D2.1 – Promoted policies providing incentives

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V2.0	27/09/2024	Preliminary version
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Abbreviation and acronyms

Acronym	Description
CH_4	Methane
DRI	Direct Reduced Iron
ECH2A	European Clean Hydrogen Alliance
EHB	European Hydrogen Backbone
EIB	European Investment Bank
EU	European Union
GHG	Green House Gases
H_2	Hydrogen
HJU	Hydrogen Joint Undertaking
HTS	High Temperature Systems
IAM	Integrated Assessment Model
IEA	International Energy Agency
IPCEI	Important Project of Common European Interest
KPI	Key Performance Indicator
LCA	Life Cycle Analysis
LTS	Low-Temperature Systems
MMT	Million Metric Tonnes
O_3	Ozone
PPA	Power Purchase Agreement
RED	Renewable Energy Directive
RFNBO	Renewable Fuel from Non Biological Origin
SAF	Sustainable Aviation Fuel
SDG	Sustainable Development Goals
TEN-E	Trans-European Networks for Energy
TRL	Technology Readiness Level

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1 Executive Summary

The HYDRA project aims to evaluate the policies related to hydrogen and its impact at global level through climate modelling and an Integrated Assessment Model (IAM). The purpose of this evaluation is to make recommendations and define mitigation actions to counteract possible negative effects linked to the development of a hydrogen economy, deriving from H2 potential leakages along the value chain. To detect and prevent H2 leakages, HYDRA will also develop a tool capable to monitor H2 leakages.

This deliverable provides a comprehensive analysis of hydrogen-related policies that currently exist at regional and national levels in the European Union (EU) and other regions of the world. In addition, it defines a classification of these policies that allows for the identification of policy transposition failures at national level, differences in expectations between various countries and regions and global hydrogen policy trends. This classification and deep analysis are also useful to support the modelling of hydrogen economy scenarios in the IAM used in this project (WILIAM).

Finally, a review and analysis of Key Performance Indicators (KPIs) related to the hydrogen economy and to the policies analysed in this document is made in order to select and prioritise those that could be more appropriate to evaluate the scenarios and results from the models, and therefore, that allow to compare the effects of different policies and hydrogen scenarios.

This task sets the basis for the project structure, creating a global hydrogen policy framework that will be used as a starting point for the other tasks and proposes a set of KPIs that set targets and a way forward for HYDRA modelling. Furthermore, it points out the main policies to be modelled in order to be able to give recommendations on hydrogen deployment.

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2 Introduction

Deliverable D2.1 "Promoted policies providing incentives" is part of Work Package WP2 "State-of-the-art knowledge on H_2 policies, market analysis, and emissions estimation", which aims to scout the policies that promote a hydrogen economy, analyse the evolution of hydrogen-based technologies and estimate the impact of hydrogen leakages; to give a background analysis for other Work packages. In particular, Task 2.1 intends to analyse and evaluate the directives and incentive schemes related to hydrogen technologies at European and global level, defining socioeconomic and environmental Key Performance Indicators (KPIs).

The European Union (EU) is aiming to decarbonise all the energy system and become energy-independent, spurred by the ongoing Russo-Ukrainian war and the European Green Deal, with the objective of zero net carbon emissions by 2050. Hydrogen (H_2) is emerging as a promising avenue for accelerating this transition and is now attracting the attention of both the public and private sector due to its potential as a carbon-free energy carrier. Despite currently being used solely as feedstock for industry, H_2 has the potential to be employed across any sector, enabling decarbonisation of hard-to-abate industries, residential heat and power, or mobility. The current carbon emissions associated with H_2 production from fossil fuels could be mitigated through methods such as water electrolysis or methane (CH_4) reforming coupled with carbon capture, utilization, and storage (Bertagni et al., 2022).

However, hydrogen's role as an energy carrier presents environmental challenges that could hinder its potential benefits in a transition to a hydrogen-based economy. While H_2 itself does not directly contribute to radiative forcing, leakages along its value chain are a significant concern. These leaks increase H_2 emissions, which, when released, can indirectly impact Earth's radiative balance by affecting greenhouse gas concentrations like methane (CH_4), ozone (O_3), and atmospheric water vapor (Bousquet et al., 2011). Additionally, concerns include potential contamination of aquifers from H_2 dissolution due to losses in underground storages; migration and accumulation in underground cavities leading to fire or explosions (Gombert et al., 2021); critical dependence on water availability for green H_2 production (i.e. hydrogen produced with renewable energy); and land use planning for infrastructure development (Woods et al., 2022). Addressing these environmental impacts is essential for sustainable development and evaluating the real benefits of a hydrogen economy, where Integrated Assessment Models (IAMs) and climate models will be key tools to address the complexities and guide climate policies towards a more sustainable future.

The HYDRA project aims to enhance understanding of the climate impacts associated with widespread adoption of hydrogen as an energy carrier or industrial input. It will achieve this by conducting climate forecasts within a large-scale hydrogen economy scenario, assessing current EU and global policies, and forecasting future market penetration of hydrogen-based technologies. HYDRA will focus on evaluating potential hydrogen emissions to the atmosphere, studying hydrogen sink processes, and analysing scenarios related to land use and water consumption. Additionally, HYDRA aims to analyse climate change projections and integrated impacts of a future hydrogen economy, identifying benefits, risks, mitigation strategies, and providing policy guidelines through policy briefs.

Task 2.1 identifies the targets and instruments about hydrogen technologies presented in different European and global policies. The role of hydrogen in future energy plans will be evaluated through the incentive schemes for renewable hydrogen production and infrastructure, providing valuable insights. Furthermore, this task will analyse the importance of international cooperation in promoting hydrogen energy solutions. Finally, T2.1 will define and prioritise KPIs based also on the broad sustainability perspective (link to current Sustainable Development Goals (SDG)) to evaluate the effects of different hydrogen-based policy scenarios in the IAM model, not only on energy or economy, but also on society and environment, that could support the analysis of policies that counteract potential negative effects of the deployment of a hydrogen economy.

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2.1 Purpose of the document

This deliverable aims to give an overview of the research done under the Task 2.1 "Directives and incentive schemes related to hydrogen technologies at EU and global level", belonging to Work Package 2 "State-of the-art knowledge on H_2 policies, market analysis, and emissions estimation". This WP2 wants to scout the prioritised policies targeting hydrogen, analyse the path that hydrogen-based technologies are taking at EU level and worldwide and make estimations of leakages in the hydrogen value chain as a whole. T2.1 focuses on the assessment of the policies, which will set the ground for modelling scenarios and mitigation policies in WP4 and WP5.

2.2 Structure of the document

The document is structured as follows:

- **Section 1** explains the executive summary of the document.
- **Section 2** introduces the document, its purpose and structure.
- **Section 3** presents the methodology followed for the analysis of policies: the nomenclature, the review process and the classification used.
- **Section 4** shows the results of the policy analysis, separately for EU, national and global level.
- **Section 5** explains the identification of KPIs.
- **Section 6** draws the conclusions and describes the future steps.

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3 Methodology of the analysis

The aim of this section is to describe the methodology used to carry out the analysis of the different hydrogen policies, and to define a common framework and working strategy in the context of the HYDRA project.

First, a list of key terms is presented to define a common nomenclature and ensuring understanding of important concepts that will be used throughout the document. Then, the approach used for policy review and the source of the literature used will be described. Finally, the third subsection (3.3) clusters the criteria used for the classification of the policies and defines each category.

3.1 Key terms

In the policy analysis area, there are many different terms to refer to similar concepts. Here, it has been considered necessary to establish a number of common terms that allows to work with the different concepts of policymaking in an aligned way. The key terms to understand the context of the analysis are explained below. These terms are based on previous documents and literature also used for modelling policies in IAMs and in particular in WILIAM, the IAM used in HYDRA (Ferreras et al., 2023).

Policy: According to the Oxford English Dictionary, a policy is "a course or principle of action adopted or proposed as desirable, advantageous, or expedient". (Ferreras et al., 2023)

Policy Measure: Intervention, typically driven by public bodies, that aims to make a change on the current trends of an area related to the people behaviour, infrastructure, technology, etc. A policy measure is implemented in a defined policy sector, seeking to achieve a policy objective and target, and through a policy instrument. (Ferreras et al., 2023)

Policy Objective: Refers to the outcome expected from the implementation of a policy expressed in broad terms, or the area where this policy impacts. The area affected by the policy can also be indirect (e.g. the implementation of new co-heat and power solutions for housing is implemented in the building sector, but can also impact on industry and mitigation). (Böck et al., 2020)

Policy Target: is a quantitative expression of the intended effect that a policy measure aims for (e.g. a reduction of CO_2 emissions by 29% compared to 1990 levels by 2030). (Böck et al., 2020)

Policy Instrument: Mechanisms implemented by public bodies to reach a defined policy target. A policy measure can be implemented through instruments alone or in a combination of different types of instruments. The policy instruments types defined for the present analysis will be defined in the classification of policies (3.3). (Böck et al., 2020)

3.2 Review process

Task 2.1 focuses on analysing and classifying as many policies related to hydrogen as possible. To achieve this goal, the first step of the task envisaged the alignment of the nomenclature used by the different partners involved in the task in order for everyone to use common terms and facilitate collaboration, as detailed in the previous section.

The following step consisted in a review of the structure of hydrogen policies published at global and European level in order to approach the search, analysis, and classification of documents in the best possible way. This review was done with a top-down approach, reviewing first the *Global Hydrogen Review 2023* (IEA et al., 2023b) for a global framework, the International Energy Agency (IEA) policy classification page and the general structure from its different documents about hydrogen. Then, this same research was carried out for the EU, resulting in a joint classification capable of encompassing hydrogen policies at both European and global level.

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This policy classification was used to develop two templates for a text document and a spreadsheet in which the analysed policies were documented in parallel: recording the main policies, the year and the link to the document of reference in the spreadsheet; and the description of the main ideas of the policies in the text document (see Annexes).

From this point onwards, the analysis of hydrogen policies began. The first part of the review consisted of finding out the background of these hydrogen policies, the dependencies they have with other policies and how new policies are being developed. In this context and taking into account the need to develop hydrogen-based scenarios for the modelling activities, the research focused on the policy targets that the European Union set for hydrogen in the medium term. Other hydrogen-related documents were then analysed to show which policy instruments are used to achieve these objectives.

Once the European framework was known, the different National Hydrogen Roadmaps of the EU countries were analysed to find out how policies are being transposed, what differences appear between countries and whether national policies are aligned with those of the EU as a whole. This process was also repeated for countries in WILIAM's different global regions[1] in order to compare Europe with the rest of the world, and to have information to set out the basis for the development global scenarios which could be used in WILIAM.

Finally, a synthesis and joint analysis of the evaluated policies was carried out and conclusions were drawn on the modelling that these policies can have in WILIAM.

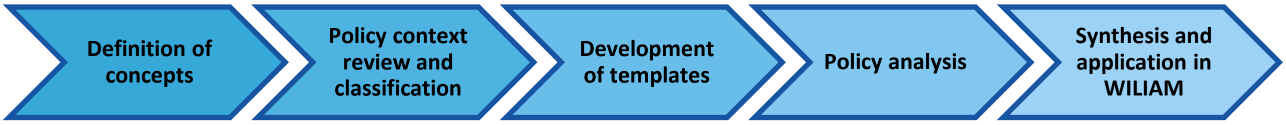

Figure 1. Process review scheme

3.3 Classification of policies

In order to cluster and compare the different policy objectives, targets, and instruments that appear in the diversity of policies, reviews, articles, etc. of global, regional or national entities it is crucial to define a categorisation system covering all of them.

For this purpose, the classification structures of hydrogen-related topics of the main global and European organisations have been reviewed. These include the European Commission's hydrogen website (European Commission, n.d.); European plans like the EU Hydrogen Strategy (European Commission, 2020a), RePowerEU (European Commission, 2022a) or the Hydrogen Implementation Plan (European Commission, 2022b); the International Energy Agency's (IEA) hydrogen website (IEA et al., 2023a) and its policy database (IEA, n.d.); and some other IEA reports like the Global Hydrogen Reviews (IEA, 2022; IEA et al., 2023b).

The first classification adopted, applied both to policy targets and policy instruments, is related to jurisdiction. It helps to differentiate the policies depending on which geopolitical level they apply to (Böck et al., 2020). There are three classes:

- **Global:** Policies adopted between countries at the global level or related to international organisations.
- **Europe:** Policies promoted by the European Union or covering several EU countries.
- **National:** Policies related to a single country.

[1]WILIAM is a global level model, with information at scale of "global regions" like India, Europe, LATAM. etc.

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It is also necessary to classify the policies according to the policy sector, which refers to the direct areas where the policies are implemented. In this case, the different policy sectors are those in which the hydrogen is used, transforming it into another energy vector (e.g. electricity) or in final energy (e.g. heat), corresponding mainly to the "hydrogen supply" link of the value chain. Since policy instruments are normally cross-sectorial, as they focus more on the way to make some changes on tendencies and not so much on the objectives, this classification only applies to policy targets (Böck et al., 2020). The policy sectors used for this project are the following:

- **Industry:** Policies related to the use of hydrogen in industrial processes and energy-generation for its own use.
- **Transport:** Policies covering transportation modes or infrastructure programmes.
- **Buildings:** Policies associated with the use of energy in buildings.
- **Electricity generation:** Policies that target energy consumption and emissions associated with power generation.
- **Fuel processing and transformation:** Policies targeting different processes of production and transformation of fuels and other energy resources.
- **General:** Policies not focused on specific policy sectors.

The policy targets are usually classified also according to the link in the hydrogen value chain. The hydrogen value chain involves the complete cycle of production, storage, transportation, distribution, and utilization of hydrogen, serving to link producers with end consumers. This integrated system facilitates hydrogen's crucial role as a clean energy carrier across different sectors (Böck et al., 2020). The value chain is segmented in the next links:

- **Hydrogen production:** Policies related to hydrogen gas generation whether through electrolysis or other methods using fossil fuels.
- **Hydrogen transportation:** Policies targeting the distribution of hydrogen in gaseous, liquid, or in chemical carriers through pipelines, tanks, or any other modes.
- **Hydrogen storage:** Policies that cover the compression of gaseous hydrogen, its liquefaction at low temperatures or its physical or chemical storage in other substances for medium or long-term. The conversion could include transforming hydrogen into electricity through fuel cells to feed the electrical grid.
- **Hydrogen supply:** Policies associated with the delivery of hydrogen to end users, which can range from industrial sites to fuelling stations for hydrogen-powered vehicles. The distribution infrastructure needs to ensure the safe and efficient transfer of hydrogen to various points of use.

Finally, the policy instruments have their own classification depending on the way of changing the tendencies (Böck et al., 2020). There are four main groups of policy instruments, which are further subdivided into more options:

- **Regulatory instrument:** An intervention from the public bodies that sets some rules or trends, banning unsustainable or inefficient technologies or practices, or setting limitations for some goods and services' production or consumption.
    - **Codes and standards:** Compulsory limitations for products or projects related to the material employed, energy used, emissions, etc. or categorisations related to these limitations.
    - **Quotas & obligation schemes:** Gives a fixed amount of products or energy to be produced.
- **Economic instrument:** Providing of financial incentives, tax benefits, and other measures by public bodies or international organisations to promote investments or certain actions or behaviours.

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  - **Direct investment:** Procurements and subsidies granted by public authorities if certain conditions are met.
  - **Fiscal incentives:** Positive (e.g. grants, subsidies, tax exemptions) or negative (e.g. taxes, loans, user charges) economic discriminations that help to regulate the market.
  - **Market-based instruments:** Tradable emissions allowance, energy certificates, etc. that set global targets through their buying and selling.
- **Soft instrument:** Partnerships or agreements or learning processes that rely on voluntarism rather than direct influence on regulations or finances looking for procedural changes.
  - **Information and education:** Awareness raising, communication and training campaigns of different topics in order to bring general audiences closer to global targets.
  - **Voluntary agreement:** agreements made between government authorities and private parties on voluntarily reducing environmental impacts. Private parties cannot be forced to join a voluntary agreement, but government authorities may provide incentives for participation.
- **Research & development instrument:** Policies promoting the research and development projects. These policies do not have a direct impact on tendencies but focus on new ideas for the future.

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4 Policy analysis

This section summarises the analysis of all the hydrogen policies reviewed, presenting all the different policy targets and instruments sorted according to the classification described in the previous section.

First, a general framework of hydrogen policies is presented to see the origin of the tendencies in this sector. Then, the following subsections focus on the jurisdiction level, clustering the policies for Europe, for the national level in the EU and the national policies in the rest of the world separately.

4.1 Framework

The initial idea of a hydrogen economy emerged during a period when worries about the exhaustion of fossil fuels, due to rapid increases in worldwide energy consumption and pollution escalation, were becoming prominent.

Recent global developments, including local environmental degradation, climate change, geopolitical instability affecting energy supplies, fluctuating fossil fuel prices and advancements in clean technology; have revived sociological and economic interest in sustainable energy systems, such as the hydrogen economy.(Dunn, 2002; Yap and McLellan, 2023)

The first step in this path was taken by the United Nations Framework Convention on Climate Change approving the Kyoto Protocol in 1997 to achieve the "stabilisation of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations, 1997). The targets presented in this agreement began to spark interest in hydrogen as a means to achieve global decarbonisation. (Yap and McLellan, 2023)

The next major breakthrough in the fight against climate change took place at the Conference of Parts (COP) 21 in 2015 with the Paris Agreement, as it promoted a legally binding transition towards a low-emission and climate-resilient economy. This treaty is based on the Intergovernmental Panel on Climate Change (IPCC)'s Assessment Reports and sets some international targets that aim to prevent the increase in extreme temperatures, sea-level rise, extreme precipitation, decrease of water availability, coral reef degradation, and loss of fertile land caused by the greenhouse gases (GHG) (United Nations, 2015). The ratification of the Paris Agreement by a total of 194 states and the EU, as well as other international agreements promoted by this treaty, led to a revitalized interest in hydrogen energy in subsequent years (Yap and McLellan, 2023).

By 2015, all Member States of the United Nations (193 countries) approved the 2030 Agenda, which aims to be an action plan to end poverty, protect the planet, and improve lives and prospects for society. This includes 17 Sustainable Development Goals (SDGs).

In this global context, the European Union has been the main driver of the response to the existing climate crisis since 1990. To achieve this, the EU developed a legal framework that has evolved to adapt to new needs and goals.

In 2008, the European Union approved the 2013-2020 Climate and Energy Package, consisting of binding regulations, which set specific targets for 2020 in the areas of renewable energy, energy efficiency, and the reduction of greenhouse gas emissions. Subsequently, the EU extended the continuity of this package until 2030 and presented the "Roadmap for moving to a competitive low carbon economy in 2050", a framework fully aligned with the Paris Agreement.

In 2019, the European Union published the Communication on the "European Green Deal" and launched a new growth strategy aimed at transforming the EU into a fair and prosperous society with a modern, resource-efficient, and competitive economy. This document begins to talk about hydrogen in the context of innovative technologies and infrastructure for climate transition, alternative fuels or energy storage. (European Commission, 2019)

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Finally, the European Climate Law translates the objectives of the Green Deal to achieve the climate neutrality in Europe by 2050, aiming for net zero greenhouse gas emissions through emission reductions, green technology investments, and environmental protection. It also sets an interim goal of reducing net greenhouse gas emissions by at least 55% of 1990 levels by 2030. In this framework, the European Commission highlights initiatives as the Clean Hydrogen Alliance as fosters in the transition to climate neutrality. (European Commission, 2021a)

Driven by the fight against climate change and decarbonisation, the hydrogen economy began to be seen as a feasible alternative. Specific hydrogen policies are being promoted both at EU and global level, setting targets and establishing the instruments to achieve them.

4.2 European policies

The European Union has made a major commitment to green hydrogen and is trying to build a policy framework that will enable all partners to reach the objectives in a joint and aligned manner. In the following sections, all the European policies that have been analysed will be reviewed in order to distinguish the hydrogen targets that the European Commission is proposing and through which policy instruments it intends to achieve these objectives.

4.2.1 Targets

In this section, the most important documents that propose policy targets at European level are analysed individually, highlighting the main indicators that mark the way forward for EU member states.

In the table below, the documents analysed are listed, together with the best measurable and most significant targets. Year of publication of the policy and the document reference are also specified. In the following subsections, each specific policy is detailed.

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Table 1. EU policy targets

Policy	Targets	Year	Reference
EU Hydrogen Strategy	40GW Electrolysers 2030 24% H_2 final energy 2050	2020	(European Commission, 2020a)
Fit for 55	42% of RFNBO's[2] in industry 2030	2021	(European Commission, 2021b)
REPowerEU	10 + 10 Mt of Hydrogen 2030 75% of RFNBO's in industry 2030 5% of RFNBO's in transport 2030	2022	(European Commission, 2022a)
ReFuelEU	5% of SAF[3] in aviation by 2030 63% of SAF in aviation by 2050	2023	(European Commission, 2023)
Alternative Fuels Infrastructure Regulation	-	2023	(European Council, 2023a)
European Hydrogen Backbone	28,000 Km pipeline 2030	2023	(EHB, 2023)
EU Renewable Energy Directive	42% of RFNBO's in industry 2030 1% of RFNBO's in transport 2030	2024	(European Commission, 2024a)
Net Zero Industry Act	-	2024	(European Commission, 2024b)

4.2.1.1 EU Hydrogen Strategy

The Hydrogen Strategy was the first document published by the European Union (2020) which objective was to foster the use of renewable hydrogen and set the targets for this sector in the near future. Given the necessity for new ways of decarbonisation of the economy, this strategy commits to hydrogen to reach the European objective of reducing greenhouse gas emissions by 55% by 2030.

This report estimates that an investment of **180-470 billion €** will be needed to deploy green hydrogen and achieving the goals of the Paris Agreement, together with **3-18 billion €** for low-carbon fossil-based hydrogen that helps on the transition. With this commitment it is estimated that hydrogen would cover **24% of the total energy demand** of the world by 2050.

To produce this hydrogen, the European Union plans to install **40 GW of electrolysis power** inside of the Union and boost the installation of another 40 GW in Europe's neighbourhood countries with a view to exporting more green hydrogen by 2030. To this end, the member states have been encouraged to include hydrogen in their National Energy and Climate Plans (NECPs) and even to develop their own national hydrogen strategies.

The EU Hydrogen Strategy establishes a roadmap to reach all the targets, divided in different stages for the short and long term. The first one aims to install at least **6 GW of electrolysers** and be able to produce up to **1 million tonnes of green hydrogen** by 2024; then grow up to reach **40 GW and 10 million tonnes** in 2030; and finally, to have a developed hydrogen economy with zero emissions and a completed structure for its value chain by 2050.

[2] Renewable Fuels from Non Biological Origin

[3] Sustainable Aviation Fuels

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The whole document proposes a list of 20 key actions to reach these targets for the European Union, grouped in 4 main areas: an investment agenda; scaling up demand and production of H_2; creating a supportive framework; and cooperation and work together of different countries.

4.2.1.2 Fit for 55

The "Fit for 55" package consists of a number of recommendations aimed at modernising EU laws and promoting new projects aligned with the European climate goals. This measure arises from the objective of reducing the European emissions by at least 55% by 2030, looking for a fair climatic transition, maintaining Europe's competitiveness and positioning Europe as a leader in the economy decarbonisation.

The package includes proposals in 14 different areas related to emissions, resources, economics, transport, and energy sources, with a direct or indirect relation to hydrogen production and usage:

- An updated emissions trading system that will include transport and fuels, fostering zero-emissions fuels like hydrogen.
- An objective of **66% of renewable and low-carbon gas fuels** in the EU by 2050
- A new road infrastructure (TEN-E) that includes a hydrogen-vehicles network and a target for **50% of the cars** running on alternative fuels by 2050
- Minimum shares for Sustainable Aviation Fuels (SAF) of **5% by 2030 and 63% by 2050**
- Minimum shares for maritime fuels of Renewable Fuels from Non-Biological Origin (RFNBO's) and biofuels: at least **5.5% by 2030**
- New taxes to energy products and electricity which levelise the costs of different fuels, preserving the European market while boosting the use of green fuels
- Industrial target of reaching a **42% share of RFNBO's by 2030**
- New buildings regulation for zero-emission from 2030 onwards, with the possibility of installing cogeneration systems based on hydrogen

4.2.1.3 REPowerEU

The REPowerEU plan arises from the need to reduce the dependence on Russia for the fossil fuels and energy sources, accelerating the European transition to a green economy, reducing the polluting emissions and creating a stable and sustainable common energy system.

This plan expands the targets presented on the Fit for 55 plan and establishes the necessary instruments for their achievement. It also increases the energy efficiency target proposed in the Energy Efficiency Directive **from a 9% improvement to a 13%**.

Related to hydrogen, the plan recognises the importance of this energy vector to replace fossil fuels and lead the decarbonisation of hard-to-abate industry and transport sectors. To this end, the European Commission set a target to **produce 10 million tons of hydrogen and import another 10 million by 2030** to cover the future demand.

To reach this target, the Commission has published **two Delegated Acts** which define the RFNBO's and the renewable hydrogen to regulate the production, supply and consumption of this fuels, and set a target of covering a **75% of the industry energy use and a 5% of the transport**. It also sets the **investment of 200 million €** from the Hydrogen Joint Undertaking (HJU) for the creation of new Hydrogen Valleys and gives hydrogen projects a priority on the election of Important Projects of Common European Interest (IPCEIs). Finally, REPowerEU focuses on creating new hydrogen regulation and standards and keep track of the hydrogen uptake with periodic reports.

The plan estimates a need of a fast deployment of infrastructure to reach the requirements of the hydrogen economy and TEN-E plan. Investments of **28-38 billion € for hydrogen supply and 6-11 billion € for new storage infrastructure** will be needed.

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Figure 2. European infrastructure map for electricity and hydrogen (European Commission, 2022a)

To encourage the adoption of hydrogen and electrification in industrial sectors, the European Commission plans to implement carbon contracts for difference and create REPowerEU-specific windows through the Innovation Fund. These initiatives aim to transition existing hydrogen production from natural gas to renewable sources and promote hydrogen-based processes in new industries, such as steel production. By 2030, the Commission anticipates decarbonizing around **30% of primary steel production using renewable hydrogen**, which will require 1.4 million tons of hydrogen and investments between **18-20 billion €** to replace traditional blast furnaces with direct reduced iron (DRI) processes. Additionally, the Commission will issue guidance on renewable energy and power purchase agreements (PPAs) for Member States and, with the European Investment Bank (EIB), establish technical advisory support for PPA-funded renewable energy projects. To stimulate industrial investment, the Commission doubled the budget for the 2022 Large Scale Call of the Innovation Fund to EUR 3 billion, focusing on innovative electrification, hydrogen applications, clean tech manufacturing, and pilot projects to test ground-breaking solutions.

To reduce fossil fuel reliance in the transport sector, the European Commission plans to combine electrification with the use of fossil-free hydrogen. To boost energy efficiency and speed up the shift to zero-emission vehicles, the Commission is considering legislation to mandate a higher proportion of zero-emission vehicles in large public and corporate fleets. It also urges swift approval of proposals related to alternative fuels and green mobility, and in 2023, the EU introduced a legislative package focused on making freight transport more environmentally friendly.

Furthermore, to reach the production capacity necessary for this plan it would be crucial to have at least an electrolysers' manufacture capacity of **17.5 GW per year by 2025**. This manufacturing capacity has grown from 3 GW/yr in 2021 to 6.8 GW/yr in 2023, and is likely to reach its target in 2025 (European Commission. Directorate General for Energy., 2023).

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4.2.1.4 ReFuelEU

The objective of this proposal is to boost the use of Sustainable Aviation Fuels in the air transport of Europe, creating a value chain from producers to consumers, without disestablishing the aviation market. The SAFs are projected to be a short and medium-term instrument for aviation decarbonisation, however, it is necessary to seek for an escape from the conditions impeding their development — a scarcity of supply and prices that remain significantly higher than those of fossil fuels. (European Council, 2023b)

The regulation aims to set obligations for a minimum share of SAF for the near future, creating a transitional period to foster the creation of a supply chain and organisation of producers and create obligations to report and keep track of the objectives, as well as fines to enforce the regulation.

The main targets of the report are the following:

Annex I (volume shares)

(a) From 1 January 2025, a minimum share of 2% of SAF;

(b) From 1 January 2030, a minimum share of 5% of SAF, of which a minimum share of 0.7% of synthetic aviation fuels;

(c) From 1 January 2035, a minimum share of 20% of SAF, of which a minimum share of 5% of synthetic aviation fuels;

(d) From 1 January 2040, a minimum share of 32% of SAF, of which a minimum share of 8% of synthetic aviation fuels;

(e) From 1 January 2045, a minimum volume share of 38% of SAF, of which a minimum share of 11% of synthetic aviation fuels.

(f) From 1 January 2050, a minimum volume share of 63% of SAF, of which a minimum share of 28% of synthetic aviation fuels

Figure 3. SAF use targets for ReFuelEU (European Commission, 2023)

4.2.1.5 Alternative fuels infrastructure regulation

This regulation aims to foster the deployment of recharging and refuelling stations for clean fuels in Europe, in order to decarbonise the transport sector.

The regulation is part of the Fit-for-55 package, and is focused on the following targets:

- To install road recharging stations for light-duty vehicles of more than 150 kW every 60 km of the European road grid, complying with the TEN-E network plan. These points must be within a maximum distance of 10 km. The target must be met by 2025.
- To install road recharging stations for light-duty vehicles of more than 350 kW every 60 km of the European road grid, complying with the TEN-E network plan; or 100 km on the larger TEN-T network. The target must be met by 2030.
- These hydrogen refuelling stations must serve at least gaseous hydrogen at 700 bar.

4.2.1.6 European Hydrogen Backbone

With the goal of creating a strong market for renewable and low-carbon hydrogen, 33 energy infrastructure providers have joined forces to form the European Hydrogen Backbone (EHB) initiative, which aims to move Europe closer to climate neutrality. With new and old pipelines, EHB hopes to expedite decarbonisation through hydrogen infrastructure. In addition to guaranteeing supply and demand security and promoting cross-border collaboration between European countries and their neighbours, the program promotes market competitiveness.

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The EHB sets a roadmap and estimates the investment and operating costs to build a **pipeline network of 28,000 km** across the whole Europe, connecting hydrogen valleys, industrial clusters, hydrogen recharging points and ports to make an international grid of hydrogen supply chain by 2030. This network is expected to grow up to **53,000 km by 2040**, deploying the necessary international framework for a hydrogen economy. The investment cost for this network is **80-150 billion €**, with additional operating costs of 1.6-3.2 billion €/year.

The majority of these projects are now in the early stages of development and should be operational by 2029–2031. It is anticipated that the projects in the front-end engineering design phase will be finished in a few years. These projects will create the first 4,000 km of the European hydrogen transmission network if FID is accepted, with other 40 projects that will be put into service by the beginning of the following ten years.

4.2.1.7 Net Zero Industry Act

This policy will assist in removing obstacles to increasing European manufacturing capacity and bolstering the continent's ability to produce net-zero technology. The EU's energy resilience will be enhanced and the net-zero technology industrial base will become more competitive thanks to the measures outlined in the Regulation. The proposal demonstrates Europe's dedication to taking the lead in the net-zero technology transition and assisting in the accomplishment of the Fit-for-55 and REPowerEU goals (European Commission, 2024c).

The Regulation covers goods, parts, and machinery required to produce net-zero technologies. It distinguishes between net-zero and strategic net-zero technologies, the latter of which are either about to hit the market or are already commercially accessible and will significantly contribute to decarbonisation by 2030. While the provisions of this law apply to all net-zero technologies, strategic net-zero technologies also benefit from additional advantages including the resilience criterion in auctions and the potential to become Net-Zero strategic projects. These projects might be given priority status in order to take advantage of shortened schedules.

In addition to making it simpler for project promoters to establish net zero industrial manufacturing, this act establishes the prerequisites for investments in net-zero technology manufacturing projects. It accomplishes this by tackling the main factors that motivate investments in net-zero technology manufacturing, like:

- reducing the administrative load for net-zero manufacturing projects by simplifying administrative procedures and easing permitting
- guaranteeing information accessibility
- making markets more accessible through public procurement processes, auctions, and consumer demand support initiatives
- supporting innovation through regulatory sandboxes

The ability to produce net-zero technology more effectively requires a sizable and highly skilled labour force. By establishing specialized training programs through Net-Zero Academies and enabling the portability of certifications in regulated professions, the policy will improve skills for net-zero technology. Within three years of opening, the academies—each concentrating on a single net-zero industry technology—will seek to train 100,000 students.

Finally, a Net-Zero Europe Platform is created so that stakeholders interested in the net-zero industry sector can provide feedback, discuss, and exchange information with the Commission and other EU member states. The platform offers financial recommendations for key net-zero initiatives. Global adoption of net-zero technologies will be facilitated via net-zero industrial partnerships, which will also support the role of EU industrial capabilities in laying the groundwork for the world's clean energy transformation.

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4.2.1.8 EU Renewable Energy Directive

The Renewable Energy Directive (REDIII) seeks to encourage the use of renewable energy sources by establishing an investment and regulatory environment that facilitates the reduction of emissions and the decrease in dependency on fossil fuels. It expressly requires industry and transportation to use RFNBO's, but establishes more abstract goals for industrial applications, requiring **at least 42% RFNBO utilization by 2030 and 60% by 2035** (Hydrogen Europe, 2024).

This policy also sets a guarantee of origin that aims to ensure the percentage of energy used for RFNBO's that comes from renewable sources, fostering the granting of support schemes on the production of this fuels. This guarantees consist of bundles of a standard size of 1 MWh that can be split into fractions of electricity of different origin, thus fixing the percentage of these fuels that are classified as low or zero CO_2 emission.

The directive must be implemented into national legislation by the member states, who must also determine how the RFNBO target in industry is to be met. Member states may choose to differentiate between sectors or impose proportionate requirements on hydrogen consumers directly. They can choose to maintain the mandate at the federal level and implement policies that encourage investment in all industries that use hydrogen. Every alternative has benefits and drawbacks, including attractiveness for investments, industrial competitiveness, market growth, and regulatory complexity.

RFNBOs, such as renewable hydrogen, can be used as a feedstock or energy source in transport (road, maritime, and aviation), industry, and chemical processes. This helps to decarbonize industries when direct electrification is neither economic nor technologically feasible. They contribute significantly to energy system integration since they may also be utilized for energy storage to balance the energy system as needed.

The directive sets the percentage shares to be achieved in the near future in the transport sector: a share of biogas, biofuels, and RFNBOs of 1% of transport energy in 2025 and 5.5% in 2030, with at least **1% of RFNBOs in 2030**. Also, member states having marine ports should make an effort to guarantee that, starting in 2030, at least **1.2% of total marine transport energy** comes from RFNBOs.

4.2.2 Instruments

The analysis in this section focuses on the classification of policy instruments described in the previous section as applied to the EU. The table below shows the number of policies for each type and sub-type of instrument and then describes how each type of instrument is applied in Europe, how it is intended to affect the current situation in order to meet the objectives and gives examples of policies which present each type of instrument.

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Table 2. EU policy instruments

Type of Instrument	Subtype of Instrument	Number of policies
Regulatory Instrument	Codes and standards	8
	Quotas & obligation schemes	0
	TOTAL	**8**
Economic Instrument	Direct investment	9
	Fiscal incentives	2
	Market-based instruments	3
	TOTAL	**14**
Soft Instrument	Information and education	2
	Voluntary agreement	5
	TOTAL	**7**
Research and Development Instrument	**TOTAL**	**2**

4.2.2.1 Regulatory Instruments

For hydrogen, the most important regulations are the standards for gases, fuels, and technologies related to H_2. The potential of decarbonisation needs to be measurable in terms of CO_2 emissions and also control the hydrogen economy and the "green label" of the gas to prevent adverse effects or misleading strategies.

In this context, many policy instruments or regulations like the "CO_2 emission performance standards for cars and vans" set the limits of CO_2 emissions for hydrogen vehicles or technologies, even considering part of their Life Cycle Analysis (LCA) to ensure that these new technologies emit less greenhouse gases (GHGs) than the current ones. This technology tracking and innovation standards appear also in other specific policies like the "Net Zero Industry Act", in many cases also to regulate the granting of incentive schemes.

Also, other policies like the "Hydrogen and Decarbonised Gas market package" or the "TEN-E Regulation" sets the differences between Low-carbon and Renewable Hydrogen and fuels, according to the emissions of the hydrogen production but also from the fuels used for this production. Also, these regulations extend to the conditions for refuelling stations. Furthermore, hydrogen is integrated into the RFNBO's family and regulated through the two delegated acts coming from the "EU Renewable Energy Directives".

Finally, other policies cover the regulation of blending of hydrogen into the gas grid to ensure safety and fair gas distribution.

4.2.2.2 Economic Instruments

Economic instruments accelerate hydrogen deployment and are the most effective policies to guide the development of a hydrogen economy.

Among these, the direct investment is the simplest and most agile. The "Important Projects of Common European Interest" focus on building a hydrogen value chain to develop the hydrogen economy at once as a whole, supporting research, innovation and deployment projects all around Europe. These projects

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have been divided into “Hy2Tech”, “Hy2Use” and “Hy2Infra”, collectively raising over 38 billion € between public and private funding.

Other policies support higher TRL projects to start with real use of hydrogen or focus on concrete regions or low-income countries for infrastructure or transport investments.

There are also policies based on fiscal incentives for the price of green H_2 like the “European Hydrogen Bank” or market-based instruments that foster indirectly the use of hydrogen penalising the CO_2 emissions, in this case the “Emissions Trading Systems I and II”.

4.2.2.3 Soft Instruments

The main focus of soft instruments around hydrogen are agreements between partners from both public and private sectors to boost hydrogen projects or technology research, as well as reports, best practice guides or web platforms with up-to-date information on hydrogen, recommendations to European or national public policies or research groups.

This is achieved through voluntary agreements constituting groups like the “European Hydrogen Backbone”, the “Hydrogen for Development Partnership” or the “European Clean Hydrogen Alliance (ECH2A)”. The “Hydrogen Public Funding Compass” or the “Safety Planning and Management in Hydrogen Projects” are examples of information and education initiatives with guides in several sectors.

4.2.2.4 Research and Development Instruments

These are the instruments whose effect is the most indirect and slowest of the four, as their effects often overlap with investment in research. They correspond to research in sectors that could potentially use hydrogen under certain conditions and with uncertain technologies.

The most similar example in the hydrogen sector is the “Clean Hydrogen Partnership” favouring joint research in hydrogen technologies, although it is itself a soft instrument and, in many cases, also introduces funding.

4.3 EU National policies

Grouped in a common framework, each EU member state has transposed joint policies according to its own national reality and expectations. In this section, the national hydrogen strategies are analysed in order to present the current reality of each country and the hydrogen targets they propose.

In Table 3, the national hydrogen strategies for each member country, the main targets, the last year of update, and the reference of each document are presented.

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Table 3. Hydrogen targets in EU member states

Country	Document	Targets	Year	Reference
Austria	Hydrogen Strategy for Austria	1GW Electrolysers 2030 80% Green industry H_2 2030	2022	(Federal Ministry Republic of Austria, 2022)
Belgium	Belgian Federal Hydrogen Strategy	150MW Electrolysers 2026	2022	(Belgian Federal Government, 2022)
Bulgaria	National Roadmap for the Hydrogen Development	150 kt/year H_2 2030 34-49 B€ invested 2030	2023	(Murginski, 2023)
Croatia	Hydrogen Strategy of the Republic of Croatia until 2050	70MW Electrolysers 2030 0.2% H_2 final energy 2030 90 M€ invested 2030	2022	(Croatian Government, 2022)
Cyprus	GreenH2CY: Green Hydrogen Project for Transport in Cyprus	2MW Electrolysers 2025 150 t/year H_2 2025 4.5 M€ invested 2025	2023	(European Commission, 2024d)
Czechia	Hydrogen strategy of the Czech Republic	101 kt/year H_2 2030	2021	(Czech Government, 2021)
Denmark	The government’s strategy for Power to X	4.7GW Electrolysers 2030 170 M€ invested 2030	2021	(Vested, 2021)
Estonia	Estonian Hydrogen Roadmap	150MW Electrolysers 2030 40 kt/year H_2 2030	2023	(Republic of Estonia, 2023)
Finland	Finish Government's resolution on hydrogen	10% EU H_2 production 2030 3 Mt/year H_2 2035	2023	(Finnish Government, 2023)
France	National strategy for the development of decarbonised and renewable hydrogen in France	6.5GW Electrolysers 2030 350 M€ invested 2030	2023	(French Government, 2023)
Germany	National Hydrogen Strategy of the German federal government	5GW Electrolysers 2030 3.4 B€ invested 2030	2023	(German Federal Government, 2023)
Greece	Greece’s revised National Energy and Climate Plan	300MW Electrolysers 2030	2023	(Greek Government, 2019)
Hungary	Hungary's National Hydrogen Strategy	240MW Electrolysers 2030 36 kt/year H_2 2030	2021	(Hungarian Government, 2021)

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Ireland	National Hydrogen Strategy	67-133 kt/year H_2 2030	2023	(Government of Ireland, 2023)
Italy	Strategia Nazionale Idrogeno Linee Guida Preliminari	5GW Electrolysers 2030 2% H_2 final energy 2030 10 B€ invested 2030	2020	(Italian Government, 2020)
Latvia	Strategy of Latvia for the Achievement of Climate Neutrality by 2050	-	2019	(Latvian Government, 2019)
Lithuania	Guidelines for the Development of the Hydrogen Sector in Lithuania in 2024-2030	1.3GW Electrolysers 2030 152.9 kt/year H_2 2030	2023	(Baringa, 2022)
Luxemb.	Luxembourg Hydrogen Strategy	300 kt/year H_2 2050	2021	(Government of Luxembourg, 2021)
Malta	Malta Low Carbon Development Strategy	-	2021	(Government of Malta, 2021)
Neth.	Hydrogen Roadmap the Netherlands	6-8GW Electrolysers 2030 670 kt/year H_2 2030	2022	(Nationaal Waterstof Programma, 2022)
Poland	Polish Hydrogen Strategy until 2030	2GW Electrolysers 2030	2021	(Polish Government, 2021)
Portugal	Portugal National Hydrogen Strategy (EN-H2)	2GW Electrolysers 2030 5% H_2 final energy 2030 7 B€ invested 2030	2020	(Portuguese Government, 2020)
Romania	National Hydrogen Strategy and Action Plan for Romania	4GW Electrolysers 2030 152.9 kt/year H_2 2030	2023	(Romanian Government, 2023)
Slovakia	National Hydrogen Strategy: Ready for the future	13% H_2 final energy 2050 200 kt/year H_2 2030	2021	(Sinay et al., 2021)
Slovenia	Integrated National Energy and Climate Plan of the Republic of Slovenia	7% H_2 final energy 2040	2020	(Mori and Krajnc, 2020)
Spain	Hydrogen Roadmap: a commitment to renewable hydrogen	4GW Electrolysers 2030 25% Green H_2 2030 8.9 B€ invested 2030	2020	(Spanish Government, 2020)
Sweden	Strategy for fossil free competitiveness - HYDROGEN	3GW Electrolysers 2030 8GW Electrolysers 2045	2021	(Fossil Free Sweden, 2021)

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4.3.1 Austria

The national hydrogen strategy is being implemented to help Austria achieve its goal of reaching carbon neutrality by 2040.

In Austria's **vision for a climate-neutral future by 2040**, the demand for renewable gases is projected to surpass national production capacities. Hence, integrating Austria's hydrogen strategy into a broader European and global hydrogen economy becomes crucial to ensure a supply of climate-neutral hydrogen and its derivatives through international markets. This necessitates close collaboration with international partners to leverage opportunities ranging from diversifying gas imports to exporting domestic technology and infrastructure development. Austria's strategic positioning as an infrastructure hub further enhances its role on a European scale.

Country targets for 2030:

- 1 GW of electrolysis capacity for hydrogen production
- 80% Green Hydrogen in energy intensive industries by 2030

4.3.2 Belgium

In its hydrogen strategy, the federal government aims to strengthen Belgium's position as a key hub for the import and transit of renewable hydrogen in Europe. Leveraging its historic hydrogen ecosystem, strong industrial network and extensive infrastructure, Belgium is poised to play a central role in catalyzing the European hydrogen market. Strategically located with access to major international industrial chains and seaports, Belgium has the potential to drive the hydrogen economy forward. By emphasizing international imports and the active participation in the European hydrogen market, the national plan prioritizes sustainability rather than focusing on mass production that would compromise the decarbonisation of their electricity supply.

The strategy consists of four key pillars, each with specific measures outlined:

- Positioning Belgium as an import and transit hub for renewable molecules in Europe
- Expanding Belgian leadership in hydrogen technologies
- Establishing a robust hydrogen market
- Investing in cooperation as a key success factor

Country targets:

- 150 MW of electrolysis capacity for hydrogen production by 2026
- 2 million tons of CO_2 avoided by 2030

4.3.3 Bulgaria

Bulgaria's National Hydrogen Roadmap aims to align with European decarbonisation goals. As hydrogen technologies currently play a minor role in Bulgaria's strategy, this roadmap, part of the **National Recovery and Sustainability Plan**, is crucial for achieving the Green Deal's targets. It outlines key actions from 2023 to 2026, including boosting renewable hydrogen production, establishing hydrogen valleys, fostering international partnerships, and revising renewable energy policies.

The roadmap also focuses on regulatory updates, pilot projects, and developing hydrogen infrastructure to decarbonize power generation. Bulgaria prioritizes research, innovation, education, and public awareness to build workforce capacity and public acceptance. Additionally, it highlights the need to revise national legislation to address hydrogen production, transport, and safety, ensuring alignment with European standards for a seamless transition to a hydrogen-based economy.

Country targets:

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- 150 kt/year of Green Hydrogen production
- 34-49 Billion € invested in hydrogen infrastructure

4.3.4 Croatia

The **Croatian Energy Strategy** identifies hydrogen as a key alternative fuel for the transport sector, aiming to meet national energy goals. The plan includes introducing legislation to support hydrogen as a new energy source, focusing on building the necessary infrastructure for its production, distribution, and supply. In parallel, it encourages the use of hydrogen-powered vehicles, ships, and trains to stimulate demand and foster a sustainable energy transition.

This strategy is a foundational step towards integrating hydrogen into Croatia's economy, with attention given to production, storage, transport, and opportunities for research and innovation. It also aligns with Croatia's commitment to reducing CO_2 emissions and increasing involvement in EU-level hydrogen initiatives. By supporting the hydrogen economy, Croatia aims to contribute to broader European decarbonisation efforts.

Additionally, Croatia's strategic location makes it an ideal hub for importing and distributing hydrogen from southern EU and African nations. Several transport sector projects, such as procuring clean vehicles, are already in advanced stages, backed by potential EU co-financing. Future plans include expanding hydrogen use in industrial processes, supported by infrastructure modernization, such as upgrading the electricity grid and gas transport systems to accommodate green hydrogen and drive industrial decarbonisation.

Country targets:

- 70 MW of electrolysis capacity for hydrogen production by 2030
- 2750 MW of electrolysis capacity for hydrogen production by 2050
- 0.2% of hydrogen in total energy consumption by 2030
- 11% of hydrogen in total energy consumption by 2050
- 90 Million € of investments for H_2

The production and consumption of hydrogen for the following years is predicted as follows:

Year	*Total energy consumption* GWh/year*	*Share of hydrogen in total energy consumption %*	*Amount of hydrogen required kt/year*	*Electrolyser capacity MW*
2020.	99.101	0,0	0	0
2025.	101.786	0,1	2,6	35
2030.	104.470	0,2	5,3	70
2035.	97.358	1,5	37	480
2040.	90.245	3,0	69	900
2045.	83.359	6,5	138	1800
2050.	76.473	11,0	214	2750

Figure 4. Croatian hydrogen targets 2020-2050 (Croatian Government, 2022)

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4.3.5 Cyprus

The **GreenH2CY project** in Cyprus focuses on producing hydrogen from renewable energy to fuel trucks and replace diesel vehicles in the transport sector. It will include a hydrogen refuelling station and storage facilities, allowing the electrolyser to operate during off-peak electricity hours. This project is expected to reduce greenhouse gas emissions by 100% over ten years compared to traditional diesel use, eliminating approximately 21,677 tonnes of CO_2-equivalent emissions. It also serves as a solution to Cyprus' challenge of managing excess renewable electricity, offering an innovative way to store energy and avoid curtailment.

A 2 MW PEM electrolyser will be installed as part of the project, producing around 150 tonnes of hydrogen annually. Hydrogen will be generated using water from wastewater treatment, aligning with circular economy principles. The hydrogen fuel will initially be used in light and heavy trucks of a bakery chain but has the potential to expand to other vehicles. The abundance of renewable energy in Cyprus suggests that green hydrogen could be produced on a larger scale for both land and maritime transport.

This pilot project is expected to build vital knowledge in hydrogen production and distribution, paving the way for wider adoption of green hydrogen in Cyprus. Supported by a 4.5 million EUR innovation grant, the project commenced on June 1, 2023, with financial closure set for August 2024 and operations scheduled to start by September 2025. The project's goal is to scale up production both at the original site and at additional locations identified for future expansion.

Country targets 2025:

- 2 MW of electrolysis capacity for hydrogen production
- 20 ktons of CO_2 avoided
- 150 t/year of Green Hydrogen production
- 4.5 Million € of investment for H_2

4.3.6 Czechia

With the framework of reaching the European Green Deal's 2050 climate neutrality objective, the Czech Republic approved a Hydrogen Strategy aligned with a clean Europe driven by green hydrogen.

To achieve these, four specific goals have been set:

- Volume of low-carbon hydrogen production
- Volume of low-carbon hydrogen consumption
- Infrastructure readiness for hydrogen transport and storage
- Progress in R&D and production of hydrogen technologies

This strategy aims for the period 2021–2050 for a climate neutral Czech Republic, using low carbon hydrogen, which is considered when its production stays below 36.4 g CO_2/MJ. On the other hand, green hydrogen coming from renewable sources depends on the wind and sunshine, which are really limited in Czech Republic due to its geographical location.

Country targets:

- 101 kt/year of Green Hydrogen production by 2030
- 1728 kt/year of Green Hydrogen demand by 2050
- 2% green hydrogen admixture in total gas consumption

4.3.7 Denmark

Denmark plans to scale up the production of renewable hydrogen and derivatives such as ammonia, methanol, and e-Kerosene with the construction of up to 200 MW of electrolysis capacity.

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The initiative involved a competitive bidding process in 2023, where companies building new electrolysers in Denmark could apply for direct grants over a ten-year period. The funding is contingent on compliance with EU rules for renewable fuels of non-biological origin, which include using additional renewable electricity sources. These new electrolysers are expected to cut annual greenhouse gas emissions by 70,000 tonnes of CO_2 in the industrial, energy, and transport sectors, contributing to Denmark's goal of reducing emissions by 70% by 2030 and reaching carbon neutrality by 2050.

This scheme is considered crucial for boosting renewable hydrogen production and decarbonizing multiple sectors in Denmark. Without public support, such investments would not happen, and the program includes safeguards to minimize its impact on EU competition and trade. The environmental benefits, which align with the European Green Deal, are seen as outweighing any potential market distortions.

Country targets 2030:

- 4.7 GW of electrolysis capacity for hydrogen production
- 4.5 million tons of CO_2 avoided
- 170 Million € of investments for H_2

4.3.8 Estonia

The country currently has no production or consumption of hydrogen, renewable or otherwise. However, hydrogen is seen as a necessity in transitioning away from imported (Russian) fossil fuels and meeting its climate goals. The country’s main focus to date has been on developing electrolyser technologies for national use and export.

Estonia has a considerable offshore wind potential compared to its size and population. Thus, renewable electricity supply is not likely to be a problem in the future. However, the rate at which this potential can be tapped into is limited by the current capacity of the national grid. Green hydrogen or synthetic fuels are expected to play a major role in decarbonized or net-zero transport, although the price of locally produced hydrogen is estimated to be higher than the global average, due to the comparatively higher cost of wind versus solar electricity and the fairly small scale.

The creation of a nationwide hydrogen valley is envisioned for the development of technologies and services along the entire value chain of green hydrogen. Due to the small size of the country, it is likely that hydrogen transportation via pipeline will not be competitive to road or rail transport.

Country targets for 2030:

- 40 kt/year of Green Hydrogen production
- 150 MW of electrolysis capacity for hydrogen production

4.3.9 Finland

Renewable hydrogen is seen as an opportunity to accelerate the green transition, while the export of hydrogen-related technologies could generate significant global emissions reductions.

The country has a high share of renewables in electricity generation and can thus easily produce green hydrogen. The government seeks to promote the country’s attraction to investors in green hydrogen across the entire value chain making it a European and global leader in the field. This will include various enabling measures as well as a clear regulatory and health and safety framework and is aimed to lead to the export of both green hydrogen and related (by)products, as well as the corresponding technologies.

The objectives are to produce clean hydrogen and electric fuels for the needs of Finnish industry, transport and the energy system, modernise the industrial sector, increase value added exports, and secure investments in Finland.

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Country targets:

- 10% of European Green Hydrogen by 2030
- 3 Mt/year of Green Hydrogen by 2035

4.3.10 France

France's green hydrogen strategy is geared towards sectors crucial for significant decarbonisation, such as refineries, the chemical industry, steel production, and transportation. Leveraging its substantial nuclear energy resources, which account for over 60% of electricity demand, France aims to lead in renewable hydrogen production and use. The existing and planned nuclear capacities have already greatly decarbonized the country's power grid. (*France's Hydrogen Strategy*, 2024)

The strategy prioritizes domestic needs, focusing first on industrial applications and then on transport, rather than pursuing international hydrogen trade. Regional efforts are also concentrated on establishing hydrogen hubs to cater to local requirements and reduce transportation costs. Despite this inward focus, France has recently agreed to develop a pipeline to transport green hydrogen from Barcelona to Marseille and onwards to Germany. Additionally, the strategy includes fostering scientific and technological cooperation within the EU and with countries like India and those in North and West Africa.

Country targets for 2030:

- 6.5 GW of electrolysis capacity for hydrogen production
- 350 Million € of investments for H_2
- 20-40% of hydrogen in industry produced through electrolysis
- Creation of over 150k direct and indirect jobs
- 10 GW of electrolysis capacity for hydrogen production by 2035

4.3.11 Germany

Hydrogen is seen as a versatile chemical feedstock and energy carrier that can be used to secure energy supplies for many sectors, eventually bringing carbon emissions down to zero. Due to the energy intensive nature of green hydrogen production, German Hydrogen Strategy emphasizes its use only where electrification is less efficient (German Federal Government, 2020).

Because hydrogen has a low volumetric energy density, the strategy also considers synthetic fuels derived from electrolysis hydrogen (e-fuels) an important component of the energy mix, especially for transport. Furthermore, due to Germany's relatively low potential for solar and wind power, the strategy envisions partnerships with countries more favourably placed for green hydrogen generation (Southern Europe, West Africa). Specifically, exporting technology and investing in production facilities in these countries and then importing the produced hydrogen. Thus, R&D into hydrogen technologies across the value chain are also a major component of the national strategy.

Country targets for 2030:

- 5 GW of electrolysis capacity for hydrogen production
- 3.4 Billion € of investments for H_2

4.3.12 Greece

Greece does not yet have a market for green hydrogen and, likewise, no regulatory expertise or legal framework for hydrogen production, transportation or use. However, it does have ambitious plans for 2030, which are focused firstly on the augmentation of renewable electricity generation and secondly on green hydrogen production. The NECP targets an electrolyser capacity of 1.7 GW (eventually reduced to

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0.3 GW) producing hydrogen for use in transport and industry. Multiple hydrogen valleys are being set up in the southern part of the country.

Country targets for 2030:

- 300 MW of electrolysis capacity for hydrogen production
- 5.6% green hydrogen in NG network

4.3.13 Hungary

The country's hydrogen plan attempts to balance its traditional relations with Russia with meeting EU sustainability targets. In other words, the strategy prioritizes blue hydrogen (i.e. hydrogen produced with fossil fuels but capturing the CO_2 generated) from Russian natural gas coupled with CCS/U, with renewable hydrogen produced from their nuclear dominated power grid and nascent photovoltaics.

The country has significant industries which could employ decarbonized hydrogen, most notably refineries, chemicals, fertilizers, steel, and cement factories. Two hydrogen valleys are envisioned, coupled to existing industrial hubs and a nuclear power plant. The country also hosts factories for many European automotive industries manufacturing heavy-duty vehicles. If hydrogen vehicles were produced in Hungary, it could make their adoption in the country more likely.

Country targets for 2030:

- 240 MW of electrolysis capacity for hydrogen production
- 20 kt/year blue and 16 kt/year green hydrogen (mostly for industry)
- 2% hydrogen blending in NG system

4.3.14 Ireland

Renewable hydrogen is seen as a key component in decarbonizing the economy and meeting the climate obligations the country has taken on. Besides this, the hydrogen strategy also considers green hydrogen important for ensuring energy security and creating industrial opportunities.
Ireland has an enormous renewable energy potential, primarily through offshore wind farming. This could enable the country to become an exporter of green hydrogen to countries like Germany and, possibly, the UK. Exports could be in the form of hydrogen or in a vector molecule like ammonia. Domestically, green hydrogen is foreseen to be used for grid stabilization and seasonal storage, as well as to decarbonize transport, especially aviation and maritime, as well as industry. The strategy also points out that the transport sector may be better served by hydrogen derived fuels, rather than hydrogen, at least in the near- to mid-term.

Country targets for 2030:

- 67-133 kt/year of Green Hydrogen production

4.3.15 Italy

Renewable hydrogen is poised to be a crucial element in achieving economic decarbonisation and climate neutrality by 2050. It is expected to drive the development of innovative industrial value chains in both Italy and the broader EU, contributing to a high-value green economy. As a sustainable energy solution, renewable hydrogen will be essential for sectors where it provides the most effective decarbonisation, such as hydrogen-intensive industries, high-temperature processes, long-distance heavy transport, maritime and rail transport, and aviation.
The potential of renewable hydrogen extends beyond these applications; its role as an energy vector makes it highly valuable for energy storage and sector coupling. The establishment of hydrogen valleys or clusters—areas where production, transformation, and consumption are concentrated—will be

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pivotal. These clusters will leverage economies of scale and support the development of pilot projects, particularly in the transport sector and isolated energy systems.
At the moment, a total of 150 hydrogen projects are being developed. Of these, 52 are hydrogen production plants expected to start operating by 2026, 48 are refuelling stations for road transport and 10 new hydrogen-based railway lines (Gandiglio and Marocco, 2024).

Country targets for 2030:

- 2% penetration of hydrogen in final energy demand
- 5 GW of electrolysis capacity for hydrogen production
- 2 million tons of CO_2 avoided
- 10 Billion € of investments for H_2 (RES investments to be added), of which half from ad hoc resources and funds
- 27 Billion € of additional GDP
- Creation of over 200k temporary jobs and up to 10k permanent jobs

4.3.16 Latvia

Latvia's National Energy and Climate Plan (NECP) identifies hydrogen as a potential future alternative to petroleum products, with a primary focus on its use in the transport sector. Since 2016, the first hydrogen refuelling station has been operative in Riga. Latvia's long-term vision for hydrogen in transport involves developing the necessary infrastructure and fostering innovation through the national RD&I Smart Specialization Strategy, which will be implemented from 2021 to 2027. Additionally, Latvia is coordinating with neighbouring Baltic countries to advance these goals, though the 2019 NECP did not specify particular objectives for hydrogen.

Latvia has not published a national hydrogen strategy at the moment. However, some private and research companies, like the Latvian Hydrogen Association, are working on the development of a hydrogen economy for the country.

4.3.17 Lithuania

A potential strategy for fulfilling Lithuania's climate change mitigation objectives, building a climate-neutral economy, and guaranteeing energy independence is the growth of the green hydrogen industry.

Creating green hydrogen production capacity, utilizing excess RES power, and producing hydrogen derivative goods for domestic and international markets are the principal objectives of Lithuania's hydrogen energy policy. Other forms of hydrogen can be used to the extent that it helps Lithuania achieve its overall aims for mitigating climate change.

The following key areas will significantly influence Lithuania's green hydrogen industry's growth in order to mitigate its adverse impacts on the environment and climate change:

- to increase energy independence by producing energy from nearby renewable resources;
- to prioritize the development of green hydrogen and its derivative products, which will be needed in the energy, heavy transportation, industrial, and other sectors;
- to support green hydrogen produced from national energy sources;
- to build a transportation network and infrastructure for hydrogen and its derivative products for both domestic and international consumption;
- to build competencies in the hydrogen value chain and develop hydrogen technologies;
- to develop and expand the possibilities of using green hydrogen and its derivative products in the road, aviation, railway, and marine transport sectors.

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In order to reduce the amount of GHG emissions, commercially based projects in the industrial and transportation sectors as well as small-scale pilot projects are planned to be implemented up until 2030. These projects will serve as the foundation for studies that will be used to identify and assess potential new activity development. The outcomes of these projects and global trends in 2026–2030 will aid in more precise planning of green hydrogen development until 2050. In order to reduce greenhouse gas emissions from industry, transportation, energy, and other sectors and to help the world reach a climate-neutral economy by 2050, green hydrogen must be incorporated into an integrated energy system.

Country targets for 2030:

- 1.3 GW of electrolysis equipment installed
- 129 kt/year of Green Hydrogen production
- 15 % of the ammonia needed for fertilizer production from Green Hydrogen
- 1200 new jobs in the hydrogen sector

4.3.18 Luxembourg

Direct electrification and energy efficiency are Luxembourg's top priorities. In the long run, renewable hydrogen may contribute to the integration of the energy sectors. However, at first, its application would be restricted to industries like heavy industry, which are challenging to directly electrify in order to reduce carbon emissions.

Prioritizing demand is necessary to prevent unnecessarily driving up the price of renewable H_2 in light of the energy efficiency first principle, the restricted supply, and the high short- and medium-term costs.

Green hydrogen will impact different sectors of economy:

- Hard to abate industrial processes;
- hard to electrify means of transport, with the development of new hydrogen technologies and synthetic fuels; and
- an integrated energy system driven by hydrogen.

Country targets:

- 5 ktons of CO_2 avoided by 2030
- 1-2 million tons of CO_2 avoided by 2050
- 300 kt/year of Green Hydrogen demand by 2050

4.3.19 Malta

According to Malta's NECP, hydrogen production, transport sector and gas infrastructure are the main pillars to focus on when talking about hydrogen deployment.

Malta also believes that strategically, hydrogen is essential to guaranteeing the security of the energy supply. The NECP did not, however, have any explicit goals.

Malta does not have a clear legal framework that governs the deployment of hydrogen. Hydrogen has only been taken into account thus far in relation to the National Transport Strategy. Even so, "as the cost of the infrastructure is greatly disproportionate to current demand and considering the limited range on the island as well as the highest energy efficiency of battery electric vehicles", Malta is prioritising a network of charging points for electric vehicles over the necessary structure for the implementation of hydrogen-based transport.

Theoretically, Malta could construct a supply pipeline to the mainland, similar to the natural gas pipeline that is currently being considered by the government, to power the island's hydrogen power plants. In fact, the government is currently proposing that the proposed gas pipeline be constructed with hydrogen

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readiness, allowing for the conversion from gas to hydrogen when any EU supply network is put into service. The current CCGT power plants could be retrofitted to serve as the basis for the hydrogen power plant. As long as it is powered entirely by green hydrogen, Malta would have a carbon-neutral energy source. Nonetheless, imports from other nations would still be necessary for the supply of hydrogen, which could put supply security or cost at risk. In addition, any hydrogen power plant could store energy over extended periods of time to stabilize the supply from wind resources or function as a backup to intermittent renewables in the event that battery storage was unavailable. In addition, research will be done on the usage of alternative fuels such synthetic and biofuels as a possible source of energy supply after 2030.

There is no national strategy for hydrogen in Malta; moreover, no plans to develop one in the nearest future have been announced.

4.3.20 Netherlands

The Netherlands is prepared and competent to take the lead in the international market. The Netherlands will need to import and produce enough hydrogen onshore and offshore due to the fast-growing need for renewable hydrogen. The country has an excellent starting position for the extensive upscaling of hydrogen due to its experience with gas infrastructure, its extensive port, transport, and storage infrastructure, its existing industry, its large-scale rollout of offshore wind energy, and its advantageous transit location relative to its neighbouring countries.

The scope of the problem is obvious: there is currently very little supply of low-carbon or renewable hydrogen, thus a rapid and substantial expansion of the entire chain, including production, import, transportation, distribution, and consumption, will be required in the near future. It is critical that the prerequisites for this development are completed on schedule. These consist of an extensive body of knowledge and safety, a successful implementation of renewable energy, onshore and offshore infrastructure, CO_2 infrastructure for low-carbon hydrogen, appropriate financial tools and legislation for development and implementation, and an adequate number of qualified workers, especially in the technical domains.

In order to supplement this, hydrogen imports will also be required, and offshore electrolysis will need to be expanded by 2030. A number of variables, such as the prompt and functional availability of hydrogen infrastructure, the existence of safety frameworks, and additional advancements in the manufacturing sector with sufficient workforce, innovations, and social acceptability, will all play a role in the upscaling of production and imports. The final need for hydrogen in the transportation and industrial sectors will also be correlated with the European objectives and related instruments.

Country targets:

- 600 MW electrolysis capacity and use of CCS in the existing production by 2025
- 6-8 GW electrolysis capacity by 2030
- 670 kt/year of Green Hydrogen production by 2030

4.3.21 Poland

Poland presently produces over 1.3 million tons of hydrogen annually, placing it third among European producers, only after Germany and the Netherlands. However, only a small portion of Poland's hydrogen comes from renewable sources.

The establishment of the entire value chain is necessary for the development of the hydrogen economy, including the building of new RES power generation capacity, installations for the production of green and blue hydrogen and derivatives, and new technologies or processes that allow the use of hydrogen in the energy, heating, transportation, and other economic sectors.

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The strategy's goals speak to the three main uses of hydrogen: energy, transportation, and industry. It also touches on the production, distribution, and storage of hydrogen as well as the necessity of establishing a stable regulatory framework.

The approved priority areas are associated with the notion of sector coupling, which denotes a rise in the utilization of renewable energy sources and their application by particular sectors to reduce reliance on fossil fuels and greenhouse gas emissions while realizing the full potential of RES-based energy systems.

Country targets for 2030:

- 2 GW capacity installed of low-carbon hydrogen production facilities

4.3.22 Portugal

Portugal's National Hydrogen Strategy (EN-H2) aims to provide stability and incentives for the energy sector by gradually introducing hydrogen as a key component in the country's transition to a decarbonized economy. It outlines hydrogen's role in the current and future energy system and sets measures and targets for its integration across various sectors.

The EN-H2 also establishes a comprehensive framework for companies and promoters working on hydrogen projects, allowing them to align their initiatives within a broader, cohesive strategy. It promotes industrial policies that guide and coordinate public and private investments in the production, storage, transportation, and consumption of renewable gases in Portugal.

Country targets for 2030:

- 7 Billion € invested in hydrogen production projects
- 5% H_2 in final energy consumption, industry consumption and transport consumption
- 15% H2 injection in natural gas networks
- 2 GW capacity installed in electrolysers

4.3.23 Romania

By establishing the following strategic directions for 2030, the **National Hydrogen Strategy (NHS)** and the **Action Plan for Romania** hope to develop a hydrogen economy that prioritizes low-carbon hydrogen at a reasonable price while also focusing on renewable hydrogen. This will help reduce carbon emissions and foster competitive and sustainable economic and technological development:

1. Decarbonisation of the economy by using renewable hydrogen in sectors that are difficult to decarbonise by other methods (e.g. direct electrification impossible);

2. Economic growth through the sustainable development of technologies for industries that are difficult to decarbonise and the creation of new jobs;

3. Technological development to ensure a long-term mobilisation of the hydrogen economy and to support the attraction of investment in the economy and the raising of living standards;

4. Energy security, using hydrogen and Power-to-X solutions to optimise the integration of renewable energy sources and achieve sectorial integration.

Country targets for 2030:

- 2 million tons of CO_2 avoided
- 152.9 kt/year of Green Hydrogen production
- 2% green hydrogen admixture in total gas consumption
- 1600 MW combined cycle turbines prepared for 50% green hydrogen
- 3985 MW electrolysis capacity

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4.3.24 Slovakia

The Slovak Republic's strategic role in utilizing hydrogen technology is outlined in the National Hydrogen Strategy, which takes current EU developments into account. In line with the Paris Agreement, which Slovakia has ratified, as well as other key Union documents like the European Environmental Convention, the New Industrial Strategy for Europe, and the Right Time for Europe: "Repairing the damage and preparing the future for the next generation", the goal of the strategy is to both significantly boost the competitiveness of the Slovak economy and contribute to the creation of a carbon neutral society. The strategy is also aligned with the long-term objectives that Europe set for 2030 and 2050 in their development strategy.

Country targets:

- 200 kt/year of hydrogen by 2030.
- 400-600 kt/year of hydrogen by 2050, 90% from low-carbon sources
- 13-14% H_2 in final energy consumption by 2050

4.3.25 Slovenia

Slovenian hydrogen project's long-term vision is to convert a region that has been heavily influenced by decades of energy production by fossil fuels into a Hydrogen valley, utilizing vast potentials of locally available renewable energy in a system focused on grid stability and pollution reduction. This concept is relevant and directly applicable to numerous regions across Europe and beyond. The project's goal is to make use of available local hydrogen sources and apply them in applications for reducing greenhouse gas emissions, starting with zero-emission public transport.

Country targets:

- 10% H_2 injection in natural gas networks by 2030
- 7% H_2 in final energy consumption by 2040

4.3.26 Spain

One important long-term strategy for the Spanish economy's decarbonisation is the use of renewable hydrogen. It is viewed as a component of the plan to create high-value, green economies with high added values, creative industrial value chains in Spain and the EU, and climate neutrality by 2050.

In applications where it is the most effective way to decarbonize an end product, such as high-temperature processes and hydrogen-intensive industries, long-distance heavy transportation, sea transportation, rail transportation, or aircraft; renewable hydrogen is expected to become a lucrative energy vector. It also has a great deal of potential as a tool for sector coupling and energy storage due to its energy vector quality.

Furthermore, the establishment of hydrogen valleys or clusters—areas where hydrogen production, transformation, and consumption are concentrated—will be crucial. These areas will also benefit from the application of economies of scale and the development of pilot projects that are connected to various sectors of the economy, including transportation and isolated energy systems.

Country targets for 2030:

- Installed capacity of 4 GW electrolysers
- 25% of hydrogen in industry produced through electrolysis
- 8.9 Billion € invested in hydrogen production
- 4.5 million tons of CO_2 avoided

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4.3.27 Sweden

The industry sectors have outlined how they plan to become more competitive by eliminating fossil fuels in the roadmaps created under the framework of **Fossil Free Sweden**. Many sectors and businesses now perceive promising opportunities for investing in hydrogen, as hydrogen technologies are one of the strategies anticipated to help reduce emissions in an industry or process cost-effectively.

The strategy's central claim is that rewards should exclusively go to hydrogen produced without fossil fuels. This means that policies and support networks should mainly encourage the development of fossil fuel-free hydrogen rather than outright prohibiting hydrogen, such as grey (i.e. produced with fossil fuels) or blue hydrogen (i.e. produced with fossil fuels but capturing the CO_2 generated).

The strategy has two purposes: hydrogen is considered as a key component for accomplishing climate goals and as a focal point for new industrial projects and employment opportunities. Instead of manufacturing and exporting fossil-free hydrogen to other nations, the strategy's main focus is on refining industry's products through multiple stages within the nation's boundaries in order to foster innovation, jobs, and export goods.

Local and regional hydrogen clusters, which could be connected to one another by the construction of additional hydrogen pipes, are the likely route of Sweden's ambitious hydrogen development.

Country targets:

- 3 GW installed electrolysis power by 2030 and at least 8 GW by 2045
- 1.5-3 million tons of CO_2 avoided by 2030 and 7-15 by 2045

4.4 Rest of the world national policies

Finally, the national hydrogen policies of the most important countries or those with the greatest potential in this sector in each of the global WILIAM regions are presented. The objective is to align the policy analysis at global level as much as possible to WILIAM scenarios-built requirements. The same analysis to that conducted for the European Union countries is carried out, allowing for a comparison of objectives both at the country level and on a global scale between regions.

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Table 4. Hydrogen targets in countries outside EU

Region	Country	Document	Targets	Year	Reference
LATAM	Chile	National Green Hydrogen Strategy	5 GW Electrolysers 2025 25 GW Electrolysers 2030	2020	(Government of Chile, 2020)
	Brazil	Lei 14.948/24	-	2024	(Brazilian Government, 2024)
	Argentina	Estrategia Nacional para el Desarrollo de la Economía del Hidrógeno	30 GW Electrolysers 2050 5 Mt/year H_2 2050	2023	(Government of Argentina, 2020)
China	China	China 2021-2035 plan on hydrogen energy development	5.4 GW Electrolysers 2025 0.2 Mt/year H_2 2025	2022	(Government of China, 2022)
India	India	National Green Hydrogen Mission. Decarbonising India, Achieving Net-Zero Vision	5 Mt/year H_2 2030 10% Global H_2 2050	2023	(Government of India, 2023)
Russia	Russia	Hydrogen Energy Development in the Russian Federation	0.2 Mt/year H_2 2024 2-12 Mt/year H_2 2035 15-50 Mt/year H_2 2050	2021	(Russian Government, 2021)
EASOC	Australia	Australia's National Hydrogen Strategy	1GW Electrolysers 2030 0.36 Mt/year H_2 2030 21% Global H_2 2050	2023	(Australian Government, 2023)
	Japan	Revised Basic Hydrogen Strategy	3 Mt/year H_2 2030 15GW Electrolysers 2030 100 B$ invested 2050	2023	(New Zealand Ministry of Foreign Affairs and Trade, 2023a)
	South Korea	Hydrogen Economy Roadmap	1.9 Mt/year 2030 38 B$ invested 2030 15 GW/year H_2 Fuel Cells	2022	(Government of Korea, 2022)
USMCA	USA	U.S. National Clean Hydrogen Strategy and Roadmap	10 Mt/year 2030 9.5 B$ invested 2030 3 GW/year Electrolysers 2030	2023	(USA Government, 2023)
	Mexico	*Mexico lacks public policy for green hydrogen*			

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	Canada	Hydrogen Strategy for Canada	4 Mt/year 2030 20 Mt/year 2050	2024	(Canadian Government, 2020)
UK	UK	UK Hydrogen Strategy	10GW H_2 production 2030 5 B$ invested 2030	2023	(UK Government, 2023)
ROW	Morocco	Feuille de route de hydrogène vert	5.2 GW Electrolysers 2030 23 GW Electrolysers 2040 52.8 GW Electrolysers 2050	2021	(Kingdom of Morocco, 2021)
	Norway	The Norwegian Government's hydrogen strategy	-	2021	(Norwegian Government, 2021)
	Saudi Arabia	National strategy under development	4 GW Electrolysers 2026 2.9 Mt/year H_2 2030	-	(Green Hydrogen Innovation Center, 2022)
	South Africa	South Africa's Just Energy Transition Investment Plan	60 GW Electrolysers 2050 6-10 MT/year 2050 98.7 B$ invested 2030	2022	(South African Government, 2022)
	Switzerland	Futur de l'hydrogène en Suisse. Éventuelle régulation du réseau d'hydrogène pour encadrer son développement	0.3-0.6 Mt/year H_2 2050	2023	(Swiss Government, 2023)
	Turkey	Türkiye Hidrojen Teknolojileri Stratejisi ve Yol Haritası	3 GW Electrolysers 2030 5 GW Electrolysers 2035 70 GW Electrolysers 2053	2023	(Grantham Research Institute, 2023)

4.4.1 Chile

The National Green Hydrogen Strategy arises from the contribution that this clean fuel could make in the context of the current climate crisis and the favourable projections of growth in the global demand for energy supplied with hydrogen in different sectors of the economy.

Through three stages, it aims to accelerate the deployment of green hydrogen in key domestic applications by 2025, enter the export market by 2030 and be the leading global exporter of green hydrogen from the cheapest production cost on the planet (below 1.5 USD/kg).

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The Action Plan for the strategy develops four main lines of action: 1) domestic market and export promotion; 2) regulatory framework; 3) social and territorial development; 4) capacity building and innovation.

It is projected that between 2025 and 2050 the Chilean markets for green hydrogen and its derivatives will grow by 15% annually, due to domestic (national) applications and exports. According to the document, such growth would be sustained in three waves:

1. First wave: large-scale domestic consumption with established demand, i.e. replacement in the short term of imported ammonia by local production and replacement of grey hydrogen used in refineries in the country. Long-distance passenger and heavy-duty transport use will become attractive.

2. Second wave: In 2025 H_2 use would be extended to transport uses and the start of exports. Competitive production to displace liquid fuels in road transport and gaseous fuels in distribution networks.

3. Third wave: In the longer term, new export markets would open up for scaling up, such as in the maritime and air transport sectors.

Country targets:

- 5 GW electrolysis capacity operating (and under development) and 200 kt/year of Green H_2 production in at least 2 hydrogen valleys by 2025.
- 25 GW electrolyser capacity and leaders in export of green hydrogen and derivatives by 2030.
- To be among the top three exporters by 2040

4.4.2 Brazil

On August 2, 2024, **Law No. 14,948/2024** was published, establishing the regulatory framework and the National Policy for low-carbon hydrogen in Brazil.

The law assigns the National Agency of Petroleum, Natural Gas and Biofuels the powers to regulate, authorize, and supervise the hydrogen production and movement (and its derivatives and carriers).

The law has controversially raised allowable lifecycle emission levels for "low-carbon" hydrogen to the highest level in the world, meaning that projects emitting up to 7 kg of CO_2 equivalent per kilo of H_2 would be eligible for subsidies and tax benefits.

This definition is much laxer than any other country that has set such a definition: the UK, EU, USA, South Korea, Japan and China set upper emissions limits of 2.4 to 4.9 kg $CO_2e/kg\ H_2$.

The new law also establishes the Special Incentive Regime for the Production of Low-Carbon Hydrogen (Rehidro) and creates the Low-Carbon Hydrogen Development Program for fostering research, innovation, and industrial capacity in low-carbon hydrogen technologies.

The PHBC tax credit program, originally included in the bill, was vetoed and will be regulated separately. This program aims to grant tax credits to projects that contribute to regional development, climate change mitigation, and diversification of Brazilian industry.

Country targets:

- The law provides incentives for research, development and innovation for hydrogen production and sets a limit intensity of 7 kg CO_2eq/KgH_2 for the various production routes in order to establish technological neutrality.

4.4.3 Argentina

The **National Strategy for the Development of the Hydrogen Economy** represents the roadmap for the industrialisation of hydrogen as a productive vector in the energy transition to 2050. This legislative

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initiative aims to promote low-emission hydrogen production projects, organise the governance of the sector and encourage productive and technological development along the entire value chain.

The vision guiding the strategy has three axes. First, it recognises the importance of fostering technological and productive development along the entire value chain, including the production of critical capital goods and the provision of technological services.

Secondly, taking into account the different resources and capacities available in Argentina, it contemplates the production of low-emission hydrogen by means of different technologies, either from renewable sources (green), from nuclear energy (pink), or from fossil fuels with carbon capture (blue).

Third, it establishes two pillars for the deployment of the hydrogen economy: the domestic market, essential for generating initial conditions, evaluating prototypes and developing domestic technology; and export markets, oriented towards highly competitive large-scale production, taking advantage of the quality of natural resources and built capacities.

It is proposed to reach a low-emission hydrogen production capacity of 5 million tonnes of H_2 per year by 2050 (20% domestic market, 80% export). This will require the installation of at least 30 GW of electrolysis capacity and 55 GW of renewable electricity generation by 2050. The expected amount of investment compatible with the expected production is around 90 billion USD by 2050.

The ENH states that access to finance for capital and technology investments is a relevant factor for competitiveness. It also highlights the importance of having an information system on financing for the green economy. It also mentions the possibility for hydrogen projects to participate in carbon markets and access new sources of finance and other incentives for climate change mitigation.

Country targets:

- 5 million tons of H_2 per year by 2050.
- 30 GW of electrolysis capacity and 55 GW of renewable electricity generation by 2050.

4.4.4 China

China is a major global player in hydrogen production and consumption, due to the size of its industry and markets. By the end of 2023, China's installed electrolyser capacity was projected to reach 1.2 GW, which represents 50% of global capacity, with another new world record-size electrolysis project (260 MW). Therefore, the existence of a national plan in this country is essential as a roadmap for the sustainable transition in hydrogen production. (IEA et al., 2023b)

Within this context, the **China's Medium and Long-Term Strategy for the Development of the Hydrogen Energy Industry (2021-2035)** was released in March 2022. In this National Plan, hydrogen is considered an important part of China's future energy system, a key player in the low-carbon energy transition, and a future emerging industry in China. However, the targets of this National Plan are not considered remarkably ambitious when it comes to green hydrogen. In general terms, the Chinese supply system is planned to combine both industrial and renewable hydrogen.

One characteristic of the Chinese context that should be highlighted is the importance of regional and municipal governments. Specifically, most ambitious renewable hydrogen goals have been implemented by provinces, cities and municipalities rather than the national government. The northwest region, for example, is planned to be the epicentre of renewable hydrogen supply due to the abundance of renewable energy sources in the region.

Country targets:

- Larger-scale facilities of 500-1000 MW are planned to be installed from 2025 onwards

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- Annual hydrogen production from renewable energy is expected to reach 100,000 tonnes to 200,000 tonnes to become an important part of new hydrogen energy consumption by 2025 and enable carbon dioxide emission reduction of 1 million to 2 million tonnes per year
- Almost 5.4 GW of electrolyser capacity in China by 2025

4.4.5 India

According to the IEA (2022), India is among the six global regions that use hydrogen the most. About 5 Million Metric Tonnes (MMT) of grey Hydrogen is consumed annually in India, and about 99% of this quantity is utilized in petroleum refining and manufacture of Ammonia for fertilizers. As the country also has the fastest growing renewable energy capacity in the world, green hydrogen is key to achieve their goal of Net Zero emissions by 2070.

The **National Green Hydrogen Mission** aims to position India as a model in the global clean energy transition creating national and international demand of Green Hydrogen and giving incentives to infrastructure, markets and skill development, as well as public awareness. To do so, it combines market and regulatory instruments, such as building standards and a regulatory framework, or promoting public-private partnerships for R&D. The Mission will promote the substitution of fossil fuels and fossil fuel-based feedstocks with renewable fuels and materials derived from Green Hydrogen.

Structured in two phases, the Mission will build capabilities to produce at least 5 MMT of Green Hydrogen per year by 2030, with potential to reach 10 MMT per year with growth of export markets. From an economic point of view, the initial outlay for the Mission will be 2.3 B $.

Country targets:

- Aiming at about 10 % of the global market, India can potentially export about 10 MMT green hydrogen/green ammonia per year
- By 2034-35, all ammonia-based fertilizer imports are targeted to be substituted by domestic green ammonia-based fertilizers
- India's green hydrogen production capacity will reach at least 5 MMT per year

4.4.6 Russia

Russia aims to position itself as a leading global producer and exporter of hydrogen, with ambitions to become a major geopolitical force in this emerging sector. To this end, the Russian Government has developed different policy documents charting a path to a national hydrogen economy. (Baker McKenzie, 2023a; Barlow and Tsafos, 2021)

In June 2020, the **Energy Strategy of the Russian Federation until 2035** was published, defining a medium-term plan for Russian energy sector, and with the objectives of reaching a national hydrogen export of 0.2 million tons by 2024 and 2 million by 2035. The strategy focuses on boosting hydrogen production from natural gas and renewables, advancing low-carbon technologies, and increasing domestic and international demand for hydrogen and its derivatives, while fostering global partnerships and localizing foreign technologies.

By October 2020, the Russian Government approved the **Action plan 'Development of Hydrogen Energy until 2035'** as a hydrogen roadmap to exploit the potential of Russia as a well-positioned market, resource base and hydrogen research pioneer. The Roadmap outlines high-priority pilot projects focusing on carbon-free hydrogen production, including developing pilot equipment, gas turbines for methane-hydrogen fuel, hydrogen-powered railway transport prototypes, low-carbon hydrogen production sites, and nuclear-based hydrogen production.

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Finally, the **Concept of Hydrogen Energy Development in the Russian Federation** was approved in August 2021, reaffirming the objectives already set and expanding the hydrogen exporting targets with the next timeline:

- In Stage 1 (2021-2024), Russia maintains the export target of 0.2 million tons of hydrogen. During this period, Russia plans to establish four hydrogen clusters: a Northwest cluster for exporting low-carbon hydrogen to European markets, an Eastern cluster focused on Asian markets, an Artic cluster to energy supply the Russian Artic zone and a Southern cluster as a future growth option.
- In Stage 2 (2025-2035), Russia aims to achieve an export target of 2 to 12 million tons of hydrogen. The plan includes launching the first utility-scale hydrogen production facilities, initiating pilot hydrogen consumption domestically, and integrating hydrogen technologies across various industries such as petrochemicals, electric power, metallurgy, housing, and transportation.
- In Stage 3 (2036-2050), the export target reaches 15 to 50 million tons of hydrogen. The focus will be on establishing Russia as a leading global exporter of hydrogen, its energy mixes, and related technologies to Asia-Pacific and the EU, while also widely implementing hydrogen technologies across transportation, power, and industrial sectors.

Country targets:

- National hydrogen export target of 0.2 million tons by 2024
- National hydrogen export target of 2-12 million tons by 2035
- National hydrogen export target of 15-50 million tons by 2050

4.4.7 Australia

Australia is well-positioned to become a major player in the global hydrogen market, leveraging its abundant renewable energy resources, broad experience in gas markets, and established reputation as a reliable energy exporter. In line with this opportunities, the Australian Governments published a Hydrogen Strategy in 2019, which was reviewed in 2023 to ensure the path to become a global leader in hydrogen by 2030, both in terms of exports and the decarbonisation of its industries. (COAG Energy Council, 2019)

A significant pipeline of projects has already been announced worth $230-$300 billion. However, the country trails behind other nations in moving from project announcements to final investment decisions. The total electrolyser capacity is projected to reach 100-300 MW by 2025 and 500-1000 MW by 2030. For the International Energy Agency, Australia is able to reach even 30 GW of electrolysis capacity for 2030.

To support industrial decarbonisation, Australia will need to produce 0.36 million tons of hydrogen by 2030, increasing to 2.23 million tons by 2050. This hydrogen will be used across various domestic sectors, including ammonia production, industrial process heat, electricity grid firming, transportation, marine bunkering, sustainable aviation fuels, green iron and steel production, and food sectors.

In addition to domestic use, a major portion of Australia's hydrogen production will be destined for export, aiming to meet around 21% of global hydrogen demand by 2050 in conjunction with the Indo-Pacific region. To this end, it is crucial to meet the target of achieving a hydrogen price lower than 2 $/kg.

Country targets:

- 1 GW electrolysis capacity by 2030
- 0.36 million tons of hydrogen by 2030 and 2.23 million tons by 2050
- 21% of global hydrogen demand by 2050
- Hydrogen price lower than 2 $/kg

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4.4.8 Japan

Historically, Japan has used low carbon hydrogen for residential and transportation application through fuel cells, becoming a pioneer in these technologies and leading the market exporting to the rest of the world. However, the new national strategies now focus on decarbonizing the industry using low-carbon hydrogen (Baker McKenzie, 2023b; New Zealand Ministry of Foreign Affairs and Trade, 2023b).

Japan released a **Basic Hydrogen Strategy** in 2017, becoming the first country to have one. This document focused on reducing the cost of hydrogen, growing a value chain and making green hydrogen competitive with CCS and fossil fuel hydrogen production. First steps were taken by creating cooperation agreements with Australian Government and the European Union.

In 2023, a **Revised Basic Hydrogen Strategy** was published, updating the targets and instruments for a hydrogen economy. The strategy focuses on five categories for the development of hydrogen: supply, power generation, fuel cells, direct use, and hydrogen compounds. The objective is to reduce the carbon intensity of hydrogen to 3.4kg-CO_2e/kg-H_2; with a price efficiency of 3 \$/kg H_2 in 2030 and 2 \$/kg H_2 in 2050; and a widespread use of fuel cell for vehicles and households. It also sets targets for use of hydrogen, electrolysis capacity and investment budget.

Country targets:

- H_2 consumption of 3 Mt/year by 2030, 12 Mt/year by 2040 and 20 Mt/year by 2050
- 15 GW of installed electrolysis capacity by 2030
- 100 Billion $ invested in hydrogen supply chain by 2050
- Price efficiency of 3 \$/kg H_2 by 2030 and 2 \$/kg H_2 by 2050

4.4.9 South Korea

South Korea is emerging as a pioneer in hydrogen technology, aiming to lead the global manufacturing of fuel cells for electric vehicles and large-scale stationary power generation. To this end, the Asian country is developing a hydrogen supply chain infrastructure and a strong regulation for promoting the deployment of green hydrogen (HyResource, 2019; Nakano, 2021).

South Korea presented its **Hydrogen Economy Roadmap** in 2019 creating a cluster between public and private sector to foster the use of renewable hydrogen. In 2021, the **First Hydrogen Law** was approved, with a clear vision to promote a hydrogen economy through public awareness, research and innovation for a hydrogen culture. This policies sets a growth strategy based on three pillars to establish a clean hydrogen supply chain for a leading hydrogen industry: “Scale-up, Build-up and Level-up”.

There are also plans for a grid of pipelines and logistics hubs for hydrogen and its derivatives and the first clean hydrogen market has been launched in 2024 to meet power generators using only hydrogen with domestic clean certification standards.

Country targets:

- Hydrogen Fuel Cells manufacturing capacity of 15 GW/year by 2040
- H_2 consumption of 1.9 Mt/year by 2030 and over 5 Mt/year by 2040
- 38 Billion $ invested in hydrogen technology by 2030
- 7.1% of the nation’s energy mix covered by clean hydrogen by 2036

4.4.10 United States of America

Interest in clean hydrogen is growing rapidly in the United States due to its potential to combat the climate crisis, enhance energy security, and generate economic benefits. As a crucial element in achieving a sustainable clean energy future, zero- and low-carbon hydrogen is part of a broad solution portfolio.

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The U.S. is accelerating progress with historic investments in hydrogen production, infrastructure, and strategic R&D efforts (HyResource, 2023).

The **National Clean Hydrogen Strategy and Roadmap** was published in 2023, outlining strategic opportunities in the hydrogen sector, and setting the target to produce 10 MMT of H_2 by 2030, 20 MMT by 2040 and 50 MMT by 2050, based on long-term demand scenarios. This strategy is based on three pillars:

- Targeting high-impact uses of clean hydrogen in sectors with limited decarbonisation options, such as heavy industry, transportation, and energy storage, while exploring long-term export potential.
- Focusing on reducing the cost of clean hydrogen through initiatives like the Hydrogen Energy Earthshot, addressing supply chain and efficiency challenges.
- Emphasising in building regional hydrogen hubs to scale production, infrastructure, and distribution near key hydrogen users, accelerating market growth.

The strategy envisions three waves of clean hydrogen applications: The first wave focuses on sectors with limited alternatives for decarbonisation, such as refining, ammonia production, and heavy-duty trucking. The second wave includes industries where hydrogen's economic value is increasing, such as steel production, aviation, and energy storage. The third wave targets sectors that will adopt hydrogen as costs decline and infrastructure expands, including cement, methanol, backup power, and stationary power generation.

In 2024, the **Multi-Year Program Plan** was released, a strategic document guiding clean hydrogen innovation and research. This includes key targets such as reducing hydrogen costs to $2/kg by 2026 and 1$ by 2031, and electrolyser system costs to $250/kW for low-temperature systems and $500/kW for high-temperature systems by 2026.

Country targets:

- H_2 production of 10 Mt/year by 2030, 20 Mt/year by 2040 and 50 Mt/year by 2050
- Reducing hydrogen costs to 2 $/kg by 2026 and 1 $/kg by 2031
- Reducing electrolyser costs to 250 $/kW for LTS and 500 $/kW for HTS by 2026
- 3 GW electrolyser manufacturing capacity by 2030
- 9.5 Billion $ invested in hydrogen by 2030

4.4.11 Canada

Canada is in the top ten hydrogen producers of hydrogen globally thanks to the abundance of resources to produce hydrogen, like natural gas. The country benefits from a robust energy sector and advantageous geographic assets, positioning it to become a leading exporter of hydrogen and hydrogen technologies (Baker McKenzie, 2023c).

In 2020, Canada’s Government released the **Hydrogen Strategy for Canada**, aiming for net-zero emissions by 2050. Developed in collaboration with stakeholders, provinces, and Indigenous partners, clean hydrogen is a strategic priority for achieving this goal.

The Strategy outlines recommendations across eight pillars: strategic partnerships, de-risking investments, innovation, codes and standards, enabling policies, awareness, regional blueprints, and international markets. Each pillar includes specific actions to foster hydrogen's development. If fully realized, Canada envisions over 5 million hydrogen vehicles, CAN$50 billion in revenue, a 190-megatonne CO_2 reduction, and becoming one of the world’s top three clean hydrogen producers by 2050.

In 2024, the **Hydrogen Strategy for Canada: Progress Report** was published, which details Canada’s hydrogen sector developments and includes new financial instruments and regulatory supports.

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Furthermore, the government has entered into 12 international agreements to enhance energy security and promote clean hydrogen export opportunities, partnering with U.S. and European and Asia-Pacific countries.

Country targets:

- H_2 covering 6% of delivered energy by 2030 and 30% by 2050
- H_2 demand of 4 Mt/year by 2030 and 20 Mt/year by 2050
- H_2 price lower than 3.50 $/kg by 2050

4.4.12 United Kingdom

The UK is well-positioned to lead in global hydrogen technology development due to its strong geology, infrastructure, and technical expertise, supported by a history of collaboration between government, industry, and innovators. The UK's hydrogen ambitions extend beyond decarbonisation, focusing on building sustainable supply chains, creating high-quality jobs, and boosting exports by leveraging British innovation. Across the UK, large-scale hydrogen projects are poised to reduce emissions, create jobs, and provide insights into hydrogen's costs, safety, and potential impact on the economy. (“Hydrogen Developments of the United Kingdom,” 2024; “United Kingdom,” 2021)

The country published the **UK Hydrogen Strategy** in 2021, which follows a ‘twin track’ approach, supporting both green (electrolytic) and blue (carbon capture-enabled) hydrogen production. Key outcomes by 2030 include achieving 10 GW of low-carbon hydrogen capacity, decarbonizing existing hydrogen supply, reducing production costs, and creating an end-to-end hydrogen system across multiple sectors. The strategy also aims to boost public awareness, drive economic growth, and contribute to emissions reductions, while laying the groundwork for further expansion post-2030. It includes a roadmap for the 2020s and key commitments across the hydrogen supply chain to support the transition.

Country targets:

- 1 GW H_2 production capacity by 2025 and 10 GW by 2030
- 5 Billion $ invested in hydrogen by 2030 and 17 Billion $ by 2050
- 9000 new jobs in the hydrogen sector by 2030 and 100,000 by 2050

4.4.13 Morocco

The World Energy Council has recently identified Morocco as one of the six countries with greatest potential for the production and export of hydrogen and green derivatives. The country is searching for hydrogen deposits to analyse the potential of the country in this field. The National Office of Hydrocarbons and Mines (ONHYM) has identified eight zones of interest, and it is still planning to cartography, model and monitor the identified sites. This will allow them to better quantify the presence of natural hydrogen in Morocco and prepare for its future exploitation.

The roadmap for the development of a Moroccan green hydrogen strategy is condensed in the **Feuille de route hydrogène vert**, where the government of Morocco forecasts the development of the green hydrogen industry based on two pillars: the use of green hydrogen as raw material to produce green ammonia, and the exports of green hydrogen. Green hydrogen is also planned to be used as a way of preserving energy and to improve the national electric system. It is contemplated support of international institutions for the advancement of this process.

To evaluate the evolution of the demand for green hydrogen, two scenarios are studied. The reference scenario estimates the minimum demand, while the optimistic scenario estimates the maximum. According to the results of both scenarios, it is thought that in 2030, most of the demand will be for feedstocks and is likely to come from exports and industry. In 2040 and 2050, demand is expected to

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increase mainly in the transport sector, as synthetic fuels become more competitive than conventional fuels. Thus, in 2050, demand appears to be broadly divided between use as a feedstock in industry, in transport and as an essential part of exports.

Country targets:

- Reference scenario: 2.8GW by 2030, 13.9GW by 2040, 31.4GW by 2050
- Optimistic scenario: 5.2GW by 2030, 23GW by 2040 and 52.8GW by 2050

4.4.14 Norway

On Wednesday 3rd of June 2020, Norwegian Minister for Petroleum and Energy and Minister for Climate and Environment presented the **Norwegian government's hydrogen strategy**.

The strategy lays the foundation for the future work with hydrogen in Norway. The government wants to prioritize efforts in areas where Norway, Norwegian enterprises and technology clusters may influence the development of hydrogen related technologies, and where there are opportunities for increased value creation and green growth.

The main elements of the Strategy cover the following areas: i) the necessary technological developments; ii) competitive production of clean hydrogen; iii) emission-free transport; iv) green public procurements; v) safety and standards; vi) national research; vii) international collaboration and research.

The government's strategy was criticised for being merely a description of the status quo rather than a full-fledged action plan with specific goals; it was also noted that new policy measures were lacking. The government responded by issuing a **hydrogen roadmap in 2021**, which was backed up by increased state-funding for hydrogen research and industry projects. This hydrogen strategy and roadmap laid out the development of low-carbon hydrogen (emission-free or close to emission-free) from electrolysis of water from renewable energy and natural gas with carbon capture and storage Two end-use sectors have been prioritised: maritime transport and energy-intensive process industries.

Country targets:

- 5 hydrogen hubs for maritime transport by 2025
- 1 or 2 industrial projects for hydrogen, to demonstrate value chains with global technology diffusion potential
- 5 to 10 pilot projects for demonstration of new, more cost-effective hydrogen solutions and technologies

4.4.15 Saudi Arabia

Even though a Saudi hydrogen strategy is not developed yet, in 2023, the government of Saudi Arabia committed 2.75 billion $ through the National Development Fund and the Saudi Industrial Development Fund to the NEOM green hydrogen and ammonia project. The planned city is thought to house the world's largest green hydrogen-based ammonia production plan, using 4 GW of renewable power from solar, wind and storage to produce 600 tonnes per day of hydrogen. The project is expected to produce about 1.2 Mt of green ammonia per year, starting in 2026.

Besides the hydrogen plant project in NEOM, there exist other hydrogen projects that are currently being developed in Saudi Arabia, based in a public-private collaboration, that contemplate the production of green and blue hydrogen in different cities by 2030. By doing so, Saudi Arabia is trying to reduce their economic and energetic dependence from oil.

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Country targets:

- Clean hydrogen production targets of 2.9 Mt/year by 2030 and 4 Mt/year by 2035

4.4.16 South Africa

In South Africa, green hydrogen is seen as a cornerstone of the decarbonisation transition, since its importance to address the reduction of GHG emissions in industries such as the transport, petrochemical, iron and steel and cement, as well as in the power sectors. It is also considered an economic opportunity in terms of competitiveness in international trade. The green hydrogen export industry would include the platinum group metals, electrolyser and fuel cells components, green iron ore and steel, and derivatives such as green ammonia and sustainable aviation fuels.

These projections for the green hydrogen sector are compiled in the **South Africa's Just Energy Transition Investment Plan (JET IP)** for the period 2023-2027. It estimates the investment needs of the green hydrogen sector in 21.2 Billion $. Public-private initiatives for the developing of this industry are being established, as well as bilateral cooperation agreements with other countries from the European Union, like Germany, through the German Agency for International Cooperation.

Country targets:

- 98.7 B$ of investment need for the period 2023-2027 for the GH_2 sector
- More than 60 GW of electrolyser capacity in 2050
- 6–10 Mt/year of demand for local production could be in play by 2050

4.4.17 Switzerland

The development of hydrogen networks is part of Switzerland's wider strategic supply strategy for this energy carrier. Currently virtually absent from Switzerland's energy mix, hydrogen could be called upon to play a role in decarbonising certain uses (such as those that are difficult to electrify) with a view to achieving zero net greenhouse gas emissions by 2050. For example, hydrogen could replace part of Switzerland's current methane consumption, which is mainly based on fossil natural gas.

Parliamentary work is currently underway to clarify the long-term importance of hydrogen in the Swiss energy mix. This clarification will be decisive for assessing the need for hydrogen transport (and possibly distribution) network infrastructure, for drawing up the corresponding regulations and for the steps involved in implementing them.

The absence of existing infrastructure in Switzerland and the uncertainty about the degree and speed of hydrogen penetration in Switzerland at the time of the study justify an approach based on network scenarios, to take into account the full range of possible development situations. This study considers 4 hydrogen network scenarios (numbered 0, 1, 2 and 3 in order of network extent). These scenarios are hypothetical, purely theoretical, and illustrative.

- 'Minimal' scenario 0: the network is limited to an H_2 transit line, based on a model similar to the transit line for methane today. Only a few large industrial plants are connected to the H_2 transit line. There are a few isolated production sites in Switzerland.

- Scenario 1 'reduced': connected to the H_2 transit line, a few regional hydrogen transport lines serve a small number of industrial centres. Most hydrogen production sites in Switzerland remain isolated.

- Scenario 2 'extended': the regional hydrogen transport network is extended to serve certain urban industrial centres and possible CHP facilities that can run on hydrogen. Most of the production sites are connected to the transport network.

- Scenario 3 'with distribution': the hydrogen network has developed to distribution level, serving certain domestic or tertiary customers for building-related needs, for example.

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The study of the various scenarios and evaluation criteria shows that the size of the hydrogen market and the maturity of the corresponding infrastructure (which may be as little as a few connections around an H_2 transit line) are decisive in determining the scope of the regulatory framework. Unlike gas and electricity, where the market was opened up and regulated as a network monopoly in a context of pre-existing infrastructure, hydrogen will probably be regulated from the infrastructure deployment phase. This regulation will therefore have to ensure that it does not hinder but rather encourages the deployment of the infrastructure corresponding to the needs identified, without leading to an over-dimensioning of the hydrogen network.

Country targets:

- 4 scenarios by 2050 with green hydrogen production from 0-60 kt/year to 300-600 kt/year

4.4.18 Republic of Turkey

Following the ratification of the Paris Agreement by the Republic of Turkey by 2021, several compromises have been adopted in order to reduce the fossil fuel dependence of the country and to increase the generation of renewable energies. This contributes to creating an environment that gives rise to the production of green hydrogen using electricity from domestic renewable sources.

The **Turkey Hydrogen Technologies Strategy and Roadmap** is part of the Turkey National Energy Plan that draws up the path until 2035 to reach the net zero emission target in 2053. Here hydrogen, together with electrification, is considered a pivotal energy source in the decarbonisation transition, given the green hydrogen production potential that Turkey has.

Long-term applications of green hydrogen in Turkey are projected to the manufacturing industry, including chemistry, iron and steel, cement, etc., to its direct use or with natural gas, and to fuel cell applications, in space programs, transportation or even domestic uses. On the other hand, the market strategy will be oriented to trade agreements mainly with the European Union, which is a crucial partner for Turkey in terms of renewable energy.

Country targets:

- To increase the installed power capacity of the electrolyser to 2 GW in 2030 and 5 GW in 2035, reaching 70 GW in 2053
- Natural gas will be blended with hydrogen and synthetic methane and the percentage of hydrogen in the gas mixture will be 3.5%

4.5 Synthesis of the reviewed policies and alignment for the modelling of hydrogen policies in WILIAM

This section will discuss and synthetize the analysis of policies that has been done and explained in the previous sections. In addition, and based on the previous analysis, we will provide information about WILIAM and recommendations for incorporating hydrogen in the scenarios building process in this model, including the modelling of specific policy objectives.

4.5.1 Synthesis of the reviewed policies

4.5.1.1 Evolution over time

As seen in Section 4.1, the importance of Hydrogen in the global energy and economy is growing faster and faster. Hydrogen has the potential to be a key agent in the decarbonisation of many different processes and must be considered as an option for future paths.

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In the analysis of hydrogen policies carried out in this document, the release year of each policy is registered, allowing to represent this growing importance that different countries and regions are giving to this energy vector. Figure 5 shows how many policies presenting hydrogen targets or instruments were published each year at EU and global level from 2018 to the current year, 2024 (year 2024 could only partially be covered due to the restriction of the deliverable date).

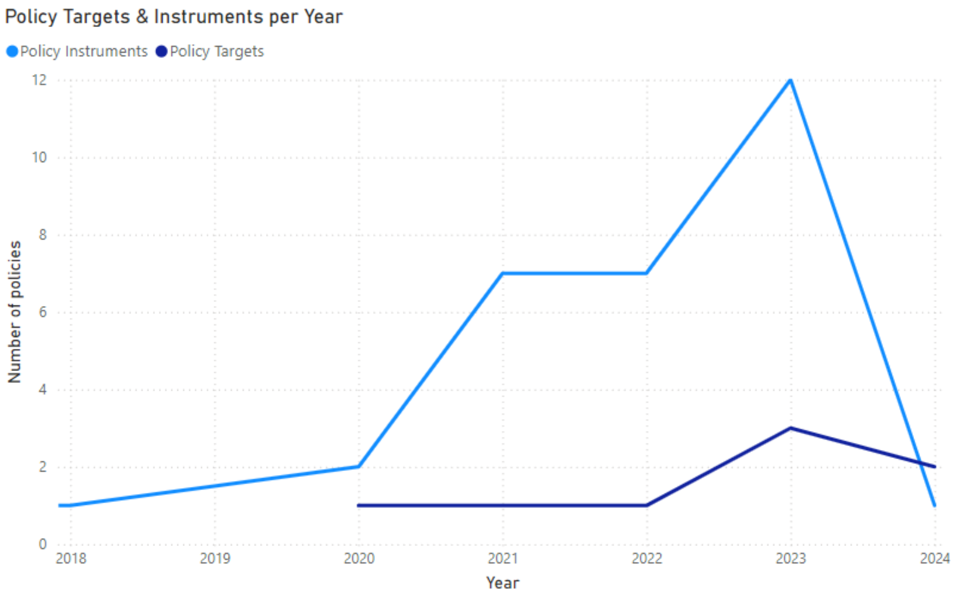

Figure 5. Number of hydrogen policies released per Year

As it can be seen, since 2018 the number of new policies related to hydrogen has been growing steadily. Policies increasingly cover more sectors and set clearer targets for the short term (2030) and even for the long term (2050). If this growth continues, hydrogen is likely to have a major impact on all economic and social sectors globally.

4.5.1.2 By sectors

Thanks to the classification of the policies done in previous sections, which define future targets for hydrogen (defined on Section 0), we can obtain a list of prioritised sectors in EU.

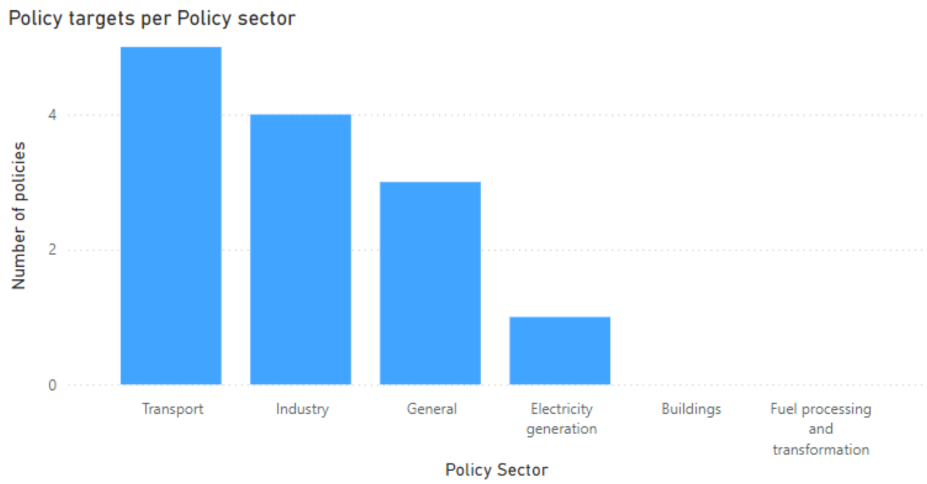

Figure 6. Number of hydrogen policies by sector

Governments are betting on transport and industry to be the main sectors decarbonised by hydrogen; mainly the hard-to-abate sectors like freight-transport or high-temperature industry; while the buildings,

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fuel processing and electricity generation sectors are either integrated into more generalist policies (i.e. policies not focused on specific policy sectors) or not seen as having enough potential to have significant effects in the medium term.

4.5.1.3 By supply chain elements

The value chain of hydrogen was divided and assessed separately to find if some links could be simplified or grouped and decide which ones should be better defined.

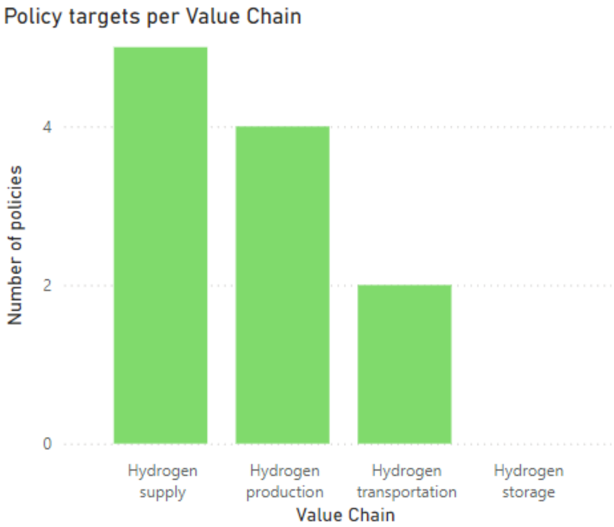

Figure 7. Number of hydrogen policies by part of the value chain

As showed in the graph, the production and supply are the main focus of the hydrogen economy, with the hydrogen transportation remaining in the background. It can also be inferred that hydrogen storage (for medium and long-term) is not a priority at the moment: the hydrogen economy is intended to use the produced fuels continuously without generating storages and its use as an electric-grid buffer does not seem to be strongly promoted either.

4.5.1.4 By type of instrument

All the policy instruments from the policies assessed in this work package have been classified and represented in the following graph.

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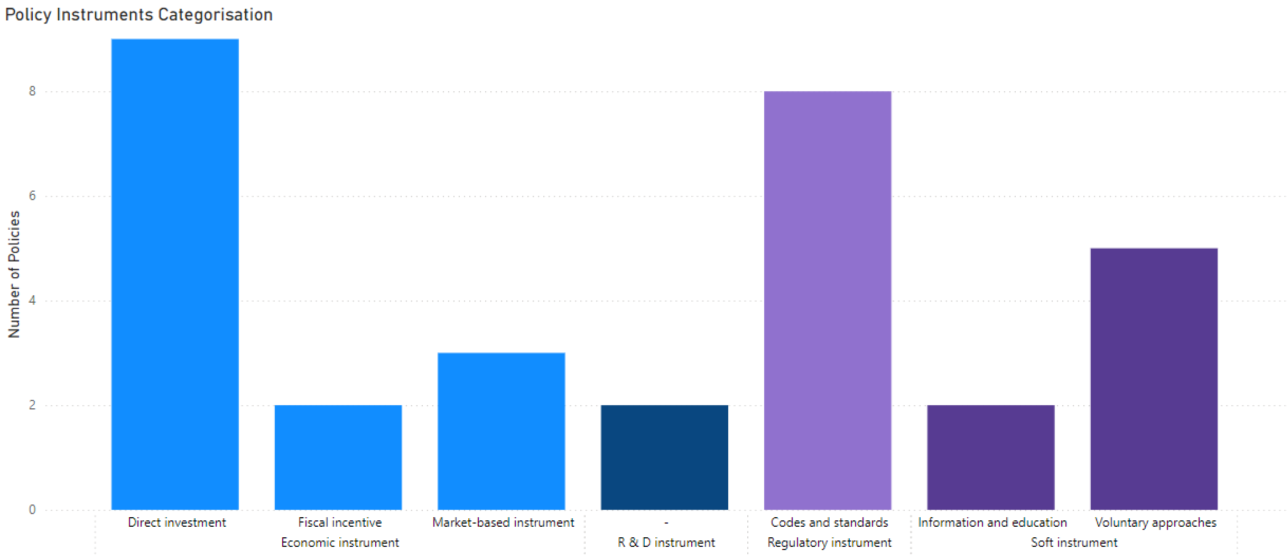

Figure 8. Number of policies by policy instrument category

By far, the most recurrent policy instruments are economic instruments. Among these, direct investment stands out, as it is probably the most efficient way to get new projects off the ground in a short period of time. The market-based instruments and fiscal incentives are more difficult to design and make them work for their intended purpose.

The regulatory instruments also have an important role to play in the deployment of hydrogen, but only through codes and standards for hydrogen production and technology. There is no quotas or obligation schemes in this sector.

4.5.1.5 By regions

It is important to understand the situation of each world region with respect to their hydrogen strategies. Hydrogen is a relatively new trend and, although it is booming, countries are joining it unevenly, so regions are often not aligned in terms of the objectives of their constituent countries. More and more countries are developing strategies to incorporate hydrogen into their economy, but the main focus is still on those countries that see it as having a very large potential and as a great opportunity for the country's economy. The hydrogen economy is much unstructured yet and needs a process of clarifying objectives, balancing between countries, dragging form the pioneer countries to those lagging behind, unification and international cooperation.

The following graph shows the years in which the hydrogen strategies of the analysed countries were published or updated at the global level.

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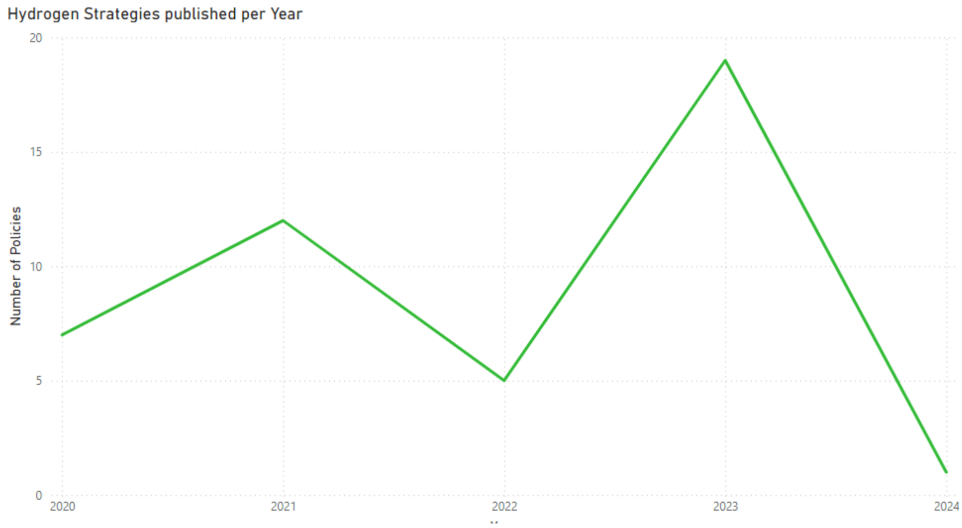

Figure 9. Number of national hydrogen strategies released per Year

The main focus of this project is to assess the importance of hydrogen in the European Union and the opportunities for the region. With this context, the analysis of policies has been focused on the policies of European countries in order to analyse the feasibility of hydrogen scenarios at EU level.

As seen in Section 4.2.1, the EU plans to install 40 GW of electrolysers to produce 10 Mt/year of hydrogen by 2030. This ratio of 0.25 Mt/GW has been used to compare electrolysis capacity installation and hydrogen production targets from the different countries.

All the objectives from the 27 EU countries for 2030 have been translated to electrolysis capacity and can be compared separately and as a whole.

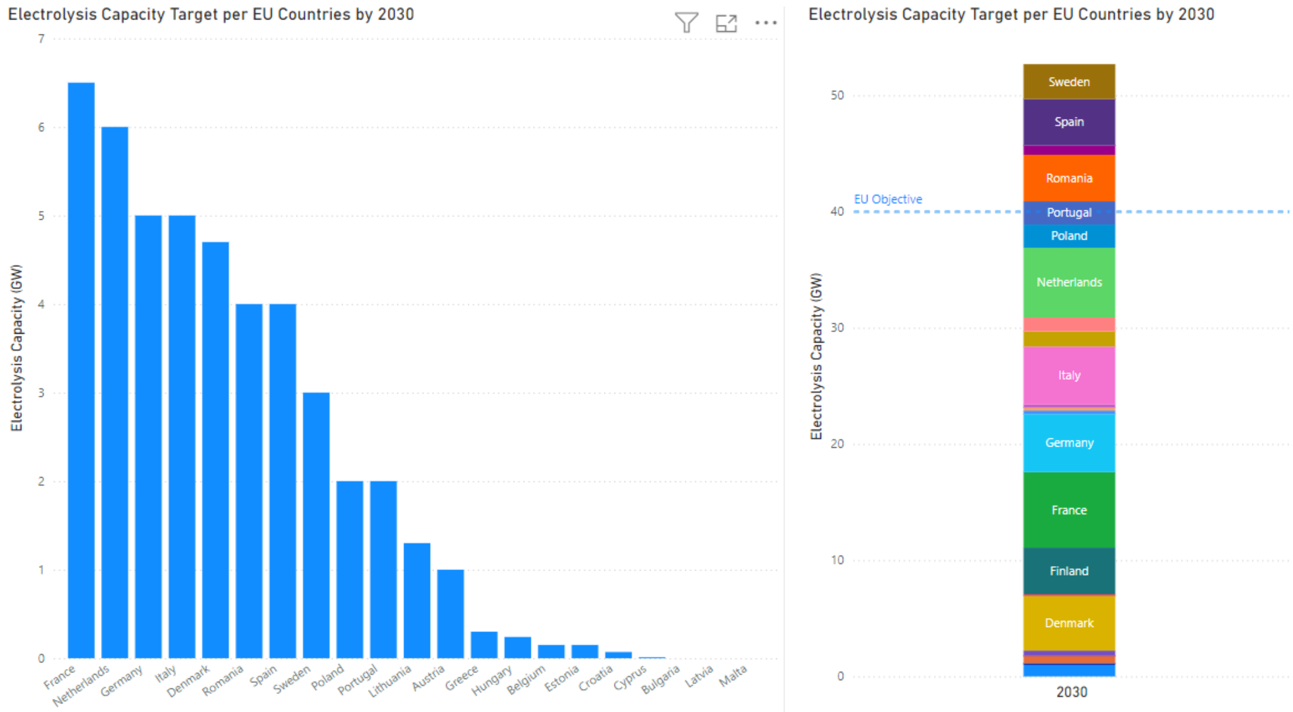

Figure 10. Electrolysis capacity target per EU country by 2030

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EU countries would need an aggregate total capacity of 52.69 GW to reach all the national targets for hydrogen, overcoming the European target of 40 GW by more than a 25%. The differences between countries are difficult to justify. Each country has set its objective based on different criteria and own expectations, but the feasibility of these objectives is not clear on the basis of the installation capacities. Nevertheless, the objectives broadly highlight the region's trends and each country's intentions to invest in and support hydrogen technologies.

A similar analysis has been done with the main countries that have developed hydrogen strategies or have the potential to do so at a global level.

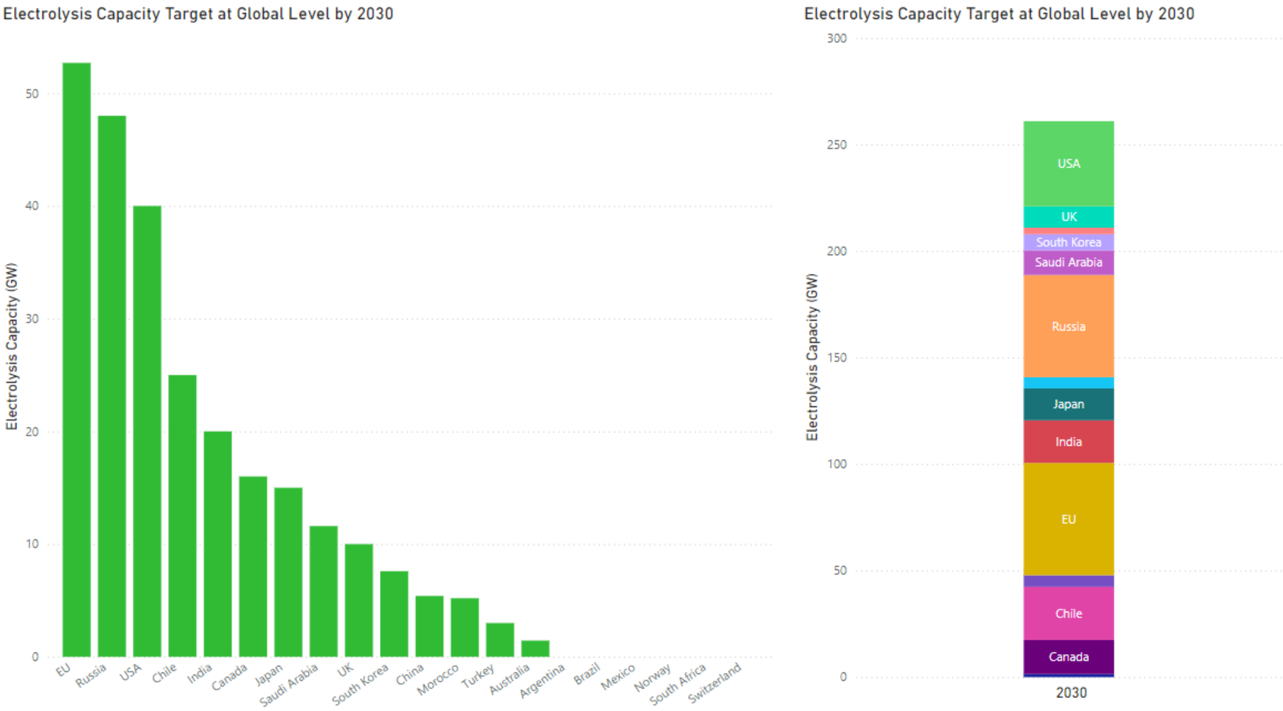

Figure 11. Electrolysis capacity target at global level by 2030

Outside of the EU, the differences are even more significant. Some countries want to influence the global hydrogen economy and compete with entire regions for international trade (e.g. Chile, India or Russia), while others focus on just meeting their domestic demand (e.g. Japan or South Korea). Moreover, some set only short-term goals, others only long-term, and some even propose strategies without setting any goals at all.

4.5.2 Implementation in WILIAM

Due to the already high complexity of WILIAM model due to its "integrated" approach, and given that this model should be easily used by decision-makers to be really useful for comparing policies (e.g. appropriate time simulation), a key aspect of hydrogen economy modelling in WILIAM when modelling hydrogen scenarios is to precisely define the scope so that it is possible to prioritise new features to incorporate or improve in WILIAM. For this purpose, it is necessary to prioritise the sectors where hydrogen is most likely to gain importance and where it may have the most impact.

The data analysed show that it will be fundamental and a priority to model the transport and industry sectors in WILIAM, while sectors like electricity generation, buildings or fuel processing and transformation have less relevance for the model.

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About the hydrogen value chain, the hydrogen generation and supply should be the main focus, while hydrogen transportation and storage take a back seat.

The most relevant instruments to model in WILIAM are the economic ones, in particular the direct investment; followed by codes and standards as regulatory instruments. The soft instruments and research and development instruments may have less relevance for this sector. The feasibility to model the more relevant policies will be assessed in Task 4.1 and 5.2 of this project, depending on the scope and capacities of WILIAM.

In addition, WILIAM is divided in 9 different regions: European Union, LATAM (Latin America), China, India, Russia, EASOC (East Asia and Oceania), USMCA (USA, Canada and Mexico), UK and ROW (Rest of the World). Furthermore, the 27 countries of the European Union can be disaggregated to design specific policies and differences for each of them for some modules such as economy, but not for energy.

The main regions of WILIAM are well defined in terms of hydrogen and can be compared and related to EU region. However, it is important to focus and consider in the scenario building process the role of the regions with the biggest targets and more relation with EU, as some others are undefined or with high uncertainty, so the approach should be more conservative.

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5 Socioeconomic and environmental KPIs for evaluating hydrogen policies

In this section, specific Key Performance Indicators (KPIs) have been analysed and defined based on literature for evaluating the effects of hydrogen-based policies (as policy scenarios to be modelled in WILIAM) so that the different alternatives can be compared. The approach to do this has been holistic, so not only the focus is done in evaluating the performance in terms of energy savings or GHGs emissions, but also covering the different pillars of sustainability: from the technological and economical point of view to the effects on society and the environment.

Finally, this work has been framed and linked to the application in WILIAM model, detecting those KPIs that are already integrated.

SDG framework

In relation to evaluating the performance of specific hydrogen policies, it should be mentioned that the sustainable development goals (SDGs) are an appropriate framework that can be used for this purpose. Integrating sustainability criteria is essential for the effective design and deployment of a resilient hydrogen economy. In this regard, climate action and sustainable development are high dependent and interlinked. In addition, climate action is part of one SDG. However, not only are climate objectives key in our societies, but also climate policy (e.g., the deployment of low carbon energy technologies as hydrogen) must be aligned with societal and environmental and economy objectives, i.e., with other objectives beyond mitigation and adaption to climate change, as for example biodiversity or food or water scarcity.

However, the integration of the SDGs in IAMs models such as WILIAM is not immediate due to the enormous number of targets and indicators listed in the SDG framework, with potential overlaps or also difficulties for being quantified in models. For these reasons, consistent evaluating frameworks (target space) have been developed in literature that constitute a list of indicators capable of quantifying the progress toward SDGs in IAMs (see Soergel et al., 2021), and they are precisely the references used also for this deliverable. For this reason, some of the KPIs have been organised around this framework in the next subsections.

In the following sections, the KPIs analysis has been divided in three different pillars or systems, where the effects can be analysed:

- Economy, energy, and materials (tecno-economic analysis)
- Society
- Environment (including natural resources and climate)

5.1 KPIs related to techno-economic analysis: economy, energy and materials

For the review conducted on energy, materials, and economic KPIs, a systematic approach was employed to identify, compare, and synthesize the most relevant sources in the field of hydrogen, drawing from studies and reports by international organizations, consulting firms and scientific papers. In the case of obtaining techno-economic KPIs, the process has been thorough, as it involves different aspects (economy, materials, and specially energy, which is directly related to hydrogen), putting special focus in avoiding KPIs overlaps. The different steps are explained below:

1. **Source Identification:** Reports from key organizations in the energy transition and hydrogen sectors were selected.

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2. **KPI Extraction:** KPIs related to hydrogen production, demand, transportation, storage, costs, and investment were extracted from each source, with attention to different technological approaches and the economic sectors involved.
3. **Incorporation of Scientific Perspectives:** In addition to institutional reports, academic studies were reviewed to include additional indicators, such as Energy Return on Energy Invested (EROI), availability of critical materials, and socio-environmental factors influenced by hydrogen use. This helped to complement the analysis with more comprehensive insights.
4. **Classification and Comparison:** The extracted KPIs were qualitatively analysed to group them, avoiding duplication and overlap. Indicators that function as input variables for the WILIAM model, along with those beyond the analytical scope of IAMs, were excluded.

KPIs from (IEA, 2023)

The IEA outlines a **Net Zero Emissions** (NZE) scenario, tracked through various global-scale indicators, particularly focusing on the role of hydrogen. These indicators include:

- Emissions intensity of hydrogen production (kg CO_2eq/kg H_2).
- Hydrogen production by technology (Mt H_2/year), covering technologies such as fossil fuels without carbon capture, utilization and storage (CCUS), by-product hydrogen, fossil fuels with CCUS, electricity, and bioenergy.
- Hydrogen demand by sector (Mt H_2/year), considering sectors like refining, ammonia, methanol, iron and steel (both direct reduced iron (DRI) and hydrogen-based DRI), and others (transport, high-temperature heat in industry, power, and buildings).
- Kilometres (km) of hydrogen pipelines (new and repurposed).
- Low-emission hydrogen (i.e. hydrogen produced via electrolysis and from fossil fuels with CCUS) shipments (including hydrogen-based fuels) (Mt H_2/year).
- Hydrogen storage capacity (TWh).

KPIs from (McKinsey & Company, 2024)

McKinsey & Company models the energy supply and demand outlook for various energy commodities under a 1.5°C pathway, aligned with the Paris Agreement, and four bottom-up energy transition scenarios. The hydrogen-related KPIs they mention include:

- Global clean hydrogen demand (including hydrogen produced via electrolysis and from fossil fuels with CCUS) (Mt H_2/year).
- Global grey hydrogen demand (hydrogen produced from fossil fuels without CCUS) (Mt H_2/year).
- Hydrogen production (Mt H_2/year), differentiated by process (electrolysis, fossil fuels with CCUS, and fossil fuels without CCUS). Regional indicator.
- Hydrogen demand by sector (Mt H_2/year), covering existing industrial uses (refining, chemicals like ammonia and methanol), new industrial uses (iron and steel via the hydrogen-based DRI route), mobility (maritime, aviation, trucking), heating, and power. Regional indicator.
- Flows of hydrogen and derivative trades across regions (Mt H_2/year).

KPIs from (Hydrogen Council and McKinsey & Company, 2023)

The report from the Hydrogen Council and McKinsey & Company primarily focuses on the hydrogen value chain's capacity (production, distribution, etc.) and categorizes each indicator based on the project's stage—announced, feasibility study, FEED, and committed (which includes FID, under construction, and operational). Only the KPIs relevant to the committed stage, applicable in the WILIAM model, are mentioned in the following bullet points:

- Total hydrogen investments (USD billion) by region, across categories: end-use, infrastructure, and production/supply.
- Electrolysis capacity in operation (MW) by region and sub-technology (alkaline, PEM, and others).

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- Operational clean hydrogen capacity (Mt/year) by region, covering renewable and low-carbon hydrogen.
- Electrolyser and fuel cell manufacturing capacity (GW/year) by region.
- Kilometres of hydrogen pipelines in operation by region.
- Number of refuelling stations by region.
- Number of fuel cell vehicles on the road, including passenger vehicles, buses, and trucks.
- Number of methanol-ready ships in service.
- Number of ammonia-ready ships in service.

KPIs from (BloombergNEF, 2020)

The Hydrogen Economy Outlook from BloombergNEF provides a global view of the hydrogen economy and identifies the following key indicators:

- Hydrogen production cost ($/kg), including the levelized cost of hydrogen (LCOH) for various production processes (renewable hydrogen, natural gas with CCUS, and coal with CCUS).
- Hydrogen storage cost ($/kg), considering the levelized cost of storage (LCOS) by storage option.
- Hydrogen transport cost ($/kg), based on distance, transport volume, method (pipelines, ships, trucks), and fuel type (compressed H_2, liquid H_2, ammonia, and liquid organic hydrogen carriers).
- Delivered hydrogen cost ($/kg), including production, transport, and storage.
- Levelized cost of steel ($/kg), using hydrogen versus coal.
- Hydrogen demand by sector (Mt/year), covering buildings, power, industry, and transport.
- Hydrogen share of total energy demand (%).
- Electricity demand for electrolysers (TWh/year).

KPIs from the International Renewable Energy Agency (IRENA, 2022)

IRENA, like IEA, also considers a 1.5°C pathway with performance indicators. (Marzouk, 2024) outlines the following hydrogen-related IRENA KPIs

- Annual clean hydrogen production and derivatives (Mt H_2/year), referring to hydrogen produced via electrolysis and natural gas with CCUS.
- Clean hydrogen's share in total final energy consumption.
- Clean hydrogen's share in transport energy consumption.
- Share of ammonia, methanol, and e-fuels in transport energy consumption.
- Clean hydrogen's share in global industrial energy use.
- Clean hydrogen's share in global building energy use.
- Annual investments in hydrogen and derivatives, including electrolysers, feedstocks, and infrastructure (USD billion/year).

KPIs from (Hydrogen Europe, 2023)

The Clean Hydrogen Europe from Hydrogen Europe tracks both quantitative and qualitative indicators related to Europe's clean hydrogen market. KPIs include:

- Hydrogen demand by country and end-use (Mt/year), covering refining, ammonia, methanol, other chemicals, industrial heat, and more.
- Clean hydrogen consumption for e-fuels production (Mt/year), covering fuels like SAF, e-methanol, and e-methane (by "clean" hydrogen, it refers to hydrogen produced through electrolysis and hydrogen generated via reforming with carbon capture.).
- Hydrogen production by country and technology, including reforming, reforming with CCUS, by-product hydrogen from ethylene/styrene production, and water electrolysis.
- Hydrogen production capacity (Mt/year) for electrolysis and reforming with carbon capture.
- Electrolysis capacity by sub-technology (GW), covering alkaline, PEM, and solid oxide electrolyser (SOEC).

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- Levelized hydrogen production cost by region, for various routes such as natural gas reforming without CCUS, with CCUS, electrolysis using grid-mix electricity, and renewable hydrogen (solar PV, onshore, offshore wind).
- Hydrogen-based storage capacity (GWh).
- Electrolyser manufacturing capacity by region (GW/year).
- Total hydrogen used in road mobility (Mt/year).
- Number of fuel cell electric vehicles (FCEVs) by region.
- Number of hydrogen-powered light-duty vehicles.
- Number of hydrogen-powered buses.
- Number of hydrogen refuelling stations.

KPIs from scientific literature

(Koneczna and Cader, 2024) propose a set of 124 indicators to analyse the performance of the hydrogen economy. The authors conducted a comprehensive review of strategies from European public authorities, as well as scientific literature, to identify and compile key metrics for quantifying the development of the hydrogen economy. The indicators identified by the authors are listed in Table 4 of their article, where each one is categorized based on its position within the transformation chain (production, transmission, distribution, and end use).

Beyond hydrogen-specific indicators, since the IAM WILIAM will be used throughout the HYDRA project, it is of particular interest to define some indicators of the model that can be influenced by the deployment of hydrogen in the energy system. In this sense, (Breyer et al., 2022) point to the EROI as one of the key indicators for assessing the viability of 100% renewable systems. This indicator has been calculated in other IAM models, such as MEDEAS (Capellán-Pérez et al., 2020), considering both the individual EROI of the technologies (De Castro and Capellán-Pérez, 2020; Pulido-Sánchez et al., 2022) and the EROI of the full system (Capellán-Pérez et al., 2019). Furthermore, this indicator is available in the WILIAM model, which allows not only to assess the influence of hydrogen deployment on the EROI of the system, but also to extend its definition to calculate the EROI of hydrogen. Related to the latter indicator, there are some studies in the literature that address its calculation (Ganzer and Mac Dowell, 2020; Lee et al., 2021; Palmer et al., 2021; Pellow et al., 2015; Sathre et al., 2014).

In addition to EROI, (Breyer et al., 2022) address concerns about the availability of critical materials needed for the transition to 100% renewable systems. They argue that research in various models indicates the existence of critical limits to the availability of these materials. In this sense, the European Union defines the criticality of a material by considering the economic importance and the risk of supply (European Commission, 2020b). On the other hand, models such as MEDEAS (Capellán-Pérez et al., 2020) assess the criticality of materials in terms of their potential scarcity, comparing the accumulated primary demand for minerals with the current estimated level of their geological availability (reserves and resources). This indicator is available in WILIAM and could be used to assess the criticality of materials for hydrogen-based technologies, as was already done in MEDEAS for the particular case of electric batteries (see (Pulido-Sánchez et al., 2022)). Another indicator related to material criticality is the "level of constraint risk" introduced by (Valero et al., 2018), which is applied to each material. This approach considers expected projections of green technologies, assumed constant metal recycling rates, and metal demand from other sectors. Likewise, not only (Pulido-Sánchez et al., 2022) but also (Valero et al., 2018) use the comparison between the cumulative demand for materials (per element) until 2050 against data on reserves and material resources as a key indicator. Finally, the latter authors consider the recycled content (RC) of each material as an important indicator of their models.

(Van Eynde et al., 2024) reviews indicators from Environment-Society-Economy models, and concludes that, in terms of environmental indicators, those related to climate change (climate change metrics such as CO_2 emissions) and energy uses are the most-modelled. In this sense, some of the indicators modelled in the MEDEAS model (Capellán-Pérez et al., 2020) can be considered as a reference, namely:

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- Total primary energy supply (TPES) mix (EJ/year).
- Share of renewables in the primary energy mix.
- Share of renewables in the final energy mix.
- Total final energy per capita (TFECpc) (GJ/person/year).
- Gross domestic product per capita (GDPpc) ($/person).
- Total final energy consumption (TFEC) intensity (defined as TFEC/GDP, in J/$).
- Total primary energy supply (TPES) intensity (defined as TPES/GDP, in J/$).
- Primary to final energy ratio (defined as TPES/TFEC, dimensionless).
- CO_2-eq intensity of primary energy (CO_2-eq/J).
- Total GHG emissions from the energy module (CO_2-eq/year).

5.2 KPIs for the analysis of the effects on society

The energy transition is not only transforming the power sector (or the economy). While hydrogen policies evaluation models (including IAMs) often focus on cost and environmental factors, social dimensions are frequently overlooked, and therefore there is a lack of appropriately and quantitatively assessed social sustainability indicators.

Some key social criteria from literature review have been identified in specific papers for the social impacts of a hydrogen economy. In particular, (De-León Almaraz et al., 2024) identifies and ranks twelve social aspects, with "Accessibility" (access to hydrogen and its infrastructure), "Information" (access to information about hydrogen which is very linked with acceptability)," "H2 Markets" (new products and applications to be bought or utilizer in different parts of the hydrogen supply chain)," and "Acceptability" (public or social acceptability of H_2 markets and infrastructure) emerging as dominant themes in hydrogen-related social research. In addition, key social implications of hydrogen could be the following, which also include challenges (Agarwal, 2022):

- **Job Creation, and industry and economic transformation**: creation of new jobs related to the hydrogen production, distribution and use, change of the structure of the industries that will affect the workforce reskilling and can generate social disruption in the region where its production is allocated. This is because although hydrogen deployment can create new jobs, this also implies a potential inadequacy of the specialized labour. Also, substantial investment in the infrastructure will be required.
- **Economic Growth**: creation of new industries, growth in the related sectors like solar, wind, hydrogen-powered transport systems, etc.
- **Energy security**: hydrogen, if appropriately planned, could foster the decentralization of energy production, and also equality in relation to the production of energy among regions (local energy production).
- **Global cooperation and geopolitical shifts**: although countries can collaborate in this hydrogen deployment, some regions can be converted to exporters (as those with solar potential) and, depending on the dynamics, global power can shift.
- **Health**: reduction of air pollution in urban and industrial areas particularly, in contrast with fossil fuel-based energy production.

In particular, specific socio-economic (financial and other societal status) and socio-political factors, related to the effects of hydrogen in society, taking into account the above, are the following:

- Income
- Taxes and subsidies
- Job opportunities (benefits and characteristics
- Social development indices as the Human Development Index

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- National economic indicator (GDPI)
- Gross national product per capita
- Development capacity indicator
- Living environment
- Security
- Quality of life
- Wellbeing
- Equality
- Social integration and participation
- International relations and political conflicts
- Energy security
- Energy justice
- Health

However, it must be said that significant gaps remained in these KPIs or societal indicators based on the literature reviewed, specifically for the hydrogen economy, such as the lack of clarity on hydrogen's societal value, insufficient research on socio-political factors (e.g., geopolitics and well-being), limited use of social lifecycle assessments, and a scarcity of studies addressing social practices and cultural considerations. In particular, only a few articles are dealing the topic of jobs and labour related to a deployment of hydrogen economy, although there are several reports in specific countries dealing with the expected job-creation.

Finally, taking into account the SDG framework (target space) previously explained, the final proposed indicators that can be feasible to be included in a model are the following (see Soergel et al., 2021). These are related to the socio-economic factors explained before:

1. **People related indicators:**
   - SDG1 (No Poverty). It covers energy security, equality:
     - Number of people living under extreme poverty conditions. Units: %.
     - Food expenditure share. Units: %.
   - SDG3 (Good Health and Well-being). Covers well-being and health (including pollution).
     - Healthy life expectancy. Units: year
     - Under-5 mortality rate. Units: %,
     - Disability adjusted life years (DALYs) lost from particulate matter (PM 2.5). Units: DALYs/yr
   - SDG4 (Quality Education). Although the relations are not so direct. It can be linked with labour skills.
     - Share of people >15 w/o education. Units: %,
     - Completion rate (primary education, lower secondary education, upper secondary education). Units: %,
   - SDG5 (Gender Equality). Relates to equality and creation of jobs, influenced by the promotion of women´s participation in STEM (science, technology, engineering and mathematics).
     - Education gender gap in (a) secondary education (age 20-24 w at least lower secondary education); and (b) primary education (age 15-19 with at least primary education). Units: %,
     - Female estimated earned income over male. Units: %,
2. **Prosperity related indicators:**
   - SDG8 (Decent work and economic growth). Relates to job creation, income and national economic indicator (GDPi).

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   - Annual growth rate of real GDP per capita. Units: %.
   - Unemployment rate. Units: %.
- SDG10 (Reduced inequalities). Relates to inequality and income level quantification.
   - Share of population with <50% of national median income. Units: %.
   - Average income of bottom 40% relative to national average. Units: %.
- SDG11 (Sustainable cities and communities). Relates to people exposed to pollution:
   - Share of people exposed to annual average PM2.5>25 μg/m3. Units: %.

3. **Access to natural resources:**
   - SDG2 (Zero hunger). Relates to food security. The impacts could be indirect due to the potential competition for land depending on the hydrogen technology type.
      - Food availability. Units: kg/cap·day
   - SDG6 (Clean water and sanitation). Relates to water security.
      - Population without access to improved water source piped. Units: %.
      - Population without access to improved sanitation facility. Units: %.
   - SDG7 (Affordable and clean energy). Relates to energy security.
      - Population without basic electricity access. Units: %.
4. Finally, another important social indicator that involves different aspects, is the following: **Human Development Index** (HDI). (This covers not only health but also education and per capita income). Units: no units (value between 0 and 1).

5.3 KPIs for the analysis of the effects on environment: land, water and climate.

Hydrogen deployment, including the low emissions option (green hydrogen deployment), has impacts in land use, water consumption and emissions (climate) that need to be evaluated to avoid unintended consequences of a large-scale deployment of hydrogen technologies. These is important, as natural resources can be a limiting factor for the appropriate large-scale deployment of a new technology as in the case of hydrogen, especially in places were some resources are already scarce (e.g. land available, water-stressed regions, etc.). In particular:

- **Land use:** these impacts depend on the renewable energy resource used (solar, which require significant land, in case especially of large-scale solar farms, or wind, which has however less footprint as can be used for agriculture or other activities). In addition, land competition can cause problems related to food security or biodiversity loss.
- **Water consumption:** especially related to the hydrogen production via electrolysis (approx. 9 litters of water per kg of hydrogen produced). This can have impacts in water sources (need of alternative water management processes, but e.g. desalination is energy-intensive), and also on ecosystems (and agriculture) related to water stress.
- **Emissions and climate**: in the case of green hydrogen, the emissions of GHGs can be hindered in the life cycle (e.g. wind turbines to generate energy for electrolysis), or in the leakages from hydrogen economy in the production, storage distribution or use. In addition, these leakages can have effects on the climate (hydrogen indirectly contributes to the radiative forcing), and also in other aspects that need to be considered as the stratospheric ozone depletion.

The environmental KPIs therefore must evaluate or monitor the GHGs emissions, water usage, land occupation and also impacts on air quality.

As in the case of social indicators, taking into account the SDG framework (target space) previously explained, the final proposed indicators that can be included in a modelling framework are the following (see Soergel et al., 2021):

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1. **Planet integrity:**
   - SDG13 (Climate action):
     - GHG emissions (Kyoto gases, AR5 global warming potentials). Units: Gt CO2 eq/yr
     - Global Mean Temperature (GMT) increase according to Paris Goals. Units: ˚C
     - Cumulative CO2 emissions, counted from 2011. Units: Gt CO2/yr
     - Cumulative land-use change emissions. Units: Gt CO2/yr
   - SDG14 (Life below water). Ocean acidification can be affected by the effects of increasing global temperatures indirectly promoted by green hydrogen leakages. However, these effects are not the most important (these are very indirect).
     - Aragonite saturation state. Units: no units.
     - 14.3.1: Average marine acidity (pH) measured at the surface Units: no units.
   - SDG15 (Life on land):
     - Biodiversity Intactness Index. Units: ha
     - Forest area as a proportion of total land area. Units: ha
     - Primary forests as share of total terrestrial land area (excluding surface water). Units: ha
     - Land area afforested. Units: km2/Year
     - Global area of forested land as % of original forest cover Units: km2/Year
     - Other natural land as share of total land area. Units: ha.
2. **Sustainable resources:**
   - SDG2 (Zero hunger).
     - Food availability. Units: kg/cap·day. (Same as the one defined in "societal" impacts).
   - SDG6 (Clean water and sanitation).
     - Agricultural water use. Units: km3/yr.
     - Fertilizer use. Units: kgN/Year.
     - Water consumption for electricity. Units: %
     - "Area under water stress (water stress index for most water- scarce month/season)". Units: %.
   - SDG7 (Affordable and clean energy). Already covered in the "techno-economic analysis).

5.4 Representation of KPIs for evaluating the effects of hydrogen in WILIAM

In this subsection, the KPIs listed above have been linked to the application in WILIAM model, detecting those that are already integrated (taking as reference version 1.3 of WILIAM), and those that could be integrated with different levels of difficulty. This can be checked in

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Annex V. Representation of KPIs for evaluating the effects of hydrogen in WILIAM. As can be seen in the Table 9 , WILIAM has an appropriate structure that allows the evaluation from an integrated perspective (sustainability approach), however, as most of the IAMs, social dimensions is not so analysed as energy, economy, and environment.

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6 Conclusions and future work

The work performed in Task 2.1 has developed a valuable unified terminology and classification for the hydrogen sector, very useful for policy analysis, as well as an assessment of the hydrogen policies that have been published so far mainly in the European Union and in countries in different regions of the world on a case-by-case basis.

The analysis carried out points to a growth in the importance of the hydrogen economy in recent times, and suggests that policies focusing on hydrogen production and its use in the transport and industrial sectors are being prioritised. It also highlights the use of direct investment as an economic instrument for the promotion of hydrogen projects and the setting of codes and standards as a regulatory instrument to foster the growth of the hydrogen economy.

This vision may be appropriate for a hydrogen economy taking its first steps and expecting slow and steady growth. However, if a significant impact on the decarbonisation of the economy and the achievement of medium- and long-term targets is expected, an aligned legislative effort is needed for all energy sectors and links in the hydrogen value chain. It is crucial that hydrogen consumption covers as many appropriate sectors as possible to make the deployment of large production plants profitable. It is also essential to plan generation based not only on consumption, but also on transport to end use, and to take into account the need for an electrolyser manufacturing industry to achieve the planned capacities.

The transition process towards a unified industry cannot be overlooked either: in the short term, generation and consumption may be unbalanced, and it will be necessary to adapt current systems to a new reality of low CO_2 emissions and hydrogen consumption. During this phase, it could be beneficial to promote hydrogen generation through fossil fuels with carbon capture (blue hydrogen) or the combined use of hydrogen with other fuels in its final application.

In this regard, hydrogen policies have been mostly promoted solely from an energy perspective, but it may also be important to consider the potential impact they could have on other sectors or systems, such as water or land use, social impact, or emissions generation, and consequently jointly promote cross-sectorial policies that alleviate the potential undesired impacts. It would be beneficial to take this integrated (and sustainable) approach to hydrogen policies into account in the future work of the project, which will be developed in tasks 4.1 and 5.2 by modelling policies to evaluate them in WILIAM, as well as in the policy brief recommendations for task 5.4. In this regard, WILIAM has good capabilities for this integrated approach, as it covers important KPIs that could be appropriate to evaluate hydrogen deployment in a sustainable way.

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Annexes

Annex I. Policy Objectives and Targets

Table 5. Policy Objectives & Targets

Policy	Jurisdiction	Policy Sector	Value Chain	Description	Year	Link
EU Hydrogen Strategy	Europe	General	Hydrogen production	40GW Electrolysers 2030 24% H_2 final energy 2050	2020	https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301
Net Zero by 2050	Global	General	Not applicable	-	2021	https://www.iea.org/reports/net-zero-by-2050
Fit for 55	Europe	Industry Transport Electricity generation	Hydrogen production Hydrogen supply	42% of RFNBO's in industry 2030	2021	https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/
REPowerEU	Europe	Industry Transport	Hydrogen production Hydrogen transportation Hydrogen supply	10 + 10 mt of Hydrogen 2030 75% of RFNBO's industry 2030 5% of RFNBO's transport 2030	2022	https://energy.ec.europa.eu/system/files/2022-05/COM_2022_230_1_EN_ACT_part1_v5.pdf
European Hydrogen Backbone	Europe	General	Hydrogen transportation	28000 Km pipeline 2030 53000 Km pipeline 2040	2023	https://ehb.eu/

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Policy	Jurisdiction	Policy Sector	Value Chain	Description	Year	Link
Alternative Fuels Infrastructure Regulation	Europe	Transport	Hydrogen supply	-	2023	https://europa.eu/!N8bWTk
ReFuelEU	Europe	Transport	Hydrogen supply	5% of SAF in aviation by 2030 63% of SAF in aviation by 2050	2023	https://www.consilium.europa.eu/en/press/press-releases/2023/04/25/council-and-parliament-agree-to-decarbonise-the-aviation-sector/
Net Zero Industry Act	Europe	Industry	Not applicable	-	2024	https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en
EU Renewable Energy Directive	Europe	Industry Transport	Hydrogen production Hydrogen supply	42% of RFNBO's industry 2030 1% of RFNBO's transport 2030	2024	https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202302413 https://hydrogeneurope.eu/wp-content/uploads/2024/06/H2Europe_RED-III_Position-Paper.pdf

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Annex II. Policy Instruments

Table 6. Policy Instruments

Policy	Jurisdiction	Type of Instrument	Subtype of instrument	Description	Year	Link
CO_2 Emission Standards	Europe	Regulatory instrument	Codes and standards	Air pollution standards	2023	https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-CO₂-emissions-vehicles/CO₂-emission-performance-standards-cars-and-vans_en
Emissions Trading Systems	Europe	Economic instrument	Market-based instrument	CO_2 trading schemes	2003	https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02003L0087-20230605
Emissions Trading Systems 2	Europe	Economic instrument	Market-based instrument	CO_2 trading schemes	2023	https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/ets-2-buildings-road-transport-and-additional-sectors_en https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2023.130.01.0134.01.ENG
IPCEI Hy2Tech	Europe	Economic instrument	Direct investment	Technology investments	2022	https://ec.europa.eu/commission/presscorner/detail/en/ip_22_4544
IPCEI Hy2Use	Europe	Economic instrument	Direct investment	Technology & infrastructure investments	2022	https://ec.europa.eu/commission/presscorner/detail/en/ip_22_5676
IPCEI Hy2Infra	Europe	Economic instrument	Direct investment	Infrastructure investments	2024	https://ec.europa.eu/commission/presscorner/detail/es/ip_24_789

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Policy	Jurisdiction	Type of Instrument	Subtype of instrument	Description	Year	Link
H2Global	Global	Economic instrument	Market-based instrument	Competition-based procurement process & sales	2021	https://h2-global.de/
European Hydrogen Bank	Europe	Economic instrument	Fiscal incentive	Green H_2 gap subsidy	2023	https://energy.ec.europa.eu/news/commission-outlines-european-hydrogen-bank-boost-renewable-hydrogen-2023-03-16_en https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0156&qid=1682349760946
			Market-based instrument	EU H_2 domestic market		
Hydrogen and Decarbonised Gas markets package	Europe	Regulatory instrument	Codes and standards	Harmonised rules on gas quality	2023	https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/hydrogen-and-decarbonised-gas-market-package_en https://www.consilium.europa.eu/en/press/press-releases/2023/03/28/gas-package-member-states-set-their-position-on-future-gas-and-hydrogen-market/
European Hydrogen Backbone	Europe	Soft instrument	Voluntary approaches	Infrastructure projection agreements	2020	https://ehb.eu/ https://ehb.eu/files/downloads/EHB-2023-20-Nov-FINAL-design.pdf
TEN-E Regulation	Europe	Regulatory instrument	Codes and standards	Hydrogen transport regulations	2022	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2022.152.01.0045.01.ENG&toc=OJ%3AL%3A2022%3A152%3ATOC
EU Renewable Energy Directive II	Europe	Regulatory instrument	Codes and standards	RFNBOs Regulation	2023	https://energy.ec.europa.eu/news/renewable-hydrogen-production-new-rules-formally-adopted-2023-06-20_en

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Policy	Jurisdiction	Type of Instrument	Subtype of instrument	Description	Year	Link
Hydrogen for Development Partnership (H4D)	Europe	Soft instrument	Voluntary approaches	Global initiative	2022	https://www.worldbank.org/en/news/press-release/2022/11/15/hydrogen-for-development-partnership-h4d-launch
H2GLASS	Europe	R & D instrument	-	Public R&D funding	2022	https://cordis.europa.eu/project/id/101092153
Clean Hydrogen Production Tax Credit (45V)	Global	Economic instrument	Fiscal incentive	Green H_2 gap subsidy	2022	https://rhg.com/research/clean-hydrogen-45v-tax-guidance/#:~:text=The%2045V%20tax%20credit%20provides,%E2%80%94up%20to%20%243%2Fkg.
Support large-scale projects	Europe	Economic instrument	Direct investment	Project funding	2022	https://climate.ec.europa.eu/eu-action/funding-climate-action/innovation-fund/large-scale-calls_en
Net Zero Industry Act	Europe	Regulatory instrument	Codes and standards	Boosting strategic technology	2023	https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en
		Economic instrument	Fiscal incentive	Investment facilitation		
		Soft instrument	Information and education	Enhancing skills		
		R & D instrument	-	Public R&D funding		
Clean Hydrogen Partnership	Europe	R & D instrument	-	R&D funding	2023	https://www.clean-hydrogen.europa.eu/call-proposals-2023-closed_en
International Hydrogen Trade Forum	Global	Soft instrument	Voluntary approaches	Global initiative	2023	https://www.cleanenergyministerial.org/launch-of-the-international-hydrogen-trade-forum-to-accelerate-global-collaboration/

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Policy	Jurisdiction	Type of Instrument	Subtype of instrument	Description	Year	Link
Hydrogen Public Funding Compass	Europe	Soft instrument	Information and education	Online guide for stakeholders	2021	https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide_en
European Hydrogen Regulation	Europe	Regulatory instrument	Codes and standards	Rules for cross-border H_2	2023	https://www.consilium.europa.eu/en/press/press-releases/2023/03/28/gas-package-member-states-set-their-position-on-future-gas-and-hydrogen-market/
		Economic instrument	Fiscal incentive	Removing tariffs for H_2		
International Partnership of Hydrogen (IPHE)	Global	Soft instrument	Voluntary approaches	Global initiative	2023	https://www.iphe.net/
European Clean Hydrogen Alliance (ECH2A)	Europe	Soft instrument	Voluntary approaches	European H_2 Alliance	2020	https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-clean-hydrogen-alliance_en
Safety Planning and Management in Hydrogen Projects	Europe	Soft instrument	Information and education	Safety planning guidance	2023	https://www.clean-hydrogen.europa.eu/get-involved/european-hydrogen-safety-panel-0/reference-documents_en
Recovery and Resiliency Facility for clean Energy	Europe	Economic instrument	Direct investment	Public Funding	2021	https://energy.ec.europa.eu/topics/funding-and-financing/recovery-and-resiliency-facility-clean-energy_en
Modernisation Fund	Europe	Economic instrument	Direct investment	Low-income countries fund	2018	https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/modernisation-fund_en https://single-market-

Policy	Jurisdiction	Type of Instrument	Subtype of instrument	Description	Year	Link
						economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide/eu-programmes-funds/modernisation-fund_en#:~:text=The%20Modernisation%20FundEN%E2%80%A2,systems%20and%20improve%20energy%20efficiency. https://modernisationfund.eu/
European Regional Development Fund	Europe	Economic instrument	Direct investment	Regional funding	2021	https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide/eu-programmes-funds/european-regional-development-cohesion-fund-react-eu_en#:~:text=Objectives,through%20grants%20and%20financial%20instruments. https://ec.europa.eu/regional_policy/funding/erdf_en
Cohesion Fund	Europe	Economic instrument	Direct investment	Capital-intensive environmental and transport investments	2021	https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide/eu-programmes-funds/european-regional-development-cohesion-fund-react-eu_en#:~:text=Objectives,through%20grants%20and%20financial%20instruments. https://ec.europa.eu/regional_policy/funding/cohesion-fund_en
Connecting Europe Facility - Energy	Europe	Regulatory instrument	Codes and standards	Infrastructure investment regulation	2021	https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide/eu-programmes-funds/connecting-europe-facility-energy_en

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Policy	Jurisdiction	Type of Instrument	Subtype of instrument	Description	Year	Link
Connecting Europe Facility – Transport	Europe	Economic instrument	Direct investment	Mobility infrastructure investments	2021	https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide/eu-programmes-funds/connecting-europe-facility-transport_en
EU Renewable Energy Directive III	Europe	Regulatory instrument	Codes and standards	RFNBOs Regulation	2023	https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202302413

Annex III. EU National Documents

Table 7. EU National Documents

Country	Document	Description	Year	Link
Austria	Hydrogen Strategy for Austria	1GW Electrolysers 2030 80% Green industry H_2 2030	2022	https://www.bmk.gv.at/dam/jcr:7788d724-3aed-4a88-a452-37f9df5e1357/bmk_wasserstoff_executive-summary_EN_UA.pdf
Belgium	Belgian federal Hydrogen Strategy	150MW Electrolysers 2026	2022	https://economie.fgov.be/sites/default/files/Files/Energy/View-strategy-hydrogen.pdf
Bulgaria	National Roadmap for the Hydrogen Development	150 kt/year H_2 2030 34-49 B€ invested 2030	2023	https://www.deloitte.com/ce/en/related-content/bulgaria-national-hydrogen-roadmap.html
Croatia	HYDROGEN STRATEGY OF THE REPUBLIC OF CROATIA UNTIL 2050	70MW Electrolysers 2030 0.2% H_2 final energy 2030 90 M€ invested 2030	2022	https://mingor.gov.hr/UserDocsImages//UPRAVA%20ZA%20ENERGETIKU//Croatian%20Hydrogen%20Strategy%20ENG%20FIN%2022%208.pdf
Cyprus	GreenH2CY: Green Hydrogen Project for Transport in Cyprus	2MW Electrolysers 2025 150 t/year H_2 2025 4.5 M€ invested 2025	2023	https://ec.europa.eu/assets/cinea/project_fiches/innovation_fund/101103240.pdf https://ec.europa.eu/assets/cinea/country_factsheets/innovation_fund/INNOVFUND_Cyprus.pdf
Czechia	Hydrogen strategy of the Czech Republic	101 kt/year H_2 2030	2021	https://www.mpo.cz/assets/cz/prumysl/strategicke-projekty/2021/9/Hydrogen-Strategy_CZ_2021-09-09.pdf

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Country	Document	Description	Year	Link
Denmark	The government's strategy for Power to X	4.7GW Electrolysers 2030 170 M€ invested 2030	2021	https://ens.dk/sites/ens.dk/files/ptx/strategy_ptx.pdf
Estonia	Estonian Hydrogen Roadmap	150MW Electrolysers 2030 40 kt/year H_2 2030	2023	https://kliimaministeerium.ee/sites/default/files/documents/2023-07/Estonian%20hydrogen%20roadmap%20ENG.pdf
Finland	Finish Government's resolution on hydrogen	10% EU H_2 production 2030 3 Mt/year H_2 2035	2023	https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/164746/VN_2023_19.pdf?sequence=1&isAllowed=y
France	National strategy for the development of decarbonised and renewable hydrogen in France	6.5GW Electrolysers 2030 350 M€ invested 2030	2023	https://www.ecologie.gouv.fr/sites/default/files/SNH2_VF.pdf https://publications.rifs-potsdam.de/rest/items/item_6002974_3/component/file_6002976/content
Germany	National Hydrogen Strategy of the German federal government	5GW Electrolysers 2030 3.4 B€ invested 2030	2023	https://www.bmwk.de/Redaktion/DE/Wasserstoff/Downloads/Fortschreibung.pdf?__blob=publicationFile&v=4 https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=1
Greece	Greece's revised National Energy and Climate Plan	300MW Electrolysers 2030	2023	https://energy.ec.europa.eu/system/files/2020-03/el_final_necp_main_en_0.pdf

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Country	Document	Description	Year	Link
Hungary	HUNGARY'S NATIONAL HYDROGEN STRATEGY	240MW Electrolysers 2030 36 kt/year H2 2030	2021	https://cdn.kormany.hu/uploads/document/a/a2/a2b/a2b2b7ed5179b17694659b8f050ba9648e75a0bf.pdf
Ireland	National Hydrogen Strategy	67-133 kt/year H_2 2030	2023	https://www.gov.ie/pdf/?file=https://assets.gov.ie/263248/f982c10f-eca6-4092-a305-90000e5213ed.pdf#page=null
Italy	Strategia Nazionale Idrogeno Linee Guida Preliminari	5GW Electrolysers 2030 2% H_2 final energy 2030 10 B€ invested 2030	2020	https://www.mimit.gov.it/images/stories/documenti/Strategia_Nazionale_Idrogeno_Linee_guida_preliminari_nov20.pdf
Latvia	Strategy of Latvia for the Achievement of Climate Neutrality by 2050	-	2019	https://unfccc.int/documents/267179
Lithuania	Guidelines for the Development of the Hydrogen Sector in Lithuania in 2024-2030	1.3GW Electrolysers 2030 152.9 kt/year H_2 2030	2022	https://enmin.lrv.lt/uploads/enmin/documents/files/AmberGrid_Draft_Lithuania_Hydrogen_Strategy_vFinalPresIndustry.pdf
Luxembourg	Luxembourg Hydrogen Strategy	300 kt/year H_2 2050	2021	https://gouvernement.lu/dam-assets/documents/actualites/2021/09-septembre/27-turmes-hydrogene/Strategie-hydrogene-LU-executive-summary.pdf
Malta	Malta Low Carbon Development Strategy	-	2021	https://unfccc.int/sites/default/files/resource/MLT_LTS_Nov2021.pdf

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Country	Document	Description	Year	Link
Netherlands	Hydrogen Roadmap the Netherlands	6-8GW Electrolysers 2030 670 kt/year H_2 2030	2022	https://nationaalwaterstofprogramma.nl/documenten/handlerdownloadfiles.ashx?idnv=2379389
Poland	Polish Hydrogen Strategy until 2030	2GW Electrolysers 2030	2021	https://www.gov.pl/attachment/06213bb3-64d3-4ca8-afbe-2e50dadfa2dc
Portugal	PORTUGAL NATIONAL HYDROGEN STRATEGY (EN-H2)	2GW Electrolysers 2030 5% H_2 final energy 2030 7 B€ invested 2030	2020	https://www.energias-renovables.com/ficheroenergias/EN_H2_ENG.pdf
Romania	National Hydrogen Strategy and Action Plan for Romania	4GW Electrolysers 2030 152.9 kt/year H_2 2030	2023	https://energie.gov.ro/wp-content/uploads/2023/05/EN-Project-Action-Plan-for-implementing-the-National-Hydrogen-Strategy.pdf
Slovakia	National Hydrogen Strategy: Ready for the future	13% H_2 final energy 2050 200 kt/year H_2 2030	2021	https://rokovania.gov.sk/RVL/Material/26128/1
Slovenia	INTEGRATED NATIONAL ENERGY AND CLIMATE PLAN OF THE REPUBLIC OF SLOVENIA	7% H_2 final energy 2040	2020	https://www.clean-hydrogen.europa.eu/system/files/2018-06/S2-Slovenia.pdf
Spain	Hydrogen Roadmap: a commitment to renewable hydrogen	4GW Electrolysers 2030 25% Green H_2 2030 8.9 B€ invested 2030	2020	https://commission.europa.eu/projects/hydrogen-roadmap_en
Sweden	Strategy for fossil free competitiveness - HYDROGEN	3GW Electrolysers 2030 8GW Electrolysers 2045	2021	https://fossilfrittsverige.se/wp-content/uploads/2021/01/Hydrogen_strategy_for-_fossil_free_competitiveness_ENG.pdf

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Annex IV. Rest of the World National Documents

Table 8. Rest of the World National Documents

Region	Country	Documents	Description	Year	Link
LATAM	Chile	National Green Hydrogen Strategy	5 GW Electrolysers 2025 25 GW Electrolysers 2030	2020	https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf
	Brazil	Lei 14.948/24	-	2024	https://www2.camara.leg.br/legin/fed/lei/2024/lei-14948-2-agosto-2024-796030-publicacaooriginal-172539-pl.html
	Argentina	Estrategia Nacional para el Desarrollo de la Economía del Hidrógeno	30 GW Electrolysers 2050 5 Mt/year H_2 2050	2023	https://www.argentina.gob.ar/sites/default/files/2023/07/estrategia_nacional_de_hidrogeno_-_sae.pdf
China	China	China 2021-2035 plan on hydrogen energy development	5.4 GW Electrolysers 2025 0.2 Mt/year H_2 2025	2023	https://en.ndrc.gov.cn/news/pressreleases/202203/t20220329_1321487.html
India	India	National Green Hydrogen Mission. Decarbonising India, Achieving Net-Zero Vision	5 Mt/year H_2 2030 10% Global H_2 2050	2023	https://mnre.gov.in/national-green-hydrogen-mission/

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Region	Country	Documents	Description	Year	Link
Russia	Russia	Energy Strategy of the Russian Federation until 2035 Action plan 'Development of Hydrogen Energy until 2035' Concept of Hydrogen Energy Development in the Russian Federation	0.2 Mt/year H_2 2024 2-12 Mt/year H_2 2035 15-50 Mt/year H_2 2050	2021	https://www.csis.org/analysis/russias-hydrogen-energy-strategy#:~:text=Russia's%20primary%20goal%20is%20to,and%202%20million%20by%202035. https://resourcehub.bakermckenzie.com/en/resources/hydrogen-heat-map/emea/russia/topics/hydrogen-developments#:~:text=August%202021%3A%20the%20Russian%20Government,target%20of%200.2%20million%20tons.

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Region	Country	Documents	Description	Year	Link
EASOC	Australia	Australia's National Hydrogen Strategy National Hydrogen Strategy Review	1GW Electrolysers 2030 0.36 Mt/year H_2 2030 21% Global H_2 2050	2023	https://www.dcceew.gov.au/sites/default/files/documents/australias-national-hydrogen-strategy.pdf https://storage.googleapis.com/files-au-climate/climate-au/p/prj277759bb48cda6df2c230/public_assets/National%20Hydrogen%20Strategy%20Review%20-%20Consultation%20Paper%20-%20July%202023.pdf
	Japan	Revised Basic Hydrogen Strategy	3 Mt/year H_2 2030 15GW Electrolysers 2030 100 B$ invested 2050	2023	https://resourcehub.bakermckenzie.com/en/resources/hydrogen-heat-map/asia-pacific/japan/topics/hydrogen-developments https://www.mfat.govt.nz/en/trade/mfat-market-reports/japan-hydrogen-strategy-november-2023

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Region	Country	Documents	Description	Year	Link
	South Korea	Hydrogen Economy Roadmap First Hydrogen Law	1.9 Mt/year 2030 38 B$ invested 2030 15 GW/year H_2 Fuel Cells	2022	https://www.csis.org/analysis/south-koreas-hydrogen-industrial-strategy https://research.csiro.au/hyresource/policy/international/republic-of-korea-south-korea/
USMCA	USA	U.S. National Clean Hydrogen Strategy and Roadmap Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan	10 Mt/year 2030 9.5 B$ invested 2030 3 GW/year Electrolysers 2030	2023	https://research.csiro.au/hyresource/policy/international/united-states/ https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf?sfvrsn=c425b44f_5
	Mexico	*Mexico lacks public policy for green hydrogen*			
	Canada	Hydrogen Strategy for Canada	4 Mt/year 2030 20 Mt/year 2050	2020	https://natural-resources.canada.ca/sites/nrcan/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf https://resourcehub.bakermckenzie.com/en/resources/hydrogen-heat-map/north-america/canada/topics/hydrogen-developments

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Region	Country	Documents	Description	Year	Link
UK	UK	UK Hydrogen Strategy	10GW H_2 production 2030 5 B$ invested 2030	2023	https://research.csiro.au/hyresource/policy/international/united-kingdom/ https://resourcehub.bakermckenzie.com/en/resources/hydrogen-heat-map/emea/united-kingdom/topics/hydrogen-developments https://assets.publishing.service.gov.uk/media/64e36b294002ee000d560c9f/hydrogen-strategy-update-to-the-market-august-2023.pdf
ROW	Morocco	Feuille de route de hydrogène vert	5.2 GW Electrolysers 2030 23 GW Electrolysers 2040 52.8 GW Electrolysers 2050	2021	https://www.mem.gov.ma/Lists/Lst_rapports/Attachments/36/Feuille%20de%20route%20de%20hydrog%C3%A8ne%20vert.pdf
	Norway	The Norwegian Government's hydrogen strategy	-	2021	https://www.regjeringen.no/contentassets/40026db2148e41eda8e3792d259efb6b/y-0127e.pdf
	Saudi Arabia	National strategy under development	4 GW Electrolysers 2026 2.9 Mt/year H_2 2030	-	https://isa-ghic.org/countries/saudi-arabia
	South Africa	South Africa's Just Energy Transition Investment Plan (JET IP)	60 GW Electrolysers 2050 6-10 Mt/year 2050 98.7 B$ invested 2030	2022	https://www.climatecommission.org.za/publications/sa-jet-ip

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Region	Country	Documents	Description	Year	Link
	Switzerland	Futur de l'hydrogène en Suisse. Éventuelle régulation du réseau d'hydrogène pour encadrer son développement	0.3-0.6 Mt/year H_2 2050	2023	https://www.bfe.admin.ch/bfe/en/home/versorgung/wasserstoff.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZnIvcHVibGljYX/Rpb24vZG93bmxvYWQvMTE1NTE=.html
	Turkey	Türkiye Hidrojen Teknolojileri Stratejisi ve Yol Haritası	3 GW Electrolysers 2030 5 GW Electrolysers 2035 70 GW Electrolysers 2053	2023	https://climate-laws.org/documents/hydrogen-strategy-2023_c310?q=green+hydrogen+turkiye&r=europe-central-asia&y=2019&y=2024&id=hydrogen-strategy-2023_4d3c

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Annex V. Representation of KPIs for evaluating the effects of hydrogen in WILIAM

Table 9. Representation of KPIs for evaluating the effects of hydrogen in WILIAM

MODULE	Proposed indicator	units	Available in WILIAM?	Proxy available?	Is it SDG?	Difficulty implementation in WILIAM	Relevance	Comments/clarifications
Energy	GHG Emissions intensity of hydrogen production	kg CO_2eq/kg H_2	yes	-	No	-	Medium	This considers CO_2 emissions associated with the production of hydrogen, including indirect emissions associated with the production of electricity used in the electrolysers.
Energy	Share of RES in hydrogen production	%	yes	-	No	-	Medium	
Energy	CO_2 emission avoidance by sector	Mt CO_2/year	no	yes	No	Low	High	This indicator quantifies the CO_2 emissions that have been avoided in end uses due to clean hydrogen (and its derivatives) uses.
Energy	Hydrogen production by technology	Mt H_2/year	yes	-	No	-	High	By technology' includes the different hydrogen production routes, e.g. electrolysis, from fossil fuels with or without CCUS, etc.
Energy	Hydrogen demand by sector (incl. H_2-based fuels)	Mt H_2/year	yes	-	No	-	High	'By sector' includes all possible categories, e.g. steel sector, chemical sector, different transport modes, etc.
Energy	Flows of hydrogen trade across regions	Mt H_2/year	no	no	No	High	Low	

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MODULE	Proposed indicator	units	Available in WILIAM?	Proxy available?	Is it SDG?	Difficulty implementation in WILIAM	Relevance	Comments/clarifications
Energy	Hydrogen production capacity by technology	Mt H2/year	no (only for electrolysis)	no	No	Medium	Medium	
Energy	Electrolysis capacity by subtechnology	GW	yes	-	No	-	High	
Energy	Electricity demand from different sources for electrolysers	TWh/year	no	yes	No	Low	Medium	
Energy	Installed power capacity connected to the electrical grid by technology	MW	yes	-	No	-	Medium	
Energy	Quantity of transmitted hydrogen by transmission mode	kt H2/year	no	no	No	High	Medium	"Transmitted" includes both transmission and distribution. The indicator also includes the different forms of transmission and distribution of hydrogen and its derived fuels, e.g. ships, pipelines, trucks, etc.
Energy	Kilometres of hydrogen pipelines (new and repurposed)	km	no	no	No	High	High	

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MODULE	Proposed indicator	units	Available in WILIAM?	Proxy available?	Is it SDG?	Difficulty implementation in WILIAM	Relevance	Comments/clarifications
Energy	Quantity of stored hydrogen (by storage mode)	kt H2/year	no	no	No	Medium	Medium	The indicator includes the different forms of storage of hydrogen and its derived fuels, e.g. compressed hydrogen, salt caverns, etc.
Energy	Hydrogen storage capacity (by storage mode)	TWh	no	no	No	Medium	High	The indicator includes the different forms of storage of hydrogen and its derived fuels, e.g. compressed hydrogen, salt caverns, etc.
Energy	Area necessary to place the installation for hydrogen storage	ha	no	no	No	Medium	Low	
Energy	Number of refuelling stations for transport	No. stations	no	no	No	High	Low	
Energy	Number of hydrogen vehicles by transport mode	No. vehicles	no	no	No	Medium	Medium	
Energy	Percentage of hydrogen vehicles in total fleet by transport mode	%	no	no	No	Medium	Medium	
Energy	Total primary energy supply	EJ/year	yes	-	No	-	Medium	The indicator comprises the full system
Energy	Share of RES in the primary energy mix	%	yes	-	No	-	Medium	The indicator comprises the full system
Energy	Share of RES in the final energy mix	%	yes	-	Yes	-	Medium	The indicator comprises the full system
Energy	Total final energy per capita	GJ/person/ year	yes	-	No	-	Medium	The indicator comprises the full system

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MODULE	Proposed indicator	units	Available in WILIAM?	Proxy available?	Is it SDG?	Difficulty implementation in WILIAM	Relevance	Comments/clarifications
Energy/ Economy	Total final energy consumption intensity of GDP	J/$	yes	-	No	-	Medium	The indicator comprises the full system
Energy/ Economy	Total primary energy supply intensity of GDP	J/$	yes	-	No	-	Medium	The indicator comprises the full system
Energy	Primary to final energy ratio	dimensionless	yes	-	No	-	High	The indicator comprises the full system
Energy	CO2eq intensity of primary energy	kg CO2eq/J	yes	-	No	-	Medium	The indicator comprises the full system
Energy	Total GHG emissions from the energy module	kg CO2eq/year	yes	-	No	-	High	The indicator comprises the full system
Energy	EROIst of the system	dimensionless	yes	-	No	-	High	The indicator comprises the full system
Energy	EROIfinal of the system	dimensionless	no	no	No	Medium	High	The indicator comprises the full system
Energy	EROIst of hydrogen	dimensionless	yes	-	No	-	Medium	
Energy	EROIfinal of hydrogen	dimensionless	no	no	No	Medium	Medium	

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MODULE	Proposed indicator	units	Available in WILIAM?	Proxy available?	Is it SDG?	Difficulty implementation in WILIAM	Relevance	Comments/clarifications
Materials	Cumulative material demand vs current reserves (for each material)	%	yes	-	No	-	High	Indicator calculated on a global scale
Materials	Cumulative material demand vs current resources (for each material)	%	yes	-	No	-	High	Indicator calculated on a global scale
Materials	Annual material demand vs 2015 demand (for each material)	%	yes	-	No	-	Medium	Indicator calculated on a global scale
Materials	Recycled content (RC) for each material	%	yes	-	No	-	Medium	Indicator calculated on a global scale
Economy	Total investments along the hydrogen chain	$ billion/year	no (only for electrolysers)	no	No	Medium	High	These are the economic investments in each part of the chain: production, transmission and distribution, storage and end uses.
Economy	Levelized cost of hydrogen (LCOH)	$/kg	no	no	No	Medium	Medium	The indicator is to be calculated per hydrogen production technology.
Economy	Levelized cost of storage (LCOS) for hydrogen	$/kg	no	no	No	Medium	Low	The indicator is to be calculated per hydrogen storage mode.

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MODULE	Proposed indicator	units	Available in WILIAM?	Proxy available?	Is it SDG?	Difficulty implementation in WILIAM	Relevance	Comments/clarifications
Economy	Hydrogen transport cost	$/kg	no	no	No	High	Low	The indicator is to be calculated per hydrogen transmission mode.
Economy	Delivered hydrogen cost (incl. production, transport and storage)	$/kg	no	no	No	High	Low	The indicator includes the three levelized costs above: production, transport and storage. It is also to be calculated by differentiating the hydrogen production technologies
Economy	Levelized cost of steel using hydrogen vs coal	$/kg	no	no	No	Medium	Low	
Economy	Gross domestic product per capita by region	$/person	yes	-	Yes	-	High	
Society and Demography	Humand Development Index (HDI).	dimensionless	yes	-	No	-	High	
Society and Demography	Number of people living under extreme poverty conditions	%	no	no	Yes			
Society and Demography	Food expenditure share	%	no	no	Yes			

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MODULE	Proposed indicator	units	Available in WILIAM?	Proxy available?	Is it SDG?	Difficulty implementation in WILIAM	Relevance	Comments/clarifications
Society and Demography	Healthy life expectancy	yr	yes	-	Yes	-		
Society and Demography	Under-5 mortality rate	%	yes	-	Yes	-		
Society and Demography	Disability adjusted life years (DALYs) lost from particulate matter (PM 2.5)	DALYs/yr	no	no	Yes	High	Medium	
Society and Demography	Education gender gap in (a) secondary eduation (age 20-24 w at least lower secondary education); and (b) primary eduction (age 15-19 with at least primary education)	%	no	no	Yes	High	Medium	
Society and Demography	Female estimated earned income over male	%	no	no	Yes	High	Low	

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MODULE	Proposed indicator	units	Available in WILIAM?	Proxy available?	Is it SDG?	Difficulty implementation in WILIAM	Relevance	Comments/clarifications
Society and Demography	Annual growth rate of real GDP per capita	%	yes	-	Yes	-		
Society and Demography	Unemployment rate	%	yes	-	Yes	-		
Society and Demography	Share of population with <50% of national median income	%	no	no	Yes	Medium	Low	For simplification, effects on employment can be represented in "unemployment rate" KPI in WILIAM
Society and Demography	Average income of bottom 40% relative to national average	%	no	no	Yes	Medium	Low	For simplification, effects on employment can be represented in "unemployment rate" KPI in WILIAM
Society and Demography	Share of people exposed to annual average PM2.5>25 µg/m3	%	no	no	Yes	High	High	
Society and Demography	Number of people living in slums	%	no	no	Yes	High	Low	
Society and Demography	Food availability	kg/cap·day	yes	-	Yes	-		

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MODULE	Proposed indicator	units	Available in WILIAM?	Proxy available?	Is it SDG?	Difficulty implementation in WILIAM	Relevance	Comments/clarifications
Society and Demography	Population without access to improved water source piped	%	no	no	Yes	High	Medium	For simplification it could be covered in the water module (relate it to water stress)
Society and Demography	Population without access to improved sanitation facility	%	no	no	Yes	High	Medium	For simplification it could be covered in the water module (relate it to water stress)
Society and Demography	Population without basic electricity access	%	no	no	Yes	High	Medium	For simplification it could be covered in the water module (relate it to water stress)
Climate	GHG emissions (Kyoto gases, AR5 global warming potentials)	Gt CO2 eq/yr	yes	-	Yes	-		This is broader than the correspondent energy related KPI (GHG emissions intensity of hydrogen production), thus evaluation indirect effects of hydrogen in GHG emissions (e.g. due to the life cycle, related land use changes, or due to leakages, etc.)
Climate	Global Mean Temperature (GMT) increase according to Paris Goals	ºC	yes	-	Yes	-		
Climate	Cumulative CO2 emissions, counted from 2011	Gt CO2/yr	yes	-	Yes	-		

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MODULE	Proposed indicator	units	Available in WILIAM?	Proxy available?	Is it SDG?	Difficulty implementation in WILIAM	Relevance	Comments/clarifications
Climate	Cumulative land-use change emissions	Gt CO2/yr	no	yes	Yes	Low		
Climate	Aragonite saturation state	dimensionless	yes	-	Yes	-		
Climate	Average marine acidity (pH) measured at the surface	dimensionless	yes	-	Yes	-		
Land	Biodiversity Intactness Index	ha	no	no	Yes	Medium	High	In future updates of the model biodiversity aspects will be included in WILIAM. In particular a proxy variable will be integrated for biodiversity: Biodiversity Habitat integrity.
Land	Forest area as a proportion of total land area	ha	no	yes	Yes	Low		
Land	Primary forests as share of total terrestrial land area (excluding surface water)	ha	no	yes	Yes	Low		
Land	Land area afforested	km2/Year	no	yes	Yes	Low		
Land	Global area of forested land as % of original forest cover	km2/Year	no	yes	Yes	Low		

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MODULE	Proposed indicator	units	Available in WILIAM?	Proxy available?	Is it SDG?	Difficulty implementation in WILIAM	Relevance	Comments/clarifications
Land	Other natural land as share of total land area	ha	no	yes	Yes	Low		
Water	Agricultural water use	km3/yr	yes	-	Yes	-		
Water	Fertilizer use	kgN/Year	yes	-	Yes	-		
Water	Water consumption for electricity	km3/yr	no	no	Yes	Medium	Medium	
Water	Area under water stress (water stress index for most water-scarce month/season)	%	yes	-	Yes	-		
Water	Water consumption of hydrogen sector	km3/yr	no	no	No	Medium	High	Still water consumed by hydrogen is not modelled. To be checked in the future.

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