture efficiency and align with refinery emission profiles**. **E-Methanol Production:** • Green H_2 and **captured CO_2 will be synthesised into e-methanol**, replacing conventional fossil-based methanol. • This process requires **effective integration with existing refinery infrastructure**, ensuring seamless operation without disrupting current production. **NIPU Production:** • Captured CO_2 will be utilised in **Fraunhofer's NIPU production** to replace conventional polyurethane in refrigerator manufacturing. • A major challenge is **scaling the technology from TRL3 to TRL7 within refinery conditions**, requiring process adaptation and new infrastructure for production.
Process integration considerations	**Electrolyser and E-Methanol Unit Installation:** • Needs **direct integration with refinery energy systems** to leverage renewable electricity sources efficiently.

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	• H_2 storage and transport solutions must align with planned H_2 fuel stations and truck-based logistics in the case for expansion strategies studies in the Turkish HUB. **CC System Deployment:** • **Integration of CC unit to the refinery streamlines** requires site-specific feasibility assessments to ensure operational **compatibility with refinery emissions** and processing systems. **NIPU Production Expansion:** • A dedicated processing unit **must be established within the refinery to support industrial-scale NIPU manufacturing by an engineering company.**
Resource needs	**Skilled Workforce & Vendor Collaboration:** • Engineering teams require **specialised training** to operate and maintain **electrolysers, CC units, and methanol synthesis reactors**. • Close collaboration with **Fraunhofer and technology providers** is necessary for **NIPU production scale-up and process optimization**. **Material & Financial Investment:** • Procurement of specialised **catalysts, membranes, and process control systems** for CCU and methanol production.
Regulatory and environmental factors	**Compliance with Carbon Reduction Policies:** • The integration of **CCU and e-methanol production** must align with national and EU **carbon neutrality targets.** **Safety Regulations & Permitting:** • Electrolyser operation, **O_2 storage, and H_2 distribution** require adherence to **industrial gas safety regulations** including storage for O_2 from electrolysis offered to other users and provision of H_2 via a fuel station and H_2 trucks to consumers reducing the need for non-renewable resources as feasibility studies. • The refinery's **hazard identification (HAZID) and hazard & operability (HAZOP) studies** will guide risk mitigation strategies.

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4.2.2. Basque HUB

To successfully implement the planned technologies at the Basque HUB, a structured approach is required to address key prerequisites across technical, process, resource, and regulatory dimensions. The main requirements include:

*Table 8: Key technical, infrastructural, resource-related, and regulatory requirements identified for the Basque HUB, essential for the effective implementation and integration of its specific technologies within the **IS2H4C** framework.*

Technical requirements	**Equipment Upgrades:** The deployment of CO_2 capture technologies, oxy-combustion systems, and carbonation processes requires significant modifications to industrial infrastructure. This includes: • Installation of PSAs (Pressure Swing Adsorption) heating/cooling systems. • Thermal insulation for pipelines to minimise heat loss. • Reactor dismantling and send it to TECNALIA to reinstall catalyst and zeolites. • Integration of flue-gas intake points for CO_2 capture. • New burner installation at SIDENOR for preheating ladles. • Equipment modifications and/or building to handle H_2 trials at SIDENOR. • Carbonatation equipment update to handle steel slags. **Process Compatibility:** Ensuring the seamless operation of CCUS (Carbon Capture Use and Storage) at CALCINOR, carbonatation at SBS and oxy-combustion technologies within existing steel production processes at SIDENOR. This requires: • Evaluating material-specific properties for carbonation. • Connection of carbonatation equipment to CO_2. • CFD simulations for oxy-combustion. • Thermal monitoring of ladles. **Data Management & Process Control:** • Developing control systems for real-time monitoring and evaluation of CO_2 capture efficiency. • Individual testing of systems for operational validation.
Process integration considerations	**IS:** The project aims to integrate CO_2 capture with further applications such as methanol synthesis and slag carbonation. This means: • CO_2 capture and storage must be compatible with downstream applications. • Carbonation testing with captured CO_2 must be planned with proper conditioning.

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	Operational Adjustments: • The use of oxy-combustion requires retrofitting ladles and implementing transient CFD simulations. • Coordination between multiple industrial players (CAL, SID, LTK, TEC) is necessary for efficient system deployment.
Resource needs	**Skilled Workforce & Training:** The complexity of the implemented technologies (oxy-combustion, CCS, carbonation) requires specialised training for personnel handling reactors, flue-gas systems, and thermocouples. **Material Availability:** • Supply of catalysts and zeolites for CO_2 capture. • Sourcing specific materials for carbonation tests. • Ensuring access to H_2 and renewable energy sources to power new systems. **Financial Investments:** Continuous funding will be needed to support: • Pilot plant construction and system installations. • Infrastructure modifications for CO_2 transport and storage. • Oxy-combustion burner
Regulatory and environmental factors	**Compliance with Emission Regulations:** • The CO_2 capture and carbonation activities must align with European carbon reduction goals and industry-specific environmental regulations. • Ensuring proper documentation for pilot plant permits. **Sustainability Goals:** • Carbonation tests must demonstrate the potential for CO_2 sequestration in industrial by-products (slag). • Oxy-combustion should enhance efficiency by reducing NG consumption while reducing emissions.

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4.2.3. Dutch HUB

The successful deployment of H_2 infrastructure, reuse of gas piping, and the H_2 feeding installation in the Dutch HUB requires a structured approach to defining key prerequisites. These are:

*Table 9: Key technical, infrastructural, resource-related, and regulatory requirements identified for the Dutch HUB, essential for the effective implementation and integration of its specific technologies within the **IS2H4C** framework.*

<table>
<tr>
<td>Technical requirements</td>
<td>
Reusing Gas Piping for H₂ Distribution
Material Compatibility & Integrity Check
• Assess existing gas pipes, seals, and gaskets for H_2 embrittlement risk, replacing non-compatible materials (e.g., high-carbon steels) with H_2-compatible stainless steel or composites.
• Conduct leak detection and structural integrity tests before H_2 introduction.
Pipeline Modifications & Safety Enhancements
• Upgrade seals, gaskets, and joints to prevent leaks and withstand H_2’s high diffusivity.
• Conduct pressure tests to verify pipeline integrity and detect potential leakage points.
• Install H_2 sensors inside connected houses to continuously monitor safety and detect any H_2 presence.
• Deploy sensors at the production site to monitor for leaks and ensure safe operation across the entire system.
• Adjust pressure regulators and safety valves for H_2-specific requirements.
Cleaning & Purging
• Thoroughly purge gas lines to remove residual natural gas and contaminants before H_2 introduction.
• Implement standardised pipeline cleaning protocols to prevent chemical reactions.
H_2 Feeding Installation
Design & Engineering
• Develop process flow diagrams (PFDs) and piping & instrumentation diagrams (P&IDs) to ensure optimal integration.
Testing & Commissioning
• Conduct pre-commissioning checks for individual components (e.g., H_2 storage tanks, compressors, dispensers).
• Perform operational testing under real conditions before implementation.
Integration with Residential H_2 Use
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- Design and install **H_2-compatible household infrastructure** (e.g., gas boilers, pressure reducers, safety shut-off valves).
- Implement **control and monitoring systems** for safe H_2 supply to residential buildings.

Stabilising Green H_2 Production

One of the main goals for H_2Hub Twente is to stabilise the Green Electricity feed to the electrolyser for Green H_2 production and to increase running hours. A way to achieve this is to peak shave the current PV field and supplement wind turbines to optimise the energy mix.

- **Battery Technology**

At the start of the project, we have defined that we would require approximately 1.4MWh of battery storage with a rated power of at least 250kw at any given time. For further flexibility, based on the property owner's requirements, to spread risk, and future (past the project's horizon) usage of the system, we have chosen to explore a battery cabinet and containerised option.

Besides the obvious power requirements above, the following requirements were used for an RFQ: direct connection with PV via MPPT trackers, implemented fire safety measures for safe use closer to a building, minimum rated power per unit of 50kw for cabinets or a minimum c of 0,5 for containerized, EMS to support energy management.

- **Wind Turbines**

In the DoA, H_2Hub Twente has requested funding for wind turbines with a rated power of 70kW. In the initial talks, planning and back-up ideas 70kW was the maximal possible outcome if large turbines would fail. In discussion with the property owner about the possibilities, the strong wish came forward for wind turbines as tall as possible. From this perspective H_2HT opened a rather simple RFQ, requiring "farm type" (medium height, up to 50m) wind turbines with a minimum combined rated power of 70kW and optimised for the two locations we marked for placement potential.

- **H_2 production through electrolyser**

70 kW alkaline electrolyser requires a **stable and constant DC power source**, fluctuations greater than ±5% can cause reduced efficiency and accelerated degradation of electrodes. Alkaline electrolysers can handle ~10–100% part-load operation, though frequent cycling reduces stack lifetime. **Deionized or demineralised water** with **conductivity < 1 μS/cm**, ideally **< 0.2 μS/cm.** Feed water needs to be **pre-heated to 60–80 °C** before entering the electrolyser stack to minimize thermal shock and improve efficiency.

Transportation of Green H_2 to Cremation Centre

One of the indirect partners of H_2Hub Twente, project partners on the creation of H_2 filling station (external, not **IS2H4C**) specialises in tube trailer transportation of H_2 throughout the Netherlands.

- **Tube trailer**

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<table>
<tr><td></td><td>Regular (as per market standards) tube trailer, supplied and operated by an indirect partner of H_2HT. All safety measures regarding transport, operation, legality are covered by the operator of the trailer. As this is not in the planning for the first months, exact technical data needs to be requested.

O_2 supply to and process water from Waterboard (synergy vi, vii)

Synergy vi and vii are tabled for the second half of the project timeline, because the focus is to reach a stable operational state. Specific specifications for the piping or transportation have not yet been determined. In close consultation with the Waterboard, we will create an implementation plan to transport O_2 to their site and transport their process water back to the H_2Hub Twente.

• O_2 Supply
  • In consultation with the waterboard, we will determine the necessary flow rates, pressure levels, and purity requirements for the implementation of O_2 supply.
  • Ensuring high safety standards is paramount due to the reactivity of O_2, requiring safety protocols and systems in place for handling and storage.
  • Implementation of the O_2 supply system will be planned collaboratively with the Waterboard, ensuring it integrates seamlessly with their operations, without disrupting their current processes.
• Process Water
  • Likely the easiest implementation and synergy to realize in this project. Initially, there are no technological constraints to transport the process water of the Waterboard to the H_2Hub.
  • A detailed evaluation of the water quality, including chemical composition and contaminants, will be performed to determine any required pre-treatment or filtration steps.
  • A return pipeline or suitable transportation infrastructure will be designed, ensuring it can handle the necessary water volumes and maintain water quality for reuse or further processing at the H_2Hub.

The transportation of process water should integrate smoothly with the existing H_2Hub systems, enabling effective reuse without causing disruptions to current operations.</td></tr>
<tr><td>Process integration considerations</td><td>Reusing Gas Piping for H_2 Distribution

• Requires assessment of existing pipelines, seals, and gaskets for H_2 embrittlement and replacement with H_2-compatible materials.
• Pressure regulators and safety valves must be recalibrated for H_2's specific flow and diffusivity characteristics.

H_2 Feeding Installation

• Demands detailed process design using PFDs and P&IDs to align with safety, control, and performance targets.
• Requires integration with storage, compression, and residential H_2 networks for seamless end-use delivery.
• Testing and commissioning activities must be synchronized with risk and HAZOP studies to ensure safe operation.</td></tr>
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	Stabilizing Green H_2 Production:
	• Needs coordination between PV, wind turbines, and battery storage systems to stabilize electrolyser feed and extend operating hours.
	• Battery EMS must synchronize renewable inputs and maintain constant DC power within ±5% fluctuation.
	• Thermal and water management subsystems must ensure 60–80 °C feed temperature and <1 µS/cm water purity for efficient operation.
	Industrial & Urban Integration:
	• **Industrial H_2 Use**
	  • H_2 must be integrated into **existing processes** at Almelo Energy and COGAS, ensuring **compatibility with the local energy grid and industrial-urban applications**.
	• **Urban & Residential Deployment**
	  • H_2 infrastructure must be tailored for **residential use**, requiring **H_2-compatible heating systems, piping, and safety mechanisms**.
	H_2 Transportation and External Use:
	• Requires alignment with certified H_2 transport operators using tube trailers that comply with ADR safety and transport standards.
	• Must ensure compression, storage, and loading systems meet trailer interface requirements and enable future scaling to refuelling applications.
	O_2 and Process Water Integration with Waterboard:
	• Involves defining O_2 purity, flow, and pressure requirements for integration with the Waterboard's aeration and oxidation processes.
	• Process water from the Waterboard must be analysed, pre-treated, and piped back to the H_2Hub to support circular resource use.
	• Implementation plans must align with the Waterboard's operational cycles and environmental compliance standards.
	Safety & Monitoring Systems:
	• Implement continuous monitoring and real-time data analysis to prevent leaks and operational failures.
	• Conduct controlled pilot tests to gradually phase in H_2 before full-scale deployment.

Resource needs	**Skilled Workforce & Training:** • Establish targeted training programmes on H_2 technologies, including installation, operation, maintenance, and emergency procedures. • Build local capacity through upskilling initiatives for technicians, engineers, and safety personnel.

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	Material & Financial Investments: • Procure H_2-compatible materials, including storage tanks, pipes, pressure regulators, and leak detection systems. • Ensure financial support for pilot projects, testing phases, and gradual scaling of H_2 deployment. • Financial aspects for compliance with Cogas requirements for transportation of H_2 in pipelines are not budgeted in the initial project proposal, these additional costs are mostly attributed to equipment. • Bill of Materials for **synergy vi** and **vii** are not yet available, these expenses have been budgeted based on a quick pre-project calculation with the Waterboard.
Regulatory and environmental factors	**Regulatory Compliance & Permits:** • Obtain permits for H_2 storage, transport, and residential use from local, regional, and national authorities. • Comply with EU and Dutch H_2 safety regulations, ensuring industrial and residential H_2 adoption follows legal frameworks. • Align with sustainability policies regarding carbon reduction, renewable energy integration, and H_2 safety standards. **Environmental & Safety Measures:** • Secure environmental impact assessments (EIA) and approvals to address potential risks. • Establish incident management protocols for H_2-related emergencies. • Define end-of-life planning for H_2 infrastructure decommissioning. **Stabilising Green H_2 Production (synergy i, iv):** • **Battery Technology** • No additional licensing issues, battery cabinets have already been placed and are pending final commissioning. • **Wind Turbines** • Due to constraints in building height (the area is a low flight zone for the military), the wind turbines are subject to licencing and a thorough approval process. H2Hub Twente is already working on this with the local municipality for months and signals are looking good. We expect constraints in building height. Normal buildings are restricted to a maximum height of 12 meters. H2Hub expects a license before the municipality elections in March 2026. **Transportation of Green H_2 to Cremation Centre (synergy v):** • **Tube Trailers** • No additional licensing constraints for the project under current legislation, trucks of our external partner are already up and running. **O_2 supply to and process water from Waterboard (synergy vi, vii):**

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	• O_2 supply • Now there are no regulatory nor environmental factors limiting the implementation of this synergy. • Process water • There is no regulatory nor environmental factor limiting this implementation.

4.2.4. German HUB

The successful deployment of CCU, CCS, H_2 Production, SAF, Waste Heat Recovery, and Circular Water Management at the Industriepark Höchst HUB requires a structured approach. The requirements can be categorised as follows:

Table 10: Key technical, infrastructural, resource-related, and regulatory requirements identified for the German HUB, essential for the effective implementation and integration of its specific technologies within the ***IS2H4C*** *framework.*

Technical requirements	**Carbon Capture & Utilisation (CCU) and Carbon Capture & Storage (CCS):** • The CO_2 capture pilot plant setup is ongoing but depends on efficient site preparation and commissioning. Delays in site preparation and authorisation issues impact the testing and integration of capture technologies. • CO_2 pre-feed studies and biogenic CO_2 measurement have been completed, providing a basis for refining capture processes. However, delayed measurements indicate the need for enhanced process monitoring and optimisation. • The successful deployment of CO_2 capture requires integration with existing energy generation systems, ensuring minimal operational disruptions. **H_2 Production & Utilisation:** • Expansion of electrolysis capacity will be crucial for increasing H_2 production, due to the lack of electricity capacities in the FrankfurtRhineMain region. Integration with waste heat recovery systems (currently under study at IPH) will enhance efficiency. • Safe H_2 storage and distribution infrastructure must be established, aligning with industry standards for transport and fuel cell applications. • The connection to the planned German H_2 core network is planned for Industriepark Höchst in 2033. **Sustainable Aviation Fuels (SAF) & E-Fuels:** • Production facilities must align with ReFuelEU Aviation regulations, requiring coordinated efforts between CAPHENIA, INERATEC, and regulatory bodies. • Integration of non-biogenic feedstocks with captured CO_2 is essential for SAF production scalability. **Waste Heat Recovery & Circular Energy Systems:**

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	• The ongoing study on heat recovery and heat pumps at IPH highlights the need for strategic deployment of heat pumps and Power-to-X (PtX) solutions. • Integration with district heating systems will require modifications to infrastructure, ensuring compatibility with industrial heating demands. **Water Management & Circular Systems:** • Membrane distillation and electrolysis for H_2 production require enhanced water recycling systems. • Hydrothermal carbonisation for biogenic waste processing must be optimised to support circular water use and energy efficiency.
Process integration considerations	**Pilot Plant Development & Testing:** • The CO_2 capture pilot plant at the sewage sludge incineration plant is ongoing, with site preparation delays. The test facility has been set up meanwhile and is in commissioning. • Seamless integration with refinery and energy systems is necessary to prevent operational inefficiencies. • Operational adjustments must be made to align CO_2 capture processes with H_2 availability and methanol synthesis technologies. **Heat Recovery & CO_2 Capture Compatibility:** • The study on waste heat recovery and heat pumps will determine the potential for circular energy utilisation within industrial operations. • Process compatibility between CO_2 capture, H_2 electrolysis, and SAF production must be assessed to maximise industrial synergies.
Resource needs	**Skilled Workforce & Training:** • Specialised training is needed for CO_2 capture technology operation, electrolysis expansion, and waste heat recovery system maintenance. • Collaboration with Fraunhofer and technology providers will be essential for knowledge transfer and upscaling. **Material & Financial Investments:** • Investment in CO_2 compression systems, electrolysers, and SAF production infrastructure is required to meet deployment targets. • Safe H_2 storage facilities and transport logistics need financial backing to support large-scale H_2 applications.
Regulatory and environmental factors	**Compliance with EU Carbon Reduction Policies:**

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	• The deployment of SAF production and CO_2 capture technologies must align with ReFuelEU Aviation and carbon neutrality mandates. • Permits for CO_2 transport, SAF blending, and H_2 distribution need to be secured before full-scale deployment. **Safety & Environmental Regulations:** • HAZID (Hazard Identification) and HAZOP (Hazard & Operability) studies must be conducted for H_2 storage and CO_2 capture units. • Industrial gas safety compliance is essential for H_2-related operations.

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5. Validation of Success and Impact

The validation of success within the transformation of HUBs into H4Cs relies on a structured evaluation framework that monitors operational performance and assesses sustainability impact. This is achieved through a set of predefined success criteria and KPIs, ensuring a comprehensive assessment of technological adoption, sustainability achievements, and industrial viability. This evaluation is linked to Task 6.3 (T6.3), which focuses on monitoring operational performance and validating resource and energy reductions in collaboration with WP4 and WP7. The insights gained from this evaluation will inform decisions on whether to continue, refine, or scale the implemented technologies.

5.1. Framework for Success Evaluation

The initial framework has been designed with the support of the Zaragoza Logistics Center (ZLC) to provide a structured approach for evaluating success. This remains flexible and can be refined as T6.3 progresses, incorporating new insights from ongoing activities. The methodology ensures continuous alignment with project objectives through iterative improvements based on data collection, stakeholder feedback, and real-time operational assessments.

The evaluation follows three main dimensions (Figure 9), each addressing specific requirements of T6.3. It also ensures alignment with WP6 by validating that the proposed approach meets the evaluation needs. This process includes assessing both the overall framework and the specific steps and methods within each section to confirm compliance with project requirements.

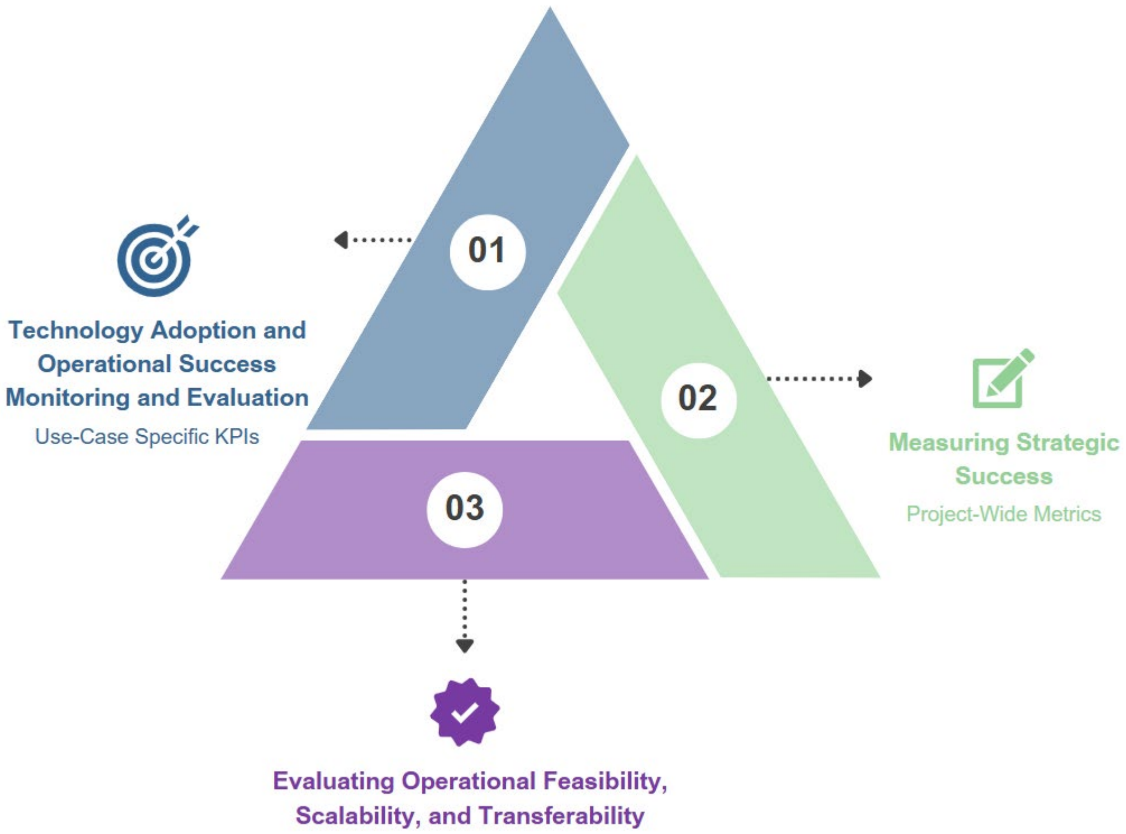

Figure 10: Three main dimensions from the evaluation of success framework.

In the following subchapters, each of the three main dimensions will be explored in greater detail, focusing on the objectives, implementation steps, and key requirements.

5.1.1. Technology Adoption and Operational Success Monitoring and Evaluation

<u>Objective:</u> The adoption and operational success of each HUB’s implemented technology will be monitored and evaluated against predefined KPIs specific to each use case. This ensures that the technologies deployed align with project goals and deliver the expected impact.

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Steps for Implementation: The process begins with identifying the technologies to be demonstrated, along with their corresponding KPIs and target values. Measurement methods and data collection mechanisms will then be defined, leveraging sensing technologies from Task 7.5 (Integration of Monitoring and Evaluation Components). A baseline assessment will be conducted before implementation to establish initial values, providing a reference point for performance evaluation. Intermediate results will be tracked throughout the project, including milestone-based assessments such as after 500 hours of operation (Milestone 6.2). These mid-term evaluations will inform any necessary adjustments and improvements. Finally, at the project's conclusion, the final results will be compared against the initial targets to assess overall success, ensuring alignment with predefined objectives and validating the effectiveness of the implemented technologies.

Key Considerations: Each KPI within each HUB will require specific measurement methods tailored to its unique context. Robust data collection mechanisms will be essential to ensure accurate and reliable monitoring. The baseline assessment will serve as a crucial reference, allowing for meaningful comparisons over time. Regular tracking of intermediate values will support timely decision-making and iterative improvements. The final assessment will provide a comprehensive evaluation of technology adoption and operational success, ensuring that the predefined targets have been met.

Use-Case Specific Metrics

To ensure an accurate evaluation of the success of technology adoption, each HUB will define and monitor specific metrics tailored to its unique use case. These metrics will provide a detailed assessment of performance while contributing to the project's overall evaluation framework.

Each HUB has established its own success metrics, aligning them with the overarching evaluation methodology. These metrics were selected based on the type of technology implemented, expected impact, and the feasibility of data collection. As these metrics are finalised, they will be systematically incorporated into the evaluation framework, ensuring that the assessment of each HUB feeds into the project's broader success criteria. A structured approach will be applied to harmonise these HUB-specific evaluations with the broader project-wide assessment.

Turkish HUB

The Turkish HUB aims to produce e-methanol by utilising green H_2 obtained from electrolysis using renewable energy and captured CO_2 from oil refining activities. Captured CO_2 will also be used in the production of NIPU which replaces traditional polyurethane in refrigerator manufacturing. Specific metrics are defined for these four subunits to evaluate and monitor developments according to the project KPIs.

Table 11: Success metrics defined by the Turkish HUB, tailored to its specific technology focus, expected impact areas, and data collection capabilities.

	Metrics	Justification
CO_2 Capture	% Purity of captured CO_2 Kg of CO_2/h	The PSA (pressure swing adsorption) gas will be used as a feed gas for the CC unit. The pre-combustion gas contains a high concentration of CO_2 (30-40%), along with other gases such as H_2, CH_4, and impurities. The captured CO_2 will be used in e-methanol production and carbamate production, making the performance and outlet stream composition (**captured CO_2 purity**) of the CC unit essential. The pre-engineering study of the unit is ongoing, and the scale will be determined based on the required CO_2 flow rate (**kg_{CO2}/h**) to produce the final product, which is the refrigerator.
H_2 Production	% Purity of H_2 Kg of H_2/h	To produce e-methanol, CO_2 and H_2 will be utilised. In this project, green H_2 will be generated from water by an electrolyser. The produced H_2 must have a specific **purity** to be classified as green H_2; therefore, the outlet stream of the electrolyser unit will be continuously monitored. The pre-engineering study of the unit is currently in progress, and the scale will be determined based on the required flow rate of H_2 (**kg_{H2}/h**) necessary for the production of the final product, which is the refrigerator.

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E-Methanol Production	% Purity of MeOH Kg of MeOH/day	The third subunit focuses on e-methanol production, which uses captured CO_2 and green H_2 for e-methanol synthesis. The produced methanol (MeOH) will be used in carbamate production. The synthesised methanol will be distilled to remove water and other impurities formed during the reaction, achieving high purity methanol. Methanol **purity** is important and will be monitored to ensure efficient carbamate synthesis. The pre-engineering study of the unit is currently in progress, and the scale will be determined based on the required flow rate of MeOH (**kg_{MeOH}/h**) necessary to produce the final product, the refrigerator.
Carbamate & NIPU Production	Kg/year of NIPU	The fourth subunit involves the production of carbamate and NIPU. E-methanol and captured CO_2 are used in carbamate production, which is then employed for batch NIPU production. The produced NIPU will be utilised directly in refrigerator manufacturing. The chemical properties and quantity of NIPU (**kg_{NIPU}/year)** are essential for defining refrigerator specifications. A mass balance of the combined unit is conducted to produce the final product, the refrigerator.

Basque HUB

The Basque HUB focuses on three key activities related to CC, alternative fuel usage in the steel industry, and the valorisation of steel production waste for construction applications. Each of these activities has defined specific metrics to evaluate success, ensuring alignment with both project-wide KPIs and activity-specific performance indicators.

Table 12: Success metrics defined by the Basque HUB, tailored to its specific technology focus, expected impact areas, and data collection capabilities.

	Metrics	Justification
CO_2 Capture	CO_2 concentration in the captured gas (>90%) SNG production from CO_2 (m^3/h)	The first activity involves CO_2 capture and conversion into synthetic natural gas (SNG) at the CALCINOR site. The objective is not only to capture CO_2 emissions but also to repurpose them into a valuable energy source. The key metrics for this process include the concentration of CO_2 in the captured gas, which must be at least 90%, and the volume of SNG produced from the captured CO_2, measured in cubic metres per hour (m^3/h). These indicators will determine the efficiency and viability of integrating CC technologies within industrial processes.
SIDENOR Ladle Preheating	Oxy-combustion and H_2: No. of tests performed with each method. No. of times the objective temperature is reached. % of natural gas savings achieved.	The second activity takes place at SIDENOR, a steelmaking company, and focuses on optimising the pre-heating process of ladles used to transport molten steel. Currently, this pre-heating is carried out using natural gas. Within the project, alternative heating methods—oxy-combustion and H_2-based pre-heating—are being tested to reduce reliance on fossil fuels. The success of this activity will be measured through the number of tests performed with each method, the number of times the target temperature of 1100°C is reached, and the percentage of natural gas savings achieved. In the case of H_2-based heating, the goal is a 100% replacement of natural gas, while oxy-combustion may yield different levels of reduction, which will be evaluated accordingly.

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Steel Slag Carbonatation	Kg of $CO_{2\text{-eq}}$ (absorbed) / Kg mass (slag)	The third activity focuses on the valorisation of steel slags, a byproduct of the steel industry, for use in the construction sector. Stainless steel slags, in particular, present challenges due to the alloys present in their composition, limiting their reuse. To address this, the project explores carbonation of the slags to enhance their suitability for construction applications. The effectiveness of this process will be assessed by measuring the amount of CO_2 absorbed per kilogram of slag (Kg CO_2 eq / Kg mass). This metric will provide insights into the potential of this approach in reducing industrial waste and contributing to circular economy principles.

By systematically monitoring these specific metrics, the Basque HUB will generate valuable data that contributes to the overall evaluation framework of the project. While some of these indicators directly align with the project's general KPIs—such as reductions in CO_2 emissions and resource consumption—others offer detailed insights into the operational success and feasibility of the technologies implemented at this HUB.

Dutch HUB

The Dutch HUB focuses on decentralised H_2 production and distribution by integrating solar, wind, and biogas resources with innovative water recycling, energy storage, and waste heat recovery systems. Green H_2 produced on-site will be used for residential applications and local infrastructure such as crematoria, while O_2 and heat by-products are valorised within wastewater treatment and energy loops. Specific metrics have been defined for each technological component to monitor progress, evaluate performance, and ensure alignment with the overarching project KPIs.

Table 13: Success metrics defined by the Dutch HUB, tailored to its specific technology focus, expected impact areas, and data collection capabilities.

	Metrics	Justification
Solar- and Wind-powered electrolysis for H_2 production	10kg H_2/day produced Electrolyser efficiency N/A (%) Electrolyser uptime 33 (%)	Measures production capacity and operational efficiency of green H_2 generation. Uptime reflects the current operational phase (8h/day), expected to increase with battery support. Efficiency metric will help benchmark system performance as operations scale.
Water recycling from wastewater to electrolysis	80–100% of electrolyser water demand met with recycled water Reduction in freshwater consumption (±87.600 litres/year) Compliance with demi-water quality standards	Ensures sustainability via closed-loop reuse. Demonstrates strong environmental performance by reducing reliance on freshwater. Quality control ensures system integrity and electrolyser compatibility.
O_2 reuse in wastewater treatment	60 to 180 Nm^3/day of O_2 from electrolysis reused in treatment systems	Validates added value of O_2 by-product integration in wastewater processes. Monitoring supports the transition from pilot to full-scale deployment.

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H_2 pipelines (residential + crematoria)	Pipeline length installed (m): ca. 300m on-site, plus connection to Aadorp 1 community centre, 2 residential homes and 1 small business buildings connected H_2 pressure stability (bar)	Tracks infrastructure deployment, connection progress, and operational performance. Ensures safety and stability for residential and industrial end-users.
Energy storage systems	1400 kWh storage capacity # of daily charge/discharge cycles 30% reduction in electrolyser downtime due to intermittency	Assesses resilience of system to renewable energy variability. Quantifies benefit to electrolyser uptime and system autonomy.
Wind energy integration	Wind power share in energy mix: 7% Installed capacity: ≥ 70 kW Contribution to electrolyser demand: 8%	Confirms renewable diversification and wind energy's role in direct H_2 production. Supports system autonomy and energy sovereignty targets.

By systematically monitoring these specific metrics, the Dutch HUB will generate high-resolution data that contributes to the overall evaluation framework of the project. While some indicators are directly tied to broader goals—such as renewable integration, water savings, and CO_2 reduction—others provide operational insights that will support technology scale-up, replication, and policy alignment across regional and European levels.

German HUB

The German HUB focuses on three key activities related to CC, methanol synthesis and waste heat usage. Each of these activities has defined specific metrics to evaluate success, ensuring alignment with both project-wide KPIs and activity-specific performance indicators.

Table 14: Success metrics defined by the German HUB, tailored to its specific technology focus, expected impact areas, and data collection capabilities.

	Metrics	Justification
CO_2 Capture	Determination of biogenic CO_2 CO_2 capture in a pilot plant of about 0,5 tpd	Measurement of biogenic CO_2 content in the flue gas of a sewage sludge incineration plant via carbon-14 method. Pilot tests in spring 2025 should demonstrate the feasibility of separating CO_2 via amine scrubbing at the waste incineration plant.
Methanol synthesis	Investigate whether the CO_2 quality is sufficient for methanol synthesis Search for a pilot plant for tests	In order to be able to set up a methanol synthesis plant at IPH, technical investigations into the separability of CO_2 and its quality must first be carried out. Subsequently, tests on a pilot plant with separated CO_2 are required to determine the lifetime of catalysts. These investigations are necessary in order to be able to carry out an economic feasibility study.
Waste heat recovery	Studies to replace steam heat supply and utilisation for process waste heat	The third activity focuses on the valorisation of waste heat to substitute fossil-based steam supply and to use waste heat for district heating. Therefore, studies are necessary to determine the availabilities of waste heat sources in the Industrial Park and to calculate the amount of electricity needed for heat pumps.

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By systematically monitoring these specific metrics, the German HUB will generate valuable data that contributes to the overall evaluation framework of the project. While some of these indicators directly align with the project's general KPIs—such as reductions in CO_2 emissions and resource consumption—others offer detailed insights into the operational success and feasibility of the technologies implemented at this HUB.

5.1.2. Measuring Strategic Success

Objective: The project will assess strategic success beyond individual case studies by measuring common KPIs across all HUBs, ensuring comparability and alignment with shared sustainability goals. This evaluation spans environmental, economic, and social dimensions, providing a holistic view of the project's impact.

Steps for Implementation: The process begins with defining a common set of KPIs and measurement methods applicable across all HUBs. Environmental KPIs focus on waste reduction through recycling, reuse, and other circular strategies, alongside energy optimisation by reducing non-renewable energy use, integrating renewable energy sources, promoting energy reuse, and exploring H_2 as an energy carrier. Additionally, CO_2 emissions and other environmental impacts, such as soil and water effects, will be monitored. Next, the project will identify existing KPI tracking mechanisms within pilots and align methodologies to ensure consistency. Economic KPIs, including operational costs, financial return rates, and other relevant indicators, will be integrated to assess economic feasibility. Social KPIs will cover job creation, job quality, collaboration opportunities, brand image, and resilience factors such as diversification, external dependency, and robustness.

Key Considerations: To support a comprehensive evaluation, potential gaps in measurement—particularly in social impact assessment—will be addressed. These indicators will be measured at the start and end of the project, enabling an evaluation of operational feasibility, scalability, and transferability of the implemented solutions.

Project-Wide Metrics

While individual HUBs will have tailored metrics, the project's success will also be measured against a set of overarching KPIs that reflect its broader impact on sustainability, energy efficiency, and IS.

The project's overall evaluation will consider the following KPIs, related to WP6:

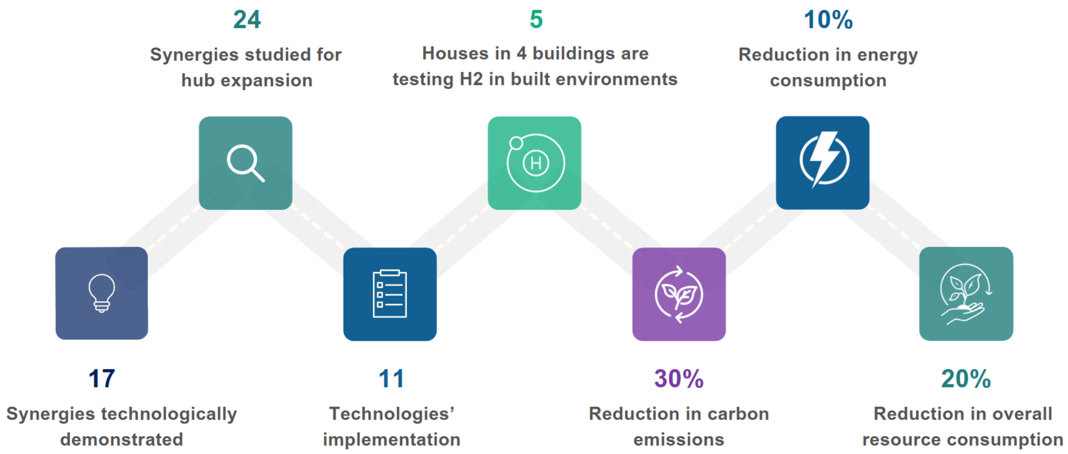

Figure 11: Project-wide pre-defined KPIs for WP6.

These metrics will be assessed at various stages of the project, ensuring alignment with the predefined objectives, and evaluating the long-term impact of the implemented solutions. By systematically tracking these indicators, the project will not only validate the effectiveness of individual HUB initiatives but also provide a clear measure of success at a systemic level. Achieving these overarching KPIs will require effective coordination across all HUBs, ensuring that individual efforts contribute to the collective goals. The methodology will integrate HUB-specific evaluations into a unified framework that validates the project's scalability, feasibility, and overall success.

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5.1.3. Evaluating Operational Feasibility, Scalability, and Transferability

Objective: This phase focuses on assessing the feasibility, scalability, and transferability of the implemented solutions, drawing on impact assessment results and lessons learned from each HUB. The evaluation involves active engagement with the CoP and relevant stakeholders to gather insights and feedback. A structured evaluation methodology is employed to identify key challenges, barriers, and opportunities for scaling and transferring technologies to other HUBs or regions.

Steps for Implementation: As part of the upcoming implementation process, the approach begins with stakeholder mapping to identify key roles and project objectives, followed by an analysis of synergies and potential symbiosis opportunities to be explored throughout the project. To ensure a comprehensive assessment, a series of workshops and surveys are planned. The first step will involve a workshop where KPI results are reviewed, challenges discussed, and the scalability and transferability of proposed solutions examined. This session will be structured in collaboration with WP4.6 and WP7.5, enabling the identification of new ideas for potential future developments. Following the workshop, a targeted stakeholder survey will be conducted to gather additional insights. This survey will assess stakeholder profiles, satisfaction with their involvement in the HUB, and perceptions of the cost–benefit of the solutions being implemented. It will also examine whether the expected benefits justify the associated costs and indirect impacts, to what extent environmental gains should drive broader public–private collaboration, and whether social benefits can foster cross-sector investment in industrial symbiosis. Finally, stakeholders will be asked to evaluate the long-term viability of the solutions, their potential for replication in other regions, and any perceived barriers to scalability and transferability.

Key Considerations: The survey also explores stakeholders' interest in future engagement, assessing their willingness to participate in further developments, incorporate new ideas into the technology roadmap, and support initiatives that enhance IS. To ensure the evaluation approach remains practical and aligned with project objectives, the methodology and evaluation plan are validated with WP6 and coordinated with pilot leaders. Once refined, the final steps and timeline for workshops and surveys are communicated to all relevant parties, ensuring a structured and effective assessment process.

5.2. Potential Challenges and Risks

The implementation of innovative solutions within the HUBs is subject to various **technical, economic, and social** challenges. A detailed description of the potential non-technological challenges is provided in *D3.2 – Methodology for Assessment of Non-Technological Issues*. From a technical and operational perspective, data collection and accuracy pose a significant challenge, as ensuring consistent and reliable data across HUBs requires robust monitoring systems. Additionally, integrating new technologies into diverse industrial environments may present difficulties, and while some solutions may demonstrate effectiveness at a pilot scale, their large-scale deployment could be hindered by unforeseen obstacles.

Economic risks are particularly pronounced regarding return on investment, as financial uncertainty may impact stakeholders' willingness to commit resources to new solutions. Market readiness for proposed innovations varies significantly, potentially affecting overall project outcomes. Furthermore, ongoing maintenance costs and potential technological obsolescence pose additional financial risks that need proactive management.

Social risks involve ensuring consistent stakeholder engagement, as varying levels of commitment from industrial and community partners could influence the initiative's overall success. Resistance to change within industrial communities, potential job displacement, and the need for extensive training for new technologies must be addressed to ensure broad acceptance and support.

Stakeholder interviews conducted under *D3.2* revealed regulatory and environmental risks such as public resistance to infrastructure projects stemming from concerns over noise, pollution, safety, and scepticism around technologies like H_2. These factors, along with misaligned priorities between communities, regulators, and technology developers, have delayed IS initiatives. Successful implementation will require alignment with EU and national regulations, early completion of permitting procedures (e.g., for H_2 and CO_2 handling), and clear communication strategies to build trust and ensure acceptance of circular technologies like carbon capture, water reuse, and waste heat recovery.

To mitigate these risks, the project incorporates structured stakeholder engagement, periodic evaluation workshops, and iterative refinement of implementation strategies. A proactive approach to risk assessment will allow for adaptive responses, ensuring the successful transformation of HUBs into H4Cs.

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5.3. Expected Outcomes and Benefits

The expected outcomes of this initiative span environmental, economic, and social dimensions. From an operational and environmental perspective, the HUBs are anticipated to achieve significant reductions in CO_2 emissions and resource consumption. This includes measurable decreases in greenhouse gas emissions, waste generation, and water use, alongside improvements in air and water quality, contributing to broader environmental sustainability goals. Enhanced energy efficiency will be promoted through optimised resource utilisation, including the integration of renewable energy sources and waste heat recovery strategies that convert industrial excess heat into useful energy. The HUBs will also play a crucial role in fostering IS by enabling resource-sharing mechanisms that drive sustainability and circularity across interconnected industrial processes.

Economically, cost savings are expected due to optimised resource use and reduced waste management expenses. The implementation of innovative industrial processes is likely to enhance operational efficiency, lower production costs, and create new market opportunities for circular products and services. The project will stimulate regional economies by generating new employment opportunities and facilitating workforce development in relevant sectors, creating a skilled labour force adept in sustainable practices and technologies. Increased competitiveness and resilience among regional businesses will also be promoted, supporting long-term economic growth.

Socially, strengthened collaboration between industrial, academic, and policy stakeholders will be encouraged, fostering a more resilient and interconnected industrial ecosystem. These collaborations are expected to improve knowledge sharing, innovation capacity, and community engagement, enhancing social cohesion and resilience. The project will also boost public awareness of sustainable practices, promoting community involvement in circular economy initiatives and supporting a broader cultural shift towards sustainability.

Scalability and transferability are key considerations, ensuring that lessons learned from each HUB can support the broader application of successful methodologies in other regions. The project will develop replicable models and best practices that can be scaled across diverse industrial contexts. Evaluation results will inform policy recommendations and guide the development of regulatory frameworks that support widespread adoption of circular economy principles. Structured stakeholder workshops and knowledge-sharing platforms will promote continuous improvement and facilitate the effective replication of successful strategies. Through a structured and adaptive monitoring approach, this initiative aims to establish a sustainable, scalable, and impactful transformation model for the HUBs, driving systemic change towards resilience and circularity.

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6. Conclusions

The D6.1 Report on HUB Starting Lines establishes a comprehensive and strategically structured foundation for the **IS2H4C** project, enabling the transformation of selected industrial zones in Turkey, Spain, the Netherlands, and Germany into H4Cs. This deliverable presents a well-rounded analysis of the baseline conditions, laying the groundwork for the deployment of circular technologies, systemic synergies, and cross-sectoral industrial symbiosis.

Chapter 1 sets the scene by outlining the rationale and objectives of WP6, emphasising the practical deployment of circular technologies within real-world industrial environments. **Chapter 2** then elaborates on the methodological framework, describing a structured approach to data collection through customised templates, stakeholder interviews, and complementary deliverables. It also introduces a coherent system for assessing baseline techno-economic conditions, organised around four key dimensions: technical, infrastructural, resource-related, and regulatory. Success criteria are also defined, encompassing technological, environmental, economic, and social indicators to ensure a holistic evaluation. **Chapter 3** delves into the conceptual foundation of HUBs for Circularity and Industrial Symbiosis, illustrated through international exemplars such as Kalundborg (Denmark) and the Port of Rotterdam (Netherlands). It also highlights the broader enabling environment required for circular transformation, including supportive policy frameworks, capacity-building initiatives, digital solutions, and harmonised metrics. **Chapter 4** offers a strategic overview of the four HUBs participating in **IS2H4C**, detailing each site's industrial profile, baseline energy and emissions data, existing technological assets, and targeted circular synergies. Specific implementation requirements are identified for each HUB, with tailored strategies that reflect regional contexts. Visual flow diagrams help convey current operations, demonstrated circular loops, and future integration pathways. Finally, **Chapter 5** introduces a preliminary success validation framework, jointly developed with the HUB partners and aligned with project-wide KPIs. This framework categorises success metrics under three pillars—technological uptake, strategic sustainability, and operational feasibility—ensuring comprehensive and consistent monitoring. It also addresses potential risks, such as data quality, financial uncertainties, and stakeholder engagement gaps, proposing mitigation strategies to support robust and adaptive implementation.

Building on these insights, the report puts forward a set of strategic recommendations and next steps to guide the continued development of the **IS2H4C** project. Firstly, improving the granularity of data collection across the HUBs is essential to enhance the accuracy of KPIs and enable more robust, data-driven decision-making—particularly in areas such as emissions tracking, energy flow monitoring, and circularity performance metrics. In parallel, fostering cross-HUB learning through a structured knowledge exchange mechanism will support the alignment of approaches to technology deployment, stakeholder engagement, and the adoption of circular business models. Furthermore, the report advocates for scaling up demonstrated synergies—such as CO_2 valorisation, the use of green H_2, and industrial heat recovery—while assessing their potential for replication across different sectors and regional contexts. Strengthening digital integration through the DigitalH4C platform is also key, allowing for real-time monitoring, resource matchmaking, and traceability of circular flows across the network.

To ensure a supportive policy environment, the report emphasises the importance of promoting regulatory harmonisation and facilitating public-private co-investment schemes that can overcome implementation barriers and accelerate systemic transitions. Finally, it calls for the embedding of continuous improvement practices through iterative assessment cycles, the establishment of living labs, and co-creation processes with local stakeholders—ensuring that HUB transformation remains agile, inclusive, and responsive to emerging challenges.

In summary, the D6.1 Report provides not only a robust diagnostic of the starting conditions of the **IS2H4C** HUBs but also a scalable model for circular industrial transformation. By aligning tailored implementation strategies with shared evaluation frameworks and future-oriented recommendations, the project positions itself to deliver impactful environmental, economic, and societal outcomes — paving the way for replicable, future-ready circular economy HUBs across Europe.

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Bibliography

1 Mendez Alva, F., De Boever, R., & Van Eetvelde, G. (2021). HUBs for Circularity: Geo-Based Industrial Clustering towards Urban Symbiosis in Europe. *Sustainability*, *13*(24), 13906. https://doi.org/10.3390/su132413906

2 Castellet-Viciano, L., Hernández-Chover, V., Bellver-Domingo, Á., & Hernández-Sancho, F. (2022). Industrial Symbiosis: A Mechanism to Guarantee the Implementation of Circular Economy Practices. *Sustainability*, *14*(23), 15872. https://doi.org/10.3390/su142315872

3 Domenech, T., Bleischwitz, R., Doranova, A., Panayotopoulos, D., & Roman, L. (2019). Mapping industrial symbiosis development in Europe: Typologies of networks, characteristics, performance and contribution to the circular economy. *Resources, Conservation and Recycling, 141*, 76–98. https://doi.org/10.1016/j.resconrec.2018.09.016

4 Abreu, M. C. S., & Ceglia, D. (2018). On the implementation of a circular economy: The role of institutional capacity-building through industrial symbiosis. *Resources, Conservation and Recycling, 138*, 99–109. https://doi.org/10.1016/j.resconrec.2018.07.001

5 Florencio de Souza, F., Bigarelli Ferreira, M., Valélia Saraceni, A., Mendes Betim, L., Lucas Pereira, T., Petter, R. R. H., Negri Pagani, R., Mauricio Martins de Resende, L., Pontes, J., & Moro Piekarski, C. (2020). Temporal Comparative Analysis of Industrial Symbiosis in a Business Network: Opportunities of Circular Economy. *Sustainability*, *12*(5), 1832. https://doi.org/10.3390/su12051832

6 Corsini, F., De Bernardi, C., & Frey, M. (2023). Industrial symbiosis as a business strategy for the circular economy: identifying regional firms' profiles and barriers to their adoption. *Journal of Environmental Planning and Management*, *67*(5), 1148–1168. https://doi.org/10.1080/09640568.2022.2154201

7 Yu, Y., Yazan, D. M., van den Berg, M., Firdausy, D. R., Junjan, V., & Iacob, M.-E. (2023). Circularity information platform for the built environment. *Automation in Construction, 152*, 104933. https://doi.org/10.1016/j.autcon.2023.104933

8 Premyanov, N., Roma-Athanasiadou, E., Metta, J., Tsoniotis, N., Angelidou, M., & Tsolakis, A. (2024). Circular Entrepreneurship via Makerspaces Towards Fostering Sustainable Cities: A Mixed-Method Approach with Case Studies. *Journal of Circular Economy*, *2*(3). https://doi.org/10.55845/QZUU6387

9 Yang, X., Hu, M., Shan, W., Zhang, C., Li, T., & Pan, Y. (2023). Integrating bottom-up building stock model with logistics networks to support the site selection of circular construction HUB. *Journal of Cleaner Production, 430*, 139677. https://doi.org/10.1016/j.jclepro.2023.139677

10 Cagno, E., Negri, M., Neri, A., & Giambone, M. (2023). One framework to rule them all: An integrated, multi-level and scalable performance measurement framework of sustainability, circular economy and industrial symbiosis. *Sustainable Production and Consumption, 35*, 55–71. https://doi.org/10.1016/j.spc.2022.10.016

11 European Commission. (2020). Circular economy action plan. European Commission. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

12 Laatsit, M., & Johansson, G. (2025). Fostering industrial symbiosis in process industries: An innovation policy perspective. *Environmental Technology & Innovation, 37*, 104027. https://doi.org/10.1016/j.eti.2025.104027

13 Babkin, A., Shkarupeta, E., Tashenova, L., Malevskaia-Malevich, E., & Shchegoleva, T. (2023). Framework for assessing the sustainability of ESG performance in industrial cluster ecosystems in a circular economy. *Journal of Open Innovation: Technology, Market, and Complexity, 9*(2), 100071. https://doi.org/10.1016/j.joitmc.2023.100071

14 Harris, S., Martin, M., & Diener, D. (2021). Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. *Sustainable Production and Consumption, 26*, 172–186. https://doi.org/10.1016/j.spc.2020.09.018

15 Franco, N. G., Almeida, M. F. L., & Calili, R. F. (2021). A strategic measurement framework to monitor and evaluate circularity performance in organizations from a transition perspective.

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Sustainable Production and Consumption, 27, 1165–1182. https://doi.org/10.1016/j.spc.2021.02.017

16 EU4Environment. (s.d.). *EU4Environment: Action for the environment in the Eastern Partnership*. https://www.eu4environment.org/

17 Beducci, E., Acerbi, F., Pinzone, M., & Taisch, M. (2024). Unleashing the role of skills and job profiles in circular manufacturing. *Journal of Cleaner Production, 449*, 141456. https://doi.org/10.1016/j.jclepro.2024.141456

18 Oluleye, B. I., Chan, D. W. M., Antwi-Afari, P., & Olawumi, T. O. (2023). Modeling the principal success factors for attaining systemic circularity in the building construction industry: An international survey of circular economy experts. *Sustainable Production and Consumption, 37*, 268–283. https://doi.org/10.1016/j.spc.2023.03.008

19 Calabretta, G., Bocken, N. M. P., & Jaskiewicz, T. (2022). Circular business models in the digital age: An overview of digital technologies for the circular economy. *Business Strategy and the Environment*, 31(2), 765–778. https://doi.org/10.1002/bse.2917

20 Baldassarre, B., Calabretta, G. (2024). Why Circular Business Models Fail And What To Do About It: A Preliminary Framework And Lessons Learned From A Case In The European Union (Eu). *Circ.Econ.Sust.* **4**, 123–148. https://doi.org/10.1007/s43615-023-00279-w

21 Chen, Q., Feng, H., & Garcia de Soto, B. (2022). Revamping construction supply chain processes with circular economy strategies: A systematic literature review. *Journal of Cleaner Production, 335*, 130240. https://doi.org/10.1016/j.jclepro.2021.130240

22 European Environment Agency (EEA). (2022). *Digitalisation and the environment: Opportunities and risks of the digital transition*. EEA Report No 2/2022. European Environment Agency.

23 Ramírez-Rodríguez, L. C., Ormazabal, M., & Jaca, C. (2024). Mapping sustainability assessment methods through the industrial symbiosis life cycle for a circular economy. *Sustainable Production and Consumption, 50*, 253–267. https://doi.org/10.1016/j.spc.2024.08.005

24 Cagno, E., Negri, M., Neri, A., & Giambone, M. (2023). One framework to rule them all: An integrated, multi-level and scalable performance measurement framework of sustainability, circular economy and industrial symbiosis. *Sustainable Production and Consumption, 35*, 55–71. https://doi.org/10.1016/j.spc.2022.10.016

25 Ehrenfeld, J., & Gertler, N. (1997). *Industrial Ecology in Practice: The Evolution of Interdependence at Kalundborg*. Journal of Industrial Ecology, 1(1), 67–79. https://doi.org/10.1162/jiec.1997.1.1.67

26 Kalundborg Symbiosis Official Website: https://www.symbiosis.dk/en

27 Novo Nordisk. (n.d.). *Sustainability: Circular solutions in production*. https://www.novonordisk.com/sustainability

28 Jacobsen, N. B. (2006). *Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects*. Journal of Industrial Ecology, 10(1–2), 239–255. https://doi.org/10.1162/108819806775545411

29 Chertow, M. R. (2007). *"Uncovering" Industrial Symbiosis*. Journal of Industrial Ecology, 11(1), 11–30. https://doi.org/10.1162/jiec.2007.1110

30 Port of Rotterdam Authority. (n.d.). Energy Transition. Energy transition | Port of Rotterdam

31 Brightlands Circular Space. (n.d.). *Circular plastics*. https://www.brightlandscircularspace.com/en/circulaire-plastics

32 Ioniqa Technologies. (n.d.). *Company*. https://ioniqa.com/company/

33 European Commission. (n.d.). *Renewable Energy Directive: Targets and rules*. https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules_en

34 Neste. (n.d.). *Sustainability*. https://www.neste.com/sustainability

35 Porthos. (n.d.). *CO_2 transport and storage in Rotterdam*. https://www.porthosco2.nl/en/

36 YES!Delft. (n.d.). Tech incubator for startups. https://yesdelft.com/

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37 Plant One Rotterdam. (n.d.). Test and demonstration location for sustainable process technology. https://plantone-rotterdam.nl/

38 Port of Rotterdam Authority. (n.d.). *Sustainable port*. https://www.portofrotterdam.com/en/building-port/sustainable-port

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Appendix I: HUB Baseline Data Collection Template

KPMG

HUB name	

	Name	Department	Contact Information
Person in charge of reporting			

Section	Indicator Name	Unit	2019	2020	2021	2022	2023	2024	TOTAL
Energy Consumption	Energy consumption (Source: Natural Gas)	MWh							-
	Energy consumption (Source: Fuel Oil)	MWh							-
	Energy consumption (Source: Fuel Gas)	MWh							-
	Energy consumption (Source: Coke)	MWh							-
	Energy consumption (Source: Diesel)	MWh							-
	Energy consumption (Source: Renewable Electricity)	MWh							-
	Energy consumption (Source: Non-renewable Electricity)	MWh							-
	Total Electricity consumption	MWh	-	-	-	-	-	-	-
	Total Energy consumption	MWh	-	-	-	-	-	-	-
Emissions Profile	Emissions to air (CH_4, CO, CO_2, others)	tCO_2eq							-
	Emissions to water (Total nitrogen, phosphorus, others)	t							-
	Total GHG emissions	tCO_2eq	-	-	-	-	-	-	-
Other Relevant Aspects	Total water withdrawn	m^3							-
	Total water discharged	m^3							-
	Total water consumed	m^3	-	-	-	-	-	-	-
	Total generation of waste	t							-
	Total waste diverted to recycling and reuse	t							-

Comments	

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