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INDUSTRIAL DEVELOPMENT ORGANIZATION

GLOBAL PROGRAMME
HYDROGEN IN INDUSTRY

GREEN HYDROGEN INDUSTRIAL CLUSTERS GUIDELINES

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About UNIDO

The United Nations Industrial Development Organization (UNIDO) supports member states in their efforts towards inclusive and sustainable industrial development and is committed to taking the lead in promoting an inclusive energy transition. With its long-standing experience in renewable energy projects and the application of clean energy technologies in industry, UNIDO successfully collaborates with a wide range of partners globally supporting industries in their pathway to net-zero emissions.

GREEN HYDROGEN INDUSTRIAL CLUSTERS GUIDELINES

First edition

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Contents

Foreword 8
Executive Summary 9
1. Introduction 10
1.1. Green hydrogen and climate change: industrial decarbonization 10
1.2. Green hydrogen and sustainable industrial development 11
1.3. UNIDO's Global Programme for Green Hydrogen in Industry 12
2. UNIDO's Green Hydrogen Industrial Clusters 14
2.1. UNIDO's green hydrogen industrial clusters model 14
2.2. UNIDO's guidelines for green hydrogen industrial clusters 16
2.3. Using the guidelines 16
3. Characteristics of Green Hydrogen Industrial Clusters 18
3.1. Types of green hydrogen industrial clusters 18
3.2. Availability of renewable electricity and electricity mix 21
3.2.1. Location and access to utilities and auxiliary facilities 22
3.2.2. Composition, scale and synergies 23
3.3. Production of green hydrogen 23
3.4. Overview of uses for green hydrogen in industry 23
4. Phases of Green Hydrogen in Industrial Clusters 28
4.1. Phases for cluster development – overview 28
4.2. Phase 1: Preparation of green hydrogen clusters 28
4.2.1. Awareness-raising 29
4.2.2. Stakeholder engagement 31
4.2.3. Preparation of the objective, strategy and work plan of a green hydrogen cluster 32
4.2.4. Feasibility studies 32
4.2.5. Financial mobilization 34

4.3. Phase 2: Deployment of technologies 36
4.3.1. Commissioning of pilot project 36
4.3.2. Production, process adaptation and use of green hydrogen 38
4.3.3. Testing of pilot projects 38
4.3.4. Commercial operation 41
4.4. Phase 3: Upscaling of green hydrogen in industry 42
4.4.1. Programmes for uptake and challenges 42
4.4.2. Development of green hydrogen networks 43
5. Challenges and Enablers 46
5.1. Overview of regulatory challenges and enablers 46
5.1.1. Regulatory challenges 46
5.1.2. Regulatory enablers 47
5.2. Technology 49
5.2.1. Technological challenges 49
5.2.2. Technological enablers 50
5.3. Economics and finance 51
5.3.1. Economic and financial challenges 51
5.3.2. Economic and financial enablers 52
5.4. Society and environment 54
5.4.1. Social and environmental challenges 54
5.4.2. Social and environmental enablers 54
6. Concluding Remarks 56

List of figures

Figure 1-1. Global Programme for Green Hydrogen in Industry (UNIDO) 12
Figure 2-1. Schematic overview of a green hydrogen industrial cluster 15
Figure 3-1. Overview of GreenLab Skive Industrial Cluster 20
Figure 3-2. GreenLab Skive Energy Park SymbiosisNet diagram 21
Figure 3-3. Overview of possible uses cases for green hydrogen 24
Figure 3-4. Overview of possible uses cases for green hydrogen 25
Figure 4-1. Phases of green hydrogen clusters and stages 29
Figure 4-2. Example of regulation at different stages of the production chain 36
Figure 4-3. Visual of the HEAVENN project 44

List of tables

Table 1-1. Types of hydrogen and current production 11
Table 2-1. Phases of the development of green hydrogen industrial clusters (GHIC) 15
Table 4-1. Elements to be considered during the awareness-raising activities 30
Table 4-2. Recommended assessments for the development of green hydrogen industrial clusters 33
Table 4-3. Categories of performance indicators for green hydrogen industrial clusters 39
Table 4-4. Sustainable Development Goals and indicators 40
Table 5-1. Overview of main challenges and enablers 47
Table 5-2. Technology readiness level (TRL) of electrolyser technologies 49

List of boxes

Box 1-1. IHEC demonstration project on commercial hydrogen fuel cell buses: lessons learned from Beijing....... 13
Box 3-1. Transformation of a brownfield site: lessons learned from the Humber Cluster 19
Box 3-2. Industrial cluster site: lessons learned from GreenLab Skive 20
Box 3-3. Green hydrogen in ammonia production: lessons learned from the Ammonia Energy Association 26
Box 3-4. Green steel projects development: lessons learned from H2 Green Steel (H2GS)... 27
Box 4-1. Awareness-raising: lessons learned from the HEAVENN project.. 30
Box 4-2. Financial mechanisms: lessons learned from the United States... 35
Box 4-3. Life Cycle Analysis model: lessons learned from GREET 37
Box 4-4. Management of industrial clusters: lessons learned from GETEC Park.EMMEN... 42
Box 4-5. HEAVENN: the first EU hydrogen valley 44
Box 5-1. Steps to develop a green hydrogen roadmap: lessons learned from Colombia 48

Foreword

Nearly all countries have committed to decarbonize their economies in the coming decades following the Paris Agreement to limit global warming to 1.5°C. The industrial sector is a significant contributor to global greenhouse gas (GHG) emissions, and therefore plays a critical role in meeting these ambitious goals.

Renewable or green hydrogen, produced using renewable energy sources, is an essential element of this transition, particularly in hard-to-abate sectors. As a game changer, green hydrogen offers enormous potential to develop both national energy systems and industrial markets, while significantly reducing GHG emissions. For developing countries, this presents a unique opportunity to leapfrog to net-zero industrial development, while accelerating economic growth.

UNIDO's Global Programme for Hydrogen in Industry is working towards accelerating a just hydrogen transition in developing countries and transition economies. As a key element of this programme, UNIDO has developed a three-phase model for establishing green hydrogen industrial clusters (GHIC), which we define as industrial clusters that share green hydrogen and renewable energy for various purposes, including material production, heating and cooling, power balancing, local mobility, and industrial feedstock. The present guidelines provide recommendations for governments and industries in the preparation, implementation, and upscaling of green hydrogen industrial clusters.

By building GHIC, developing countries can reduce their dependence on imported fossil fuels, promote investment, create employment, and drive innovation. These clusters provide a framework for decarbonizing industries, and developing local production and application capacities. They also offer a unique opportunity to create a new low-carbon industry, opening up new markets and generate new economic opportunities for developing countries.

UNIDO is committed to promote the establishment of GHIC in developing countries, leveraging a versatile and scalable model that supports multi-stakeholder engagement and coordination in the design and implementation of said clusters.

It is my great pleasure to introduce these guidelines for developing green hydrogen industrial clusters. I would like to thank the UNIDO team and the international experts who provided insights for the preparation of these guidelines. It is my hope that it will be useful for policymakers, industry leaders, and other stakeholders as we work together to achieve the goal of sustainable and inclusive industrial development, and create a better future for all.

Gerd Müller

Director General

Executive Summary

Nearly all countries have committed to decarbonize their economies in the coming decades following the Paris Agreement to limit global warming to 1.5°C. Currently, industrial production accounts for 23% of global greenhouse gas (GHG) emissions. Green hydrogen is considered a key technology to accelerate industrial decarbonization to replace fossil fuels in hard-to-abate sectors. It can also help develop both national energy systems and industrial markets. Several countries are already developing green hydrogen roadmaps and strategies. These provide a framework on how to decarbonize industries, secure green hydrogen imports, and develop local production and application capacities.

Today, an estimated 99% of global hydrogen production (95 million tonnes in 2021) is produced with fossil fuels. Electrolysis-based green hydrogen production using renewable energy (e.g. solar, wind) can help accelerate the clean energy transition, but accounted for only 0.035 Mt in 2022. With decreasing renewable electricity costs, the introduction of carbon pricing and production advancements for electrolysers, green hydrogen is predicted to expand rapidly, covering up to 14% of the world's total final energy consumption by 2050.

With its long-standing experience in promoting sustainable and inclusive industrial development reflected in Sustainable Development Goal 9 (SDG9) and the application of clean energy technologies in industry, the United Nations Industrial Development Organization (UNIDO) successfully collaborates with a wide range of partners globally supporting industries in their pathway to net-zero emissions.

Launched in 2021, UNIDO's Global Programme for Hydrogen in Industry aims to stimulate and accelerate the uptake and deployment of green hydrogen in industries of developing countries and transition economies. It supports industrial decarbonization, particularly of hard-to-abate sectors, and the development of new low-carbon industries.

As a key element of the programme, UNIDO developed a model for green hydrogen industrial clusters (GHIC), which we define as industrial clusters that share green hydrogen and renewable energy for different purposes, including material production, heating and cooling, power balancing, local mobility and industrial feedstock. The GHIC can reduce greenhouse gas emissions, promote investment, create employment and foster economic growth that is environmentally sustainable and socially responsible. The model provides guidance for governments and industries in the preparation, implementation and upscaling of the GHIC. Several challenges persist regarding technological readiness, socio-ecological impact and particularly market creation as well as access to finance. Thus, the guidelines provide an overview of potential policy enablers, notably regulation that fosters investment security and stimulates market demand.

The development of the GHIC can be broadly divided in three phases. During Phase 1, industrial clusters will be brought to a level of readiness in which pilot green hydrogen projects can be developed during Phase 2. At this stage, initial pilot projects will be supported as well as the adaptation of the cluster to ensure sector coupling and future upscaling. Phase 3 will lead to a successful implementation of the green hydrogen strategies and a full provision of green hydrogen to meet the hydrogen demand of the production cluster. This will create success studies and examples of good practices for replicability. In all phases, monitoring and evaluation exercises will be carried out to track progress and update the model based on technological, cost and environmental developments, and in line with compliance of the Sustainable Development Goals (SDGs).

The development of the clusters requires multi-stakeholder engagement and coordination in the design of the overarching policy framework and in its implementation. These guidelines provide information on its development and dialogues among government, the private sector and academia. They are published with the aim to support the establishment of the GHIC, leveraging a versatile and scalable model. As a result, the clusters will promote the uptake of green hydrogen in local industry, its decarbonization and the development of new low-carbon industries, all contributing to achieving inclusive and sustainable industrial development and the Nationally Determined Contributions (NDCs) under the Paris Agreement.

1. Introduction

Green hydrogen, also known as renewable hydrogen, is a crucial component for the future of energy systems and industrial development. Green hydrogen not only contributes to decarbonization of the energy intensive industrial sector, but also opens new possibilities for industrial growth, especially in nations with abundant renewable energy resources. For this reason, developed and developing nations are making significant investments in green hydrogen as well as global partnerships to guarantee long-term access. To attract or develop the new low-carbon industries and numerous downstream sectors, these countries can construct new industrial clusters based on green hydrogen and renewable energy.

1.1. Green hydrogen and climate change: industrial decarbonization

Nearly all countries have committed to decarbonizing their economies in the coming decades following the Paris Agreement to limit global warming. Likewise, many large corporations have announced plans to cut their carbon footprint to net zero. Currently, industrial production accounts for a quarter of global GHG emissions.[1] This requires a significant upscaling of renewable electricity generation to replace fossil fuel-based power, while still meeting the increased global demand for electricity. At the same time, a considerable share of renewable energy will be needed to substitute fossil fuels in hard-to-abate activities that cannot be easily electrified. These include the production of steel, cement and base chemicals and some applications in the transport sector (e.g. aviation and shipping). Within these sectors, green hydrogen can be used as a chemical feedstock and as a fuel to complement initiatives towards net-zero emissions.

Green hydrogen is produced via water electrolysis using renewable electricity. Today, approximately 99% of global hydrogen is produced from fossil fuels[2] (6% of global natural gas and 2% of global coal are currently used for producing hydrogen[3]). According to the International Energy Agency (IEA), hydrogen production in 2018 was 75 million tonnes (Mt) globally, whereas electrolysis-based hydrogen production in 2022 accounted for only 0.035 Mt of global production. Hence, production is currently dominated by fossil fuels.[4] This is collectively responsible for CO_2 emissions of around 830 $MtCO_2$ per year.[5]

To accelerate the clean energy transition away from fossil fuels, increasing and upscaling green hydrogen production are essential. With significantly decreasing

[1] IEA (2022): Industry, URL: <https://www.iea.org/reports/industry>.

[2, 3, 4, 5] IEA (2022): Global Hydrogen Review.

costs for renewable electricity, the introduction of carbon pricing/standards, and production advancements and roll-out for electrolysers, green hydrogen is expected to expand rapidly and cover up to 14% of the world's total final energy consumption by 2050. However, here are large uncertainties associated with the deployment.[6]

Table 1-1 summarizes currently discussed types of hydrogen, a brief description and production levels. These guidelines focus on the opportunities for green hydrogen (last row).

Table 1-1. Types of hydrogen and current production

Term used	Description	Current production
Grey hydrogen	Grey hydrogen is produced from fossil fuels (natural gas or oil) through steam reforming and causes process-related CO_2 emissions.	74 Mt (2018)
Blue hydrogen	Blue hydrogen is based on the same processes as grey hydrogen, but additional carbon capture and storage technologies are applied to permanently store the process emissions underground (carbon sequestration) or bind it in a solid product (e.g. bricks).	0.75 Mt
Green hydrogen	Green hydrogen is produced via water electrolysis using non-emitting (renewable) electricity.	0.035 Mt

Many governments have recognized the strategic importance of green hydrogen and have started to develop strategies and roadmaps to deploy hydrogen and invest in new production facilities. Their interest is shared by the private sector, which has registered a growing number of industry alliances and investments, as well as international energy partnerships and networks.

1.2. Green hydrogen and sustainable industrial development

Governments, industry and other stakeholders are increasingly adapting their industrial development strategies to new framework conditions to include green hydrogen. Already, several countries have or are currently developing green hydrogen roadmaps and strategies. These strategies aim to decarbonize industries, secure imports of green hydrogen and develop their own production capacities.

The gaining momentum has created new opportunities for industrial development, particularly for countries within Africa, the Middle East, Southern Asia and Latin America, which have significant potential for renewable power generation. With appropriate framework conditions, such countries can develop promising new industrial systems based on green hydrogen and renewable power and then gradually attract energy-intensive industrial sectors in addition to those from manifold downstream industries. The uptake of green hydrogen, therefore, presents an opportunity for many countries to both augment their future industrial strategies and increase their shares of renewable energy sources for electricity generation.[7]

Green hydrogen can contribute to inclusive and sustainable industrial development (ISID) in the following ways besides the reduction of industrial greenhouse gas emissions: it can support the development of new low-carbon production clusters and process routes. These can create green jobs and improve local economic opportunities where the new industries locate and decrease the risk due to dependence of external production of certain goods such as fertilizers or steel. The use of green hydrogen stipulates upstream investments in renewable electricity generation and infrastructure. For providing the large quantities of electricity, additional capacities for renewable electricity generation will be required. This can improve energy access to the local communities where green hydrogen is produced. In addition, hydrogen can be used as a functional storage to avoid curtailment of renewables (e.g. at bottlenecks of the electricity grid, or at time of surplus electricity production) and store electricity for which there are no storage technologies in place and for longer periods of time. Green hydrogen will also require water. In areas where there is water scarcity or stress, water desalination can be used and distributed with the communities where hydrogen is being produced.

[6] Odenweller, A., Ueckerdt, F., Nemet, G.F. et al. Probabilistic feasibility space of scaling up green hydrogen supply. Nat Energy 7, 854–865 (2022). <https://doi.org/10.1038/s41560-022-01097-4>.

[7] <https://www.worldenergy.org/assets/downloads/Working_Paper_-_National_Hydrogen_Strategies_-_September_2021.pdf>.

1.3. UNIDO’s Global Programme for Hydrogen in Industry

In line with UNIDO’s mandate to promote inclusive and sustainable industrial development, reflected in SDG 9, UNIDO launched its Global Programme for Hydrogen in Industry (GPHI) to support developing countries overcome the barriers and encourage a just hydrogen transition that puts social and environmental aspects in focus. Through its programme, UNIDO aims to influence and guide the development of market polices, standards, skills, financing instruments, innovation and coordination between key stakeholders that play an essential role in the development of a just and sustainable hydrogen economy. Promoting tangible projects to accelerate the local uptake of green hydrogen in industries of developing countries and transition economies is a key element of the programme.

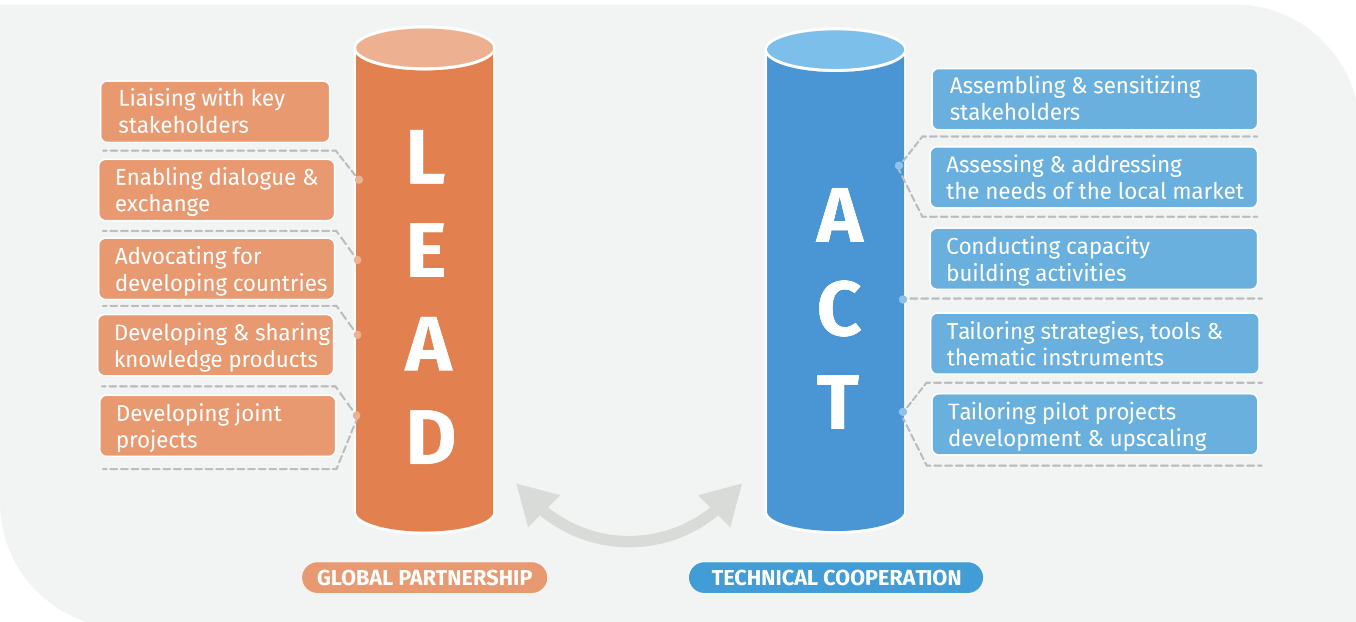
Given the complexity and dynamism of a just hydrogen transition, UNIDO has built its global programme around two pillars “LEAD” and “ACT” which draw on and feed into each other’s resources, expertise and networks. The GPHI also counts on cooperation with the International Hydrogen Energy Centre (IHEC) in China.

The Programme consists of: The Global Partnership for Hydrogen in Industry and the Technical Cooperation with country-specific tailored interventions, as summarized in the figure below.

The global partnership is a global platform for member states, industries, private sector, investors, research and academic institutions. Through the partnership, UNIDO regularly liaises with key stakeholders by conducting regional and global dialogue sessions with member states to explore developing countries’ needs and to enable dialogue and information exchange among them. These dialogues provide substantial material for UNIDO to articulate developing countries’ interests and needs and advocate for them in global fora (e.g. COP, G7, and G20). Moreover, based on dialogues’ outcomes, UNIDO joins forces with renowned knowledge partners to address countries’ needs and to develop training as well as innovative tools and solutions. These include designing and promoting policies, regulations, standards, financial instruments, and innovation programmes. The exchanges with stakeholders also give rise to ideas for joint projects development and active engagement of women and youth in the hydrogen market.

UNIDO’s technical cooperation adapts and applies knowledge and tools developed globally to country-specific interventions for green hydrogen in industry. This is done in close collaboration with the governments and industries of developing countries and transition economies. Such technical assistance entails sensitizing stakeholders, sharing best practices, as well as assessing local market needs and devising strategies, tools and instruments. UNIDO reviews countries’ institutional and technical capacities and conducts capacity development where gaps have been identified. One key component of technical cooperation is its green hydrogen industrial cluster

Figure 1-1. Global Programme for Green Hydrogen in Industry (UNIDO)



model, which is based on a co-location approach to local green hydrogen production, storage, transport and end-use.

In addition, both components are supported by the IHEC in Beijing, as a valuable knowledge partner. The centre aims to work together with government and industrial entities to scale up hydrogen technologies through promoting capacity-building and knowledge dissemination, as well as strengthening international cooperation with international organizations. The box summarizes its activities.

To sum up, green hydrogen could support the reduction of greenhouse gas emissions while building up new supply chains and creating green jobs. The guidelines provide an overview of the current and potential use of hydrogen in industrial clusters and describe the characteristics of green hydrogen industrial clusters.

Box 1-1. IHEC demonstration project on commercial hydrogen fuel cell buses: lessons learned from Beijing

The Government of China and UNIDO jointly established the International Hydrogen Energy Centre (IHEC) in June 2021. IHEC is headquartered in Beijing, China. It is mainly engaged in core technology R&D, key equipment development, industrial-scale applications and the promotion of carbon neutrality to support the SDGs. IHEC leads four key demonstration projects on commercial fuel cell vehicles (FCVs) in Zhangjiakou, FCV logistics, the world's largest refuelling station in Daxing, and the largest and most comprehensive green hydrogen metallurgical chemical demonstration park in Baotou, Inner Mongolia.

Preparation of the project started in 2016. The first batch of 25 hydrogen fuel cell buses (FCBs) was put into operation in 2018. By 2021, 444 FCBs were in operation, covering 21 million kilometres, directly benefiting 65 million passengers, safely refuelling more than 140,000 times, and consuming around 1,700 tonnes of green hydrogen, saving an estimated 17,000 tonnes of carbon.

All FCBs were operated by the Zhangjiakou Public Transport Group. The vehicle manufacturers were Foton, Yutong Bus, Geely, Zhongtong Bus and ZEV (Zhongzhi Yike Chengdu Automobile Co., Ltd.). The supplier of the fuel cell engines was SinoHytec, and the main producer of green hydrogen was HyPower.

The total investment for the 444 FCBs was about $170 million, with support from the Zhangjiakou Municipal Government and a state subsidy of $7.5 million. SinoHytec invested $18 million in the construction of a green hydrogen production plant and $4.5 million in the construction of two hydrogen filling stations.

The project achieved the following results:

- The performance of the fuel cells was significantly improved and the operation of the fuel cells in extreme cold conditions was demonstrated. Hydrogen fuel cell engines were able to operate at -30°C with the support of new technologies, and their waste heat was used to heat the passenger compartment.
- The safe support of the Beijing 2022 Olympic Winter Games was successfully realized; a total of 357 FCBs served the Games without any accidents.
- The International Hydrogen Energy Centre, together with Zhangjiakou Municipal Government, founded the Zhangjiakou Hydrogen Energy and Renewable Energy Institute, established the Hebei Provincial Hydrogen Energy Industry Innovation Centre, and built the first big data monitoring platform for the whole hydrogen energy chain in China.

2. UNIDO's Green Hydrogen Industrial Clusters

UNIDO defines green hydrogen industrial clusters (GHIC) as industrial regions or clusters[8] that share green hydrogen (production, transport and use) and renewable energy electricity, in addition to other resources, for different purposes including material production, heating and cooling, local mobility and industrial feedstock. Such clusters are characterized by internal linkages enabling cooperation, specialized expertise, services, resources, suppliers and skills, and further generate various advantages among the participants, including the distribution of the investment and mitigation of risks. Green hydrogen industrial clusters can reduce greenhouse gas emissions, promote investment, create employment and foster economic growth that is environmentally sustainable and socially responsible.

2.1. UNIDO's green hydrogen industrial clusters model

As a key element of the programme, UNIDO developed a model for "green hydrogen industrial clusters". This model aims to accelerate the application of locally produced green hydrogen in industrial zones, clusters and parks. Its aim is to serve as a replicable model through which countries can deploy green hydrogen technologies to achieve their emissions reductions and industrial production goals as well as to generate economic and social opportunities. This requires significant amounts of green hydrogen and coordination among the stakeholders within the clusters. The model provides guidance for governments and industries in the preparation, implementation and upscaling of green hydrogen industrial clusters.

This model was developed by UNIDO and informed by its extensive experience on industrial cluster models and projects, including the Eco Industrial Parks,[9] Integrated Agro-Industrial Parks,[10] and Sustainable Industrial Parks[11] projects, as well as resource efficiency and cleaner production initiatives including the Na-

[8] Industrial clusters are agglomerations of interconnected companies and associated institutions. Firms in a cluster produce similar or related goods or services and are supported by a range of dedicated institutions located in spatial proximity, such as business associations or training and technical assistance providers.

[9] <https://hub.unido.org/about-eco-industrial-parks>.

[10] <https://www.unido.org/integrated-agro-industrial-parks>.

[11] <https://sipp.unido.org>.

tional Cleaner Production Centres.[12] The model is also based on an exhaustive analysis of 20 different hydrogen and renewable energy clusters and valleys.[13]

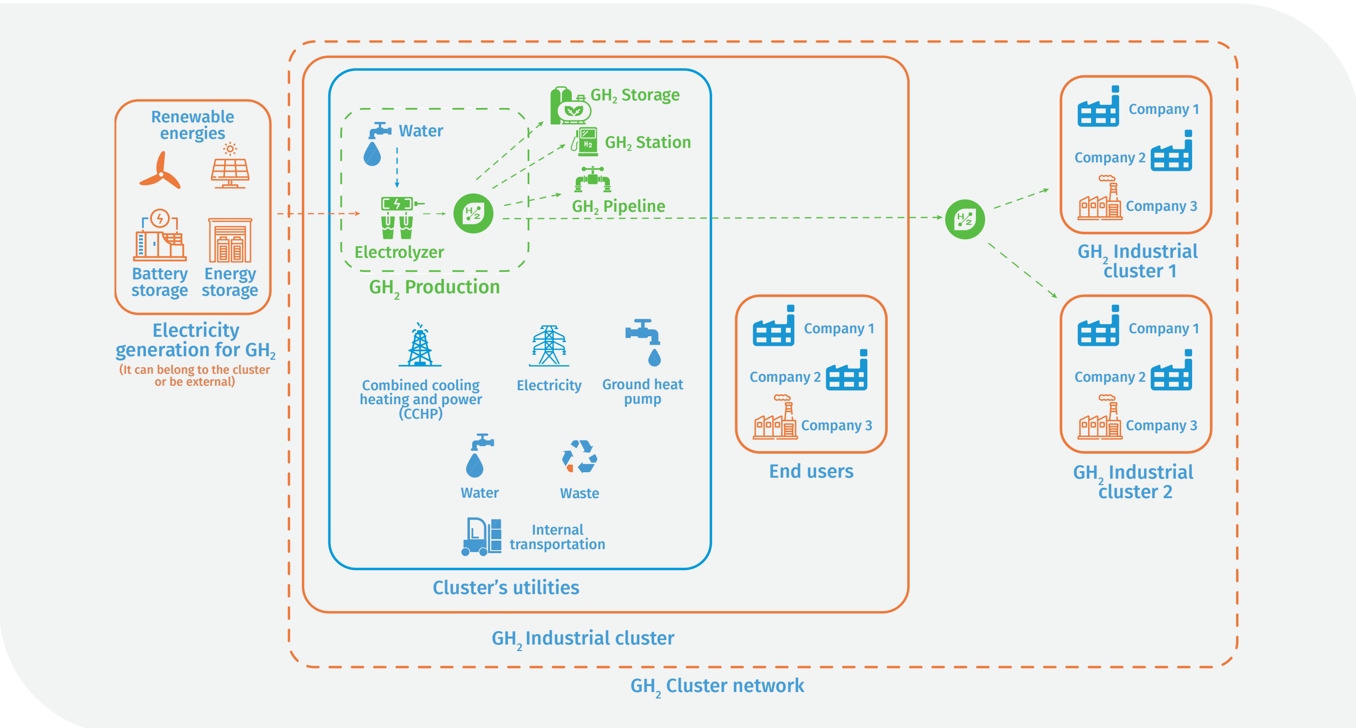
The model has three stages that are summarized in Table 2-1 and are explained below. Throughout the phases, monitoring and evaluation exercises will be carried out to track progress and update the model based on technological, cost and environmental developments. The model was presented and discussed at an expert group meeting in October 2021 with different stakeholders from hydrogen clusters and valleys.

During Phase 1, industrial clusters will be brought to a level of readiness wherein pilot green hydrogen projects can be developed during Phase 2. At this stage, initial pilot projects will be supported as well as the adaptation of the cluster to ensure sector coupling and the future upscaling. Phase 3 will lead to a successful implementation of the green hydrogen strategies and a 100% provision of green hydrogen to meet the hydrogen demand of the production cluster. This will create success studies and examples of good practices for replicability.

Table 2-1. Phases of the development of green hydrogen industrial clusters (GHIC)

Phase	Activities in the phases
Phase 1: Preparation of green hydrogen clusters	• Awareness-raising • Stakeholder engagement • Preparation of the objective, strategy and work plan of a green hydrogen cluster • Feasibility studies • Financial mobilization
Phase 2: Deployment of technologies for green hydrogen	• Commissioning of pilot projects • Production, process adaptation and use of green hydrogen in industrial processes • Testing of pilot projects • Commercial operation
Phase 3: Upscaling the use of green hydrogen in industry	• Programmes for uptake and challenges • Development of green hydrogen networks

Figure 2-1. Schematic overview of a green hydrogen industrial cluster



[12] <https://www.unido.org/our-focus/cross-cutting-services/partnerships-prosperity/networks-centres-forums-and-platforms/national-cleaner-production-centres-ncpcs-networks>.

[13] The hydrogen clusters and valleys evaluated include: Germany Hydrogen Valley HyWays for Future, South Africa Hydrogen Platinum Valley, Italy Puglia Green Hydrogen Valley, Denmark GreenLab industrial park, China Suzhou Industrial Park, HEAVENN, Ukraine Danube Hydrogen Valley, United Kingdom Humber Industrial Cluster, Austria WIVA P&G Energy Model Region, HyChico Argentina, NEDO Japan, Green Hysland Spain, Hamburg Green Hydrogen Hub, Green Hydrogen at Blue Danube Romania, Green Energy Oman (InterContinental Energy, OQ, EnerTech, Shell Consortium).

2.2. UNIDO's guidelines for green hydrogen industrial clusters

In line with UNIDO's support within its Global Programme for Hydrogen in Industry, UNIDO is publishing the first edition of these guidelines with the aim to support the establishment of green hydrogen industrial clusters, leveraging a versatile and scalable model. These clusters aim to promote the uptake of green hydrogen in local industry, thereby supporting decarbonization and the development of new low-carbon industries – all contributing to achieving inclusive and sustainable industrial development, including industrialization goals and Nationally Determined Contributions (NDCs) to the Paris Agreement.

2.3. Using the guidelines

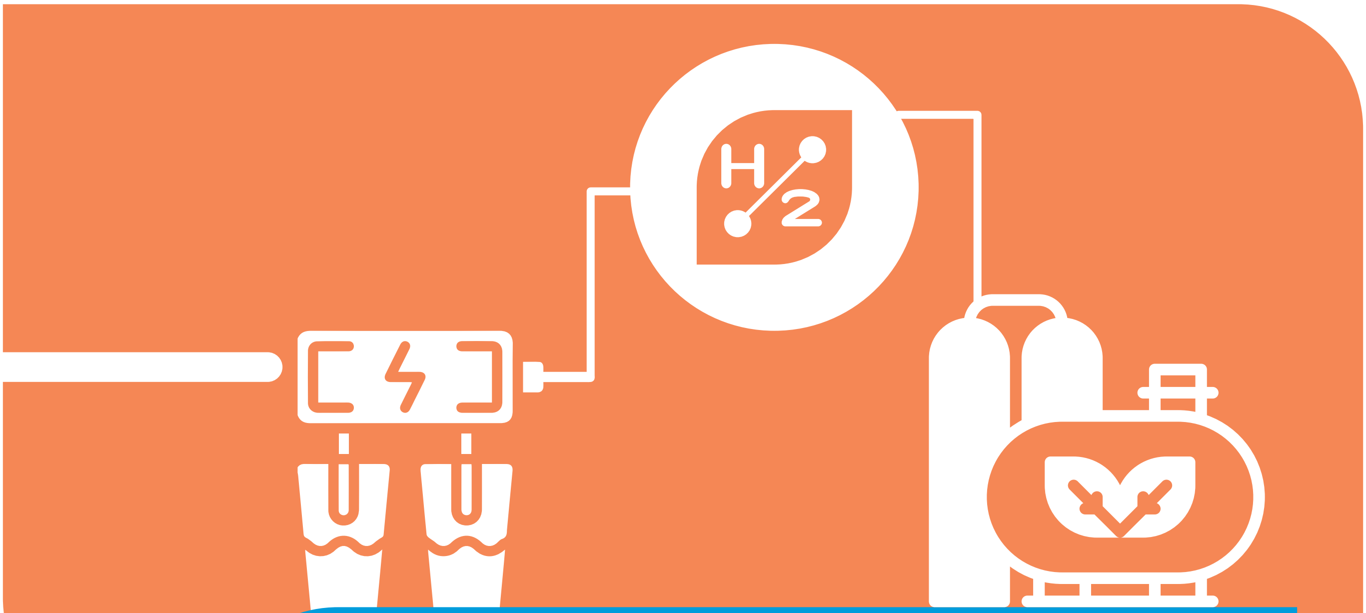
The development of green hydrogen industrial clusters requires multi-stakeholder engagement and coordination. Governments, the private sector, academia and other stakeholders should all be empowered to participate in the design of the overarching policy framework and in its implementation. These guidelines will provide the information and steps to their development and dialogues among a variety of stakeholders.

The guidelines are aimed at key stakeholders with an interest in industrial parks include, but are not limited, to the following: international institutions, national government, local governments, park developers, park operators, companies (tenants) and renewable power providers.

The guidelines consist of the following sections:

- **Chapter 1**: Provides an overview of industrial development and the use of green hydrogen in industry
- **Chapter 2**: Describes the UNIDO's approach for promoting hydrogen use in industrial production and the objective of the guidelines.
- **Chapter 3**: Presents an overview of the characteristics of green hydrogen industrial clusters
- **Chapter 4**: Discusses the challenges and enablers of green hydrogen industrial clusters
- **Chapter 5**: Gives an overview of the road to the application of green hydrogen in industrial production
- **Chapter 6**: Provides some conclusions

UNIDO defines green hydrogen industrial clusters as industrial regions or clusters that share green hydrogen (production, transport and use) and renewable energy electricity, in addition to other resources, for different purposes including material production, heating and cooling, local mobility and industrial feedstock.



3. Characteristics of Green Hydrogen Industrial Clusters

This chapter provides an overview of the characteristics of green hydrogen industrial clusters in four sections. First, the types of GHIC will be introduced. Then, the generation of green hydrogen using available renewable electricity is discussed. The production and provision of hydrogen as well as uses of hydrogen are presented in the third and fourth section. The chapter describes criteria and requirements that a country or region and the industrial cluster must have to convert it into a green hydrogen industrial cluster. This will help decision-making for the selection of the cluster and the different activities that must be carried out to develop the cluster.

3.1. Types of green hydrogen industrial clusters

The use of green hydrogen can lead to green growth (including in rural areas), new green jobs, local business contracts, local investments and income streams, business tourism/conferences and new green profiles/brands (e.g. for local authorities/hosts). It can also drive new renewable energy sources and the reduction of greenhouse gas emissions in industrial and agricultural production. In other words: acceleration of the green energy transition.

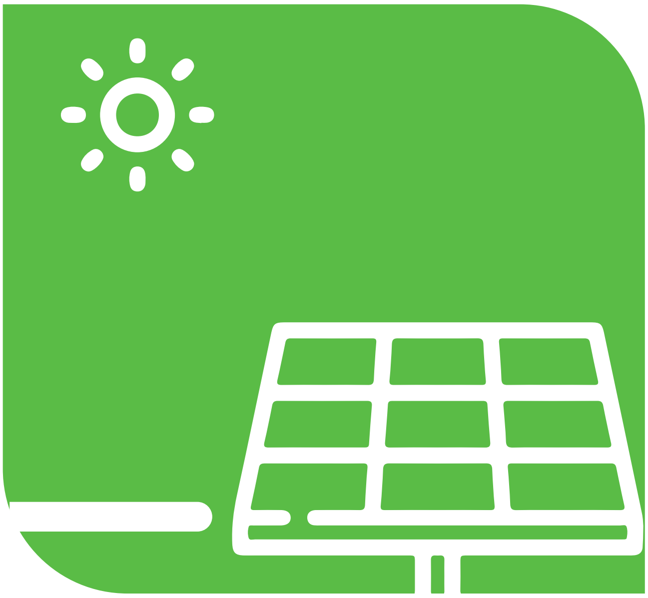
This section provides an overview of types of green hydrogen industrial cluster conversions or developments. There are two broad categories: greenfield sites, which are new production clusters, and brownfield sites, which are transformed using green hydrogen. Eventually, both can share the same type of green hydrogen.

Green hydrogen offers an opportunity to decarbonize important energy-intensive industrial processes such as steel and ammonia production. These industries tend to be in industrial clusters. Green hydrogen industrial clusters can be developed, either by building them from scratch (so-called greenfields) or by transforming existing ones while using and adapting their existing infrastructure (brownfields).

A greenfield industrial cluster would typically evolve in a rural location that lives up to some of the characteristics addressed further on in this chapter. This is often where resources and space are available to create large-scale industrial clusters and capacities for electricity generation.

Examples of brownfield industrial clusters that are suitable for green hydrogen production include clusters with easy access to large-scale renewable energy (e.g. offshore wind cable to shore points), existing industrial parks with energy profiles that are suitable as anchor processes for an industrial symbiosis, industrial ports, and combined heat and power plant facilities (CHPs) that can be exploited to transition into low-carbon alternatives. A case example is the conversion of blast furnace steel production sites to ones using hydrogen-based direct reduced iron (DRI). This is one of the options for using green hydrogen in industrial production processes.

The following box provides a case study of the Humber Cluster, which is an existing industrial cluster (brownfield) that will be transformed over the next few years. The cluster currently uses significant amounts of fossil-based hydrogen for the chemical production processes. As part of the Humber strategy, 720 MW blue hydrogen and 100 MW green hydrogen will be deployed.[14] The long-term vision for the cluster is to operate with net-zero emissions by 2050.



Box 3-1. Transformation of a brownfield site: lessons learned from the Humber Cluster

The Humber region provides the United Kingdom's biggest challenge for industrial decarbonization, and therefore the country's largest opportunity. It is estimated that 80% of the region's CO_2 emissions will be eliminated via decarbonization projects.

The Humber industrial cluster is home to multiple low-carbon projects, each providing a key piece to achieve the UK government's net-zero 2050 targets. In addition to UK government funding, over £15 billion ($18.5 billion) of private investment will provide security to one in 10 jobs, while creating thousands more. There will, however, be challenges to ensure the region has the transformative skills required, and that policy and regulation at the local and national level is transformed to enable the projects move forward at pace. The associated supply chain, from consultants to equipment suppliers, will be required to provide proactive support.

The 2023 Humber Industrial Cluster Plan includes a comprehensive and dynamic plan for the Humber Cluster to achieve net zero by 2040. The project team, composed of lead partners HEY LEP and CATCH, alongside eight industrial partners, are bringing together all the strands of research, studies and modelling that has taken place over the last 24 months to inform the final plan. CATCH is determined to follow through with the plan's recommendations, cementing its status as the leading low-carbon industrial cluster in the UK.[15]

[14] <https://www.humberindustrialclusterplan.org/title-humber-hub-–-uniper's-flagship-hydrogen-project-in-the-humber.htm>.

[15] Humber Cluster, URL: <https://www.humberindustrialclusterplan.org>.

The following case study of GreenLab provides an overview of a new industrial cluster planned (greenfield).

Box 3-2. Industrial cluster site: lessons learned from GreenLab Skive

GreenLab Skive is in a rural area of Denmark. The location is ideal for testing energy conversion and sector integration, as it is close to the national 150 kV power grid and the 40-bar gas pipeline. A 60-hectare industrial cluster is being built in this area, as a greenfield, integrating carefully selected companies aiming to contribute to the green transition. The GreenLab model fully converts natural resources into value chains – internally, using energy flows (thanks to the co-location of production and consumption), and externally, through the production of green products and fuels, ultimately enabling the decarbonization of vertical sectors.

Figure 3-1. Overview of GreenLab Skive Industrial Cluster

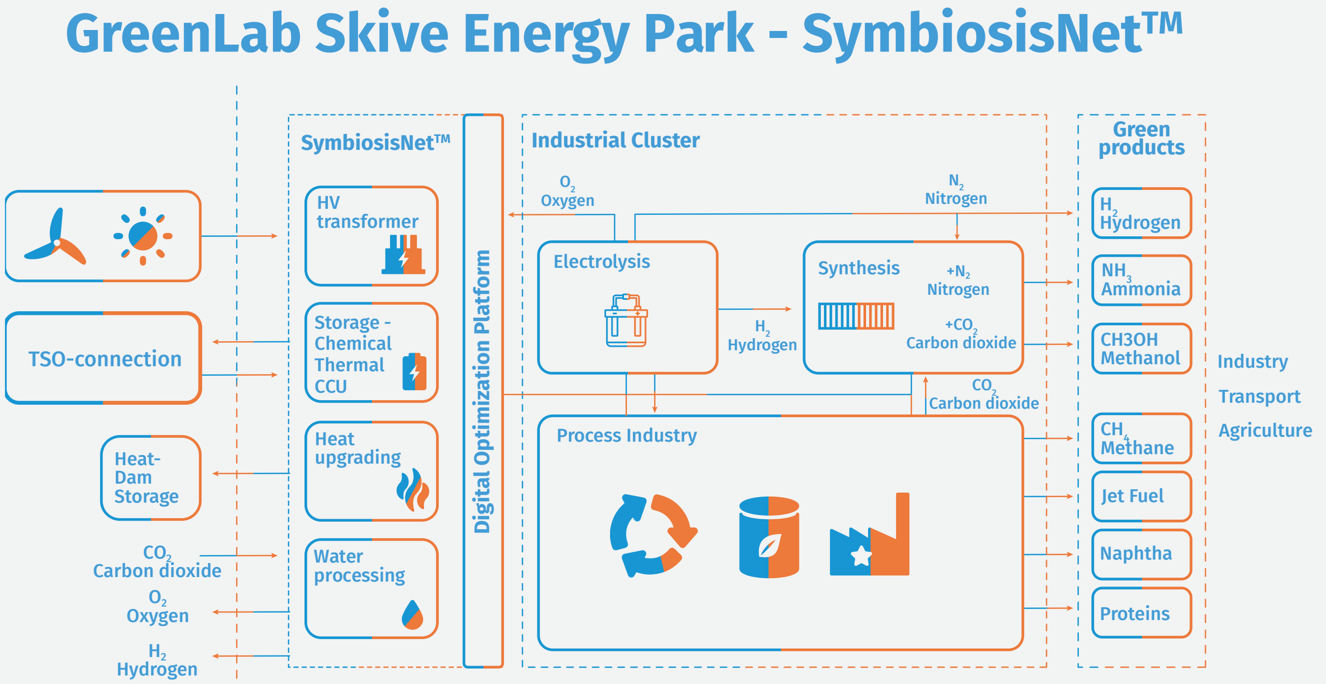
The industrial cluster is composed of:

- A renewable energy supplier that provides 80 MW of directly connected wind and solar power.
- A large biogas plant with an organic line, which produces biogas/biomethane from manure and waste from the production units of various premises.
- Two pyrolysis process companies that are using green hydrogen – one that replaces virgin fossil fuels with syngas-based oil from end-of-life plastics, and another that uses straw and other agricultural bio-waste to make biocarbon.
- A protein extraction company that produces protein-rich feed from starfish and other locally sourced marine waste.
- A municipal waste treatment facility.
- A factory that produces high-density fibreboard without glues or resins from wastepaper and cardboard.

- Two pioneering green hydrogen and Power-to-X projects will start operating in the coming years with an electrolyser capacity of 112 MW; potential on-site electrolyser capacity is estimated at 400 MW, with more projects in the pipeline.

GreenLab establishes and manages the cluster infrastructure and utilities for its customers through the SymbiosisNet™.

Figure 3-2. GreenLab Skive Energy Park SymbiosisNet diagram



3.2. Availability of renewable electricity and electricity mix

A green hydrogen industrial cluster requires abundance and affordability of renewable energy. Typically, a combination of sources, for example hydropower, wind and solar energy, is ideal to secure stability of supply. A direct connection between Power-to-X (PtX) installations and renewable energy sources is encouraged. To promote new installations of renewable energy sources, it is recommended that the energy installation comes into operation at the same time or after the PtX installation.

Proximity of renewable energy sources to the industrial cluster is preferable to avoid efficiency losses and enable documentation of origin. Ideally, renewable energy is directly connected to the industrial cluster and vertically integrated into the cluster to increase efficiency of delivery and economic feasibility. For the continuous provision of (green) hydrogen with intermitting renewable electricity, some form of electricity storage is needed.

If not directly connected to the green hydrogen cluster, it is important to consider the national electricity grid infrastructure and its ability to process large amounts of renewable energy. Green hydrogen industrial clusters can be an effective means of balancing the grid, which means using renewable energy sources to the maximum and avoiding time off, such as wind turbines standing still while the wind blows. In that sense, countries with grid capacity issues have additional incentives to consider a green hydrogen industrial cluster model.

It is an advantage if the country already has close to 100% renewable energy in the electricity mix. For example, the electricity mix in the national grid in Costa Rica is almost exclusively from renewables. This will prevent competition with fossil-based alternatives and makes certification of green hydrogen and PtX products easier. A country's current plans or ambitions for renewables as well as the life cycle analysis of the hydrogen produced should be considered. As a rule of thumb, 1 MW of power can generate between 10-15 kg of hydrogen per hour, depending on the electrolysis technology employed.

3.2.1. Location and access to utilities and auxiliary facilities

In addition to having access to renewable electricity, the clusters need to be in the area where hydrogen is produced, with access to the grid and other utilities and infrastructures such as CO_2 storage and utilization facilities.

Proximity to the electricity grid (with so-called certificates of origin of the renewable electricity) or to the renewable electricity generation facilities is useful to ensure adequate renewable electricity supply. For users, proximity to these is an advantage. Conversion of green hydrogen back into electricity using fuel cells is an option considered in some reports. Given the expected loss due to low energy efficiency of about 50%, this is a relatively poor reuse of the green hydrogen compared to transportation, green fuel synthesis applications, or other direct uses in industrial processes. However, an associated shipping port connection creates new synergies for offtake and supply chain integration.

Access to an offtake market for larger volumes outside the cluster will need to be considered, not just for green hydrogen, but for all accumulated outputs, such as heat from electrolysis, as described in the GreenLab case. For every 1 MW of installed electrolysis, one can expect between 200-250 kWh of heat output, depending on electrolysis technology. An interplay with external district heating or cooling for low temperature excess heat is ideal, just as heat offtakers within the industrial setting will make sense. Collaboration with the local district heating and cooling company is ideal for long-term success and could support scaling a green hydrogen industrial cluster.

Proximity to the existing gas grid or other gas transmission sectorial hubs, and a national willingness to upgrade the infrastructure to be able to transmit hydrogen, provides an opportunity for grid injection for transporting green hydrogen to end use. Some countries will also have international connections and opportunities for green hydrogen export. Green hydrogen can also be stored, for example, in salt caverns or other potential storage infrastructure. This allows for buffering of supplies for further regional distribution.

Electrolysis requires water, and it needs to be of high quality. In cases where the quality standard is not met, metal ions from the water can contaminate the electrodes and affect electrolyser performance and lifetime. Depending on the electrolysis technology, it is estimated that between 150-180 kg of water per hour is required for every 1 MW of installed electrolyser. Ideally, local sources of water other than drinking water are found, chemically treated and demineralized for electrolysis. This could be contaminated or percolate water from beneath a landfill facility, gas station, heavy industry, or similar. Bringing the dirty water into the water loop of a green hydrogen cluster solves several problems: It maximizes utilization of available resources, contributes to a cleaner groundwater, and is often cheaper than acquiring and treating water of drinking quality. Close collaboration with the local water is an option to consider during the design stage of the desalination plant.

The conversion of green hydrogen to green methanol requires biogenic carbon source (e.g. from agricultural waste) or direct air capture technologies. Onsite production of biogas as a biogenic carbon source will typically not be sufficient due the small scale of carbon availability relative to carbon needs for methanol production and other synthetic fuels including synthetic aviation fuels. Hence, regional piping must be considered. Regional advantages such as access to and abundance of biomass from agriculture in rural areas or marine products in harbour settings should be assessed as part of the energy mix, even though not directly related to green hydrogen production. It is, however, a central component when developing entire value chains, and creating secondary side stream material synergies. Direct air capture (DAC) technologies are often discussed as a source of CO_2 for carbon capture and utilization (CCU). However, the IEA highlights in a recent report that DAC is currently only available at very small scale and rapid deployment and availability is unlikely before 2030.[16]

Green hydrogen can be converted into other green fuels onsite through methanol synthesis, with the addition of a biogenic CO_2 source (e.g. from biogas) or to ammonia with the addition of nitrogen, which can be

[16] IEA (2022), Direct Air Capture, IEA, Paris <https://www.iea.org/reports/direct-air-capture>.

derived from the air. This requires an internal infrastructure to facilitate these flows between the cluster entities. To sum up, the basic infrastructure requirements to link production and end-use are:

- Internal electricity distribution, including energy storage, and transformer station if renewable energy is directly connected
- Heat upgrading, distribution and storage at high and low temperatures (e.g. in rocks or molten salt, phase-change materials, or dam storage, respectively)
- Process water and wastewater treatment and distribution
- Carbon capture and utilization (CCU): CO_2 sourcing/piping, upgrading and distribution
- Hydrogen (or gas) distribution, storage and tank areas
- Infrastructure for oxygen storage and transport (if used in other processes or sold to other companies)

3.2.2. Composition, scale and synergies

Building bridges and utilizing synergies can contribute to driving down the costs of green hydrogen production, making the end products green hydrogen and other e-fuels price competitive. The potential for synergies can only happen in energy-intensive industrial settings. These may consist of existing industrial parks with high demands for energy or excess energy in significant volumes, harbours, or around existing energy infrastructure such as combined heat and power plants (CHP) that need to transition into greener alternatives. Such settings, where entities may currently rely on fossil-based hydrogen, or energy, would be ideal for conversion into a green hydrogen industrial cluster.

In the case of GreenLab, this infrastructure is part of the "Facility as a Service" concept that is offered to the industrial park tenants besides land lease. The concept is that the site owner manages the central and in-between companies/facilities energy streams, reducing CapEx (capital expenditures) and OpEx (operating expenses) for the industrial tenants. Effective cluster and stakeholder management is key to success and should be prioritized.

3.3. Production of green hydrogen

The essential ingredients to produce green hydrogen are non-emitting electricity and purified water. Electrolysis requires water (H_2O) as well as electricity. Around 9 litres of water are needed to produce 1 kilogram of hydrogen.[17] This can produce 8 kilograms of oxygen as a by-product, which at a smaller scale can be used in the health care sector (pure oxygen), or at a larger scale for industrial purposes as a resource or even in water sanitation. Applications of oxygen can support building a successful business model of green hydrogen production.

The basis of the production of green hydrogen is the availability of or access to renewable energy sources, e.g. solar, wind, hydropower and possibly other upcoming technologies able to use sustainable electricity. If renewable energy is available and combined with for instance grid power, it should be possible to create a constant electricity flow enabling a high uptime of the system. Regulatory conditions such as RED II or RED III have to be taken into account to make sure that the hydrogen produces counts as "green".

The other essential ingredient for hydrogen production is purified water. The availability of sufficient volumes of water is essential. The water needs to be of a specified high quality because the water needs to be demineralized and filtered. The demineralization assures that minerals such as salt (sodium chloride) are removed to bring the water up to the desired quality level for adequate operation of the electrolyser. In many cases, it will be required to have a dedicated water treatment system.

The production of green hydrogen using electrolysis is the next step in the value chain. After the (renewable) electricity is generated, it can be used to split the water into hydrogen and oxygen. The hydrogen and oxygen are then 'collected' in separate storage systems to be utilized further. There are several ways to produce green hydrogen of which electrolysis (of water) is the most common and important technology.

3.4. Overview of uses for green hydrogen in industry

Green hydrogen can be used in every application where grey hydrogen is currently used. Natural gas can also be directly replaced with (green) hydrogen

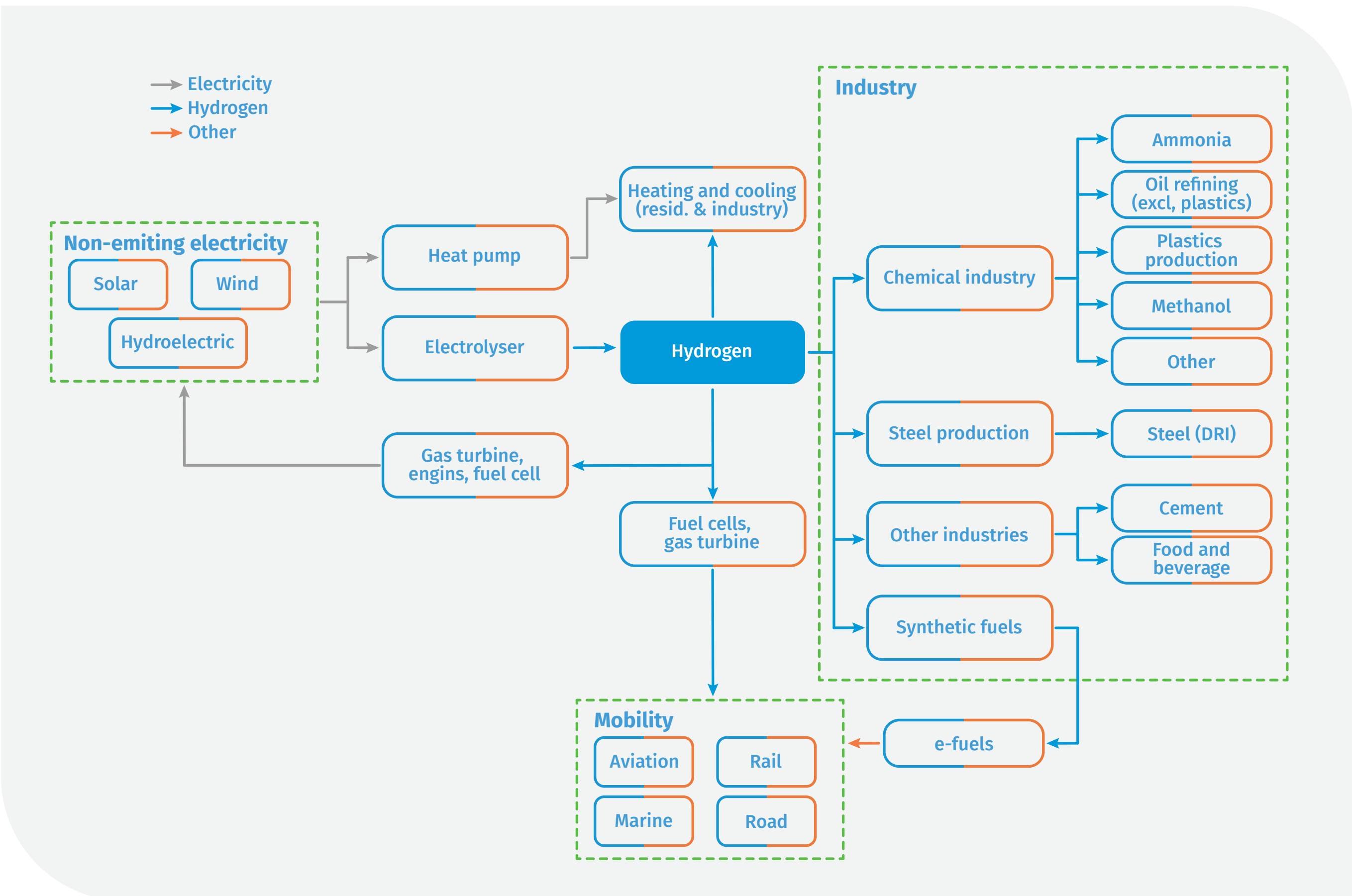
[17] IEA (2019), The future of hydrogen, sizing today's opportunities, IEA, <https://www.iea.org/reports/the-future-of-hydrogen>.

in many applications either by replacing a percentage of the natural gas by hydrogen or replacing in full. Hydrogen can be and is used in industry (feedstock for chemicals, for products, source for high temperature processes), energy, mobility/transport (fuel for transport) and the built environment (low temperature heat for buildings. Global hydrogen demand reached 94 Mt in 2021.[18] This hydrogen is produced based on fossil fuels and it is mostly used in industrial processes including chemicals production (e.g. ammonia production). Green hydrogen can replace grey hydrogen and be used in new processes. The following section presents an overview of the current and potential uses of green hydrogen.

Figure 3-3 provides an overview of possible use cases for green hydrogen in an industrial cluster and mobility sector. Hydrogen is already used in refining, ammonia and methanol production. In the future, it could be used in industrial processes such as in steel production (to produce direct reduced iron), transport and heat generation. Also, investigations are ongoing to use hydrogen to replace natural gas in glass manufacturing, production of bricks and building materials (e.g. cement).

A recent report by IRENA summarizes the use cases of green hydrogen as well as policy tools and challenges for the uptake of green hydrogen as a guide for policy making.[19] The report highlights current use of hydrogen as well as promising areas for the use of green hydrogen. The main applications of hydrogen could be in industrial production since a direct electrification of some of the processes is not possible with current production routes and technologies. Consequently, current industrial clusters might move to locations with excellent renewable resources. (See Figure 3-4.)

Figure 3-3. Overview of possible uses cases for green hydrogen



[18] IEA (2022), <https://www.iea.org/reports/hydrogen>.
[19] IRENA (2022), Green Hydrogen for Industry: URL: <https://www.irena.org/publications/2022/Mar/Green-Hydrogen-for-Industry>.

The following sections give an overview of hydrogen use in ammonia production, steel production and other industrial processes (e.g. for providing process heat).

3.4.2.1. Ammonia and chemicals production

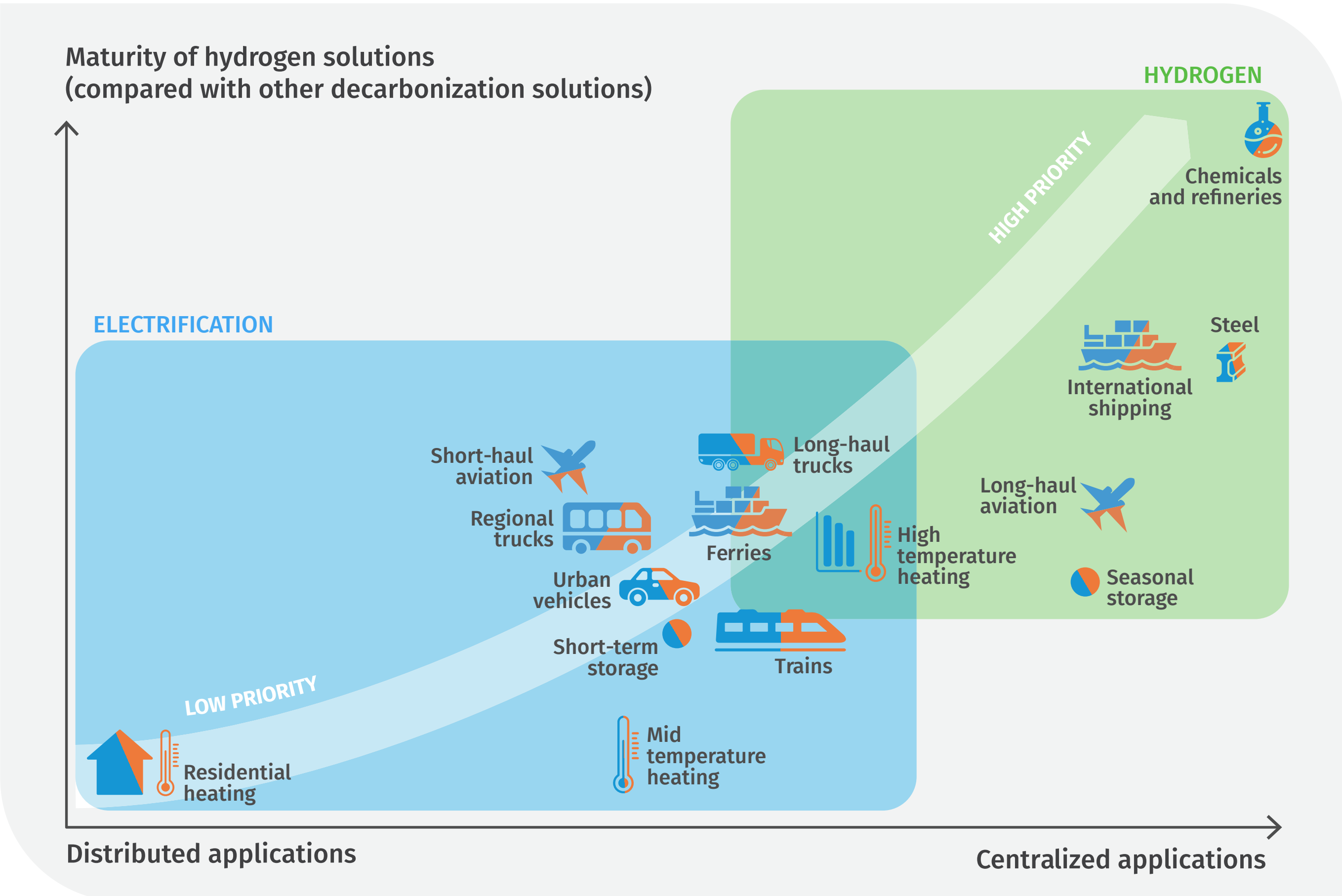
Approximately 40 Mt of hydrogen are used in ammonia production every year. Ammonia (NH3) is produced in chemical reactions with nitrogen and hydrogen. Per kg of ammonia, approximately 0.18 kg of hydrogen are needed. The hydrogen is currently based on fossil fuels using steam-methane reforming. The Box 3-3 of the Ammonia Association provides an overview of some projects deploying green ammonia.

Global demand for chemicals (including ammonia fertilizers and plastics) is increasing significantly globally.[20] Current hydrogen production is approximately 94 Mt and used in various chemical processes, including oil refineries (hydrocracking), fuel treatment, ammonia synthesis as well as other chemical reactions. The IRENA study on hydrogen use in industry provides an overview of use cases for hydrogen in industrial production.[21] Similarly, hydrogen would be needed for the all processes for CCU. Hydrogen for refining oil will be needed less in a decarbonized future, but represents a key initial market for replacing grey hydrogen. While this might enable the expansion of green hydrogen production, further demand markets must be established. Other chemical processes require pure hydrogen that can be sourced as green hydrogen without any changes to the processes.

3.4.2.2. Iron and steel

Primary production of iron could occur via two routes: Blast furnace (BF) (1291 Mt) and direct reduced iron (DRI) (1.8 Mt). In both cases, iron ore is chemically reduced.

Figure 3-4. Overview of possible uses cases for green hydrogen[22]



[20] IEA (2018), The Future of Petrochemicals, IEA, Paris <https://www.iea.org/reports/the-future-of-petrochemicals>, License: CC BY 4.0

[21] IRENA (2022), Green Hydrogen for Industry: URL: <https://www.irena.org/publications/2022/Mar/Green-Hydrogen-for-Industry>.

[22] Figure from IRENA report: URL: <https://www.irena.org/publications/2022/Mar/Green-Hydrogen-for-Industry>. Taken from IRENA (2022). On the x-axis the end uses are placed according to the estimated average daily hydrogen demand for industry, refuelling stations and combustion devices, with a power relationship. On the y-axis the end uses are placed according to the differences between the technological readiness levels of hydrogen-based versus electricity-based solutions.

This means removing the oxygen as CO_2 or water, leaving the metal. Great quantities of energy are required for this, but more importantly a chemical energy carrier is needed to react with the oxygen. The BF route uses treated coal (coke) stacked together with the ore in the furnace. Therefore, it can only use limited quantities of added hydrogen (10-20%), as the coal fulfils a structural purpose as well. This means that the BF route cannot be fully decarbonized with green hydrogen. The DRI route uses a reducing gas (e.g. natural gas derived carbon monoxide and hydrogen to reduce iron ore lumps). Green hydrogen can replace these fossil reducing gases relatively easily.

The Box 3-4 of H2 Green Steel (H2GS) provides an overview of the challenges of deploying green steel.

3.4.2.3. High temperature industrial heat

Hydrogen can be burned to generate high temperatures of >1000C. However, its application has been very limited so far, as fossil fuels are cheaper for such purposes and technologies for hydrogen combustion have yet to be scaled up. While renewable electricity can in theory be converted to high-temperature heat at almost perfect efficiency, significant technical difficulties remain in practice, leading to considerations of green hydrogen as a method of achieving high temperatures indirectly, i.e. by first converting the electricity into green hydrogen, despite the significant additional effort of electrolysis this would require.

For the cement industry, zero-emission heating alternatives are important but not enough to fully decarbonize. This is because combustion is only responsible for around 30% of the overall emissions of the production process. In practice, hydrogen is not a convenient fuel here: hydrogen flames exhibit low rates of radiative heat transfer[23] compared to fossil fuels, such that the temperature profile is very different. Consequently, this requires burner redesigns and additives for hydrogen use in kilns,[24] and even then, it

Box 3-3. Green hydrogen in ammonia production projects: lessons learned from the Ammonia Energy Association

In the coming decades, hundreds of millions of tonnes of low-carbon ammonia will be required annually to decarbonize current markets and meet demand for future applications, such as zero-carbon fuel. Currently, only a few commercial projects have been realized. One of these is the partial decarbonization of Fertiberia's fertilizer facility in Puertollano, Spain, which has a total ammonia production capacity of 200,000 tonnes per year. The new solar to hydrogen facility will produce about 3,000 tonnes of renewable hydrogen per year (or 17,000 tonnes of renewable ammonia) from 100 MW solar PV, a 20 MWh battery, 20 MW electrolysis capacity and 11 pressurized hydrogen storage tanks. The first drops of renewable ammonia have recently been produced. Fertiberia plans to fully decarbonize the site in the coming years.

Another interesting example at a larger scale is the ammonia plant being carried out by first-movers at Ammonia Energy – NEOM, Yara and Fertiberia – in Saudi Arabia scheduled to start production in 2026. It will be powered by 4 GW of wind and solar, with battery storage, using 120 electrolyser units (each 40m long) to produce the hydrogen for 1.2 Mt of renewable ammonia per year.

Many large-scale projects are expected to permanently sequester the CO_2 emissions from existing ammonia plants. Technologies and operational strategies have been developed for the management of variable power inputs and, while economies of scale still matter, technologies are coming to market for renewable ammonia plants ranging from 4 tonnes per day to 10,000 tonnes per day. These projects are a fraction of what needs to come. According to the Ammonia Sector Transition Strategy, near-zero emission ammonia plants need to produce at least 50 Mt per year by 2030, and at least 560 million tonnes per year by 2050. Certification will be crucial. The real challenge is not the project scale, but the speed at which is needed to deploy all these new plants at a cost-competitive level.

[23] Hoenig, 2008, Carbon dioxide control technologies for the cement industry: <https://gcep.stanford.edu/pdfs/2RK4ZjKBF2f71uM4uriP9g/Volker_Hoenig_Stanford_2008_upload.pdf>.

[24] El-Emam et al., 2021, Synergizing hydrogen and cement industries for Canada's climate plan – case study: <https://doi.org/10.1080/15567036.2021.1936699>.

seems that hydrogen will need to be mixed with other alternative fuels. For example, Heidelberg Cement's "Hanson Cement", which is still in the development stage, uses a fuel mix with around 40% hydrogen.[25] The future role of hydrogen in supplying heat for cement-making is therefore still an open question. Similarly, hydrogen could be used in the processes in aluminium production that are currently using natural gas as an energy carrier or for treatment of bauxite and other feedstock.

To sum up, there are several use cases for hydrogen in industrial production. This chapter provided an overview of possible applications and a brief description of current and potential uses. The next chapter will describe challenges and enablers for scaling up the supply of green hydrogen in industrial clusters.

Box 3-4. Green steel projects development: lessons learned from H2 Green Steel (H2GS)

During the summer of 2022, H2GS initiated land-preparation for its first project in Boden, Sweden, where it intends to build a large-scale green hydrogen production to support an integrated green steel plant. Production is scheduled to start in 2025. By 2030, H2GS aims to reach a production capacity of five million tonnes of high-quality steel.

H2GS's green hydrogen use focus will be to reduce iron ore to direct-reduced iron (DRI). Using green hydrogen instead of coking coal reduces CO_2 emissions from the reduction process by more than 90% compared to the traditional iron-making process. In the traditional steelmaking process, the reduction of iron ore occurs in a blast furnace by combining it with coking coal at high temperatures. This triggers a chemical reaction that separates the oxygen from the iron, forming and emitting large amounts of CO_2. In H2GS's production process, green hydrogen is used as the reducing agent, thereby resulting in emissions of water vapour instead of CO_2.

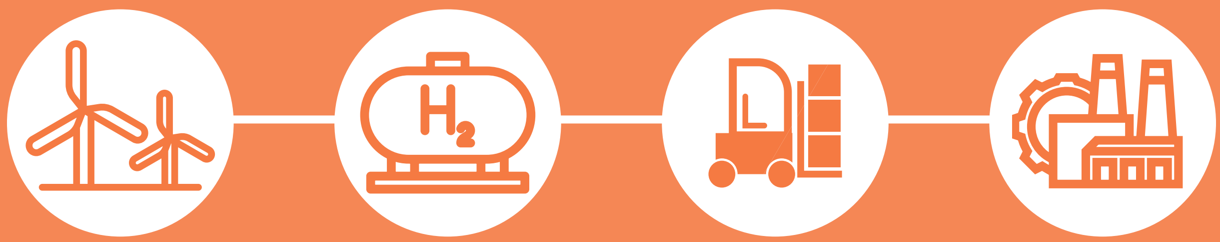
The DRI is then fed into the Electric Arc Furnace (EAF), where renewable electricity heats a combination of DRI and steel scrap. During the continuous casting and rolling process, the liquid steel is converted into solid products. The plant is fully integrated with hot charging at every step of the production chain, limiting the amount of energy used, storage and material handling.

One of the most crucial challenges for decarbonizing hard-to-abate industries is access to renewable electricity and related infrastructure. The most electricity-intensive parts of green steel production are the hydrogen production and the DRI reactor. Therefore, the most electricity-intensive part of the green steel industry can be advantageously located in regions with high levels of renewable electricity production, or with potential to further develop low-cost renewable energy assets.

Another challenge is the cost and price difference between traditional and green steel production. Many customers in the automotive, construction and other sectors are willing to pay a premium for a green product. To accelerate and increase the demand for green steel, there are some policy issues that should be considered globally, among them:

- A price for greenhouse gas emissions needs to be introduced worldwide.
- Markets with higher prices for GHG emissions can support their market by introducing border adjustment mechanisms.
- Early movers can act as facilitators and play an important role in the introduction of an ambitious harmonised standard for net-zero steel and its premium.

[25] Heidelberg materials: URL: <https://www.heidelbergmaterials.com/en/pr-01-10-2021>.



4. Phases of Green Hydrogen in Industrial Clusters

Chapter 4 presents three phases of UNIDO's model of green hydrogen industrial clusters and describes the steps for their development.

4.1. Phases for cluster development – overview

The use of green hydrogen in industrial clusters supports the reduction of GHG emissions and a cleaner production. This section presents a general overview before the following sections describe the phases in detail.

The road towards the application of green hydrogen in industrial clusters can be divided into three phases. These phases are intended as a step-by-step plan that will allow various stakeholders to jointly develop an industrial cluster that will produce and use green hydrogen.

The first phase, prepares the environment where the cluster will be developed, thus mitigating the risks, by engaging the different stakeholders in the development process, raising awareness about green hydrogen, its uses and industrial clusters, the joint formulation and definition of the objective, strategy and roadmap of the green hydrogen industrial cluster, and the financial mobilization. The second phase provides an overview of the different activities to be considered during the development of the pilot project and to start the production and application of green hydrogen. The third and final phase will prepare the industry cluster for expansion by expanding green hydrogen production within the cluster, covering other industries that were not targeted in the pilot phase, and connecting it to other industrial clusters.

The figure below illustrates this journey for an existing cluster to be transformed into a green hydrogen industrial cluster.

4.2. Phase 1: Preparation of green hydrogen clusters

Phase 1 of the cluster model seeks to prepare the cluster for the production and application of green hydrogen. This phase comprises the awareness-raising, successful engagement of the different stakeholders involved in the process, the identification of the green hydrogen cluster objectives, the elaboration of a strategy and roadmap to successfully develop and operationalize the cluster and, finally, the elaboration of exploratory assessments and feasibility studies and how to mobilize the necessary funds for its implementation.

4.2.1. Awareness-raising

To develop green hydrogen industrial clusters, it is important that the stakeholders of the clusters and local communities are aware of the benefits of green hydrogen and the opportunities that this might bring. Green hydrogen and its potential industrial application remain a relatively new topic and not all stakeholders are aware of the possibilities and how they, their community, or their businesses can benefit from green hydrogen. It is, therefore, important to address the awareness-raising aspect by providing objective information in every project about hydrogen itself, the technical possibilities, the objective and the work plan of a project. Awareness-raising enables stakeholders to make informed decisions and to choose whether to participate in the development of the cluster.

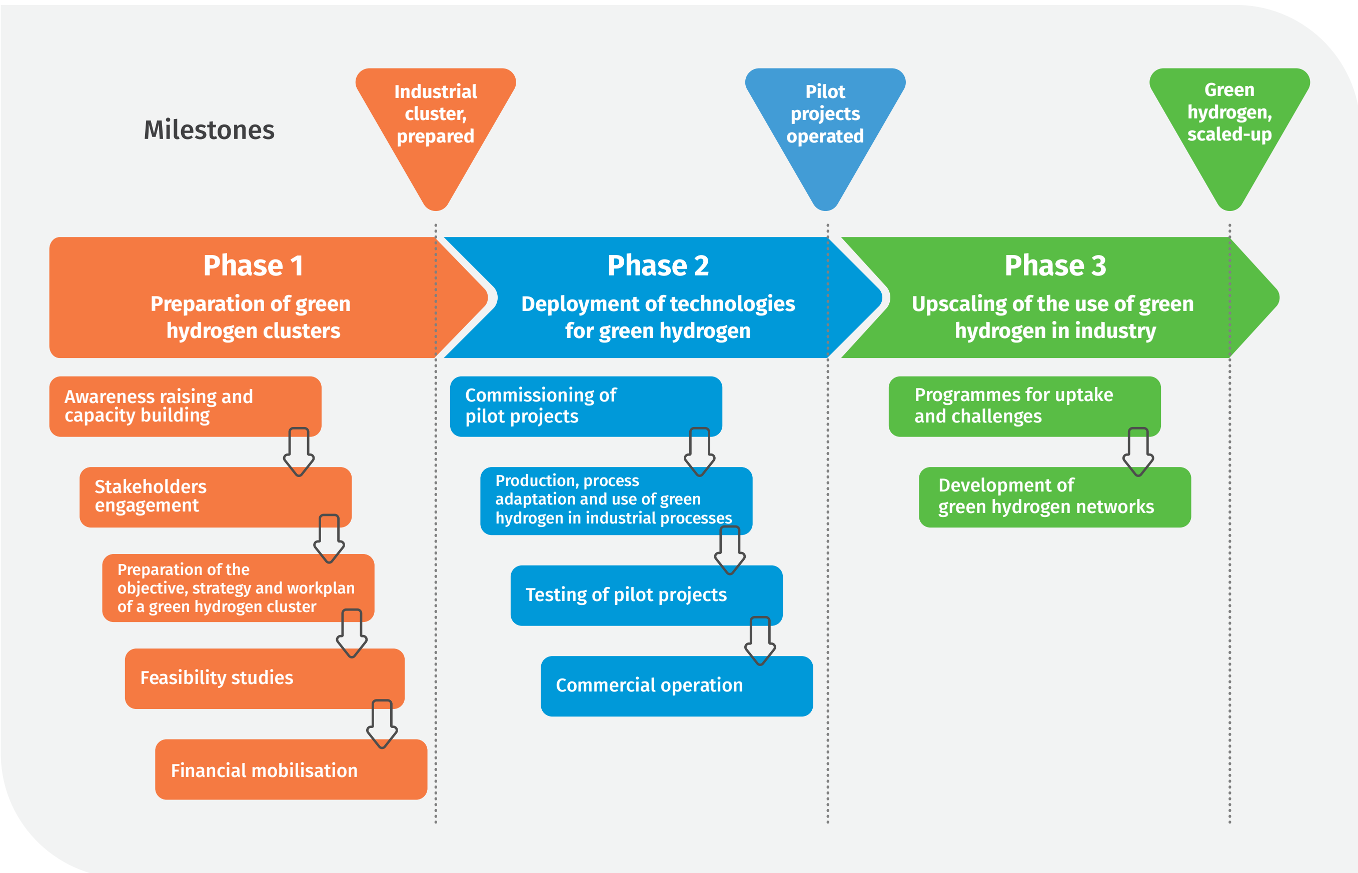
Awareness-raising activities can be accompanied with exploratory assessments that could provide relevant information to the stakeholders on the conditions of the cluster and its potential to become a green hydrogen industrial cluster, such as types of offtakers, proximity to renewable energy and water, and the interest of the main stakeholders.

4.2.1.1. Developing an awareness-raising strategy

The strategy for awareness-raising and capacity-building activities should cover at least four objectives: empowering stakeholders with guidance and providing information; motivating stakeholders and beneficiaries; supporting stakeholders through tailored activities and knowledge products; and being in synergy with other awareness-raising and capacity-building activities of associations, governments and other stakeholders.

The table 4-1 provides an example of what could be considered when formulating the strategy for awareness-raising and capacity-building activities.

Figure 4-1. Phases of green hydrogen clusters and stages



The start of operations of the awareness-raising strategy would also be preparing the path for the stakeholder engagement step, which will be further elaborated in Section 5.2.2.

The following box provides an overview of awareness-raising carried out by the HEAVENN project as an example of a successful hydrogen project.

Table 4-1. Elements to be considered during the awareness-raising activities

Questions	Reasoning	Examples
Who are the stakeholders receiving the awareness-raising?	Once the assessment of the cluster stakeholders and their engagement is carried out (part of the feasibility studies), a better understanding of the stakeholders will be available.	Cluster stakeholders, regional and national governments, associations, regional and national banks, and financial institutions. In case a new cluster is initiated, it would be desirable to consider SMEs as well.
What skills/ competences need to be addressed in the awareness-raising activities?	It is recommended that once the assessment of cluster stakeholders and their engagement has been conducted, the knowledge gaps of stakeholders will be identified.	The skills and competences to be addressed will vary depending on the location and knowledge of the stakeholders.
What type of awareness-raising would be useful?	Each type of awareness-raising should be chosen upon the previous knowledge gap identified and knowledge materials will be tailored accordingly.	Awareness-raising can be done through documents (reports and studies), events (webinars, seminars, and workshops) and informative visits to the production site, among others.

Box 4-1. Awareness-raising: lessons learned from the HEAVENN project

The EU-funded HEAVENN project introduces a sizeable demonstration project aimed at the development of a methodology for and design of a fully integrated and functioning “hydrogen valley”. By bringing together the central elements of hydrogen production, distribution, storage and local-end use, the goal is to demonstrate how this hydrogen valley could – through the use of green hydrogen across the value chain – reduce carbon emissions as well as potentially benefit businesses along its value chain.

When it comes to awareness-raising for the project, the dissemination of information is the responsibility of the project execution organization in order to ensure that information and communications are easily accessible and appropriate for different target groups. It is most effective if the distribution of information starts at an early stage and is made available over a longer period, and the best way to do this would be through the project organization. Involving knowledge institutions and authorities, as well as businesses, in the dissemination of accurate and consistent information also contributes to awareness-raising.

The elaboration of a roadmap and timeframe to achieve the common objective allows estimating the technical competences needed during the different phases of the green hydrogen cluster development. For each company, business park or region, it is possible to outline, in cooperation with knowledge institutions, the competences currently available, the ones that will be needed in the future, and the training and education pathways that will be needed. In this way, insights can be given to any specific target groups.[26]

[26] HEAVENN: URL: <https://heavenn.org/heaven-projects>.

4.2.2. Stakeholder engagement

Working together at the level of an industrial cluster has the advantage that it can lead to innovations and the associated (qualitative) employment. This new way of cooperating in both the hydrogen production chain and consumption streams require intensive stakeholder engagement.

Step 1: Stakeholder identification and engagement activities

Stakeholder engagement should be done at the same time as awareness-raising as both are dependent on each other. The stakeholder identification step should identify the stakeholders and their interests, and examine the possible structure of the industrial cluster. After that assessment, it should be clear who are the relevant stakeholders involved (internal and external to the cluster), their interest and role, as well as the importance of the different stakeholders in the industry cluster.

To successfully develop a green hydrogen industrial cluster, the minimum required types of stakeholders to be involved in the process are representatives of business from the production, transport, storage and (industrial) use of hydrogen, including small and medium-sized enterprises (SMEs) and representatives of government, research institutions, civil society organizations (CSOs) and non-governmental organizations (NGOs). Once the internal and external stakeholders have been mapped out, it is possible to identify those that are missing and approach them.

In parallel, engagement activities should be organized (e.g., meetings, workshops) and non-legally binding agreements could be signed (e.g. Memorandum of Understanding). For these, an engagement plan could be developed. This plan should explain the role of each stakeholder and what the engagement activities are. The following questions could provide guidance:

- Can the cluster function without the stakeholders identified?
- What value do the stakeholders add for example, in the organizational and financial investment requirements?
- How relevant are the stakeholders to the achievement of the cluster's objectives?

Step 2: Exploratory assessments

At this stage, it is useful to first perform exploratory assessments, including assessment of the location of the cluster, proximity to renewable energy and water, challenges and unique requirements of the entire value chain that the stakeholders will face, and identification of the offtakers and industrial processes where hydrogen can be applied. These assessments will determine how much additional energy, hydrogen, or water can be made available to support economic development, social and environmental benefits for the area. It is important to be aware, when deciding on the type of studies, that they will have an impact on decision-making on the development of the cluster. The exploratory assessments will ensure a better-informed decision-making process; however, in depth feasibility assessments are required and are further explained in Section 5.2.4.

It is recommended to gather and involve in the formulation of the assessments a broad group of stakeholders representing hydrogen production, transport and use in both industry and SMEs. These should be complemented by the government, project execution organization, knowledge institutions, CSOs and NGOs.

Step 3: Developing a communication plan and mechanism

The third and last step is to develop an active communication plan and mechanism, targeting the broad spectrum of private and public stakeholders: the level of the stakeholder's involvement is kept at a high level through active communication through meetings, events, site visits and social media, but also by answering questions from stakeholders outside the cluster and CSOs.

Often, different industry clusters might have many similarities, which means that they can learn from each other. Not only can knowledge be shared, but also how to finance themselves and what insurance, permits and policies are needed. It is important that not only companies and governments, but also financial institutions, environmental organizations and other stakeholders share information with each other on actions taken, success stories and areas for improvement. Industrial associations (e.g. producers' associations) and international organizations could facilitate this transfer of knowledge and best practice.

By having an active communication mechanism, the government will be able to understand current and future challenges and propose supportive policies, and the industry will be able to communicate its current needs.

Policies are an essential element in the development of an industrial cluster and should be acknowledged. Governments should consider green hydrogen industrial clusters in their industrial decarbonization and industrial development strategies; not only as simply projects to apply green hydrogen. These strategies require continuous collaboration with industry to put in place an industrial emissions reduction roadmap and corresponding government support programmes to develop the clusters.

4.2.3. Preparation of the objective, strategy and work plan of a green hydrogen cluster

Different stakeholders play different roles in supporting the decarbonization of industrial clusters and the uptake of green hydrogen. Having a long-term objective outlined in co-creation facilitates the integration of the different options and their alignment. A common objective, strategy and work plan will strengthen the willingness of stakeholders to work together and solve problems. They also make it possible to identify the existing gaps earlier and find more suitable partners.

Step 1: Setting the objective

Setting the objective must involve the different stakeholders that will be necessary for the development of an industrial cluster. In this case, the key stakeholders are clusters of businesses, energy providers and distributors, consumers, public local and regional authorities, including the community representative.

The objective describes what is to be achieved within the cluster. For example, decarbonizing ammonia, steel production, the cluster's internal transport system with hydrogen vehicles, etc.

Step 2: Developing the strategy

Once the objective has been set and agreed upon by all stakeholders, the strategy can be defined. The development of the strategy should be done by the companies in the cluster and the public sector. The strategy is the plan of action that defines the direction that will be taken to achieve the objective of the cluster. For it to be a successful strategy, it must identify the objectives to be achieved, establish a guide for achieving these objectives and propose a coherent set of actions to implement that guide. It is recommended that it contains the following elements:

- Objectives to be achieved in terms of green hydrogen and cluster activities.
- Regional and national green hydrogen status quo, fields of action and markets; it should include information regarding the production, transport and infrastructure, trade and market creation, capacity-building, funding mechanisms and cooperation.
- Steps and actions required for success of the strategy.
- Governance structure – who oversees implementing and monitoring the strategy; it is recommended to have a centralized entity responsible for the strategy and the progress of the development of the cluster.

Step 3: Developing the work plan for the cluster

After the strategy is defined, the work plan can be developed. The development of the work plan should be done jointly by the stakeholders, companies in the cluster and public sector, and management entity of the cluster.

The work plan is a tool for strategic planning that defines a goal (or set of goals) and includes the milestones needed to reach it. It shows what is wanted to be achieved, and how and when it will be achieved. To develop a work plan that can address the industrial transformation needed for hydrogen use, it must have SMART (specific, measurable, achievable, realistic and timely) goals.

4.2.4. Feasibility studies

Feasibility studies depend on the context in which the cluster is to be developed, assessing the existing and future conditions, and possible scenarios at an early stage, gives time to respond to emerging challenges and to apply additional measures that increase the cluster's chances of success. Feasibility studies should be conducted once the goal is set. It is important to consider that these studies are expensive and stakeholders might need to request financing. The strategy specifies who will be responsible for the development of the studies and who will oversee them all. These feasibility studies should be conducted before starting Phase 2.

Table 4-2 summarizes in further detail the basic recommended studies for the development of green hydrogen clusters. The table is composed of three columns. "Type of study" indicates the type of assessment; "Content" indicates in more detail what the assessment should cover; and "Impact areas" indicate what areas in the value chain are analysed. It should be noted that these studies do not exclude others and should be adapted to the particularities of the cluster site.

Table 4-2. Recommended assessments for the development of green hydrogen industrial clusters

Type of study	Content	Impact areas
Assessment of renewable Energy	Mapping of available capacity of renewable energies and assessment of the potential capacity of new developments.	Potential production of green hydrogen
Energy storage assessment	Mapping of the available capacity of energy storage and assessment of the potential capacity of new developments.	Stable production of green hydrogen
Land assessment	Assessment of land needed for the development of renewable energy (for hydrogen production), electrolyser and cluster; the use of this land should not affect nearby communities, or other land uses that have more priority.	Potential production of green hydrogen
Water availability assessment	Assessment of available groundwater and whether it is environmentally feasible to use this water for hydrogen production. If it is not feasible to use groundwater, a feasibility study on the use of desalination is recommended.	Potential production of green hydrogen
Infrastructure assessment	Assessment of the electrical, control, water, gas and waste infrastructure in place.	Production and usage of hydrogen
Potential production of green hydrogen	Assessment of potential green hydrogen production capacity. To carry out this assessment, it is necessary at least to have completed the renewable energy and water capacity assessments, as well as back-up capacity.	Potential production of green hydrogen
Assessment of the potential demand of green hydrogen	Assessment of the potential demand within the cluster and nearby clusters and/or other applications.	Potential demand of green hydrogen
Assessment of the social-economic impact	Evaluation of the benefits and the drawbacks that could generate the development of a green hydrogen industrial cluster at regional, national and international level.	Usage of green hydrogen
Environmental impact assessment	Evaluation of how the production of hydrogen, and the industrial processes within the cluster, affect the environment.	Production and usage of green hydrogen
Security and risk assessment	Identify the potential risks of the hydrogen value chain and the different industrial processes, and the security measures needed to be followed.	Production and usage of green hydrogen
Regulatory and policy assessment	Identify the regulation and policies in place, the permitting process and the gaps.	Feasibility of cluster, demand of green hydrogen and green products
Financial mechanism assessment	Identify the existing financial mechanism with the country/region and other clusters.	Feasibility of the cluster, demand of green hydrogen, demand of green products
Sustainable Development Goals impact assessment	Identify the SDGs affected by the development of the industrial cluster and map their indicators to the cluster's KPIs.	Impact of the cluster to the SDGs

4.2.5. Financial mobilization

Industry clusters are seen as a strategy to foster innovative production and R&D activities, while also promoting sustainable energy transition, local development and employment. For this reason, the creation of clusters has been and can be financed by the private or public sector, or a combination of both. The financing of the creation of green hydrogen industrial clusters or the transformation of existing ones can follow the same approach as the financing of normal industrial clusters.

Step 1: Developing a financial plan

The first step would be for the cluster stakeholders to jointly develop a financing plan to support their objective and strategy. A financial plan is a document containing information about the current financial situation and identifying financial goals, as well as strategies (business plan) to achieve those goals. It will determine whether the green hydrogen industrial cluster is financially feasible. The financial plan should at least consider the following aspects:

- **Investment budget**: it should include all the investments needed to start a cluster and those at a later stage. This will give insight into the minimum amount of money required to start the cluster.

- **Financial budget**: it should detail how the investment budget of the cluster is intended to be financed.

- **Operating budget**: it should determine whether the cluster is profitable. It will estimate the turnover and analyse the costs of the cluster.

- **Cash flow budget**: it should include all income and expenditure during a given period.

The financial plan should leverage existing public funds (if available) and financing mechanisms, while also identifying new mechanisms to strengthen their business models. The investment must be made in developing and strengthening the business cases. In the case of developing and emerging economies that are interested in being exporters of green hydrogen, the development of green hydrogen industrial clusters could be part of the business case. Hence, part of the revenue or hydrogen produced is invested in the development of the production cluster in the exporting country. It is also recommended to connect and consult with other green hydrogen industrial clusters on their financing scheme, thus gaining a better insight into business and financial models to support green hydrogen scale-up.

Step 2: Identification of financial mechanisms

Given that the green hydrogen value chain is highly complex, it is also useful to use some tools to help identify which financial mechanism is most useful in each part of the value chain. Some available tools are:

- Challenges faced by stakeholders in a green hydrogen industrial cluster value chain.

- A financing mechanism along the green hydrogen industrial cluster value chain.

A 2022 report by Accenture, *Investing in industrial clusters: A U.S. perspective on financing industrial decarbonization*, outlined three key steps to consider when determining which financing mechanisms will have the greatest impact on accelerating industrial decarbonization:[27]

- Adopt a whole system approach (whole green hydrogen value chain in an industrial cluster) to understand the challenges and unique requirements of the entire value chain. It requires identifying the different stakeholder and perspectives across the value chain and understanding the key barriers each of them are facing to participate in the market. Users of hydrogen are dependent on the structural supply of hydrogen on a large scale and the purchase of their products. Therefore, a long-term contract for hydrogen supply and purchase at fixed prices are important for feasible financing.

- Identify and evaluate existing or potential funding mechanisms (this is the reason why it is important to have an open communication channel with the government) to address specific challenges, reduce market risk and unlock additional capital.

- Leverage these mechanisms to decarbonize all industries within the cluster.

In all cases, transparency in financing is an important concern. Transparency also allows businesses and investors to demonstrate that they are contributing to the SDGS by investing in the development of green hydrogen and green hydrogen industrial clusters. By

[27] Accenture (2022), Investing in Industrial Clusters: URL: <https://www.accenture.com/content/dam/accenture/final/industry/utilities/document/Accenture-Financing-US-Industrial-Clusters-POV.pdf>.

working together with different stakeholders and, for example, by contributing to local sustainability through the provision of sustainable energy and water for SMEs and local communities, or by making fresh water available for nature, agriculture, or deforestation, they can meet the increasingly demanding requirements set by the capital market to contribute to the SDGs with their investments.

For developing and emerging economies, these instruments may not yet be in place. In this case, the international community, through international organizations and associations, and experienced experts can provide valuable assistance.

The following box provides an overview of the financial regulations and mechanisms in place in the US.

Box 4-2. Financial mechanisms: lessons learned from the United States (US)

In the United States, the Infrastructure Investment and Jobs Act (IIJA),[28] also known as the Bipartisan Infrastructure Law (BIL), provides an opportunity to leverage funds toward industrial decarbonization through the development of industrial clusters. The IIJA allocates up to $164 billion of potential investment for industrial clusters, including $8 billion to establish at least four clean hydrogen clusters, $1 billion for green hydrogen and $500 million for R&D. Moreover, the Energy Act 2020[29] allocates $500 million to decarbonize hard-to-abate industries.

The Inflation Reduction Act (IRA)[30] provides additional funding opportunities to target industrial emissions, including through the $5.8 billion Advanced Industrial Facilities Deployment Program,[31] which provides industrial facilities with finance to switch to clean fuels, carbon capture and electrification. In addition, the IRA leverages the federal government's purchasing power by financing the purchase of clean goods, thereby creating and expanding new clean markets. Within this act a relevant tax credit is the clean hydrogen tax credit, which establishes a maximum of $3/kg of hydrogen produced over 10 years for qualified clean hydrogen.

The Advanced Research Projects Agency-Energy (ARPA-E) programme allocates $2.9 billion to scale new energy technologies, and the Office of Energy Efficiency and Renewable Energy (EERE) allocates $72 million for hydrogen projects under the H2@Scale Programme. Based on this regulation and depending on the part of the hydrogen value chain, the US has some financial mechanisms in place to develop a clean hydrogen economy and to accelerate the uptake of clean hydrogen:

Part of the value chain	Demand	Developer	Equipment supplier	Labour and community	Financer
Example of financial mechanisms in the US	• Tax credit/reduction in fuel use to compensate for high cost of transition • Subsidy to fully depreciate and replace existing equipment • PTC/ITC to reduce the capital costs of new fuel equipment • Price/tariff support to guarantee demand	• Soft loan/equity loan sharing to encourage private lenders to offset the risk of the new technology • Subsidy or partial subsidy to subsidise the cost of the electrolyser and improve project economics • Contract for difference to attract more capital and improve project economics	• Grant/part subsidy to develop the ecosystem to increase supply/demand from partners • Concessional loan for supply chain development to mature the supply chain and improve unit economics	• Grants to provide training funding and upskill local workforces • Grants for the creation of hydrogen industrial clusters, which remove initial funding barriers	• Contract for difference after initial power purchase agreement (PPA) contract term ends with offtaker to reduce long-term risk and enable short-term PPAs • Concessionary loan within larger capital stack to incentive private lenders to offset new technology and credit risk

28 117th Congress (2021-2022), Infrastructure Investment and Jobs Act (P.L. 117-58). URL: <https://www.congress.gov/117/bills/hr3684/BILLS-117hr3684enr.pdf>.

29 116th Congress (2019-2020), Consolidated Appropriations Act (P.L. 116-260). URL: <https://www.congress.gov/116/bills/hr133/BILLS-116hr133enr.pdf>.

30 117th Congress (2021-2022), H.R.5376 - Inflation Reduction Act of 2022. URL: <https://www.congress.gov/bill/117th-congress/house-bill/5376/text>.

31 117th Congress (2021-2022), S.3112 - Hydrogen for Industry Act of 2021. URL: <https://www.congress.gov/bill/117th-congress/senate-bill/3112/text>.

4.3. Phase 2: Deployment of technologies

Phase 2 of the cluster model aims to operationalize the technology to ensure the production of green hydrogen. This phase addresses the deployment of green hydrogen technologies in industrial clusters, the utilization of green hydrogen in the processes, and the monitoring and evaluation of the progress of the cluster.

4.3.1. Commissioning of pilot project

The commissioning or the project implementation could be defined as the process of ensuring that all systems and components of a particular industrial site are designed, deployed, tested, operated and maintained according to the operational requirements of the owner, local authorities, or end-user. The goal of the project is to develop and operate a green hydrogen industrial cluster.

4.3.1.1. Complying with local regulations

To be able to implement the project, the cluster developer must apply for the project deployment permits through the local, regional and national authorities. The main aspects that could be involved in the project permit procedure will vary depending on the structure of the country's public administration. Aspects to consider are:

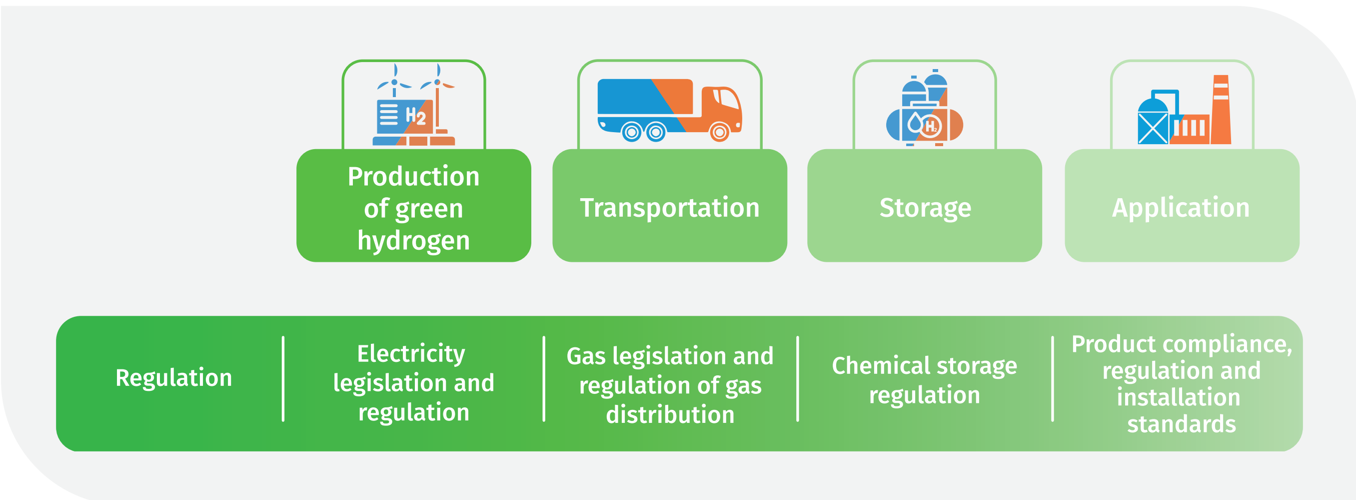
- **Financing** (e.g. permit process is affected by the participation in different support programmes for the deployment of green hydrogen).
- **Environment** (e.g. it could be affected by the environmental impact requested by the local authorities; this is normally a common procedure, but for green hydrogen it could have new limitations).
- **Industry** (it could be affected by the communication among industries and with the local authorities).
- **Energy** (e.g. synergies with permit process for renewable energy supply) and local government (e.g. urban land conditions).

The project must also comply with local regulations at each stage of the value chain. Four stages of the value chain can be identified, which may be repeated or placed in different order depending on the project. The following figure is an example of the type of regulation that could be in place in each part of the value chain.

Some challenges that the cluster developer could face are:

- How local authorities consider the production of green hydrogen could complicate permitting procedures and deadlines for urban planning and environmental aspects.
- How green hydrogen is considered in the permitting process (e.g. as a fuel, as an industrial feedstock and/or as an electrolyte in a fuel cell).

Figure 4-2. Example of regulation at different stages of the production chain



- Complex and time-consuming environmental and grid management permitting processes.
- New types of installations or products do not fit well into current regulations.
- In terms of energy planning and management, if there are continuous changes in energy regulations, this could influence the type of installations in which investors are interested; this could lead to shifts in investment choices that affect the entire value chain.
- National, regional and local jurisdictional frameworks may interact with each other; legislation and regulation need to be addressed in close dialogue between the different administrative levels together with the experts and companies involved in the development of the cluster.

In the feasibility studies step, the environmental impact assessment could have been already conducted. In case no further environmental impact is required by the local authorities, this could be sufficient. In case a specific environmental impact is required, this should be developed according to local regulations. Local authorities require the environmental impact at the permitting stage (Section 5.3.3) of the project, as without the permission of the local authorities the project cannot start its development.

One useful methodology for calculating environmental impacts is Life Cycle Assessment (LCA), which is used to assess the environmental impacts associated with all stages of the life of a product, process, or service, thereby evaluating the potential cumulative environmental impacts. LCA involves a comprehensive inventory of the energy and materials required along the value chain of the product, process, or service industry, and calculates the corresponding emissions to the environment.

In the case of a green hydrogen industrial cluster, the value chain is highly complex. It is recommended to split the LCA along the value chain.

The following box from GREET gives an overview of the model they created to perform the Hydrogen Life Cycle Analysis.

Box 4-3. Life Cycle Analysis model: lessons learned from GREET

The Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET)[32] model is a one-of-a-kind analytical tool that simulates the energy use and emissions output of various vehicle and fuel combinations. The tool, developed by Argonne National Laboratory and is sponsored by the US Department of Energy, provides a complete picture of the energy and environmental impacts of a wide range of technologies from well to wheel.

The hydrogen production pathway included in the model provides several options for computing greenhouse gas and criteria pollutant emissions. At a high level, the calculation estimates direct and indirect emissions associated with hydrogen production resulting in grams per MMBtu of the following pollutants: CO_2, N_2O, CO, NOx, PM10, PM2.5, SOx, BC, OC, CH4 (combustion and leakage) and VOC. These values are provided both for hydrogen used as a process feedstock as well as for hydrogen used as a transportation fuel, where the latter includes emissions associated with hydrogen transmission, distribution and compression/liquefaction.

In more detail, options for hydrogen production at a centralized plant include natural gas, solar, nuclear (water cracking), electrolysis (HTGR), coal, coke oven gas, biomass, integrated fermentation and high temperature electrolysis with SOFC. Decentralized hydrogen production includes options for natural gas, electrolysis and ethanol steam reforming at refuelling stations. Electrolysis would use the mix on the grid, or any combination of solar PV, wind, hydro, or nuclear. Where applicable, carbon capture and sequestration as well as credits for electricity displaced by steam, whether sold on the market or used at the facility, are included in the calculation.

[32] GREET: URL: <https://greet.es.anl.gov/greet_hydrogen>.

4.3.1.2. Taining of operators

One of the most important points to be addressed is the training of the operators that will operate and maintain the pilot project. This training should be done in parallel with the design phase, feasibility studies and permitting process.

Green hydrogen may be new, but the skills needed to operate and maintain the projects are not. The installations for the production, storage, supply and use of hydrogen require specific skills in hydrogen gas, working pressures, effects on materials, etc., which require specific training that should complement the skills of gas installers. The operators must comply with training for the operation and maintenance of gas receiving installations, systems in which gas is stored or conducted. They should have theoretical and practical knowledge of gas industry technology and regulations and meet the requirements to perform and supervise the operations involved.

Their knowledge can be extended to cover:

- Hydrogen installation regulations
- Hydrogen production, hydrogen production system and installations
- Hydrogen combustion, flame temperatures and pressures
- Materials suitable for hydrogen flame temperatures
- Welding qualifications and welding on materials operating at cryogenic temperatures

In addition, some new requirements may emerge during the development of the green hydrogen economy, which also would need to be met.

4.3.2. Production, process adaptation and use of green hydrogen

The uptake of green hydrogen requires changes to the infrastructure of the industrial clusters – capacities for renewable electricity; electrolysers for producing hydrogen and transport infrastructure (pipelines); and process adaptation (smaller process configuration for ammonia production, but major changes for steel production due to different key process technologies). The processes, as well as the technologies involved, are outlined in detail in Chapter 3.

This section covers the adaptation of infrastructure and industrial processes needed for the application of green hydrogen.

Adapting industrial processes infrastructure to make the transition from fossil hydrogen to green hydrogen is not complex. Once green hydrogen is available, it could be introduced into industrial processes already using “grey” hydrogen infrastructure. The challenge is to produce the huge volumes of green hydrogen required via electrolysers. Once grey hydrogen has been replaced by green hydrogen, there is an enormous potential for reducing CO_2 emissions. Where there is already a strong industrial base in place, available gas infrastructures can be evaluated and reused for transporting green hydrogen.

If the gas or hydrogen infrastructure does not exist, it is necessary to analyse which part of the industry can be transformed to use green hydrogen and which part can be decarbonized through direct electrification.

The transition to decarbonize the transport sector is complex for it requires the adaptation of the vehicles with fuel cells or adapted internal combustion engine (ICE) systems, and it requires the availability of the fuels hydrogen or hydrogen derivatives like methanol, ammonia or SAF. It also requires the deployment of fit-for-purpose fuelling systems infrastructure for the various fuels and considering the specific requirements per (sub)sector.

4.3.3. Testing of pilot projects

A pilot project is an initial small-scale deployment used to test the feasibility of a project idea. To test it, a series of test cases are designed and executed; once the results have been evaluated, the project can be operationalized and scaled up.

A test case is a set of actions performed by a system that produces an observable result that validates a specific aspect of the system. Test cases must include all functional requirements of a given system or process and part of its non-functional requirements (performance, security, or interoperability).

Some important aspects to consider when designing the test case include checking the electrolyser system and its equipment around it for leaks, faults, or other deficiencies that need to be addressed, checking all emergency and safety procedures, automatic shutdown modes and safety devices, and checking all documentation, such as operating manuals.

The execution of test cases can vary depending on the complexity of the project, its size, the problems encountered and the time to fix the problems. One of the objectives of the test cases is to quantify key performance indicators (KPIs)[33] during continuous operation of the facility.

[33] Investopedia: URL: <https://www.investopedia.com/terms/k/kpi.asp>.

The progress of industrial hydrogen clusters development (in the initial stages) and its performance (in the operational phase) can be measured through a variety of KPIs.

KPIs are a set of metrics that are used to monitor the progress of a development (technology, project, organization, employees, etc.), compare its performance with that of other developments that deliver similar outputs, and can be used to achieve a strategy or objectives.

KPIs should be designed according to the objectives that the green hydrogen cluster aims to achieve. Therefore, KPIs will depend on the specific circumstances of the cluster's development. Nevertheless, they should provide insight into the conditions, improvements and failures of the cluster. These should be designed in cooperation with the relevant stakeholders involved in the development of the cluster and the industries that will use hydrogen.

Green hydrogen industrial clusters can have an impact on the following:

- Decrease environmental footprint of industries
- Technological learning impact
- Viable economic business cases of using green hydrogen in industrial processes
- Creation of green jobs

These can lead to six KPIs categories: technical; economic; health, safety and environmental; social; cluster management; and specific projects and processes. Furthermore, it is necessary to distinguish between general cluster performance indicators and those that are project or industry specific. For the latter, additional performance indicators need to be designed.

When designing KPIs it is recommended to keep in mind that there are descriptive and operational indicators. Descriptive KPIs are those that do not change over time; operational KPIs are the result of the performance of the cluster and will therefore vary from year to year.

In addition, it is recommended to consider four levels of analysis. The electrolyser stack KPIs comprise the stack, where the electrolysis takes place. The electrolyser system KPIs comprise the stack and the power conversion before entering the electrolyser (AC to DC). The plant KPIs comprise the electrolyser system and the auxiliary systems such as power supply, control system and automation, system cooling, water pumps, water demineralisation, etc. The industrial cluster KPIs comprise all the utilities and industries within the cluster.

Table 4-3. Categories of performance indicators for green hydrogen industrial clusters

Category	Type of key performance indicators (KPIs)[34]
Technical	• Energy KPIs (e.g. electricity consumption for hydrogen production, power usage of the auxiliary equipment at nominal capacity) • Water KPIs (e.g. water consumption, water purity) • Technology KPIs (e.g. start-up time, transient response, maximum overload operation, hot idle ramp time, cold start ramp time, degradation) • Infrastructure KPIs (e.g. compressor lifetime, energy consumption of the pipeline, transmission pressure)
Economic	Financial KPIs (e.g. CapEx electrolyser, electrolyser price, CapEx electrical grid, OpEx electrolyser, cost of electricity, end of life replacement, hydrogen generation cost per kg, storage cost per kg).
Health, safety and environmental	Health, safety, or environmental KPIs (e.g. fraction of renewable energy input in the total electricity consumption, number of incidents, carbon footprint of produced hydrogen, number of emergency stops, amount of Pt recycled from FC/electrolysers at end-of-life, amount of ionomer recycled from FC/electrolysers at end-of-life, solid waste disposal)
Social	• Labour market KPIs (e.g. number of jobs created) • Education KPIs (e.g. number of universities/institutes offering courses on hydrogen, number of trained professionals; qualified workers, technicians and engineers)
Cluster management	• Administrative and general data KPIs (e.g. deployment date, electrolyser manufacturer, type of electrolyser) • Value chain KPIs (e.g. number of global and local companies involved, number of new companies created, number of local SMEs involved, number of enabling stakeholders engaged) • Production KPIs (e.g. average hydrogen rate production, electrolyser operating pressure, electrolyser operating temperature, stack nominal power, electrolyser maximum overload capacity, hydrogen purity, power usage, rated stack electrical efficiency, hours of operation, days of operation, quantity of hydrogen produced, electricity consumed)
Specific projects and processes	Specific projects and industrial processes (e.g. steel, ammonia, etc.) KPIs (e.g. production volume, cost per unit, load smoothing factor in the steel making process)

[34] H2 Future: URL: <https://www.h2future-project.eu/images/Publications/H2F_WP2_D28_v12_final_2020-02-21.pdf>.

Once the categories are defined, detailed KPIs can be designed according to the SMART acronym; they should be specific, measurable, achievable, realistic and time-bound metrics. Therefore, it is recommended to focus on the information that is available and that meets the SMART acronym requirements. The most appropriate KPIs will then be applied. To achieve the objectives proposed in the cluster roadmap, the following step would be to set specific targets for the KPIs.

In addition, the cluster can also consider using the SDGs as KPIs to measure its sustainability. Combining the principles of the SDGs to create sustainable green hydrogen industrial clusters ensures that developing and emerging economies benefit from their development, thereby improving regional economies, resulting in higher living standards and reduced dependence on foreign energy imports.

The Sustainable Development Goals (SDGs) were adopted by United Nations Member States in 2015 as part of the 2030 Agenda for Sustainable Development. The SDGs include 17 Goals and 169 associated targets, which are a universal call to action to end poverty, protect the planet and ensure that by 2030 all people enjoy peace and prosperity. These are integrated, which means that action in one area will affect the outcomes in others, and that development must balance social, economic and environmental sustainability.

In Phase 1 of the green hydrogen industrial cluster model, an assessment of the impact of the cluster to the SDGs should be undertaken to assesses which are the most critical SDGs that will be affected by the development of the industrial clusters and which SDGs are most at risk of being negatively and positively affected by the green hydrogen industrial cluster development. Once the relevant SDGs targets have been identified, the targets can be mapped into KPIs of the green hydrogen industrial cluster.[35]

The following table summarizes the relevant SDGs, the targets affected by the green hydrogen industrial cluster and a description of indicators that could

Table 4-4. Sustainable Development Goals and indicators

SDG	Description of impact	Description of indicators
SDG7: Affordable and clean energy	Investing in renewable energies, improving energy productivity and energy security.	• Renewable energy share in the total of energy consumption. • Energy intensity measured in terms of primary energy and GDP.
SDG9: Industry, innovation, and infrastructure	Investment in infrastructure and innovation, promoting sustainable industries and investing in research and innovation to find solutions to economic and environmental challenges.	New employment, number of research, CO2 emissions per value added.
SDG12: Responsible consumption and production	Efficient management of natural resources and disposal of toxic and polluting waste, recycling and waste reduction.	Hazardous waste generated, material footprint.
SDG13: Climate action	Address the needs of developing countries to both adapt to climate change and invest in low-carbon development.	Investments made in low-carbon technologies and/or development, CO2 savings when using low-carbon technologies in industrial processes.
SDG15: Life on land	Reducing the loss of natural habitats and biodiversity and supporting global food and water security, climate change mitigation and adaptation, and peace and security.	No habitats and biodiversity are lost, water usage for local communities is not used to produce green hydrogen.
SDG17: Partnerships for the goals	Improving access to technology and knowledge to enable the sharing of ideas and foster innovation, coordinating policies, as well as promoting investment.	Number of partnerships, policies, new investments, approved funding for developing countries to promote the development of industrial clusters.

[35] SDG Compass: URL: <https://sdgcompass.org/business-indicators>.

measure the targets at national level. Additional KPIs, based on the national level indicators, should be designed to measure the effect that industrial clusters have on the SDGs.

4.3.4. Commercial operation

The commercial operation phase starts the date after all testing and commissioning has been completed. At this phase, the green hydrogen industrial cluster can apply for a green hydrogen certification, monitor and evaluate its continuous operations.

4.3.4.1. Green hydrogen certification

The deployment and uptake of green hydrogen will depend on the establishment and acceptance of the certification systems. A certification system is a system, which has its own operational and management rules, to provide written assurance that a product, process, or service complies with a specified standard or other specified requirements, and which is managed by an entity independent of both the party requesting the certification assurance and the party providing the product, process, or service.[36]

These tools are needed to document the attributes of green hydrogen along the entire value chain and create transparency. This strengthens customer confidence and ensures an advantage over other competitors.

There are different publications that provide an overview of the technical considerations for green hydrogen tracking systems and the challenges that need to be addressed for the creation of such instruments. One example is the IRENA Coalition for Action brief "Decarbonising End-use Sectors: Green Hydrogen Certification". The report makes key recommendations to policymakers for the successful establishment of green hydrogen monitoring systems based on internationally accepted standards.[37]

4.3.4.2. Monitoring and evaluation

The KPIs previously used in the test phase (Section 5.3.4) introduced the monitoring and evaluation (M&E) system. On this basis, the environmental, technical and economic performance indicators previously used could be used or modified to track progress over time and identify areas for improvement.

Monitoring progress on green hydrogen industry cluster targets and milestones is an ongoing process through which continuous improvements can be made. KPIs targets are set for the entire green hydrogen value chain within the cluster, based on best practice references or pilot projects already implemented.

The cluster monitoring and evaluation can be done and shared through reports, which should contain the previously defined KPIs targets, what has been achieved, what is missing to achieve the targets, identification of what went wrong and what needs to be done to overcome the challenges encountered. The purpose of evaluations is to interpret the progress towards the objectives to inform strategic decision-making.

Finally, the entity responsible for the management of the industrial cluster should oversee monitoring the performance of the cluster, assessing the results achieved and reporting on the operations of the cluster to the stakeholders involved in the value change of green hydrogen and to other stakeholders of the cluster who might not be directly involved.

At this point, it might be worth considering the digitization of the cluster's industrial processes to collect data regarding emissions, electricity and green hydrogen produced, as well as the different information needed to achieve the previously established KPIs. In this way, this data could be more easily analysed, facilitating the optimization of large-scale production of green hydrogen, enabling its cost-effective production, progress monitoring and thus the subsequent obtaining of a green hydrogen certificate.

The following box of GETEC Park.EMMEN provides an overview of the management of an industrial cluster.

Communications about the cluster's internal and external operations In Section 4.2.2, it was recommended to have a communication mechanism and strategy in place, which not only enables the communication of operations within the cluster and between cluster stakeholders, but also outside the cluster. The strategy for communicating the cluster's operations can also be designed at that phase.

In terms of communication in Phase 2, the monitoring and evaluation reports of the green hydrogen industry cluster should be accessible (digitally) to all stakeholders of the cluster, including employees and representatives of regional communities, such as local governments, education and training institutes and CSOs. In addition, management decisions of the companies involved in the green hydrogen value chain, the cluster consortium board (if applicable) and their impact should also be available on their websites for those outside the cluster.

[36] Law insider: URL: <https://www.lawinsider.com/dictionary/certification-system>.

[37] IRENA (2022), Decarbonising End-use Sectors: Green Hydrogen Certification: URL: <https://www.irena.org/publications/2022/Mar/The-Green-Hydrogen-Certification-Brief>.

4.4. Phase 3: Upscaling of green hydrogen in industry

This section provides an overview of the upscaling of green hydrogen in industry. The first section summarizes some of the challenges companies and policymakers might face when upscaling production and use of green hydrogen in an industrial cluster. The second section addresses the different activities for the development of green hydrogen networks, including the network of green hydrogen industrial clusters.

4.4.1. Programmes for uptake and challenges

To support green industrial clusters on their transition to the full use of green hydrogen in new industrial clusters aligned with net-zero emissions, several challenges must be addressed which were outlined in the previous chapters. The key challenges are a provision of sufficient amounts of renewable electricity, the building of new infrastructure for production, transport and storage of green hydrogen and the reconfiguration of industrial processes to use green hydrogen instead of natural gas or other fuels.

In Phase 3 of the production clusters, there might be other challenges which are described below. These include challenges associated with the transformation of production sites, achieving full provision of green hydrogen and cost-competitiveness. The advantages of the transformation include sector coupling, energy security and emissions reductions, embeddedness in a cluster of green hydrogen production, and supporting inclusive and sustainable development.

Currently, no industrial cluster exists that uses only green hydrogen at scale since the technology is at an early stage. Over the past five years, however, there have been significant innovations and cost reductions for electrolysers as well as policy programmes to support and accelerate the uptake of green hydrogen in industry.

In Phase 3, full provision with green hydrogen is envisioned. For this, enough renewable electricity needs to be provided. Alternatively, green hydrogen could be provided via hydrogen imports. For that, the in-

Box 4-4. Management of industrial clusters: lessons learned from GETEC Park.EMMEN

GETEC Park.EMMEN, located in Emmen in the north-east part of the Netherlands, aims to become a CO_2 neutral industrial park. The strategy is to increase the energy efficiency and reduce the CO_2 footprint of the park while attracting more companies to set up business there.

Companies in the park that have higher margins can decarbonize more easily and can switch directly to green hydrogen. At the same time, the site is preparing the infrastructure to be used with green hydrogen, so that when the time is right, and green hydrogen becomes cheaper, the transition will be smooth.

To increase efficiency, the park is continuously increasing the current conversion efficiency. For example, by recovering residual heat and using it again at the park, or, on the fuel side, by using green gas. In the park, hydrogen will flow through the pipelines instead of gas.

GETEC Park.EMMEN manages, maintains and operates the industrial park. It oversees the facilities and the delivery of utilities (heat, electricity, maintenance, water treatment, etc.) through an integrated utility infrastructure. With several laboratories on site and nearby, it also assists companies develop a product idea, through the pilot plant phase, to full production scale.

GETEC Park.EMMEN works in close cooperation with several education and research institutes (Stenden PRE, Green PAC, University of Groningen, Wageningen), and university students are trained in company-focused research facilities (StendenLab - Real World Learning).[38]

[38] GETEC Park.EMMEN: URL: <https://www.getec-energyservices.nl/en>.

frastructure to import and transport hydrogen needs to be in place. To avoid potential shortages and bottleneck of the provision, long-term production contracts (e.g. power purchase agreements or hydrogen purchase agreements) need to be in place. If more hydrogen is produced than needed in the cluster, the cluster could also be an exporter or net producer of green hydrogen. The key challenge of Phase 3 is to achieve cost competitiveness with a production cluster that does not yet use green hydrogen, but rather grey hydrogen. However, there are large uncertainties associated with the uptake of green hydrogen and overall supply might be smaller than demand it. The economic competitiveness of the cluster should, therefore, be analysed as a key component of the feasibility study in Phase 1.

A green hydrogen cluster has three main advantages over a fossil-based production cluster. First, it has significantly lower GHG emissions due to the use of hydrogen. This reduces climate risks and risks related to increasing costs for emissions certificates. Second, the production cluster has also high energy security and is aligned with the Paris Agreement and SDGs. This helps to attract additional funding from investors, banks and governments. Third, the cluster generates green growth and provides green jobs. This is essential for sustainable development.

In Phase 3, exchange of best practice and shared services is a key to achieve cost competitiveness. In Europe, there is the initiative for hydrogen valleys (see box below) to facilitate an exchange of knowledge, technical skills and best practices. To address this, the cluster organizes regular meetings, publishes reports and other forms of knowledge dissemination.

The Box 4-5 from HEAVENN gives an overview of the first hydrogen valley structure in Europe.

The demand for green hydrogen is expected to increase significantly over the next decades. New production clusters and existing ones can use green hydrogen as a fuel and chemical feedstock to replace fossil fuels. For achieving net-zero emissions in industrial production by 2050, the use of hydrogen is essential. There are, however, technical, economic and political challenges associated with the uptake, but adequate policies can address them and thereby reduce uncertainty in the deployment.

4.4.2. Development of green hydrogen networks

The scalability of green hydrogen industrial clusters has an important role to play in the global hydrogen economy. Industrial clusters have different profiles depending on their companies, their location, and consequent energy availability and the amount of energy and feedstock they need. However, they also have many similarities, which means that they can share their expertise and exchange infrastructure.

The idea of a green hydrogen network goes beyond green hydrogen industrial clusters, but follows the same principle. A green hydrogen clusters network is also an association of green hydrogen industrial clusters, and/or independent companies (hydrogen applications) that produce, store, distribute and consume green hydrogen, and that are integrated.

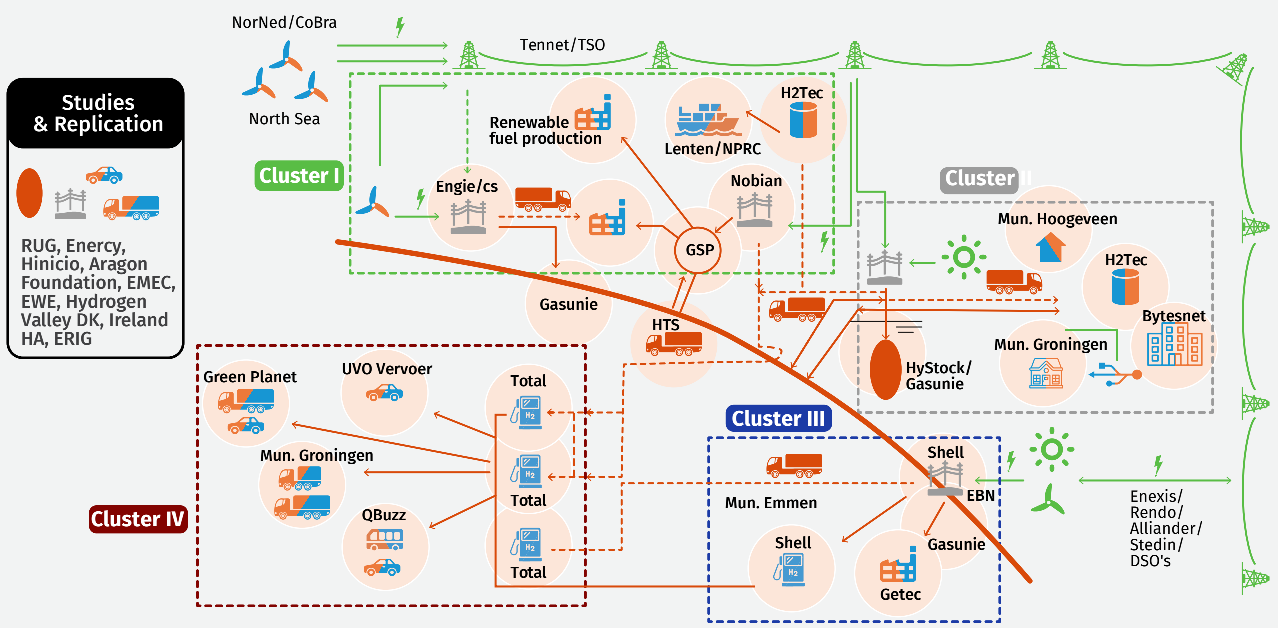
These networks share green hydrogen resources, and therefore their distribution infrastructure, making it possible for other members of the network to easily purchase and obtain green hydrogen when there is surplus green hydrogen at one location in the network, as well as exchange of knowledge, best practices and replication of successful projects.

Box 4-5. HEAVENN: the first EU hydrogen valley

HEAVENN is a large-scale programme of demonstration projects that brings together the key components of the green hydrogen value chain in a fully integrated and functioning "hydrogen valley" (H2V). The objective is to use green hydrogen across the entire value chain, while developing replicable business models for wide-scale commercial deployment of hydrogen across the entire regional energy system.

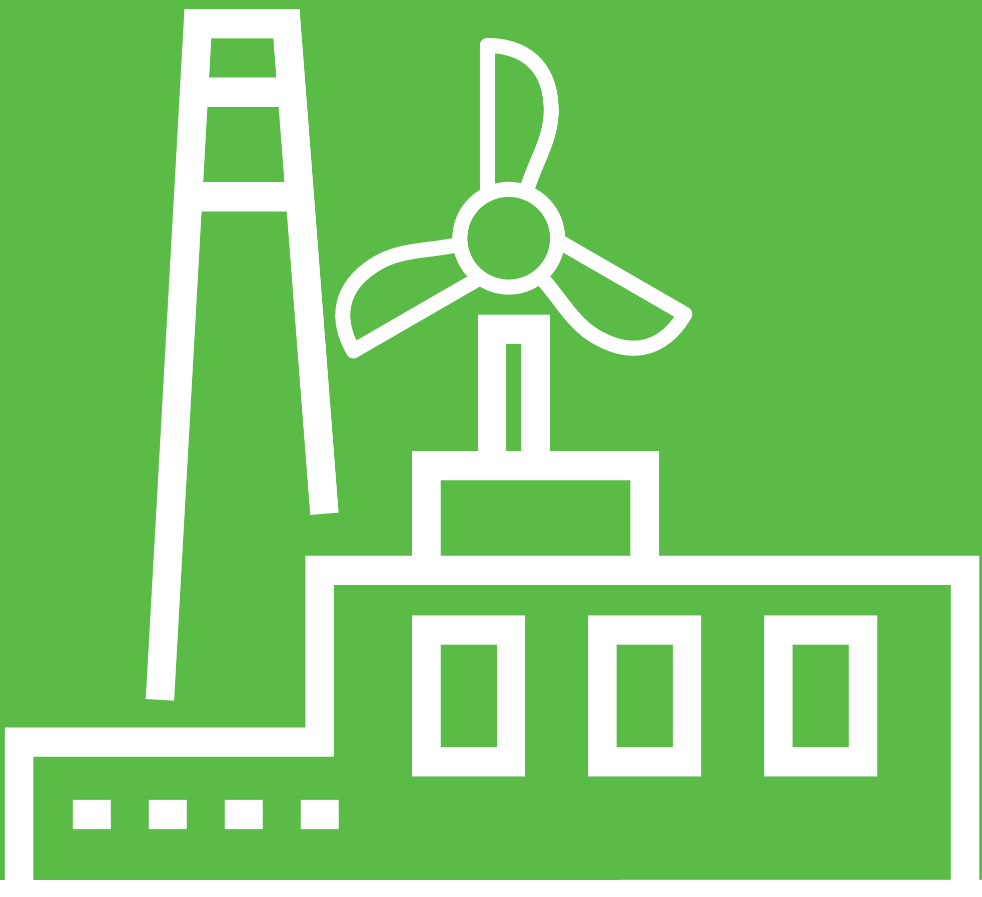
The project is situated in the north of the Netherlands and funded by the European Commission. It has been recognized by the EU and supported by the Clean Hydrogen partnership as the first hydrogen valley in Europe. The approach is based on the deployment and integration of industrial clusters of existing and planned projects in six locations. There are 20+ connected projects to create a green hydrogen ecosystem where the projects are interrelated to each other.

Figure 4-3. Visual of the HEAVENN project



The development of hydrogen valleys and/or hydrogen clusters is gaining momentum, triggering the acceleration of hydrogen development, including in developing countries. Hydrogen valleys provide a stepping stone to promote the development of hydrogen ecosystems from individual and isolated projects that enable the deep penetration of hydrogen into society.

Although HEAVENN has a defined time scope and budget, the systemic approach is raising awareness and acting as a model for growth. The next step is to establish more hydrogen valleys and connect them to each other, which will enable the creation of a green hydrogen market.



5. Challenges and Enablers

This chapter highlights the challenges and enablers that may affect the development of green hydrogen industrial clusters. It will help the green hydrogen industrial cluster developers to identify potential barriers early on and provide an overview of what measures can be employed to overcome them. In Table 5-1, these challenges and enablers are presented in four thematic sub-sections: regulatory, technology, economics and finance, and society and environment.

5.1. Overview of regulatory challenges and enablers

Green hydrogen and green hydrogen industrial clusters present new development opportunities, but also regulatory challenges to governments around the world. This section addresses the details of regulatory environment for green hydrogen projects to thrive in.

5.1.1. Regulatory challenges

A lack of green hydrogen strategies, industrial goals and policies create uncertainty for stakeholders aiming at investing in green hydrogen industrial clusters and in the green hydrogen supply chain in general. The weak presence and visibility of green industrial policies and funding programmes, as well as an unclear long-term vision, can hinder investments.

Allowing access to an emerging market, while fostering industrial development synergies, requires proof that the hydrogen used and the green products produced fulfils a defined sustainable criteria.

Reliable regional and national governance and regulation enforcement systems are required and, therefore, essential to implement green hydrogen industrial policies and regulations, thereby allowing green products to be quantified, certified and monetized.

Missing or inadequate permitting procedures and a lack of capacity in permitting authorities can delay project implementation for years. Given the novelty of the green hydrogen market, permitting processes for green hydrogen production and application may be lacking.

The skillset of the locally available workforce can also become a bottleneck. As such, priority should be training and upgrading labour skills in line with the expected green hydrogen industrial deployments to avoid shortages of needed occupational profiles.

5.1.2. Regulatory enablers

Hydrogen strategies and roadmaps can be useful instruments to create enabling environments for the development of green hydrogen industrial clusters. In different and diverse regions, they have increased the visibility of policies and funding programmes, thereby helping to guide investment decisions, and further supported public engagement.

The Box 5-1 provides an overview of the steps followed to develop Colombia's green hydrogen roadmap.

Binding goals for market actors across the entire green hydrogen value chain (production, transmission, offtake) can create a tangible starting point for green hydrogen industrial policy and regulation efforts. Policymakers can set decarbonization goals that explicitly refer to green hydrogen and green products as a solution for market actors, segments and/or sectors across the whole green hydrogen value chain. This could include production goals, blending mandates and offtake mandates.

As the development of the entire green hydrogen supply chain is of interest to green hydrogen industrial clusters, standardizing technological requirements early on can aid developing industrial development synergies. Policymakers can support the development through dedicated policies, regulations, public-private cooperation initiatives and roundtables, working groups, bodies, or other support mechanisms. The aim is to comply with/adopt existing international standards and certifications to allow access to a broader, potentially international market both for imports and exports on green hydrogen and green products, but also of the technological components along the supply chain required for the development of green hydrogen industrial clusters.

Table 5-1. Overview of main challenges and enablers

	Challenges	Enablers
Regulatory	• Lack of regulatory certainty • No uniform compliance for entire value chain • Slow permitting procedures • Lack of international alignment	• Strategies and roadmaps • Certifications • Enhance permitting, monitoring and public awareness • Comply with international standards and certifications
Technology	• Limited electrolyser and renewable energy capacity • Transport not energy efficient • Risk of stranded assets • Supply chain bottlenecks	• Repurposing and optimization • Binding international agreements on technology and value chain • Public R&D • Exploit cluster synergy potential
Economic and financial	• No mature markets • Green product prices no competitive enough • High CapEx of green hydrogen industrial clusters • Low perceived investment security and bankability • Missing long-term contracts	• Demand creation through offtake agreements or subsidies • Carbon pricing schemes • Public funding to spur private investment
Social and environmental	• Water use can worsen scarcity • Land use for infrastructure • Carbon leakage • Energy justice	• Water and energy standards • Environmental compliance • Local content requirements • Transparency and inclusiveness

Box 5-1. Steps to develop a green hydrogen roadmap: lessons learned from Colombia

Colombia's hydrogen roadmap has five key objectives:

- National strategy: To be developed with the participation of several ministries and national entities, as well as universities and private companies that have experience in developing projects or using hydrogen in their industrial processes.
- Tool to decarbonize the economy: Since hydrogen can be used in several energy-intensive industries and currently use fossil fuels.
- Tool for the promotion of economic growth: Hydrogen is seen as a possibility for the stimulation of economic activity post-COVID-19.
- Enable a just transition for some regional economies: There are some regions in Colombia that are economically highly dependent on fossil fuels and need options to transition to cleaner sources of income.
- Social enabler for the development of local communities in different parts of the country: The development of hydrogen projects will bring investment and job creation to communities.

In addition, a clear scope of action was defined, including four main areas to be analysed: hydrogen production opportunities and prices, demand estimates, regulatory factors, and guidelines for the development of pilot projects. The second step, to ensure the success of the development of the roadmap, is to address the following challenges:

- Analyse international cases to learn from best practices and avoid replicating mistakes.
- As hydrogen impacts on various sectors of the economy, the development of the roadmap must be inclusive and involve the participation of different ministries, academia and private companies.
- Lack of knowledge about hydrogen in terms of its uses and benefits, for which it is important to implement communication and public consultation strategies.

Finally, as hydrogen is a new market, different types of financial instruments are needed to implement the roadmap:

- Technology funds to promote research, development and innovation in new technologies.
- Direct financing, such as technical assistance funds, investment capital and preferential rate funds to develop projects.
- Venture capital funds, angel investors and public and private financing to promote new types of business.

Rapid project-permitting procedures alongside sufficient permitting authorities' workforce can shorten project implementation times significantly. It can be addressed by streamlining permitting procedures and permitting authorities' capacities.

Capacity-building activities can foster the skills required for the uptake of green hydrogen in industry. A specialized workforce is likely to be missing in most regions. Therefore, policymakers can establish regional and/or national training curricula and institutions to address this point.

Public awareness and acceptance raising campaigns can highlight co-benefits and facilitate the development of green hydrogen industrial clusters. Through dedicated policy actions, policymakers can leverage co-benefits for local populations like job creation and economic growth.

5.2. Technology

This section explores the prevalent technical challenges and enablers associated with green industrial hydrogen clusters, from electrolysis, storage and distribution, safety and stranded assets, to end-use applications.

5.2.1. Technological challenges

There are manifold technical barriers to the development of large-scale green hydrogen projects and clusters. On the production level, these include but are not limited to limited technological readiness, high technological complexity, risk of stranded assets, and lack of dedicated (transport) infrastructure as well as a shortage of required technical skills, expertise and maintenance capacity. There are additional technological challenges for the application of green hydrogen in the processes of the end-use sectors (e.g. steel, chemicals, and cement).

The technology readiness level (TRL) is a method to estimate the maturity of a technology during its acquisition phase. It enables a consistent discussion of technical maturity across different types of technology, applications and sectors. TRLs are based on a scale from 1 to 9, with 9 being the most mature stage with proven successful operations (compare Table 5-2). For an example, refer to the EU guidance principles for renewable energy technologies.[39]

Table 5-2. Technology readiness level (TRL) of electrolyser technologies

Level	Description
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or proof of concept
TRL 4	Component validated in laboratory environment
TRL 5	Component validated in relevant environment
TRL 6	System or sub-system demonstrated in relevant environment
TRL 7	System prototype demonstration in an operational environment
TRL 8	System complete and qualified through test and demonstration
TRL 9	Actual system proven through successful operations

The TRL concept is employed to outline the readiness and challenges for the provision of renewable electricity, the infrastructure requirements and the issue of stranded assets.

The large amounts of renewable electricity required for industrial green hydrogen clusters will present challenges in terms of availability and grid capacities. Given the variability and geographical variation, as well as the distributed nature of renewable energy generation, significant electricity transmission capacity is needed to supply the cluster. Insufficient grid capacity could, therefore, limit the size and productivity of a green hydrogen cluster, especially considering the long lead times associated with grid upgrades. Renewable energy generation will have to be expanded significantly to be able to supply green hydrogen clusters on top of the existing and growing energy demands in most places. This includes the necessity of scaling up energy storage capacities to compensate for the intermittent and variable nature of this energy source. Overall, these various types of storage capacities could pose a bottleneck since large amounts of electricity storage need to be available to account for the temporal and seasonal intermittency of solar and wind energy.

[39] European Commission (2017). Technology readiness level - Guidance principles for renewable energy technologies: <https://op.europa.eu/en/publication-detail/-/publication/d5d8e9c8-e6d3-11e7-9749-01aa75ed71a1>

For new industrial clusters, infrastructure for transporting hydrogen to the cluster is needed. New pipelines are capital-intensive projects with decade-long lead times, but repurposing can be difficult. Distances of several thousand kilometres can be bridged with pipelines, similar to existing pipelines for natural gas. Repurposing existing natural gas pipelines is often considered as an alternative to expensive and slow new construction.[40] While this would certainly address issues such as rights of way, whether pipelines can be repurposed or not depends on the specific material they are made of. Significant retrofitting is necessary in any case due to key differences between hydrogen and natural gas: the lower volumetric energy density of hydrogen leads to a commensurately lower energy flow in the pipe and higher compressor work. Therefore, the development and deployment of new compressors, as well as three times higher power usage, is required.[41] The presence of hydrogen is also known to have a negative effect (embrittlement, higher fatigue crack growth) on the mechanical properties of certain types of steel in pipelines.

Many fossil-based facilities in hydrogen production and hard-to abate sectors are set to become stranded assets. Repurposing natural gas pipelines for hydrogen is often proposed because these would otherwise become stranded assets in the decades to come as the world phases out all fossil fuels. While this may be possible for some pipelines (though not all), this is not the case for the rest of the core infrastructure for natural gas. In particular, liquid hydrogen will require entirely new tanks and liquefaction facilities because of the significantly lower temperatures (-253°C) and lower volumetric energy density. Some parts of the infrastructure of LNG terminals (jetty, foundations, power connection) can be re-used and thus shorten lead times, but they are minor contributors to the system cost.

The same can be said for gas-fired plants for power generation. Facilities for producing black or grey hydrogen will become stranded assets. Blast furnaces for steelmaking face the same fate, as they will likely be replaced by green hydrogen-based DRI plants with electric arc furnaces. Natural gas-based DRI plants can likely be retrofitted relatively easily, meaning they are not at risk of becoming a stranded asset. Similarly, there could be stranded assets of local electrolysers if imports become available to a cluster.

5.2.2. Technological enablers

While green hydrogen itself and its clusters face significant technical challenges, there are several enablers that can, where appropriate, speed up development and decarbonization. These could include, but are not limited to, multilateral agreements, supporting R&D and developing markets for green hydrogen and by-products including oxygen.

Legally binding definitions of hydrogen value chain components provide guidance to players of the new green hydrogen market. By setting legally binding definitions for components such as hydrogen pipelines and producers, policymakers can allow stakeholders within the entire hydrogen value chain to define their roles and responsibilities, and ultimately guide them towards creating a green hydrogen market, including hydrogen clusters.

Multilateral agreements help avoid bottlenecks in accessing crucial technological equipment for the development of the green hydrogen supply chain. Building green hydrogen clusters, and in general green hydrogen supply chains, requires highly specialized technologies such as electrolysers, high-pressure storage tanks and pipelines. Depending on the region implementing a hydrogen cluster, global supply chains might be needed. As green hydrogen markets are being developed globally, and to avoid competition issues for said technological components, governments can establish multilateral agreements with other governments and technology providers, for example through chambers of commerce, or energy partnerships.

Public R&D creates rapidly diffusible knowledge that private projects can build on. Emerging economies must achieve growth and adequate living standards. If this is to be done without significant carbon emissions, the technological gaps existing for global scale use of green hydrogen and other cleantech must be closed. Therefore, innovation in developed economies must be accelerated and, crucially, knowledge transfer must be part of all R&D efforts. Furthermore, technological research is costly, and results are not guaranteed, so public R&D can mitigate the risk such efforts carry for private actors. Materials worthwhile of further research include:

- Cheaper, abundant and more active electrochemical catalysts

[40] European Union Agency for the Cooperation of Energy Regulators, 2021, Transporting pure hydrogen by repurposing existing gas infrastructure: URL: <https://www.acer.europa.eu/news-and-events/news/repurposing-existing-gas-infrastructure-pure-hydrogen-acer-finds-divergent-visions-future>.

[41] Topolski, Kevin, Evan P. Reznicek, Burcin Cakir Erdener, Chris W. San Marchi, Joseph A. Ronevich, Lisa Fring, Kevin Simmons, Omar Jose Guerra Fernandez, Bri-Mathias Hodge, and Mark Chung. 2022. Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-81704. <https://www.nrel.gov/docs/fy23osti/81704.pdf>.

- Stabler and inexpensive bipolar plates carrying the active electrochemical materials
- Better porous transport layers that facilitate the transport of charges and chemicals between the bipolar plates to the catalysts
- High conductivity solid electrolytes for PEM, AEM and SOE technologies

Pure oxygen is a by-product of electrolysis which is valuable. It has many uses, including potentially within the cluster: it can go into oxyfuel combustion for high-temperature processes (for example in a cement plant), which makes it much easier to then capture the CO_2 emissions since the stream is pure. Nhuchhen et al.[42] calculate that the cost of this by-product oxygen would be 73% cheaper than a dedicated air separation unit,[43] and that with oxy-combustion, the abatement cost would reach \$39-53/tCO_2. Another possibility is using the oxygen for wastewater treatment.[44] More broadly, the market for pure oxygen[45] was worth around \$50 billion in 2020 and is growing at almost 8% annually, with the largest consumers being industry. Assuming a price of \$3/kg,[46] this equates to 16 Mt of oxygen; if all of that came from electrolysis, then based on molecular masses, the associated hydrogen production would be around 130 MtH_2, i.e. more than the current 94 MtH_2 produced annually from all sources, including fossil-based.[47]

In sum, there is significant potential for the value of oxygen as a by-product to be utilized and therefore bring down the cost of green hydrogen (with the added benefit of saving the energy that would have been used for oxygen separation otherwise).

5.3. Economics and finance

A supportive economic and financial ecosystem is a vital precondition for the development of green hydrogen industrial clusters. There is currently no market without production and little willingness to invest into production without a proven market record. For this to be possible, direct government support is essential, particularly in the early stages and for first movers, through both supply- and demand-side policies (e.g. offtake agreements).

5.3.1. Economic and financial challenges

This section will present the main challenges that the development of green hydrogen industrial clusters currently faces in the realms of economics and finance. The overarching themes are lagging supply and demand for green products and green hydrogen market, along with low investment security and high financing needs for green hydrogen industrial clusters.

5.3.1.1. Economic and market challenges

Cost competitiveness is key in this regard; green products must be cost competitive. This translates into the cost of producing green hydrogen, which can be achieve by reducing the input and energy costs of production as well as carbon pricing or demand-stimulating policies.

The current production of hydrogen happens mainly on site or as a by-product of industrial processes and is consumed within the facility, as it would happen in the case of a green hydrogen industrial cluster. The lack of a functioning market is, therefore, stopping companies from making large-scale investments in the required infrastructure to produce, transport, store and use green hydrogen in industrial processes. However, there is increasing momentum as companies and countries are making decarbonization commitments – net-zero pledges cover > 70% of global GDP – that rely on the fact that sufficient green hydrogen is available to decarbonize certain industries and processes.[48] This is an important first step to minimize the risk of green hydrogen-related projects, encourage investment, and establish efficient green products and green hydrogen markets.

Green hydrogen needs low-cost, renewably generated electricity to be cost competitive. In the case of green hydrogen industrial clusters, there is a vertical integration between the electricity produced and the green hydrogen and its use within the cluster, and it is therefore independent of variations in electricity costs.

5.3.1.2. Financing and investment challenges

Due to the high CapEx involved in green hydrogen industrial clusters due to production of hydrogen and modification of industrial processes, private

[42] Nhuchhen et al, 2022, Decarbonization of cement production in a hydrogen economy. <https://doi.org/10.1016/j.apenergy.2022.119180>.

[43] For a distance of 20 km; this cost increases with distance, hence the importance of clusters.

[44] Woods et al., 2022, The hydrogen economy – Where is the water? <https://doi.org/10.1016/j.nexus.2022.100123>.

[45] Facts & Factors 2020, <https://www.fnfresearch.com/oxygen-market>.

[46] Woods, Phil et al. "The hydrogen economy - Where is the water?" Energy Nexus (2022): n. pag.

[47] IEA (2022), *Global Hydrogen Review 2022*, IEA, Paris <https://www.iea.org/reports/global-hydrogen-review-2022>, License: CC BY 4.0

[48] IEA (2021), *Net Zero by 2050*, IEA, Paris. URL: <https://www.iea.org/reports/net-zero-by-2050>, License: CC BY 4.0

investment will be crucial for the development of green hydrogen industrial clusters. However, it faces several challenges on a project financing level, particularly in the early stages due a perceived lack of investment security. Without investment, it is challenging to formulate cost benefit analyses and business models, which may in turn hamper the preparation of public policies. This gridlock between investors, developers, policymakers and offtakers must be resolved to kick-start initial developments.

Since CapEx makes up 30% of the levelized cost of hydrogen, it needs to be considered when setting up clusters. Private institutions have a limited willingness to finance projects when facing regulatory uncertainty. If regulations, policies and goals fail to specify, and fail to guarantee where green hydrogen is to be employed long-term, the subsequent increased risk of stranded assets can strongly limit access to private investments.[49]

Project financing in developing and emerging economies can be expensive due to risk factors such as security of offtake agreements and political stability. This translates to a relatively high weighted average cost of capital (WACC) compared to industrialized economies, which increases the overall project costs and costs for green hydrogen production.

A high likelihood of funding required by different actors along the entire value chain poses risk for funding institutions[50,51]. Green hydrogen industrial cluster projects require parallel investments across the whole value chain, for example, in production, processes and offtake of green products. These kinds of projects can be developed by different stakeholders and financed by different entities. This causes high co-dependencies.

A lack of established long-term green hydrogen offtake schemes hampers investment. As both green hydrogen markets and local green hydrogen value chains (e.g. within industrial clusters) are a recent and emerging phenomenon, there are little to no precedents to offtake schemes for green hydrogen projects that have proven to be bankable. This bears difficult to quantify project risks and hinders investors towards final financing decisions.[52]

A lack of public funding dedicated to green hydrogen projects slows down adoption. Public funding is essential for the market ramp up of green hydrogen as willingness to pay for green hydrogen's green premium does not cover the cost gap to fossil fuels on the free market in most cases.[53] Governmental funding schemes are crucial to achieve economic viability and enable early-stage green hydrogen projects. Thus, innovative financial measures and instruments must be adopted to leverage the available funding to the furthest extent possible, thereby de-risking and crowding in private investment (e.g. via blended public, private financing schemes, sovereign guarantees, etc.).

5.3.2. Economic and financial enablers

This section presents potential measures to overcome the market challenges and financing barriers of green hydrogen industrial clusters.

5.3.2.1. Economic and market enablers

Enablers such as partnerships or regulations have the potential to accelerate the use of green hydrogen in industry. Considering the strong need for innovation, it is vital that decision makers follow the best scientific advice on stimulating technological progress.

Long-term offtake agreements within the value chain can improve supply and demand security. It therefore makes sense for two companies to reach an offtake agreement before they start their respective investments. Industrial clusters are especially helpful to facilitate such agreements as the players might already work together on other topics and have a common basis of trust.

Putting a price on CO_2 emissions incentivizes the replacement of fossil fuels. Carbon prices internalizes the externalities of CO_2 emissions. In other words, they put a price on the climate damage resulting from the use of fossil fuels, thus reducing, or even eliminating, the green premium that must be paid for more sustainable alternatives such as green hydrogen.

[49] S&P Global (2021) Hydrogen projects face funding gap in Europe: URL: <https://www.spglobal.com/commodity-insights/en/market-insights/latest-news/electric-power/112521-hydrogen-projects-face-funding-gap-in-europe-banks>.

[50] Norton Fulbright (2021) Financing hydrogen projects brings unique challenges: <https://www.nortonrosefulbright.com/en/knowledge/publications/cd725de6/financing-hydrogen-projects-brings-unique-challenges>.

[51] Dena (2021) Public funding for powerfuels: <https://www.powerfuels.org/fileadmin/powerfuels.org/Dokumente/Public_Funding_for_Powerfuels_Projects/Public_Funding_for_Powerfuels_Projects_01.pdf>.

[52] IEA (2021), Global Hydrogen Review 2021. <https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf>.

[53] Dena (2022) Public funding for powerfuels projects: <https://www.powerfuels.org/fileadmin/powerfuels.org/Dokumente/Public_Funding_for_Powerfuels_Projects/Public_Funding_for_Powerfuels_Projects_01.pdf>.

Subsidies for green hydrogen producers can help develop economies of scale. Complementary to carbon pricing, enabling green products to be cheaper is an effective tool to allow for economies of scale to develop. Compared to a higher carbon price, temporary subsidies for green products are likely to meet less resistance from incumbent industries, as it does not directly impact their margins.

Commercial deployment can be scaled up using demand-side policies that "pull" investment throughout the value chain, making projects bankable.[54] This can take the form of fiscal policies to stimulate demand for green hydrogen in the industrial and mobility sectors, including direct support schemes mediating the hydrogen market price by establishing direct procurement systems (as an end-user) or mediating market access to producers via tendering or auctioning schemes (where price, performance, environmental and volume capacity can be requirements for participation).[55]

Introducing quotas for potential end-user markets of green products (e.g. green ammonia, green steel) or markets further down the value chain (e.g. car manufacturers) will guarantee a certain demand for green hydrogen. Establishing a quota further down the value chain has the positive effect that the entire value-chain will be incentivized.

5.3.2.2. Financing and investment enablers

At the very core of the green hydrogen paradigm, there is its cost premium (green premium), which must be compensated. It is important that green products are remunerated as a valuable premium through:

- Private (market) driven: voluntary/market driven willingness to pay
- Public (government) driven: compensation for the premium through public funding for the local government to comply with renewable energy, GHG reduction, or other green hydrogen industrial clusters-related targets
- Public-private driven: e.g. in line with efforts on international organizations to enhance inclusive and sustainable industrial development (ISID)

The cost premium can be redistributed across the supply chain, or the value chain of green hydrogen industrial clusters, with international organizations playing possibly enabling roles as donors covering said premium.

Direct public funding schemes and indirect incentives are fundamental to support the creation of green hydrogen industrial clusters.

Public CapEx funding schemes constitute an efficient option to guarantee access to funding. In the early stage of technological development, funding for R&D, piloting and demonstration is essential. CapEx-specific public funding can enable the realization of a technology, or concept for smaller projects where the relative bulk of the total project cost are capital costs.

OpEx-specific public funding can provide access to funding for a specific set of larger projects where operational costs constitute the bulk of green hydrogen production costs[56,57]. This requires larger funding volumes, dedicated financial instruments and longer duration of financial support potentially over the whole project lifetime.

Given governments' ability to take on more risk, they can engage in public-private partnerships that aim to develop and deploy capital-intensive green hydrogen industrial cluster projects. Carbon contracts for difference (CCfD) are useful in this regard, where a private actor is guaranteed a certain return on investment by governments making up the difference between actual return and the guaranteed return, while if the project is more successful, the excess returns flow back to the government for the benefit of the public. This mechanism provides companies with some downward protection limiting financial risks and thereby unlocks investments.

Publicly managed digital matchmaking platforms can facilitate the connection of relevant project stakeholders and funding. Accessible to green hydrogen project developers, such platforms would enable the identification of suitable stakeholders and public funding options for green hydrogen project development.

Any matchmaking platform should be managed or supervised publicly to enhance transparency. Transparency of ongoing projects along the green hydrogen

[54] European Investment Bank, Gilles, F., Brzezicka, P. (2022). *Unlocking the hydrogen economy: stimulating investment across the hydrogen value chain: investor perspectives on risks, challenges and the role of the public sector*, European Investment Bank. <https://data.europa.eu/doi/10.2867/847677>.

[55] Griffiths, S., et al, (2021). Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options. *Energy Research & Social Science*, Volume 80, October 2021, 102208.

[56] Dena (2021): Abschlussbericht Leitstudie Aufbruch Klimaneutralität: <https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/Abschlussbericht_dena-Leitstudie_Aufbruch_Klimaneutralitaet.pdf>.

[57] NOW (2020): <https://www.now-gmbh.de/wp-content/uploads/2020/09/indwede-studie_v04.1.pdf>.

value chain may foster additional synergies and leverage more funding. An existing matchmaking platform for producers, funding and offtakers is the H2 Global platform.[58]

Long-term government strategies (e.g. national hydrogen roadmaps) or targets contribute to creating investment security. This provides all stakeholders with more confidence that there will be a future marketplace for green hydrogen and related technologies.

5.4. Society and environment

At every industrial project, green hydrogen industrial clusters will affect their surroundings through the construction, infrastructure, energy and material inputs as well as the work involved in making them function. This section provides a brief overview of some of the challenges and enablers. The socio-environmental aspiration of any green hydrogen cluster should be to minimize its negative externalities while providing benefits to the people around it.

5.4.1. Social and environmental challenges

The development of green hydrogen clusters carries several implications for energy, water and food supply security, and its potential impacts on land use, ecosystems and biodiversity cannot be ignored, either. Similarly, the social component of community involvement in decisions and profits through stakeholder engagement and local content in operations is important (e.g. access to clean energy, water and employment).

The water consumption of green hydrogen production can significantly affect local water availability, increase water stress and cause water levels to decline. Water requirements for green hydrogen projects can compete with domestic needs and can cause further environmental sustainability concerns.[59] This is particularly the case in already water-scarce areas, where many favourable green hydrogen project locations are situated due to their ample endowment with solar energy potential. Seawater desalination requires substantial energy inputs. It can also result in significant amounts of waste brine, which once disposed, may lead to local contamination or loss of local ecosystems, both on land and at sea, and therefore disruption of food security and food safety.[60]

Land requirements for green hydrogen projects can cause competition with other land uses and decrease local project acceptance. The significant amount of renewable power infrastructure required for green hydrogen production does itself require significant amounts of land. Sufficient amounts of production facilities for renewable electricity will be required, however, to ensure the uptake of green hydrogen production to avoid an overall increase in GHG emissions (if fossil electricity is used). Sometimes, the installation of additional renewable power plants could meet opposition from local communities. This can in turn potentially lead to project delays or halts.

The chemical attributes of hydrogen make it a safety and environmental hazard. Due to its small molecular size, hydrogen is highly permeable through many materials and leaks more easily than other gases. Fugitive emissions could be a problem for the environment. Leakage also presents a safety risk because hydrogen's wide range of flammability.[61] These environmental risks need to be addressed as well, for example, by complying with relevant standards and norms for safe transport and storage of hydrogen.

5.4.2. Social and environmental enablers

Both the environmental impact and the livelihoods of local communities must be considered when planning green hydrogen production rollouts. The business case and climate benefits of producing green hydrogen should not come at the expense of energy, water, or food security. The key is inclusiveness: the involvement of local communities in the formulation of strategies to ensure that all stakeholders' voices are heard and their concerns considered.

By highlighting co-benefits for local communities, support for such projects could increase. Campaigns can focus on four main points. First, green hydrogen

[58] H2 Global: URL: <https://www.h2-global.de>.

[59] Dena, 2021. <https://www.powerfuels.org/fileadmin/powerfuels.org/Dokumente/Water_Consumption_of_Powerfuels/20211025_GAP_Discussion_Paper_Water_consumption_final.pdf>.

[60] National Geographic (2019) Desalination plants produce more waste brine than thought. <https://www.nationalgeographic.com/environment/article/desalination-plants-produce-twice-as-much-waste-brine-as-thought>.

[61] Abohamzeh et al., 2021, Review of hydrogen safety during storage, transmission, and applications processes <https://doi.org/10.1016/j.jlp.2021.104569>.

can substitute fossil fuels, thereby decreasing fossil consumption while increasing air, soil, and water quality at the local level. Second, green hydrogen projects can provide additional renewable electricity to the local grid. Third, clusters can either provide additional potable water for human consumption or productive uses or reduce wastewater streams. Last and perhaps most importantly, green hydrogen can be a means to transform local resources into local green jobs, enabling inclusive growth in rural settings. Local communication efforts could be developed in cooperation with the stakeholders involved in green hydrogen projects and be described within the SDG framework.

Policy can require green hydrogen production plants to provide surplus drinking water in water-scarce areas. With a purification cost of about 1€/1000l if extracted from seawater through desalination,[62] desalinated water only comprises about 0.1€cent/kgH2 of the total cost of hydrogen.[63] Doubling the installation of water desalination plants at suitable green hydrogen clusters would increase the production cost of hydrogen by a negligible amount, while generating significant amounts of drinking-grade water. This could then be made available to the neighbouring communities, with the key condition that any regulation of such vital water resources needs to ensure a just and fair distribution.

Sustainability criteria, including strict conditions for the use of renewable electricity, can help ensure that the carbon footprint of green hydrogen production is as low as possible. Such criteria could be based on the European renewable energy directive and include three main pillars: additionality of the electricity source, temporal correlation between the moment of electricity generation and consumption (or alternatively direct connection between the green hydrogen plant and the renewable power plant), and a geographical correlation criterion.

Environmental compliance for green hydrogen projects can generate co-benefits and thereby enhance acceptance in the local community. For example, a requirement for surplus renewable power generation capacity could be introduced, meaning that the excess electricity would be fed into the local electricity grid. Even before construction commences, integrated socio-environmental impact assessments can safeguard community resilience and ecosystems by shedding light on the true costs and feasibility of green hydrogen-related infrastructure projects.

Pricing or regulatory interventions to internalize environmental externalities on a broad scale can mitigate harmful impacts. They could even enhance the competitiveness of green hydrogen if applied widely, as the cost gap to fossil-based hydrogen production methods would be reduced. This is particularly true for carbon pricing schemes which may significantly penalize fossil-based and thus carbon-intense hydrogen production.

[62] Food and Agriculture Organization of the United Nations (2006): Water desalination for agricultural applications. Proceedings of the FAO Expert Consultation on Water Desalination for Agricultural Applications, checked on 7/12/2021. URL: <https://agris.fao.org/agris-search/search.do?recordID=XF2006427423>.

[63] Dena, 2021.

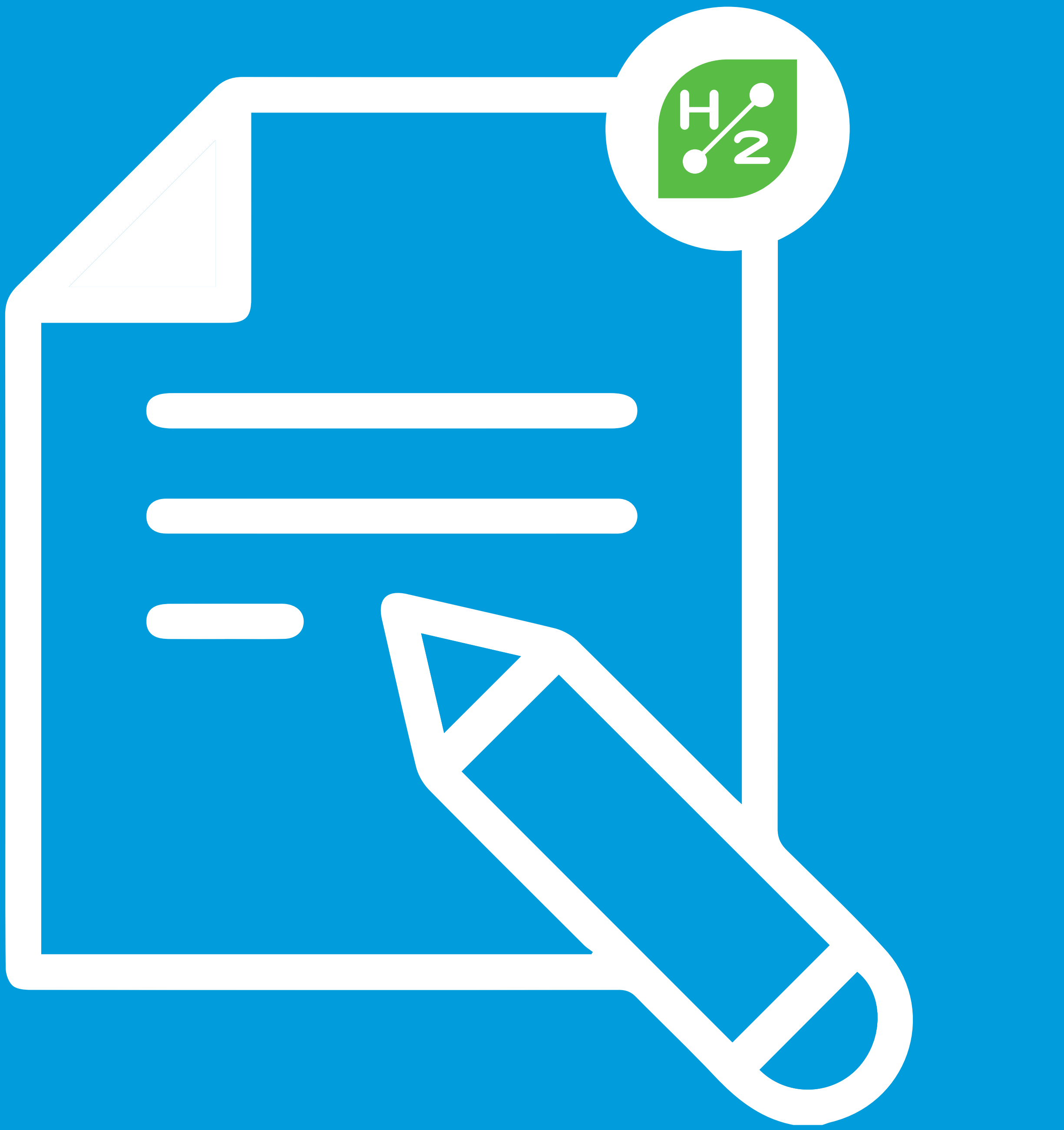
6. Concluding Remarks

These guidelines introduced the concept of green hydrogen industrial clusters, which are production clusters that use only green hydrogen to support sustainable development. Current use of green hydrogen in industry is limited, but there are already several initiatives that support a rapid uptake of green hydrogen in industry to create green jobs and mitigate emissions. UNIDO aims to support and accelerate this deployment and help governments and companies develop policies and projects related to green hydrogen in industry.

Green hydrogen currently faces several challenges that can be overcome by cooperation and collaboration among stakeholders as well as further research and development. Currently, green hydrogen is not cost competitive with grey hydrogen. This leads to a situation where material production with green hydrogen is not yet competitive with alternatives based on fossil fuels. Recent developments, however, indicate that hydrogen production with renewable electricity could be cost competitive over the next decade and relevant at scale. To support this, governments have introduced several R&D programmes and demand-based support instruments. These activities are key to support the uptake of green hydrogen.

The previous chapters described use cases for hydrogen, characteristics of production with hydrogen and challenges, as well as policies to address those challenges. It also proposed UNIDO's green hydrogen industrial cluster model, which consist of three phases. The model will be further developed and updated in the coming years to support governments and industrial stakeholders to develop production clusters.

UNIDO supports the development of green hydrogen industrial clusters through project development, stakeholder engagement and dialogue, and by providing best practices and guidelines. These guidelines are a first step towards compiling relevant information and documents for the early phases of the cluster development.



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