Study of the Development Plan and Implementation of the Croatian Hydrogen Strategy by 2050

REPORT

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LIST OF ABBREVIATIONS

ABBREVIATION	DESCRIPTION
AEL	Alkaline Electrolyser
AFIR	Alternative Fuels Infrastructure Regulation
BEV	Battery Electric Vehicle
CCU / CCS	Carbon Capture and Usage / Storage
CEF	Connecting Europe Facility
CHA	Croatian Hydrocarbon Agency
EHB	European Hydrogen Backbone
ETS	Emission Trading System
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
HRS	Hydrogen Refuelling Station
ICE	Internal Combustion Engine
IPCEI	Important Projects of Common European Interest
LNG	Liquefied Natural Gas
NECP	National Integrated Energy and Climate Plan
NPCC	National Programme for Cohesion and Coherence
NPOO (NRRP)	National Recovery and Resilience Plan
NUTS	Nomenclature of Territorial Units for Statistics
OG	Official Gazette
PEM	Proton Exchange Membrane (Electrolyser)
RED	Renewable Energy Directive
RFNBO	Renewable Fuel of Non-Biological Origin
SMR	Steam Methane Reforming
SOE	Solid Oxide Electrolysers
TEN-T	Trans-European Transport Network
TRL	Technology Readiness Level

1. INTRODUCTION

1.1. Background: The Croatian Hydrogen Strategy

The **European "Hydrogen Strategy for a Climate-Neutral Europe"**, adopted in July 2020, highlights the significance of scaling-up hydrogen applications as essential for the comprehensive decarbonization of the economy, particularly within the energy sector, to meet the **2050 climate neutrality goals**. Although the use of renewable hydrogen is not yet widespread in the European Union and hydrogen is predominantly produced from natural gas (resulting in CO_2 emissions), lower costs of renewable electricity, technological advancements, and the urgent need to significantly reduce greenhouse gas (GHG) emissions present new opportunities for increased hydrogen utilization.

In alignment with the EU's hydrogen policy, Croatia adopted the **Hydrogen Strategy of the Republic of Croatia Until 2050**[1] in 2022, outlining a **national framework for hydrogen production and use**, focusing on renewable and low-carbon hydrogen as alternatives to fossil fuels. This Strategy emphasises the role of hydrogen and a hydrogen-based economy as pivotal elements of the **green energy transition**, aiming to meet clean energy targets and reduce GHG emissions. Hydrogen is deemed crucial for decarbonizing the national economy, particularly in sectors with limited alternative technological options or where electrification would not be economically viable.

The **Renewable Energy Directive (RED)**[2], including recent amendments, sets ambitious goals for the transport and industrial sectors regarding the use of renewable hydrogen, introducing the category of 'Renewable Fuels of Non-Biological Origin' (RFNBOs). RFNBOs encompass gaseous and liquid fuels derived from renewable sources other than biomass, specifically highlighting hydrogen produced via water electrolysis using renewable electricity, and synthetic liquid fuels produced from such hydrogen.

The Croatian Hydrogen Strategy for 2050 concentrates specifically on the production of hydrogen and related synthetic fuels as defined by the RED. The Strategy's development plan devised in the present Study aims at strategically positioning Croatia by leveraging its unique strengths in the hydrogen value chain, encompassing production, storage, transportation, distribution, and use of hydrogen, as well as related technologies. The Study will also outline cooperative modalities with essential stakeholders and partners, including governmental bodies, institutions, research entities, professional associations, NGOs, financial institutions, public economic entities, and hydrogen project promoters, establishing clear guidelines and a timeline for implementation. Based on the current status of hydrogen projects in Croatia and the **institutional and regulatory framework**, priority activities until 2030 are proposed in the form of pilot projects.

[1] [OG40/22 2022]
[2] [REDIII 2023]

1.2. Strategic Position and Objectives of this Study

The present "**Study on the Development Plan and Implementation of the Croatian Hydrogen Strategy by 2050**", hereinafter referred to as the Study, outlines a detailed roadmap for integrating hydrogen into Croatia's energy system. The Croatian Hydrogen Strategy, hereinafter referred to as the Strategy, in alignment with the European Union's climate neutrality goals, already highlights the pivotal role of **renewable hydrogen** in the **green energy transition**. By leveraging its unique geographical position and existing infrastructure, Croatia aims to establish a robust **hydrogen economy** that will significantly reduce greenhouse gas (GHG) emissions, enhance energy security, and foster economic growth. Regarding scenario development the main background documents are:

- Hydrogen Strategy for Climate-Neutral Europe (Communication from the Commission: A hydrogen strategy for a climate-neutral Europe, 2020)
- Hydrogen Strategy of the Republic of Croatia Until 2050 (Hydrogen Strategy of the Republic of Croatia Until 2050 (Hrvatska strategija za vodik do 2050. godine), 2022)
- Integrated National Energy and Climate Plan for the Republic of Croatia for the Period 2021-2030 (including revision of June, 2023) (Ministry of Economy and Sustainable Development Croatia (Ministarstvo gospodarstva i održivog razvoja), 2023)
- Low-Carbon Development Strategy of the Republic of Croatia Until 2030 with a View to 2050 (Low-Carbon Development Strategy of the Republic of Croatia Until 2030 with a View to 2050 (Strategija niskougljičnog razvoja Republike Hrvatske do 2030. s pogledom na 2050. godinu), 2021)
- Scenario for Achieving Climate Neutrality in the Republic of Croatia by 2050 (2021) (Ministry of Economy and Sustainable Development Croatia (Ministarstvo gospodarstva i održivog razvoja), 2021)
- Energy Development Strategy of the Republic of Croatia until 2030 with an Outlook to 2050 (Energy Development Strategy of the Republic of Croatia until 2030 with an Outlook to 2050 (Strategija energetskog razvoja Republike Hrvatske do 2030. s pogledom na 2050. godinu), 2020)
- Transport Strategy of the Republic of Croatia for the Period 2017 to 2030 (Transport Strategy of the Republic of Croatia for the Period 2017 to 2030, 2017)
- National Resilience and Recovery Plan 2021 – 2026 (Government of the Republic of Croatia (Vlada Republike Hrvatske), 2023)
- Renewable Energy Directive and related regulation (Renewable Energy Directive, 2023)
- Main strategic documents in other relevant sectors.

The Strategy sets out several key activities and projects essential for achieving these objectives. Firstly, the focus will be on **increasing renewable hydrogen production** by using solar, wind, and hydropower resources. Strategic locations, particularly in Northern Croatia and along the Adriatic coast, will be developed to utilise existing industrial capacities and abundant renewable energy sources.

Infrastructure development is another critical area, involving the adaptation and expansion of the current natural gas infrastructure to accommodate **hydrogen storage and distribution**. This includes upgrading gas pipelines and storage facilities to ensure a seamless transition to hydrogen. Additionally, a comprehensive **network of hydrogen refuelling stations** (HRSs) will be developed across major transport corridors and urban areas, such as Zagreb, Rijeka, and Split. This infrastructure will support the deployment of **hydrogen-powered public transport (buses and trains) and private vehicles**, notably medium and heavy-duty vehicles, facilitating widespread adoption. The potential for the use of hydrogen in Croatia's maritime sector, including ferries, small ships, and boats, presents a unique opportunity to both decarbonisation of the commercial shipping sector and enhancement of green tourism. Hydrogen in aviation has a more longer-term perspective.

Pilot projects play a significant role in demonstrating the feasibility and benefits of hydrogen. Notable initiatives include the **implementation of hydrogen fuel cell buses in various Croatian cities**, completed with the necessary hydrogen refuelling infrastructure as self-sustaining (pilot) projects.

Establishing a **supportive regulatory framework** is crucial for the successful adoption of hydrogen. This involves **aligning national policies with EU regulations and directives** and providing **financial incentives and subsidies** to encourage investment in hydrogen projects. In parallel, **promoting research and development** (R&D) in hydrogen technologies will be essential. Efforts will focus on improving efficiency, reducing costs, and developing new applications through collaboration with academic institutions and industry stakeholders.

Public awareness and education are also key components of the Strategy. Educational campaigns will be implemented to raise awareness about the benefits and safety of hydrogen fuel, targeting both the general public and specific industry sectors. By building a comprehensive understanding and acceptance of hydrogen technologies, Croatia aims to create a supportive environment for the hydrogen economy to flourish.

2. THE ROLE OF HYDROGEN IN ACHIEVING CLIMATE GOALS

The following section explores how the European Union's legislative framework is driving the shift towards sustainable energy, with a focus on hydrogen. Initiatives like the "European Green Deal" and the "European Hydrogen Strategy" are shaping policies to promote renewable hydrogen adoption and infrastructure development. The next section explores the hydrogen value chain, from production to application, focusing on its role in decarbonization. It highlights renewable hydrogen production methods like electrolysis and addresses the crucial infrastructure needed for transport and storage.

2.1. European Union Legislative Framework

In 2019, the European Commission presented "The European Green Deal" (EU Commission, 2024) – a roadmap for making the EU's economy sustainable by turning climate and environmental challenges into opportunities across all policy areas and making the transition just and inclusive for all.

In 2020, the European Hydrogen Strategy defined the role of hydrogen to achieve climate neutrality by 2050. The 2022 REPowerEU Plan accelerated hydrogen deployment by setting a target of domestic production of 10 million tonnes of hydrogen per year by 2030, importing another 10 million tonnes per year, and distributing the combined quantities throughout Europe.

Hydrogen is recognised as essential to support the EU's commitment to reach carbon neutrality by 2050 and for the global effort to implement the Paris Agreement while working towards zero pollution. Hydrogen can be used as feedstock, fuel, energy carrier, and energy storage medium and has many potential applications across industry, transport, power, and buildings sectors. Most importantly, its use does not cause CO_2 emissions and produces zero or near zero air pollution. Thus, it offers a solution to decarbonise industrial processes and economic sectors, where reducing GHG emissions is both urgent and hard to achieve.

The "Fit-for-55 Package", presented in July 2021 and subsequently adopted, puts forward several legislative proposals that translate, among others, the European Hydrogen Strategy into a concrete European hydrogen policy framework. This includes proposals to set targets for the uptake of renewable hydrogen in industry and transport by 2030. Furthermore, the "Hydrogen and Decarbonised Gas Market Package" puts forward proposals to support the creation of optimum and dedicated infrastructure for hydrogen, as well as an efficient hydrogen market. Also, EU legislation defines requirements and other instruments related to clean vehicles e.g., fostering the market adoption of hydrogen vehicles (Clean Vehicles Directive), alternative fuels infrastructure implementation such as installation of hydrogen refuelling stations (AFIR), etc.

The EU legislative framework thus covers major elements of the hydrogen value chain. The Renewable Energy Directive (RED) as a centrepiece defines Renewable Fuels of Non-Biological Origin (RFNBO), i.e. hydrogen produced from non-biogenic renewable electricity, and derivatives synthesised from such hydrogen, and sets targets for its use in transport and industry. This is complemented by further legislation:

Table 1: EU Legislative Framework Related to Hydrogen

Value chain element	Sectors	Legislation
Hydrogen production	All sectors	Renewable Energy Directive (RED) and related Delegated Acts
Hydrogen use	as fuel in transport, industry, and other sectors	Renewable Energy Directive (RED), ReFuelEU Aviation, FuelEU Maritime, Emission Trading System (ETS)
Hydrogen refuelling infrastructure	Transport	Alternative Fuels Infrastructure Regulation (AFIR)
Hydrogen vehicles	Transport	Clean Vehicles Directive, CO_2 emission standards for cars, vans, and heavy-duty vehicles
Hydrogen transport and distribution infrastructure	All sectors	Hydrogen and Decarbonised Gas Market Directive and Regulation

This is complemented by funding and financing mechanisms at EU level, including the following selected instruments:

Table 2: Selection of EU Funding Instruments Related to Hydrogen

Instrument	Sectors	Funding of
Connecting Europe Facility (CEF)	Transport	Hydrogen refuelling infrastructure
Connecting Europe Facility (CEF)	Energy: Projects of Common Interest, Projects of Mutual Interest	Hydrogen production through electrolysis, hydrogen pipelines
Recovery and Resilience Facility*	Transport, etc.	Hydrogen refuelling infrastructure, etc.
European Hydrogen Bank	All sectors	Hydrogen production in the EU
Important Projects of Common European Interest (IPCEI)	Industry, Transport	Focus on end-users

* Temporary instrument based on National Recovery and Resilience Plans

2.2. Hydrogen Value Chain and Role in Achieving Climate Goals

The hydrogen value chain comprises production, distribution, storage, and application, see Figure 1. At both European and national levels, the concrete configuration of this value chain is under discussion with respect to regional characteristics to develop a robust hydrogen economy. Evaluating suitable production sites and optimal distribution strategies is crucial from economic, ecological, and political perspectives.

Renewable hydrogen production is key to reducing CO_2 emissions and supporting renewable energy strategies. Electrolysis, using electricity from renewable sources, is the primary method to produce hydrogen to be classified as a renewable fuel of non-biological origin (RFNBO). Other methods, such as pyrolysis and biomass gasification, are also being explored. Currently, much hydrogen is produced from natural gas through steam methane reforming (SMR), known as grey hydrogen. Transitioning to low-carbon and renewable hydrogen involves CO_2 capture and storage technologies (CCS; blue hydrogen) and the expansion of electrolysis capacity alongside renewable power generation (green hydrogen).

Hydrogen transport and storage infrastructures are vital for connecting production and consumption areas. Countries like Croatia, strategically positioned, can serve as hubs for hydrogen export, import, and (regional) distribution. Therefore, repurposing of natural gas pipelines for hydrogen transport, the construction of new pipelines, and the development of maritime transport terminals are essential steps. Hydrogen storage, typically in gaseous or liquid form, is essential for managing fluctuations in demand and supply. Innovations like metal hydride hydrogen storage and large-scale storage solutions, such as depleted oil and gas fields, salt caverns, or (saline) aquifers are under investigation.

Hydrogen applications are diverse, spanning multiple sectors. In the **transport sector,** hydrogen is crucial for decarbonisation, particularly where electrification is challenging. Hydrogen can power fuel cells in cars, buses, trucks, trains, etc. Hydrogen combustion engines and gas turbines are also under development, offering alternative power sources for heavy-duty vehicles, aviation, and maritime transport.

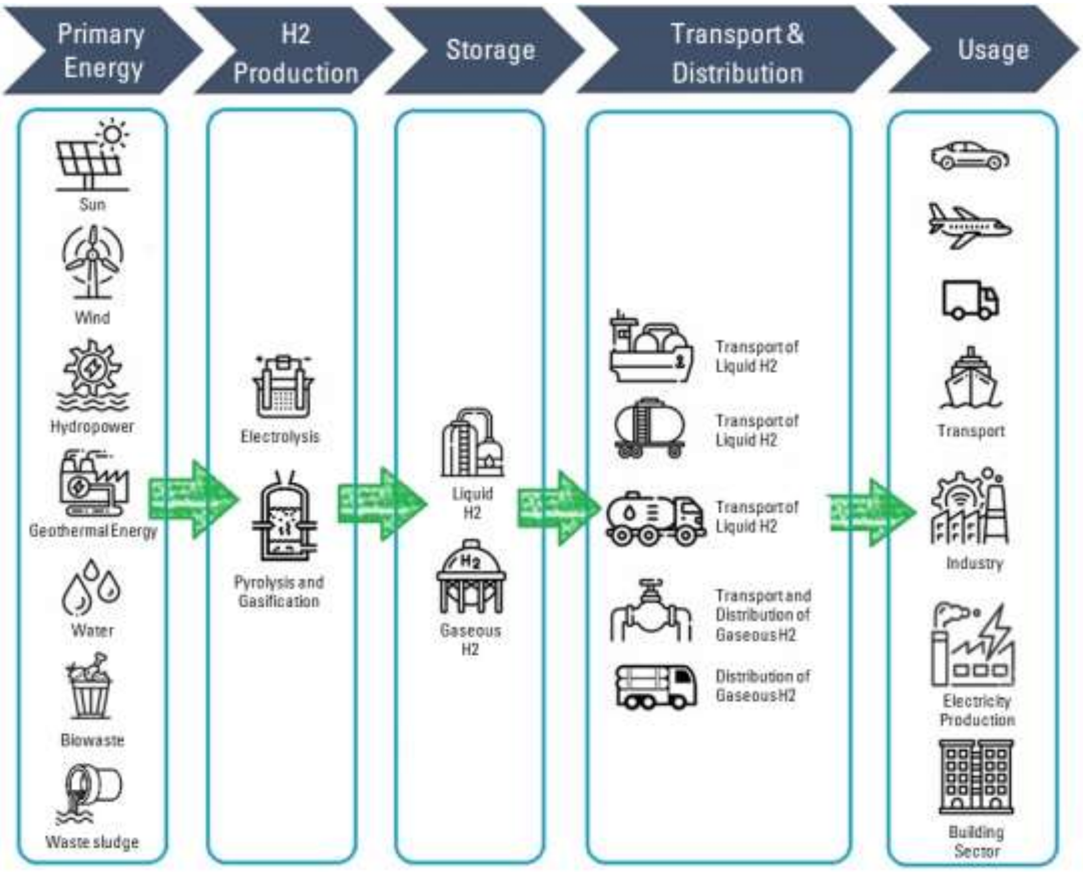


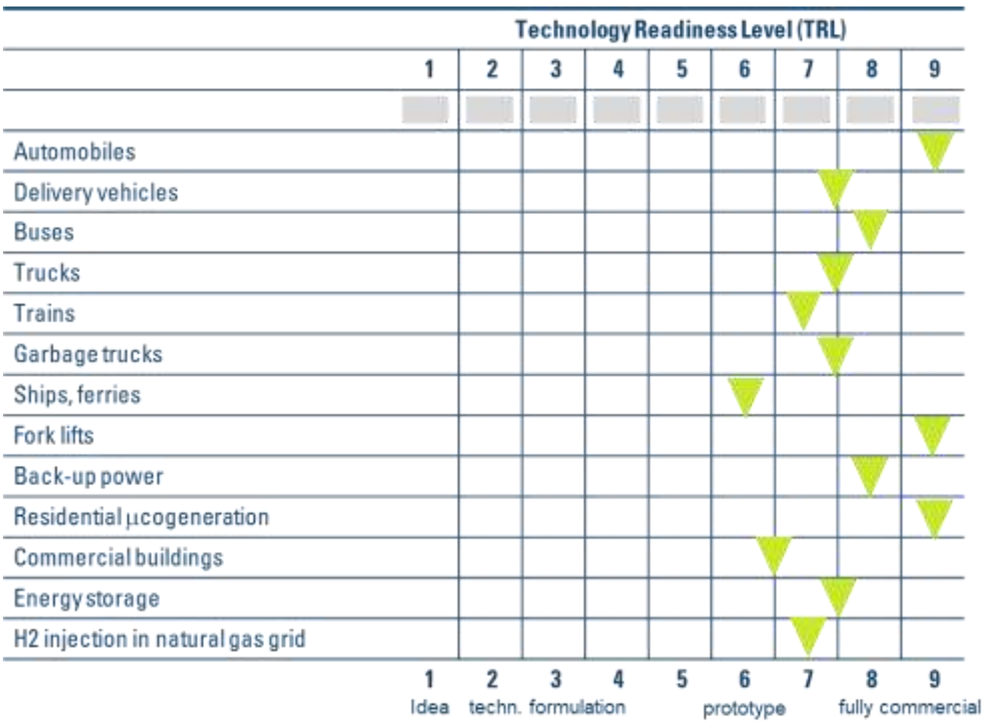
Figure 1: Overview of the Hydrogen Value Chain

Industrial applications of hydrogen include chemical production and refining, reducing fossil fuel dependency and CO_2 emissions. In cement manufacturing, hydrogen serves as a clean fuel alternative in kilns, lowering CO_2 emissions and providing the necessary high temperatures. The glass industry benefits from hydrogen's clean combustion, which improves glass quality and reduces emissions. Ammonia production, essential for fertilizers, can transition to green hydrogen, eliminating CO_2 emissions from conventional methods and promoting sustainable agriculture. These are only a few examples for the decarbonisation of industrial sectors with a transition to the use of green hydrogen.

In the energy sector, hydrogen plays a crucial role as an energy carrier to balance seasonal fluctuations of renewable energies and to stabilize the electricity grid. By storing surplus renewable energy as hydrogen, it can be converted back into electricity during periods of high demand or low renewable power generation. This capability is essential for maintaining grid stability and ensuring a reliable energy supply. Hydrogen can be used in gas turbines and combined cycle power plants to produce electricity and heat, offering a clean alternative to fossil fuels. For heating, hydrogen can be blended with natural gas or used in hydrogen-ready boilers, thus supporting decarbonisation.

The maturity of hydrogen applications varies. Hydrogen-powered vehicles and electricity generation technologies are operational but need further development for efficiency and cost reduction, see Table 3. Fuel cell technologies for vehicles have reached commercial use, converting hydrogen directly into electricity. Hydrogen internal combustion engines are under development, using hydrogen to produce mechanical energy. The future potential of hydrogen technologies in grid integration, industry, and transport is promising, supported by ongoing advancements and infrastructure developments. However, methods like pyrolysis and biomass and waste gasification for hydrogen production are still in premature stages and not yet commercially viable.

Table 3: Technology Readiness Level of Various Hydrogen Applications



3. PERSPECTIVES FOR HYDROGEN IN THE REPUBLIC OF CROATIA

The following sections will provide a comprehensive analysis of the opportunities and framework conditions for establishing a hydrogen economy in Croatia.

Initially, a brief overview of the regions of Pannonian Croatia, Adriatic Croatia, the City of Zagreb, and Northern Croatia will be given. Each region has unique characteristics and economic conditions that will be considered in the development of a hydrogen economy.

Subsequently, the status quo of hydrogen production and application in Croatia will be examined, providing an overview of existing hydrogen production facilities and technologies. The objectives for developing a hydrogen economy will then be outlined, identifying both national and regional targets for hydrogen production and use, and establishing strategic objectives for integrating hydrogen into the various end-use sectors.

Following this, the potential for green hydrogen production will be assessed, evaluating the renewable energy capacities in different regions and their potential for producing green hydrogen. This section will include a detailed evaluation of solar, wind, and other renewable energy sources across Croatia. The next section will focus on the various potential applications of hydrogen in the various regions of Croatia, including transport, industry, energy, and residential sectors.

An assessment of the existing infrastructure supporting hydrogen production, storage, and distribution will be conducted to identify regional gaps and requirements for expansion. This will be followed by a plan for the development of a hydrogen refuelling network, detailing the establishment of hydrogen refuelling stations along key transport corridors and considering logistical and regulatory challenges.

Finally, the establishment of local hydrogen hubs will be discussed, conceptualising them for production, storage, distribution, and application of hydrogen. Potential locations for these hydrogen hubs will be identified based on regional consumption patterns and industrial activities. This structured approach aims at providing a thorough understanding of Croatia's regional capabilities and the strategic steps necessary to foster a robust hydrogen economy, with each section delving into the specifics of regional potentials and the strategic measures required to harness them effectively.

3.1. Regional Divisions of Croatia

Croatia's regional division follows the Nomenclature of Territorial Units for Statistics (NUTS) classification used by the European Union. This classification system facilitates the collection, comparison, and analysis of regional statistical data, which is e.g., crucial for determining the maximum amount of European financial aid for specific projects. Croatia is divided into four NUTS-2 regions: Pannonian Croatia, Adriatic Croatia, the City of Zagreb, and Northern Croatia, see Figure 2.

Figure 2: Croatia's NUTS-2 regions

Pannonian Croatia encompasses the continental part of the country. This predominantly flat, agriculturally rich region has significant industrial presence in petrochemicals, cement, and food processing, and hosts thermoelectric power plants and gas infrastructure. Hydrogen potential here focuses on industrial use, public transport, and storage in geological formations.

Adriatic Croatia covers the coastal areas, islands, and regions like Istria and Dalmatia. Known for its extensive coastline and tourism, this region also hosts industries such as refineries and cement plants and has great potential for solar and wind energy. Hydrogen applications include maritime and public transport, as well as industrial uses.

The **City of Zagreb**, a distinct region due to its population density and economic importance, boasts extensive public transport, a large gas distribution network, and significant waste production. Potential hydrogen uses include public transport, blending into the gas network, and electricity production through hydrogen co-firing.

Northern Croatia is characterised by hilly terrain and industries such as food processing and textiles. While immediate hydrogen applications might be limited, there is potential for its use in public transport and blending into the gas distribution network. The region is also suitable for the construction of solar power plants and small hydroelectric power plants.

3.2. Production and Use of Hydrogen in Croatia Today

In Croatia, hydrogen is presently produced and utilised predominantly within the Rijeka Oil Refinery and for ammonia production at Petrokemija Kutina. At the Rijeka Oil Refinery, hydrogen is produced through steam methane reforming of natural gas with an annual rated production capacity of 61,200 tonnes. This hydrogen is crucial for hydro-processing operations such as hydro-desulphurisation and hydrocracking, which are necessary to meet sulphur content regulations in fuels. Modernisation efforts at the refinery have increased its capacity to process up to 4.3 million tonnes of crude oil annually, significantly increasing the demand for hydrogen.

Petrokemija Kutina, the largest producer of mineral fertilisers in Croatia, also relies heavily on hydrogen. As in the refinery, hydrogen at Petrokemija Kutina is produced via SMR. This hydrogen is essential for synthesising ammonia from nitrogen, which is then used to produce fertilisers such as urea and nitric acid. While the annual rated production capacity of hydrogen at Petrokemija Kutina is 80,000 tonnes, the facility's annual production for ammonia in 2021 was 450,000 tonnes, requiring approximately 51,000 tonnes of hydrogen.

Hydrogen use in other industries such as metals, food processing, and construction is quite small at around 0.02 kt_{H2}/year, primarily limited to specific processes like thermal treatment in metallurgy and hydrogenation in food processing.

Overall, the total hydrogen consumption in Croatia in 2021 was approximately 71 kt_{H2}/year, with a production capacity of 141 kt_{H2}/year, see Table 4.

Table 4: Actual Production and Consumption of Hydrogen in Croatia in 2021 (based on communications with producers)

Industry	Maximum Production Capacity [kt/year]	Consumption in 2021 [kt/year]	Technology
Rijeka Oil Refinery	61.2	20	SMR
Petrokemija Kutina	80	51	SMR
Other Industries	-	0.02	N/A
Total	141.2	71.02	

3.3. Goals for Croatia

3.3.1. Goals for Croatia as a Whole

Croatia's hydrogen goals are directly influenced by the EU Hydrogen Strategy and the European Green Deal which emphasise the reduction of GHG emissions and the transition to renewable energy sources. The alignment with these EU directives, as shown in Table 5, ensures that Croatia's hydrogen initiatives are supported by EU policies and potentially funded by EU financial instruments. Additionally, these goals support the broader EU legislative framework aiming at a decarbonised energy sector by 2050, increasing the share of renewable energy in the overall energy mix and reducing dependence on imported fossil fuels. In developing hydrogen infrastructure, Croatia is committed to adhering to EU technical and safety standards, ensuring that all new developments are sustainable, safe, and efficient.

The overall goals for Croatia include the expansion of renewable hydrogen production through solar and wind energy and from municipal waste. The Study scenario targets comprise significant hydrogen production capacities with required electrolysis power projected to be 510 MW by 2030, scaling up to 4,693 MW by 2050 (see Table 8Table 8 in section 3.4.1). The enhancement of existing natural gas infrastructure will accommodate hydrogen transport and distribution, while hydrogen use will be promoted across various sectors, including industry, transport, energy, and heating.

Table 5: European Regulations Affecting the Use of RFNBO in Various Sectors

Sector	INDUSTRY	TRANSPORT	MARITIME	MARITIME	AVIATION
Regulation	**RED III**	**RED III**	**RED III**	**FuelEU Maritime**	**ReFuelEU Aviation**
RFNBO Targets	**2030:** 42% RFNBO **2035:** 60% RFNBO of H2 energy and non-energy consumption	**2030:** 5.5% of fuels must be advanced biofuels or RFNBO, Minimum share of 1% RFNBO	**2030:** RFNBO: 1.2% of the total amount of energy supplied to maritime transport section	• Incentives for RFNBO use until **2031** • mandatory share of 2% from **2034** if RFNBO < 1% in 2031	Synthetic fuel share: **2030:** > 0.7% **2040:** > 8% **2050:** > 28%
	⬇	⬇	⬇		⬇
Minimum Hydrogen Demand for Croatia to meet the RFNBO targets 2030	21.5 kt	3.81 kt	0.13 kt	-	0.017 kt
	TOTAL Minimum Demand 2030: ~ 25.5 kt				

Furthermore, Croatia aims to strategically develop hydrogen infrastructure, which includes the establishment of hydrogen production facilities, storage systems, and refuelling stations, particularly along the Trans-European Transport Network (TEN-T). This infrastructure development is designed to support both domestic needs and the potential for hydrogen export. Additionally, the country is focused on fostering innovation through research and development in hydrogen technologies. This involves collaborations between academia, industry, and government bodies to advance the knowledge and practical applications of hydrogen.

3.3.2. Goals for Individual Regions

Pannonian Croatia will see significant use of hydrogen in industry, particularly for ammonia production and high-temperature processes, with limited use in transport and buildings. The focus will be on solar power plants dedicated to renewable hydrogen production, investigate the possibility of hydrogen storage in saline aquifers and depleted gas fields Existing natural gas pipelines will be modified for hydrogen transport, and local distribution systems will be enhanced for hydrogen blending. Hydrogen applications will be promoted in industry, cogeneration plants, and public transport.

Adriatic Croatia has significant potential for hydrogen applications in public transport, industrial plants, and maritime transport. The region will focus on solar and wind power plants for renewable hydrogen production, with consideration of seawater use for electrolysis. Investigations into the use of saline aquifers and the construction of hydrogen storage facilities at ports will be conducted. The gas pipeline system will be enhanced for hydrogen transport, and hydrogen refuelling stations will be constructed along highways and at ports. Hydrogen will be used in thermal power plants, the cement industry, and in public transport in urban areas.

The **City of Zagreb** has the largest potential for hydrogen use in public transport, domestic heating, and high-temperature processes in industry. The city will focus on hydrogen production from waste sludge due to limited potential for renewable electricity production. The extensive gas pipeline network will be utilised for hydrogen blending and distribution. Hydrogen buses will be encouraged in public transport, and central heating systems will be adapted to hydrogen use.

Northern Croatia's contribution will be the smallest among all regions, with hydrogen use primarily in transport and heating. There is potential for small hydro power, solar power, and geothermal plants for renewable hydrogen production. Investigate the possibility of hydrogen storage in saline aquifers and depleted gas fields and support pipeline modifications and the construction of hydrogen refuelling stations along major transport routes. The region will encourage hydrogen use in buses and trucks and adapt gas systems for hydrogen use in buildings for co-generation and heating.

These aspects are summarised in Table 6.

Table 6: Regional Goals and Strategies to Establish a Hydrogen Economy in Croatia

City of Zagreb	Pannonian Croatia	Northern Croatia	Adriatic Croatia
Production Alongside electrolysers, focus more on hydrogen production from waste, including waste sludge.	**Production** Increase renewable hydrogen production using solar power plants.	**Production** Utilize small hydropower and solar plants for local hydrogen production.	**Production** Enhance renewable hydrogen production through solar and wind power, both onshore and offshore. Develop infrastructure for hydrogen import via maritime routes. Focus more on hydrogen production from waste.
Distribution and Storage Adapt the existing gas distribution network, or parts of it, for hydrogen.	**Distribution and Storage** Upgrade the existing gas infrastructure, transmission, distribution and gas storage system for hydrogen. Investigate the possibility of hydrogen storage in saline aquifers and depleted oil and gas fields.	**Distribution and Storage** Investigate repurposing of depleted oil and gas fields for hydrogen storage.	**Distribution and Storage** Investigate the possibility of hydrogen storage in saline aquifer.
Usage Promote use of hydrogen in public transport, heat distribution system, and gas grids. Construction of HRS.	**Usage** Promote use of hydrogen in public transport, heat distribution system, gas grids and industry. Construction of HRS.	**Usage** Promote use of hydrogen in public transport gas grids and industry. Construction of HRS.	**Usage** Promote use of hydrogen in public transport, both road and maritime. Construction of HRS on roads and in maritime ports.

3.4. Potential of Hydrogen Production in Croatia

The exploitation of Croatia's potential for green hydrogen production is underpinned by a series of strategic initiatives and plans aiming at leveraging its geographical advantages, enhancing energy security, and achieving sustainability goals. Central to these efforts is the alignment with European energy strategies, particularly the European Hydrogen Backbone initiative, which envisages a pan-European hydrogen pipeline network.

Croatia's geographical location at the crossroads of Central, Eastern, and Southeastern Europe provides a strategic advantage for the production, transportation, and distribution of hydrogen. The country's extensive coastline and access to deep-water ports, particularly in the Rijeka Bay, makes it a viable hub for the import and export of hydrogen. Additionally, Croatia's connection to the European natural gas network facilitates the integration of hydrogen infrastructure, thus enhancing energy security and contributing to the diversification of energy sources.

The production of green hydrogen in Croatia is expected to grow significantly by increased electrolysis capacity, see Figure 3. The primary technologies under consideration include alkaline electrolysers (AEL), proton exchange membrane (PEM) electrolysers, and high-temperature solid oxide electrolysers (SOE). Alkaline electrolysers are currently the most prevalent due to their lower costs, ranging from 500 to 1,500 €/kW. PEM electrolysers, while more expensive (1,000 to 2,000 €/kW), offer higher efficiency and flexibility. SOE technology is still in the developmental stage and not yet commercially available.

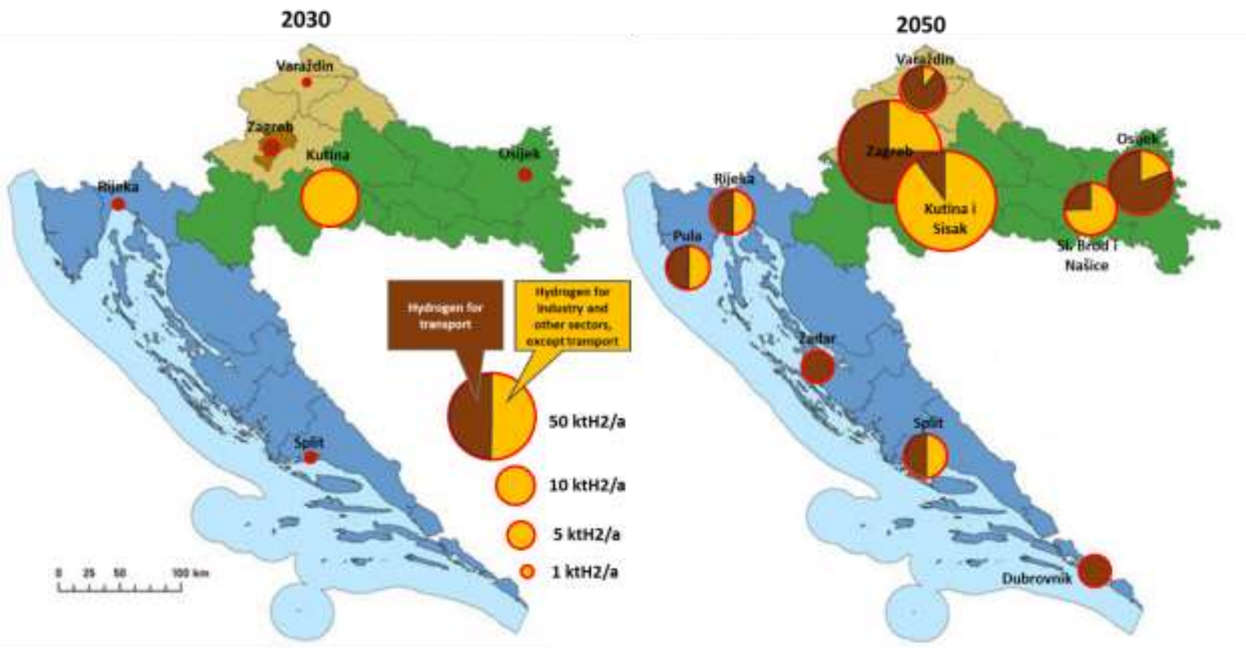


Figure 3: Expected Hydrogen Production in Croatia in 2030 and 2050

Figure 3 presents the territorial distribution of hydrogen production according to the Study (baseline scenario). It assumes that production is in balance with demand, export or import of renewable hydrogen is not assumed. The territorial distribution is based on the locations of industrial facilities, and for transport it is assumed that hydrogen production will be close to locations of consumptions (HRS). In the year 2030, production is dominated in Kutina where an ammonia production facility is located, and in Zagreb for public transport, near urban TEN-T corridor, and for rail. In 2050, production for industry is related to energy intensive industries that will partially use hydrogen, mainly facilities covered by the ETS system (cement plants, mineral products industry, food production, pulp and paper). Also, regional production will grow in 2050 due to increased use in transport, on the Adriatic coast including for maritime transport.

Croatia does not currently produce electrolysers domestically. Major manufacturers are located in Germany, Norway, France, China, and the United States. However, Croatia is developing alternative hydrogen production technologies, such as pyrolysis and biomass regasification, which can produce renewable hydrogen. These technologies, while still in the research phase and not yet commercially available, hold promise for contributing to the national targets for renewable energy use.

The selection of suitable technologies varies by region, influenced by local renewable energy resources. Coastal regions, with significant potential for wind energy, are ideal for deploying offshore wind farms coupled with hydrogen production facilities. Inland areas, which can harness solar energy, are suited for photovoltaic systems integrated with hydrogen production plants. This regional approach ensures optimal use of local resources and contributes to the overall efficiency and cost-effectiveness of hydrogen production.

Croatia’s existing natural gas infrastructure presents a valuable asset for the transition to a hydrogen economy. Dedicated plans foresee repurposing parts of the natural gas network for hydrogen transport, especially the 75 bar and the 50 bar systems. Key projects like the Croatia-North pipeline and the Croatia-South pipeline will facilitate the distribution of hydrogen from coastal production sites to consumption centres in northern Croatia and beyond to international connections with Slovenia and Hungary. Additionally, the development of smart gas networks incorporating advanced digital systems will enhance the monitoring and management of hydrogen and other low-carbon gases e.g., blended natural gas in a transition phase.

Numerous research initiatives and pilot projects are underway to advance Croatia's hydrogen capabilities. These include studies on the integration of hydrogen production with renewable energy sources, and the development of hydrogen storage solutions. Notably, the Slovenian Hydrogen Backbone project and its interconnections with Croatia aim to facilitate cross-border hydrogen transport, further integrating Croatia into the European hydrogen network.

3.4.1. Potential of Renewable Energy Production in Croatia for Hydrogen

Croatia is making significant strides in enhancing its renewable energy production capacities, aligning with a broader role of hydrogen in the energy system and thereby meeting EU energy and climate targets. This comprehensive strategy involves various renewable energy sources and strategic initiatives. Croatia’s technical potential of renewable energy sources is shown in Table 7.

Croatia's renewable energy sector is diverse, with significant contributions from hydro power, wind energy, and solar power. Hydro power represents about 44-57% of the country's total electricity production (in the years 2016-2021 (Ministry for Economy and Sustainable Development Croatia (Ministarstvo gospodarstva i održivog razvoja), 2023a)) with an installed capacity of approximately 2,200 MW. Wind energy is rapidly growing and currently produces about 14% of Croatia's electricity, with an installed rated capacity of around 1,000 MW. Solar power with an installed capacity of around 140 MW accounts for around 1% of the total electricity production of Croatia.

The Energy Development Strategy of the Republic of Croatia until 2030 with an Outlook to 2050[3] presents RES potentials for electricity consumption in Croatia. Solar, wind, and hydro are identified as priority renewable sources to be used for renewable hydrogen production (RFNBO) and are presented in Table 7.

Table 7: Croatia's Technical Potential of Renewable Energy Sources

Renewable sources	Technical potential [MW]
Solar	8,000
Onshore wind	7,000 – 9,000
Hydro	3,700 – 4,250
Total	**18,700 – 21,250**

Croatia is actively expanding its renewable energy capacities through various projects and initiatives, taking advantage of its diverse geographical conditions. The expected expansion of renewable energy in Croatia is shown in Figure 4. The government plans to double the current wind and solar energy capacity from 1,125 MW to about 3,522 MW in 2030, (Ministry for Economy and Sustainable Development Croatia (Ministarstvo gospodarstva i održivog razvoja), 2022). New wind farms are being developed in high wind potential areas, particularly along the Adriatic coast and higher altitude zones, known for consistent and strong wind patterns. These projects aim at increasing renewable energy output and support green hydrogen production through water electrolysis. Efforts are also underway to increase solar capacity to over 500 MW by 2030. This includes large-scale solar parks and rooftop solar panels on residential and commercial buildings. Inland regions, characterized by high solar irradiation, are prioritized for these projects. The increased solar capacity will stabilize the energy supply and support hydrogen production facilities.

According to the baseline scenario of the Study, for the production of renewable hydrogen about 808 MW in wind and solar power capacities will be needed in 2030, 2,966 MW in 2040, and 7,430 MW in 2050, see Table 8.

Table 8: Needed RES, Electrolyser and Water Capacity

		2030	2040	2050
Hydrogen demand – Study baseline scenario	**kt/a**	**26.4**	**97.1**	**243.2**
Electrolyser capacity	**MW**	510	1,873	4,693
Water intake required	**1,000 m³**	528.9	1,941.6	4,863.3
Additional RES capacity (wind/solar)	**MW**	**808**	**2,966**	**7,430**
	GWh/a	1,454	5,339	13,374

[3] [OG25/20 2020]

Figure 4 shows the required addition to the already planned renewable electricity capacities. In 2050, the required RES solar and wind capacities are close to the estimated technical potential (excluding offshore wind; see Table 8).

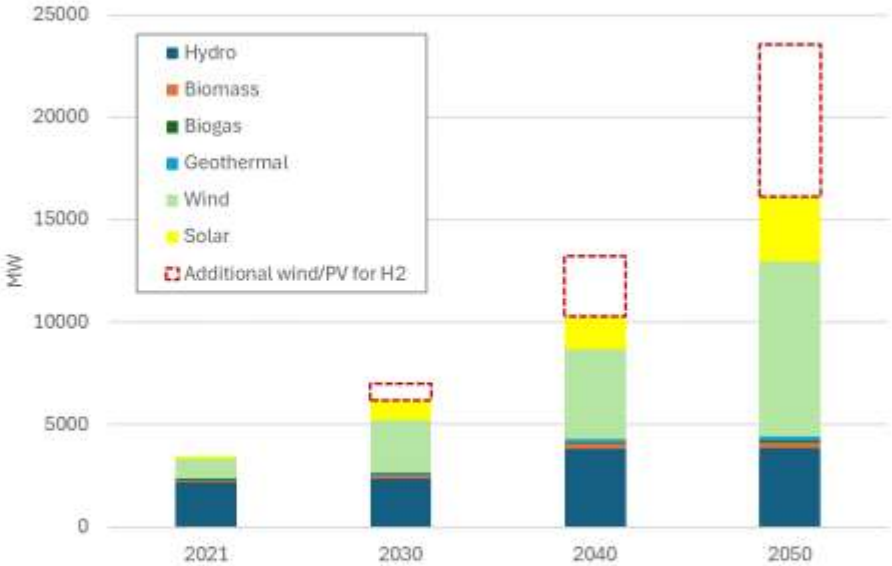


Figure 4: Expected Renewable Electricity Production Capacity in Croatia in 2030, 2040, and 2050 (NECP and the Study Results Added for Indication of Proportion)

While large-scale hydro power expansion is limited due to environmental considerations and the nearly exploited potential of current river systems, ongoing initiatives aim to upgrade existing hydro power facilities to enhance their efficiency and output. Additionally, new small-scale hydro power projects are being explored in mountainous areas to contribute to local energy demand with limited environmental impact. By utilizing agricultural and forestry residues, Croatia is also boosting its energy production from biomass. This not only supports waste management but also provides energy for hydrogen production.

The expansion of renewable energy capacities directly encourages green hydrogen production. Increased wind and solar capacities provide the necessary electricity for electrolysers, essential for producing green hydrogen cost-effectively. Proximity of renewable energy production and hydrogen production facilities can reduce energy transport costs and increase overall efficiency. Coastal areas, with wind power and potential hydrogen use in maritime and road transport, are particularly suitable for such integrated systems.

To promote investments in renewable energy technology, grants, support schemes and subsidies for renewable energy sources are needed. Such measures aim to accelerate the deployment of renewable technologies and ensure their economic viability. Additionally, Croatia leverages EU funds for the technical support and the development of its renewable energy projects. This includes accessing funds dedicated to energy and climate change initiatives, supporting the infrastructure development necessary for a robust renewable energy and hydrogen production ecosystem.

Water is raw material for hydrogen production through the process of electrolysis. It can be sourced from public water supplies, extracted from underground, or even obtained from seawater. For an efficient electrolysis process, water needs to be further treated to remove minerals and other impurities. This treatment may include filtration, demineralization, and deionization. When using seawater, the treatment process is more complex due to the need to remove salt and other ions that are not present in freshwater.

The Study concludes that the required amounts of water for hydrogen production are small compared to the current water consumption in the public water supply system. For comparison, water losses in the public water supply system in 2021 amounted to 201.6 million m^3, while the water requirement for hydrogen production in 2050 is estimated at some 4.9 million m^3. It is also worth noting that seawater represents a practically unlimited source of water for hydrogen production, while costs for desalination and environmental impacts, e.g. of brine disposal, need to be considered.

3.4.2. Renewable Fuel of Non-Biological Origin (RFNBO)

Delegated regulation EU 2023/1184 defines a methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin, which are explained below:

Additionality

Fuel producers must generate or procure an equivalent amount of renewable electricity to the amount they claim as fully renewable. This can be through their own installations or renewable power purchase agreements (PPAs). The renewable electricity must meet the following criteria:

(a) The installation generating renewable electricity must have started operation no more than 36 months before the fuel production installation. If a PPA ends, the installation is considered to have started operation simultaneously with the new fuel production installation under a new PPA. Additional capacity at the same site must be added within 36 months of the initial installation's operation.

(b) The generating installation must not have received operating or investment aid, except for certain exclusions like support for repowering, land, grid connections, or non-net support.

Temporal Correlation

Until 31 December 2029, temporal correlation is met if the renewable fuel is produced in the same calendar month as the renewable electricity under a PPA or from a new storage asset charged in the same month.

From 1 January 2030, temporal correlation is met if production occurs in the same one-hour period. Member States can apply these rules from 1 July 2027.

Temporal correlation is always met if the fuel is produced when the electricity price is ≤ € 20 per MWh or less than 0.36 times the carbon allowance price.

Geographical Correlation

Geographical correlation is met if:

(a) The renewable electricity installation is in the same bidding zone as the electrolyser.

(b) It is in an interconnected bidding zone with equal or higher electricity prices during the relevant period.

(c) It is in an offshore bidding zone interconnected with the electrolyser's bidding zone.

Member States may add criteria to ensure compatibility with national hydrogen and electricity grid planning, without negatively impacting the internal electricity market.

3.4.3. Renewable Hydrogen from Waste

According to the Waste Management Plan (Waste Management Plan of the Republic of Croatia for the Period from 2023 to 2028 (Plan gospodarenja otpadom Republike Hrvatske za razdoblje 2023. – 2028. godine), 2023), there is a need to establish an appropriate waste management system for sludge that would include both material and energy recovery. Since RED considers sludge from wastewater treatment plants to be a renewable energy source, implementing a new waste management system in Croatia represents additional potential for renewable hydrogen production. Sludge is currently primarily stored or disposed in landfills and only smaller quantities are used for agricultural purposes or subjected to composting.

In larger municipal wastewater treatment plants, it is common for sludge to undergo anaerobic digestion. This process reduces the number of pathogenic microorganisms and produces biogas, which is used to meet the energy needs of the treatment plant itself. After anaerobic digestion, and assuming the maturation of advanced thermochemical conversion technologies, renewable hydrogen generation can be expected in the range of 20 to 50 grams per kilogram of dry matter, depending on the technological solution used and operational parameters. Projection of renewable hydrogen production for each region in Croatia is shown in Table 9.

Table 9: Renewable Hydrogen Production Potential from Waste Sludge

	Pannonian Croatia	**Adriatic Croatia**	**City of Zagreb**	**Northern Croatia**	**Total**
			Waste sludge [t/a]		
2021	n.a.	n.a.	15,797	n.a.	**25,074**
2030	23,337	23,534	19,282	8,405	**74,558**
2035	24,824	25,035	20,511	9,941	**79,311**
			Renewable Hydrogen Potential [t/a]		
2030	467 – 1,167	470 – 1,177	386 - 964	168 - 420	**1,491 – 3,728**
2035	496 – 1,241	501 – 1,252	410 – 1,026	179 - 447	**1,586 – 3,966**

Other waste streams could also have potential for renewable hydrogen production, if they fulfil sustainability and greenhouse emissions savings criteria. In case of hydrogen production from waste and residues, other than agricultural, aquaculture, fisheries and forestry residues, it needs to fulfil only the greenhouse gas emissions savings criteria, as follows:

(a) At least 65% for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations starting operation from 1 January 2021.

(b) At least 80% for electricity, heating and cooling production from biomass fuels used in installations started operating after 20 November 2023.

In case of mixed waste, produced hydrogen can be considered as “renewable” only if fossil materials are removed. According to the Waste Management Plan (Waste Management Plan of the Republic of Croatia for the Period from 2023 to 2028 (Plan gospodarenja otpadom Republike Hrvatske za razdoblje 2023. – 2028. godine), 2023), Croatia plans to implement a system based on regional waste management centres that will process approx. 900,000 to 1,000,000 tons of mixed municipal waste annually. Output products of waste processing include separated recyclables suitable for material recovery, solid recovered fuel suitable for further energy processing and residual waste ready for disposal, which consists of stabilized biodegradable waste and other waste that is not suitable for any other treatment. None of the output product is suitable for renewable hydrogen production. Only solid recovered could have potential for production of low carbon hydrogen amounting to approx. 29,700 to 38,200 tons.

3.4.4. A Brief Description of Technology, Displayed Cumulatively and by Region

Hydrogen Production Technologies

Hydrogen production technologies can be broadly classified into various categories based on their source of energy and production method. Five technologies for hydrogen production can be found today with different relevance and different TRL: methane reforming, coal gasification, electrolysis, biomass conversion, and waste gasification. Electrolysis using renewable energy, biomass conversion, and waste gasification enable the production of green hydrogen. In contrast, hydrogen produced through methane reforming and coal gasification results in CO_2 emissions and is therefore classified as grey hydrogen.

1. Methane Reforming

Methane reforming involves converting methane (CH_4, typically from natural gas) into hydrogen (H_2) and carbon dioxide (CO_2). Around 75% of the hydrogen produced worldwide today stem from methane reforming. The main methane reforming types include:

Steam Methane Reforming (SMR): This is the most common method for industrial hydrogen production. It involves reacting methane with steam at high temperatures to produce hydrogen and carbon dioxide. Despite being mature and widely used, SMR produces significant CO_2 emissions. In 2021, SMR contributed 2.2 % of Croatia’s total CO_2 emissions, and emission is about 10 kg CO_2 per kg of hydrogen produced.

Partial Oxidation and Autothermal Reforming: These are variations of methane reforming that use oxygen or a combination of oxygen and steam to convert methane into hydrogen and CO_2. These methods also face challenges related to CO_2 emissions.

2. Coal Gasification

This method involves reacting coal with oxygen and steam to produce H_2, CO, and CO_2. Coal gasification accounts for about 23% of global hydrogen production, primarily due to its significant use in China.

3. Electrolysis

Electrolysis is a method of producing hydrogen by splitting water into hydrogen and oxygen using electricity, producing hydrogen classified as a renewable fuel of non-biological origin (RFNBO) if electricity stems from renewable sources. The primary types of electrolysers discussed are Alkaline (AEL), Proton Exchange Membrane (PEM), and Solid Oxide Electrolysers (SOE).

Alkaline electrolysis is a well-established technology that uses potassium hydroxide (KOH) or sodium hydroxide (NaOH) as the electrolyte. Alkaline electrolysers have been in use for over a century and are known for their durability. They operate at relatively low temperatures (60-90°C) and are cost-effective, with production costs expected to remain stable.

PEM electrolysers are more compact as they can operate at higher current densities. They use a solid polymer membrane and are capable of quick start-up and rapid load changes, making them suitable for integration with fluctuating renewable energy sources. However, they are currently more expensive due to the use of noble metal catalysts like platinum and/or iridium. The cost of PEM technology is expected to decrease, potentially becoming comparable to alkaline electrolysers by 2030.

SOE operates at high temperatures (700 to 900°C), providing higher efficiency by using both electricity and heat. Despite its potential, SOE is still in the development phase and not yet commercially viable. It holds promise for future applications once technical and economic challenges are addressed.

4. Biomass Conversion

Hydrogen can also be produced from biomass through thermochemical processes such as gasification and pyrolysis.

In the process of gasification solid biomass is converted into a gaseous mixture (syngas) containing hydrogen, carbon monoxide, and other gases by reacting the biomass at high temperatures with controlled amounts of oxygen and/or steam. Gasification is relatively advanced and nearing commercialisation.

Pyrolysis involves the thermal decomposition of organic material at elevated temperatures in the absence of oxygen, producing bio-oil, syngas, and biochar. The syngas produced can be further processed to extract hydrogen. This technology is also progressing towards commercial viability.

5. Waste Gasification

The waste-to-hydrogen technology involves converting waste materials into hydrogen gas through processes such as gasification. This technology not only reduces landfill waste and sludge from wastewater treatment but also produces clean fuels.

Technologically, waste-to-hydrogen is advancing but still in the developmental stage, facing challenges like high operating costs and efficiency improvements.

Commercially, it is in the early phase of adoption, with a few pilot projects across the world. The scalability of this technology depends on technological breakthroughs and economic viability. Thus, while promising, waste-to-hydrogen requires significant research and investment to achieve broader commercial implementation.

Regional Specifics in Croatia

Croatia's hydrogen Strategy emphasises a diverse mix of production technologies tailored to regional conditions and resources. Electrolysis, particularly when powered by the country's significant solar and wind potential, offers a clean and scalable solution, especially in coastal regions like Adriatic Croatia.

Biomass conversion utilises agricultural and forestry residues, while methane reforming serves as a bridging technology that can be partly decarbonised with carbon capture and storage (CCS). Coal gasification will play no role in Croatia.

Croatia faces significant challenges in waste management due to the shortage of waste treatment and missing consensus on the need for incineration facilities, despite long-standing EU requirements mandating such infrastructure. The country aims to address both the waste management issue and contribute to hydrogen production simultaneously. However, the commercial availability of waste gasification technologies for hydrogen production remains a major hurdle. Current announcements from manufacturers lack robust supporting data. The Technology Readiness Level (TRL) of waste-to-hydrogen technology is estimated to be between 4 and 6, indicating that these technologies are still in the developmental and demonstration phases.

Regional specifics, including renewable energy potential and industrial synergies, are crucial in determining the most suitable hydrogen production methods across the country, enhancing the feasibility, financial viability, and sustainability of hydrogen projects.

Regions with existing industrial infrastructure, such as the petrochemical and ammonia production facilities, can adapt their processes to incorporate hydrogen produced from renewable sources. This includes retrofitting existing plants to capture CO_2 emissions and produce low-carbon hydrogen as long as CO_2 deposits are available.

Urban areas, like the City of Zagreb, have substantial amounts of waste sludge from wastewater treatment plants that potentially can be utilised for hydrogen production. This approach would not only provide a renewable source of hydrogen but would also address waste management issues.

The existing natural gas infrastructure in Croatia can be leveraged for hydrogen distribution. Blending hydrogen with natural gas and using it in the current natural gas grid can facilitate a gradual transition. However, the proportion of hydrogen in the gas mix must be carefully managed to ensure compatibility with existing appliances and infrastructure.

3.5. Potential of Hydrogen Use in Croatia

Based on its properties, the use of hydrogen can be divided into two categories: firstly, its use as an energy carrier, which makes it attractive as a fuel in the transport sector, as a storage medium in a green energy economy, or as a fuel in industrial high-temperature processes. Secondly, it is already being used today as chemical molecule H_2, particularly in ammonia production (NH_3).

The expansion of hydrogen applications in Croatia is strongly supported by EU directives and regulations such as RED III and by the Croatian government policies and is aiming at reducing GHG emissions and promoting clean energy technologies. In the following sections, it will be explained how hydrogen applications, which were generally described in section 2.2, can be specifically implemented in Croatia considering its regional characteristics. The focus will be on the strategic deployment of hydrogen in the transport sector, in industry, and in the energy and heating sector to ensure a sustainable and resilient energy future for the country.

3.5.1. Scenario Methodology

For road transport analyses, a simplified model of transport structure with four main categories was applied: passenger vehicles (small, medium, large), trucks, tractor-trailers, and buses. An equal increase in the number of vehicles across all categories was assumed: 1.25% annually until 2030, 0.75% annually for the period 2031-2040, and 0.5% for the period 2041-2050. By replacing road ICE vehicles with FCEV vehicles, energy consumption of vehicles is reduced because FCEV vehicles have higher fuel conversion efficiency to mechanical energy. An improvement in FCEV vehicle efficiency over time is assumed by 7.5% till 2050. The calculation was based on the assumption that hydrogen will be used in vehicles that cover slightly higher mileage on average than today's average mileage for each vehicle category. CO_2 emission savings are calculated methodologically according to RED III, which is a lifecycle (LCA) approach.

Two scenarios were simulated in road transport by 2030: the baseline scenario and the high consumption scenario. The baseline scenario was constructed assuming a slightly higher consumption of RFNBOs than the binding targets for RFNBO according to the RED III directive to ensure the achievement of the goal. FCEV vehicle penetration is through all categories of road vehicles, with higher substitution rates for heavy vehicles and buses. Consumption is aligned with the planned increase in the number of refuelling stations and the production of domestic renewable hydrogen.

The high consumption scenario aims for renewable hydrogen to reach a total of 7.4% of energy consumption in transport by 2030. This would enable the Republic of Croatia, with the application of other renewable fuels, to reach the target share of RES of 29% in transport by 2030. Also, an analysis was conducted to determine how much renewable hydrogen would be needed to achieve the goal of reducing CO_2 emissions in transport by 14.5% by 2030, according to the calculation methodology prescribed by the RED III directive.

Stronger use of hydrogen in road transport will be between 2031 and 2040. It is assumed that CO_2 emission costs will become part of the fuel price, which will start with the introduction of the ETS II market for transport and buildings from 2027. A comparison of costs per kilometre of passenger vehicles showed that with a hydrogen price falling below 7 €/kg and a CO_2 price of 100 €/t, hydrogen vehicles become fully competitive with ICE vehicles and very close to BEV vehicles, with specific cost amounting to approx. 0.25 €/km.

In the period up to 2050, it is necessary to achieve carbon neutrality; transport will rely on electric energy, biofuels, renewable hydrogen, and synthetic and other low-carbon fuels. According to this Study, the total demand for renewable energy sources in 2050 along with additional needs for hydrogen production for transport and industry, will reach the maximum available natural capacities for solar and wind power as was estimated by the Croatian Energy Development Strategy (Energy Development Strategy of the Republic of Croatia until 2030 with an Outlook to 2050 (Strategija energetskog razvoja Republike Hrvatske do 2030. s pogledom na 2050. godinu), 2020).

The methodology for other modes of transport and for industry are described below.

3.5.2. Transport

Hydrogen offers advantages over batteries in transport applications where high energy density, rapid refuelling, and extended range are crucial. It is particularly beneficial for long-haul trucking, maritime transport, aviation, and large industrial vehicles, where the weight and size of batteries required to provide similar performance would be impractical, see Figure 5. Hydrogen is also considered for public transport buses and trains in regions lacking extensive electrification infrastructure, offering a cleaner alternative to diesel while ensuring operational efficiency and flexibility. By 2050, hydrogen-powered vehicles are expected to constitute a significant portion of the national fleet in Croatia, with projections indicating up to 40% of the buses and 10% of the trucks being powered by hydrogen.

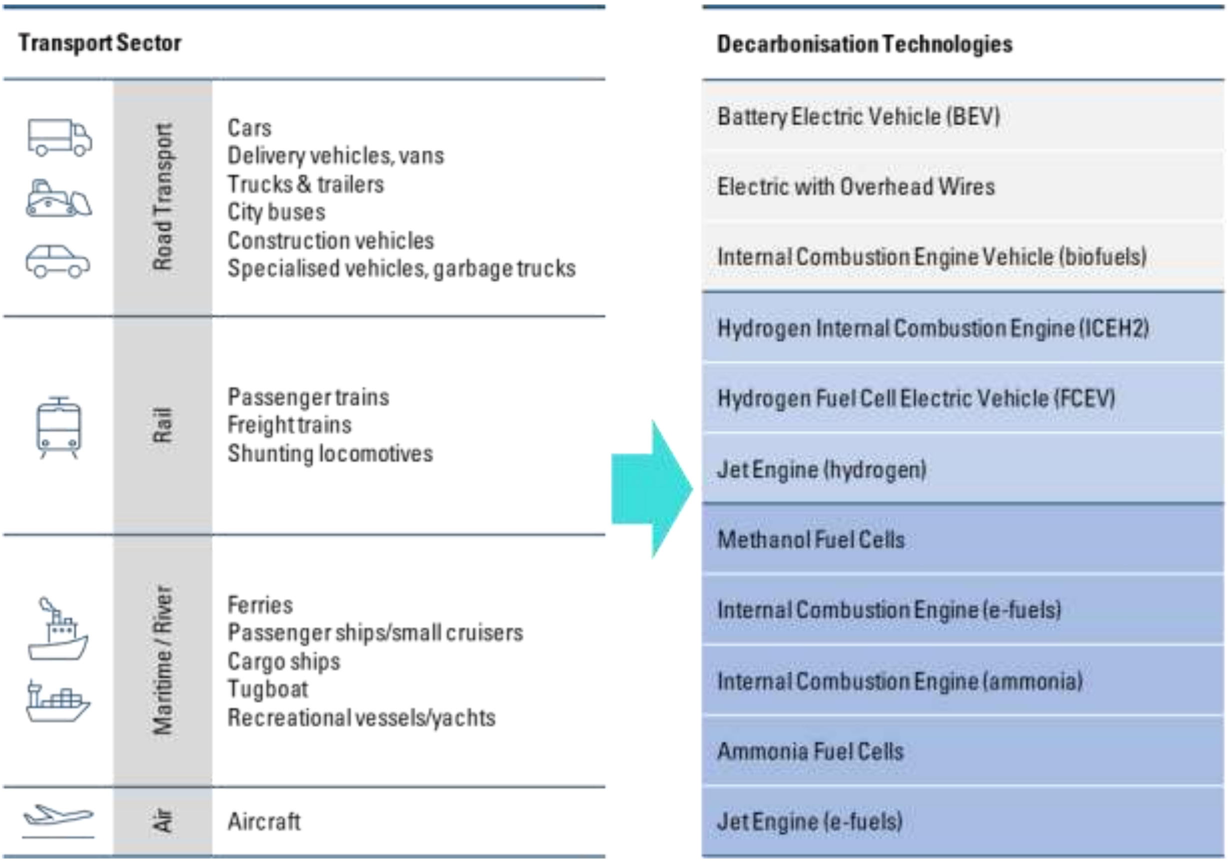


Figure 5: Decarbonisation Technologies for the Transport Sector (Hydrogen-based Technologies marked in blue)

Regulatory Framework

A supportive policy framework is essential for fostering the hydrogen economy in the transport sector. Regulations that encourage the use of green hydrogen are critical to ensure that activities and investment decisions in the transport sector align with broader environmental goals. This regulatory framework includes specific incentives, standards, and dedicated targets designed to promote the adoption of hydrogen technologies in this sector.

Role of RFNBO in the Transport Sector

According to RED III, by 2030, at least a 29% share of renewable energy in final consumption of all energy used in the transport sector must come from renewable sources, including Renewable Fuels of Non-Biological Origin (RFNBOs). The directive mandates that by 2030, a minimum combined share of advanced biofuels, biogas, and RFNBOs should reach 5.5%, with at least 1% from RFNBOs. RFNBOs are essential for decarbonising segments of the transport sector that are difficult to electrify, such as long-haul trucking, aviation, and maritime transport. To qualify as RFNBO under EU regulations, hydrogen has to be produced via electrolysis using electricity from renewable sources, ensuring near-zero life-cycle GHG emissions.

The NECP2023 sets a target of reducing greenhouse gas emissions by -16.7% compared to 2005 emissions in the non-ETS sector (small industry, transport, households and services, energy emissions from agriculture and buildings, agriculture, waste management). If the non-ETS sector does not meet the target, the achieved reduction credits may be taken from the LULUCF (Land Use, Land Use Change and Forestry) sector, provided that the LULUCF has a sink above the target defined in LULUCF regulation 2023/839 EU. It is also possible vice versa, if a reduction above the target is achieved in the non-ETS sector, it can be transferred to the LULUCF sector. All units of reduction can be traded with EU countries. The Table 10 shows share of RES in transport sector.

Table 10: RES in Transport – Today's Share and Goals for 2030

		Goals for 2030		
	Status quo in 2021	**The goal from RED II**	**Croatia NECP 2023**	**The goal from RED III**
The share of RES in transport	7.1%	14%	21.6%	29%

Use of Hydrogen in Various Transport Sectors

Transport in Croatia represents the biggest challenge in terms of reducing greenhouse gas emissions, it is the only sector, apart from the waste management sector, in which emissions grew continuously from 1990 to 2020, with an amount of 61 % (see Figure 6).

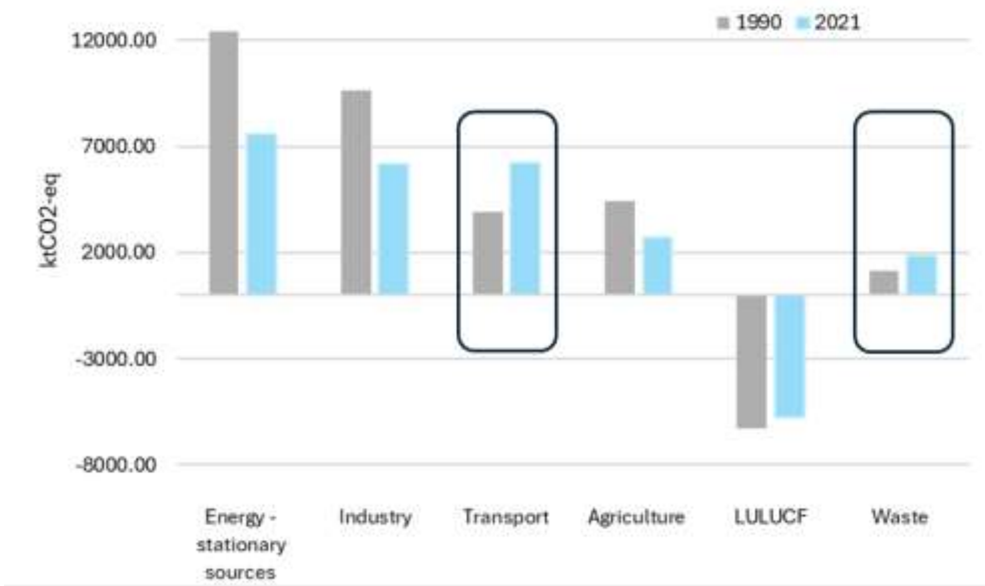


Figure 6: GHG Emission Trend 1990 to 2021 (Ministry of Economy and Sustainable Development Croatia (Ministarstvo gospodarstva i održivog razvoja), 2023b)

Road transport emits 25.6% of greenhouse gases in the Republic of Croatia. Passenger vehicles account for the largest share of transport emissions at 17% and freight vehicles and buses at 4.8%. The share of individual types of transport in greenhouse gas emissions is shown in Figure 7.

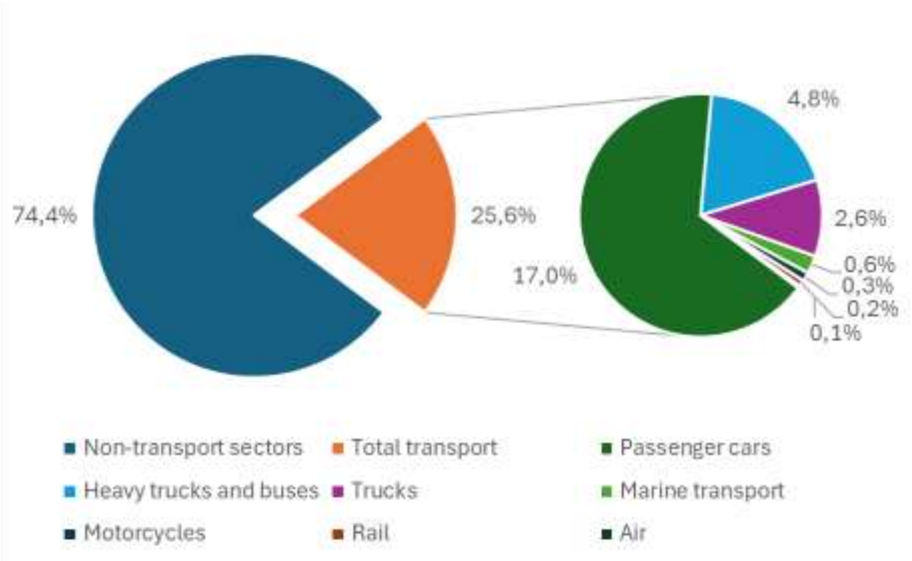


Figure 7: Share of Certain Types of Transport in Greenhouse Gas Emissions of the Republic of Croatia in 2021, Expressed in % (Source: Ekonerg, 2023)

About 1.8 million passenger vehicles are registered in the Republic of Croatia. Of these, about 6 thousand are electric vehicles and 3 thousand are plug-in hybrids. When vehicles used for demonstration purposes are excluded, there are no registered hydrogen-powered passenger vehicles.

In road transport, the use of hydrogen should be directed towards heavy goods transport, bus transport and passenger vehicles with high annual mileage (delivery vehicles, taxis, other services) and vehicles with a higher load.

Buses

Hydrogen fuel cells are identified as a viable option for public buses, especially in urban areas where reducing local emissions can be critical. Plans are in place to introduce hydrogen-powered buses into municipal bus fleets and service vehicles, aiming at decreasing urban air pollution and reducing dependency on fossil fuels and thereby demonstrating hydrogen's viability in daily use.

The “Ordinance on the Obligation to Report to the European Commission and Minimum Goals in Procedures for the Public Procurement of Vehicles for Road Transport” (Official Gazette 86/2021) defines minimum public procurement targets for the share of clean light and heavy vehicles, for public institutions and public service providers in road transport. By 2025, 27% of new buses should be clean vehicles. From 1 January 2026 to 2030, 38% of new buses are to be clean vehicles, of which 50% are zero- CO_2 vehicles.

There are 1,337 buses (CBS) in urban transport in 2022. In the period 2026-2030, about 500 new buses will be purchased, of which 190 vehicles should be 'clean vehicles' and 45 zero-emission vehicles (BEVs or FCEVs).

A comparative analysis indicates that the lifetime costs of operating public city buses are approximately equal for all three types of fuel, at around €1.45 per kilometre. Although battery electric buses were found to be slightly more advantageous, this assessment did not account for the construction costs of charging stations or the downtime during charging. In contrast to hydrogen refuelling stations, building a charging station for battery electric buses requires significantly more space and entails additional costs for power grid connection. For instance, charging approximately ten battery electric buses simultaneously necessitates a power output contract of at least 1.5 MW.

Heavy-Duty and Long-Haul Transport

Hydrogen is particularly highlighted for its potential for heavy-duty vehicles that require long-range capabilities and quick refuelling times, which are limitations of current battery electric vehicles. Pilot projects are expected to test and challenge the feasibility and efficiency of hydrogen trucks on major transport routes.

Passenger Cars

The development of a comprehensive hydrogen refuelling network is crucial to support the adoption of hydrogen vehicles. Plans include setting up multiple hydrogen refuelling stations across major highways and in large cities to ensure accessibility and convenience for hydrogen vehicle users. The government should consider tax incentives and subsidies for buyers of hydrogen vehicles, which could include both private cars and commercial fleets, to make hydrogen vehicles a competitive alternative to conventional and electric vehicles.

The composition of the transport sector is shown in Table 11. The number of passenger cars and trucks is growing, an increase was also recorded in the years of the COVID crisis. The number of buses was decreasing. Croatia has 475 passenger vehicles per thousand inhabitants, in the European Union the range is from 400 (Romania) to 700 (Poland).

Table 11: Composition of the Transport Sector in Croatia (Croatian Bureau of Statistics, 2017 - 2023)

Vehicle category	2016	2017	2018	2019	2020	2021	2022
Land vehicles							
Passenger cars	1,552,904	1,596,087	1,666,413	1,724,900	1,724,285	1,795,465	1,840,767
Buses	5,513	5,698	5,877	6,041	5,237	5,206	5,633
Trucks	146,230	156,724	169.175	180,674	188,505	193,316	208,352
Heavy trucks	10,443	11,334	12,229	12,976	13,781	14,586	15,371
Locomotives	284	285	298	285	306	260	254
Marine boats, > 100 BT							
- passenger boats	197	210	228	247	251	261	261
- cargo ships	157	149	152	153	152	151	152

Figure 8 depicts the projected number of FCEV vehicles in road traffic up to 2030, aligning with the 2030 target for the use of RFNBO. The most notable data point is the number of buses. From announced potential projects, the City of Zagreb is considering 20 buses, with other cities in Croatia collectively planning for a total of 50 hydrogen buses.

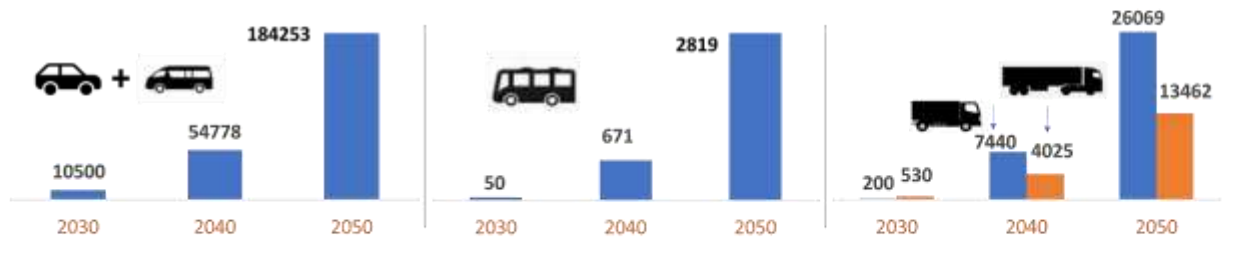


Figure 8: Expected Number of FCEV According to the Study Baseline Scenario

Table 12: Share and Renewable Hydrogen Consumption in Road Transport – Study's Baseline Scenario

Year	Category	Share	t_{H2}
2030	Personal Cars	0.52%	1,502
	Trucks	0.09%	367
	Tractor-Trailers	3.12%	2,114
	Buses	0.80%	289
	Total		**4,272**
2040	Personal Cars	2.50%	7,051
	Trucks	3.00%	12,461
	Tractor-Trailers	22.00%	14,639
	Buses	10.00%	3,529
	Total		**37,681**
2050	Personal Cars	8.00%	22,130
	Trucks	10.00%	40,742
	Tractor-Trailers	70.00%	45,687
	Buses	40.00%	13,846
	Total		**122,405**

Rail Transport

According to European Commission statistics (Eurostat, 2023) as of 2022, electricity as a power source for locomotives has increased over the years in most EU Member States. However, still about 50% of the current fleet in Europe is diesel, and in the Republic of Croatia, diesel was used for about 48% of locomotives and 53% of trains. In the Republic of Croatia, 2,617 km of railway lines have been built, and only 980 km have been electrified. The railway infrastructure is in the process of renewal and modernization. By 2030, it is planned to reconstruct about 750 km of the line. There are 19 key investment projects in the process of preparation and implementation. The projects are part of the Trans-European Transport Network (TEN-T), i.e. they are located on the Croatian part of the Mediterranean corridor.

In rail transport, the use of hydrogen comes into consideration where electrification of the network has not been implemented. On such sections, the use of battery-electric hybrid trains and purely battery-powered trains, which for now still have a relatively short range, up to 100 km, is also suitable.

According to available information, HŽ is waiting for the delivery of two battery electric trains, one hybrid and one battery, for which a total of six charging stations will be built, namely in Zagreb, Osijek, Split, Bjelovar, Varaždin, and Virovitica.

The use of hydrogen may become justified on sections that have a lower frequency of traffic and that are therefore not justified to be electrified. According to research, competitiveness is achieved on longer non-electrified sections of 100 km and with low utilization – up to 10 trains per day. The range of hydrogen trains can be up to 800 km. In the Republic of Croatia, several sections that have a low daily usability have not been electrified: the section Oštarije-Split (320 km), Varaždin-Dalj (250 km), Lupoglav-Pula (58 km). Sections suitable for hydrogen trains are shown in Figure 9.

Figure 9: Railway Sections Suitable for Hydrogen Trains in light blue (Map source: HŽ Cargo)

Due to the expected increase in total rail freight by 100% by 2050, the total number of locomotives will have to be increased. As full electrification of the rail network is not possible, rail transport needs technologies that will allow it to gradually switch from diesel to remain the most sustainable form of land transport. In addition to the purchase of new hydrogen trains, the modernization of existing diesel locomotives and the replacement of diesel engines with hydrogen propulsion can also play a significant role in this.

Table 13: Expected Use of Renewable Hydrogen in Rail Transport According to the Study’s Baseline Scenario

	2030	2040	2050
Share of renewable hydrogen in total rail consumption	1.33%	4.08%	8.55%
Consumption of renewable hydrogen in rail transport	153 t	459 t	919 t

Maritime Transport

As a major strength of Croatia, the extensive Adriatic coastline and its numerous islands are prominent tourist destinations, renowned for their natural beauty and appeal. This region also hosts significant transport infrastructure, including major ports like Rijeka, as well as industrial facilities such as refineries and cement plants.

In the Republic of Croatia, about 310 vessels larger than 100 GT participate in maritime traffic. Around 85% of these vessels are passenger ships and the rest are used for the transport of goods. There are about 120 ships in river traffic. The smallest number of these ships, around 10%, are motor freighters and motor tankers, while the largest part are non-self-propelled vessels.

Shipping is a large consumer of fossil fuels, so the potential for the use of hydrogen as a fuel is high. To this end, it will be necessary to build appropriate infrastructure (filling points in ports) and replace or convert existing ships.

The potential for the use of hydrogen in Croatia’s maritime sector, including ferries, small ships, and boats, presents a unique opportunity to both decarbonisation of the commercial shipping sector and enhancement of green tourism. This synergy between green tourism and hydrogen technology can position Croatia as a leading destination for sustainable travel in Europe.

Table 14: Expected Use of Renewable Hydrogen in Maritime Transport According to the Study's Baseline Scenario and Target Share

	2030	2040	2050
Share of renewable hydrogen in total maritime transport consumption	2.65%	5.00%	8.0%
Consumption of renewable hydrogen in maritime transport	432 t	784 t	1,200 t
Target according to RED III	>1.2%	-	-

Aviation

With regards to aviation, hydrogen is considered a longer-term alternative for reducing aviation's carbon footprint, though this is recognised as a more complex and longer-term goal due to stringent safety and technology requirements.

In air transport, fuel consumption for domestic flights is relatively small compared to the fuel supplied for international flights. According to Regulation (EU) 2023/2405, aimed at ensuring fair competition in sustainable aviation (ReFuelEU Aviation), aviation fuel suppliers have specific obligations until 2050. The scenario projects that by 2030, 1.2% of fuel consumption will come from hydrogen, approximately 29 tonnes per year. By 2040, this will increase to 6%, or 145 tonnes per year, and by 2050, it will reach 20%, or 483 tonnes per year. During the first ten years, these quantities will need to be imported.

Based on model calculations considering market developments and regulatory frameworks, expected shares of hydrogen-powered vehicles are derived for the years 2030, 2040, and 2050 as listed in Table 15.

Table 15: Expected Use of Renewable Hydrogen in Aviation According to the Study's Baseline Scenario

	2030	2040	2050
Share of renewable hydrogen in total aviation consumption	1.2%	6.0%	20.0%
Consumption of renewable hydrogen in air transport	29 t	145 t	483 t
ReFuelEU Aviation target (synthetic low-carbon and hydrogen-based fuel)	>0.7%	>8%	>28%

Table 16 shows a recapitulation of the targets for all forms of transport by 2030 according to the Study's baseline scenario.

Table 16: Expected Use of Renewable Hydrogen in Transport According to the Study's Baseline Scenario

Vehicle type	2030 [t/a]	2040 [t/a]	2050 [t/a]
Passenger cars	1,502	7,051	22,130
Trucks	367	12,461	40,742
Heavy trucks	2,114	14,639	45,687
Busses	289	3,529	13,846
Rail	153	459	919
Maritime	432	784	1,200
Air	29	145	483
Total	**4,885**	**39,069**	**125,008**

As already pointed out above, the baseline scenario for determining the potential assumes that obligations under the RED III Directive and delegated acts related to air transport are fulfilled.

High consumption scenario

In addition to the baseline scenario, the Study analysed a scenario of high hydrogen consumption. The high-consumption scenario simulated hydrogen consumption, which corresponds to 7.4% of the total energy consumption in transport (calculated according to the RED III methodology). With this kind of spending, Croatia would raise the share of RES from 21.6% to 29%, which is the goal from the RED III directive. This scenario is very challenging due to the short time frame. Also, an analysis of how much renewable hydrogen would be needed to achieve the goals of reducing CO_2 emissions in transport by 14.5% by 2030, according to the calculation methodology prescribed by the RED III directive. The calculation shows that this would require approximately a similar amount of renewable hydrogen as needed to increase the share of RES by 7.4%.

Table 17: Comparison of Baseline and High Consumption Scenarios of Hydrogen Use in Transport

	Renewable hydrogen in transport	Share of total transport consumption (calculated according to the RED III methodology)
Baseline scenario	4.88 kt	1.25%
High consumption scenario	28.2 kt	7.4%

The baseline scenario of the Study would reduce GHG emissions compared to 2021 by:

- **59 kt CO_2-eq in 2030,**
- **457 kt CO_2-eq in 2040 and**
- **1,462kt CO_2-eq in 2050.**

In the numbers above, it was assumed that CO_2 equivalent emissions would be reduced by 70% compared to fossil fuel use (LCA approach). In practice, the savings are expected to exceed the minimum 70% reduction prescribed by the RED III directive.

Additional Measures to Support Hydrogen Adoption in the Transport Sector

Supportive Infrastructure Development

Additional hydrogen refuelling stations are planned along key transport corridors and near industrial hubs transitioning to hydrogen use. This strategic placement ensures that hydrogen vehicles have consistent access to refuelling options across the country. Innovations such as high-capacity pumps and advanced storage solutions are being introduced at hydrogen refuelling stations to improve service efficiency and safety, making the hydrogen refuelling experience comparable to conventional fuels. The Study proposes 16 hydrogen refuelling stations along TEN-T routes and in urban hydrogen hubs. The NRRP allocates funding for six hydrogen refuelling stations by 2026 and four charging stations through the NPCC envelope from 2021 to 2027. Additional refuelling stations will need to be financed through other mechanisms, such as private investments, development and commercial banks. In March 2024, the Minister of Economy and Sustainable Development approved €23 million from the NRRP and NPCC 2021-2027 for hydrogen refuelling stations, with half of this amount allocated for implementation in 2024.

Research Support

Continued investment in research and development is planned to address the technological and economic challenges associated with hydrogen fuel. This includes improving fuel cell efficiency, reducing hydrogen production costs, and ensuring the safety of hydrogen transport and storage solutions.

Technological Integration and Demonstrations

Several pilot projects are planned or underway to showcase the effectiveness of hydrogen-powered vehicles in both urban and rural settings. These projects help in assessing the practical challenges and operational real-world efficiencies of hydrogen transport. Efforts are being made to link hydrogen production directly with renewable energy installations, such as solar or wind farms, especially in areas where these resources are abundant. This integration aims at ensuring that hydrogen production for transport is as green and sustainable as possible.

Stakeholder Engagement and Public Awareness

There is a significant push towards collaboration with vehicle manufacturers and energy companies to accelerate the adoption of hydrogen technologies in transport. These partnerships help align technological developments with market needs. Campaigns and informational programs are being rolled out to educate stakeholders and the general public about the benefits and the safety of hydrogen fuel, aiming at increasing acceptance and adoption rates.

3.5.3. Industry

As industries worldwide seek to reduce their carbon footprints and embrace sustainable practices, hydrogen's versatility and potential for integration into various industrial processes makes it a key component in the transition to cleaner energy sources and the shift away from fossil fuels. Its applications range from feedstock in chemical production (non-energy applications) to fuel in industrial processes characterised by intensive energy demands, positioning hydrogen as a cornerstone of the green industrial revolution. Industries with own renewable electricity sources will produce hydrogen from excess electricity. This hydrogen could be stored and utilised as needed, thereby reducing the dependency on electricity from the grid.

There is great potential in the transition to green hydrogen of today's main industrial applications of grey hydrogen in Croatia, i.e. oil refining and production of oil derivatives at the Rijeka Oil Refinery and ammonia production at Petrokemija Kutina.

The cement industry is a major emitter of CO_2 in Croatia together with other mineral industry accounting for approximately 11% of national emissions. Potential measures to reduce these emissions include the improvement of energy efficiency along the production process, the application of carbon capture and storage (or usage) (CCS / CCU) technologies, the use of biofuels and alternative fuels, and the application of RFNBOs. Though technically feasible, Croatian cement plants do not plan to introduce hydrogen as a replacement fuel before 2030. However, global experiences, such as those from CEMEX plants in Mexico, are expected to be transferred to Croatian plants in the future. HOLCIM, another major cement company, is also testing the feasibility of hydrogen use in its plants.

Additional industrial sectors in Croatia that might incorporate hydrogen in their decarbonisation efforts include:

- Glass and insulation materials production: Hydrogen can replace fossil fuels in high-temperature processes essential for glass and insulation materials manufacturing.
- Food processing: Hydrogen could be increasingly used for hydrogenation processes in the food industry, such as margarine production.
- Pulp and paper industry: Pilot projects in Europe suggest that hydrogen could theoretically replace all fossil fuels used in these industries.
- Lime and lime products manufacturing
- Brick, tile, and ceramic industry
- Manufacturing of insolation based on minerals

In the Republic of Croatia, hydrogen is used in Petrokemija Kutina and in the Rijeka Oil Refinery, and very small quantities in other industries. According to INA data, the share of hydrogen in products not used by the transport sector is negligible (currently less than 5% of products).

According to the above, it follows that the goal of the RFNBO will not apply to the Rijeka Oil Refinery. If the Rijeka Oil Refinery uses RFNBO instead of grey hydrogen from SMR, it can be counted as a contribution towards the transport sector's target.

Table 18 shows the calculation of the target, assuming production in the range from that achieved in 2021 to the maximum possible production

Table 18: Calculation of the Target (Indicative) for RFNBO in Industry until 2030 and 2035

Item	Amount of H_2 [kt]
SMR Hydrogen Production	71.0 – 141.2
Hydrogen for products in industry	51.0 – 80.0
RFNBO target by 2030 (42%)	21.4 – 33.6
RFNBO target by 2035 (60%)	30.6 – 48.0

The substitution of 42% of 'grey' hydrogen with renewable hydrogen (RFNBO) using water electrolysis would require about 1,500 MW of renewable electric power (for maximum ammonia production). This shows that achieving the goal of 42% substitution with renewable hydrogen by 2030 will be a challenge for Petrokemija, and thus for the Republic of Croatia. It is necessary to start negotiations with the European Union on the manner of transposing the provisions into national legislation and the specifics of the Republic of Croatia in time. Regarding the achievement of the target of 42% in industry, it should be pointed out that the Republic of Croatia is in a special position because it has only one industrial plant to which the target of the RFNBO applies. The objectives of RED III apply to the whole sector. Direct transfer to individual entities is not required by the directive, and it will be up to member states to decide how to achieve this sectoral target. This is the subject of reflection when transposing RED III into Croatian legislation and harmonizing with the interpretations of the European Commission.

As it was noted earlier cement plants are the largest source of CO_2 emissions in industry. In 2021, 2,825 kt of Portland cement were produced. The production of special aluminate cement is about 100,000 tons per year. In cement production, about 60% of CO_2 emissions are from the production process. The direct emission of CO_2 in the cement production process is caused by the chemical reaction of clinker production in kilns.

With modifications, it is technically possible to completely replace fossil fuels with hydrogen in the cement industry. Cement plants do not plan to introduce hydrogen as a replacement fuel until 2030. The CEMEX Corporation, the owner of the factory in Split, has two cement factories in Mexico where hydrogen has begun to be used. It is expected that the experience gained will be transferred to factories in other countries, including Croatia. The Holcim Group is also conducting hydrogen usability tests.

The assessment of the use of hydrogen in industry is presented in Table 19, and by industrial branches in Figure 10.

Table 19: Projection of the Use of Renewable Hydrogen in Industry

Industry	2030 [kt_{H2}]	2040 [kt_{H2}]	2050 [kt_{H2}]
Energy consumption	0.1	6.1	32.7
Non-energy consumption	21.4	37.2	51.0

It is estimated that the use of hydrogen will reduce greenhouse gas emissions in industry sector (industry that has potential for reduction) by 5.5% in 2030, by 11.5% in 2040 and by 24.6% in 2050 (see Table 20).

Table 20: Reducing CO2 Emissions in Industry by Using Hydrogen

	2030 [kt_{CO2}]	2040 [kt_{CO2}]	2050 [kt_{CO2}]
Energy consumption	1.4	56.4	323.1
Non-energy consumption	153.4	266.6	365.5
Total	154.8	323.0	688.6
Reduction of industry emissions compared to 2021	-5,5%	-11,5%	-24.6%

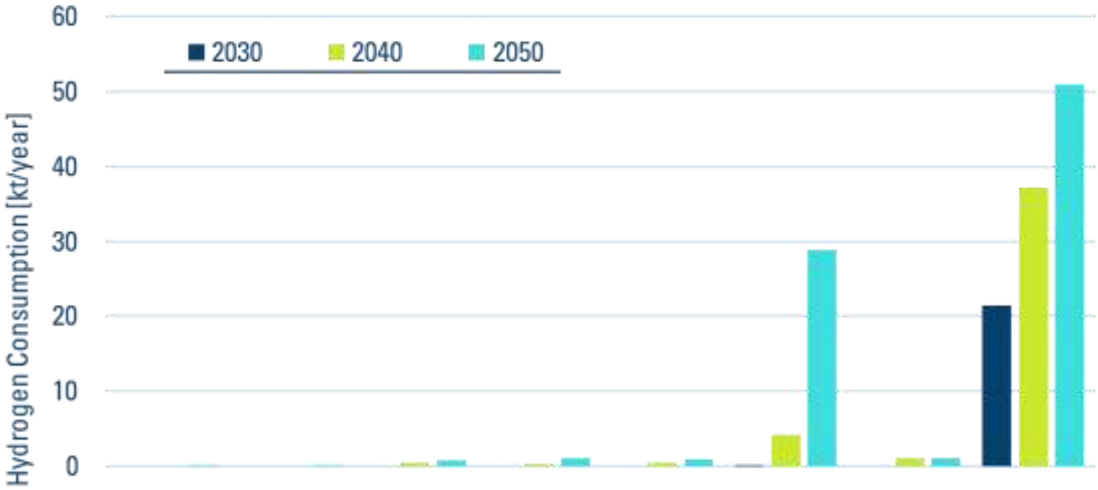
Based on these outlooks, it is expected that **by 2030**, the oil processing industry and ammonia production in Croatia will remain the largest consumers of hydrogen, reflecting current usage patterns, see Figure 10. RFNBO is expected to account for 42% of the total hydrogen used in ammonia production. Hydrogen use in other industries will be limited to research and small pilot projects, with production levels maintained at 2021 levels.

By 2040, the ammonia production industry will utilise over 73% RFNBO to meet Croatia's 60% target by 2035. The cement industry will be preparing to implement Carbon Capture, Utilisation, and Storage (CCUS) plants, operational by 2040, using hydrogen as an additional CO_2 reduction measure. Industries will plan solar power plants primarily for their own electricity needs, with surplus potentially used for hydrogen production. Large solar installations will require additional space and compliance with the RED III Directive for grid electricity use. It is anticipated that 3% of fossil fuels in the non-metallic minerals industry, including cement, will be replaced by hydrogen, with 1% substitution in other industries.

By 2050, ammonia production will achieve a 100% RFNBO target, with renewable hydrogen prices becoming competitive with fossil fuels. Cement factories are expected to replace 15% of fossil fuels with RFNBO, while other non-metallic mineral industries could see a 30% substitution rate, as they will not have CCS plants.

Overall, the use of hydrogen in industry will depend on the following factors:

- the price of hydrogen compared to other fuels and in relation to electricity,
- the price of CO2 emission allowances on the ETS market,
- the cost of capital investments for hydrogen-related modifications (e.g., of production processes),
- complementarity with the application of CCS / CCU technologies,
- the penetration of new technologies into the market,
- the commitment of industries / companies to the goals and objectives of the green transition,
- market requirements for low- and zero-carbon products,
- security of supply.



	Iron and Steel	Non Ferrous Metal	Chemical Industry	Pulp and Paper Industry	Product. of Food, Drinks and Tobacco	Non-Metallic Mineral Products	Other	Ammonia Prod. (Process Part)
2030	0.0	0.0	0.0	0.0	0.0	0.13	0.0	21.4
2040	0.0	0.0	0.4	0.2	0.4	4.1	1.0	37.2
2050	0.1	0.1	0.7	1.1	0.8	28.9	1.0	51.0

Figure 10: Expected Hydrogen Consumption in Industry by Sectors

3.5.4. Energy and Heating

Hydrogen is poised to play an important role in the future energy and heating sectors. As a versatile energy carrier, hydrogen offers substantial potential for reducing GHG emissions, for enhancing energy security, and for integrating renewable energy sources in the overall energy system. Its applications in electricity generation, energy storage, and heating systems are being actively explored and developed, promising a significant transformation in how energy is produced, stored, and utilised.

Use of Hydrogen in the Energy Sector

Green hydrogen can be utilised as an energy storage solution for excess renewable electricity. Surplus electricity from renewable sources such as wind and solar can be converted into hydrogen and stored. This stored hydrogen can then be reconverted into electricity during peak demand periods or when renewable sources are unavailable. This capability makes hydrogen an indispensable component in managing the variability of renewable energy sources, thereby ensuring a stable and reliable energy supply.

Moreover, hydrogen can be used for decentralised electricity supply and grid balancing. It can be utilised in fuel cells or gas turbines for electricity generation, as well as a supplement in conventional power plants to reduce GHG emissions. The use of hydrogen in such systems supports the sustainability of electricity generation and aligns with broader environmental goals.

Furthermore, the potential of hydrogen is being explored in regional energy systems. Specific regions could specialise in certain types of hydrogen ecosystems based on the availability of local renewable energy and industrial needs. This regional approach allows for the optimisation of local supply and demand and the creation of tailored energy solutions.

Use of Hydrogen in the Heating Sector

Hydrogen can potentially be integrated into existing gas networks by blending it with natural gas. This approach allows for a gradual transition, reducing the carbon intensity of the gas used for heating without requiring significant changes of current heating systems. The compatibility of hydrogen with existing natural gas pipelines and heating systems is currently under evaluation to determine the maximum percentage of hydrogen that can be safely blended without necessitating major modifications to pipelines, household appliances, or industrial burners. Potential for safe blending of hydrogen into existing gas distribution network in Croatia, until the year 2035, was estimated to 2 – 3%. This amounts to approx. 0.8 kt of hydrogen and a CO_2 emission reduction of 5 kt. Higher percentages of hydrogen blending requires further research and testing. In comparison, some of EU countries already allow blending of hydrogen with natural gas, even up to 10% (Wang, et al., 2021).

Since renewable hydrogen is more expensive than natural gas, blending will increase the overall energy cost for the final consumers. If system modifications are needed to accommodate hydrogen, these costs will also be transferred onto final consumers, further raising the energy price. Additionally, the economic benefit of reducing GHG emissions is minimal, as 10% hydrogen share reduces CO_2 emissions by 3.25%.

Pilot projects are being implemented to test the feasibility and safety of using hydrogen in residential heating. These projects aim at identifying necessary adjustments and gather data on consumer safety and acceptance. Additionally, ongoing research is focused on developing hydrogen-specific burners and boilers that can operate efficiently with high hydrogen blends or even with 100% hydrogen fuel. This technology is crucial for enabling wider adoption of hydrogen in the heating sector.

Ensuring the safety of hydrogen use in heating systems is a priority. This involves stringent regulations and standards to manage the risks associated with hydrogen, particularly its flammability and the need for robust leak detection systems. Croatia is actively participating in the development of European standards for hydrogen use in heating, which will help to harmonise safety protocols and technology specifications across the EU.

The primary benefits of using hydrogen for heating include significant reductions in CO_2 emissions, thus aligning with Croatia's climate goals and the EU's Green Deal objectives. Hydrogen can also enhance energy security by diversifying the energy sources used for heating, potentially reducing dependence on imported fossil fuels. This diversification supports a more resilient and sustainable energy system.

Due to the geothermal potentials in the Pannonian Basin, it is more likely that hydrogen will not become the dominant energy source for heating but rather a complementary one.

3.5.5. Summary and Quantitative Expectations

Figure 11 summarises the expected hydrogen demands for the years 2030, 2040, and 2050 for the Croatian regions in the various sectors described above (the corresponding data is listed in Table 21 to Table 23).

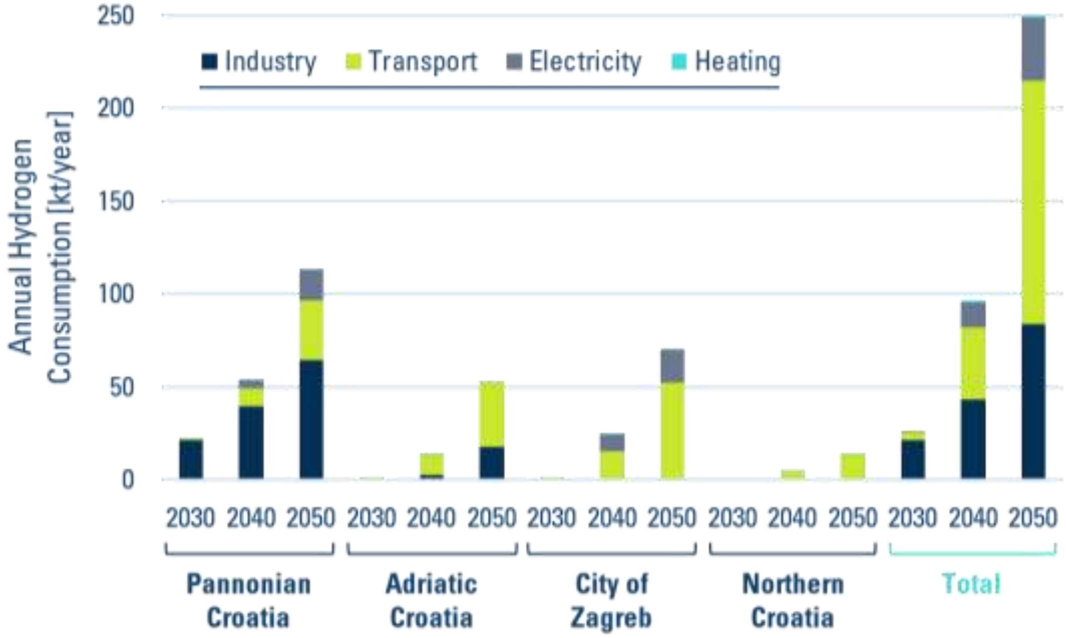


Figure 11: Expected Hydrogen Consumption for 2030, 2040, and 2050 for the Croatian Regions in Various Sectors

Table 21: Expected Annual Hydrogen Consumption by Region and Sector

YEAR	Pannonian Croatia	Adriatic Croatia	City of Zagreb	Northern Croatia
		Industry [kt/year]		
2030	21.5	0.1	0	0
2040	39.6	2.8	0.3	0.5
2050	64.6	17.9	0.4	0.8
		Transport [kt/year]		
2030	1.1	1.7	1.7	0.4
2040	9.4	10.8	15.1	3.8
2050	30.5	32.9	49.0	12.2
		Electricity [kt/year]		
2030	0	0	0	0.02
2040	4.2	0	8.9	0.04

YEAR	Pannonian Croatia	Adriatic Croatia	City of Zagreb	Northern Croatia
2050	16.2	0	17.6	0.06
		Heating [kt/year]		
2030	0	0	0	0
2040	0.5	0.1	0.5	0.5
2050	0.3	0.1	0.4	0.4

Table 22: Total Expected Annual Hydrogen Consumption by Region

			TOTAL [kt/year]		
YEAR	**Pannonian Croatia**	**Adriatic Croatia**	**City of Zagreb**	**Northern Croatia**	**Total**
2030	22.5	1.8	1.7	0.4	26.4
2040	53.7	13.7	24.9	4.8	97.1
2050	111.6	50.8	67.3	13.4	243.2

Table 23: Total Expected Annual Hydrogen Consumption by Sector

			TOTAL [kt/year]		
YEAR	**Industry**	**Transport**	**Electricity**	**Heating**	**Total**
2030	21.5	4.9	0.02	0	26.4
2040	43.3	39.1	13.1	1.6	97.1
2050	83.7	124.5	33.8	1.1	243.2

Figure 12 shows the expected regional growth of hydrogen use in Croatia for the years 2030 and 2050.

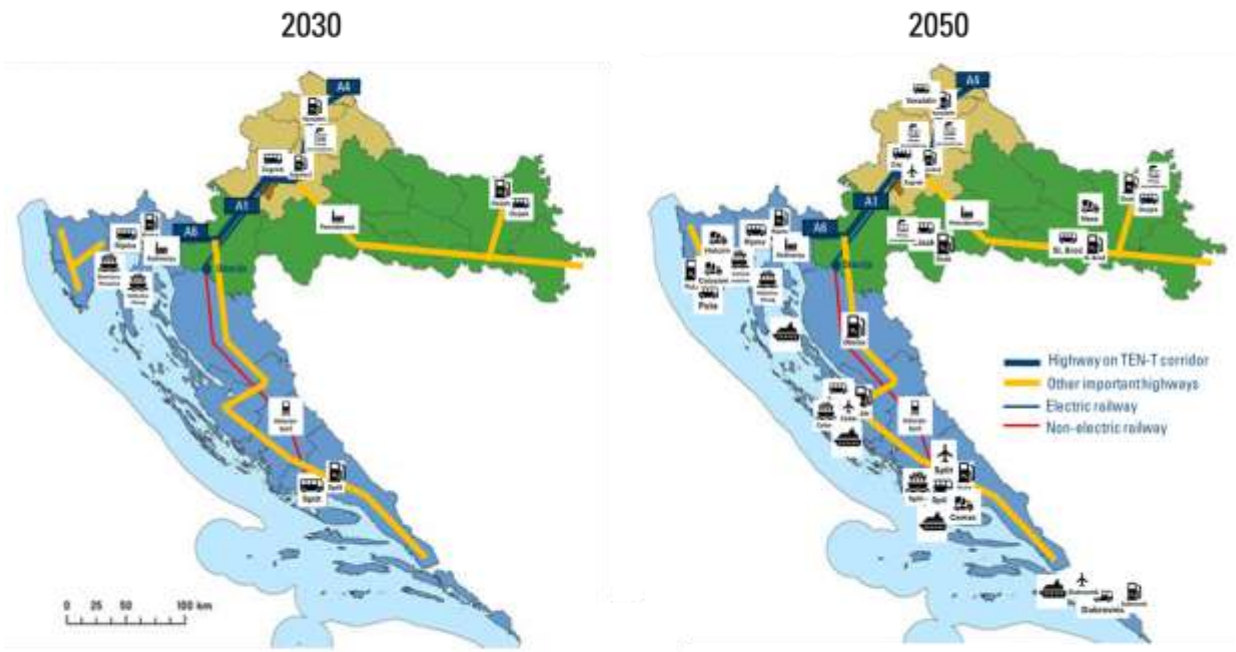


Figure 12: Expected Regional Growth of Hydrogen Use in Croatia

Figure 13 depicts the baseline scenario for renewable hydrogen consumption in Croatia up to 2050 across various sectors, including industry, transport, households, services, and heat and power consumption. It also compares this scenario with other available projections. The Study's scenario falls between the two scenarios from the Hydrogen Strategy and is higher than the scenario from the Study on Climate Neutral Scenario (2021). The NECP 'With Additional Measures' (WAM) scenario predicts lower hydrogen consumption in 2030. According to the NECP, the industry sector will dominate hydrogen consumption, with a minimal amount used in the transport sector. In the Study's baseline scenario for 2030, the transport sector accounts for 17.2% of hydrogen consumption, while the industry accounts for 82.8%.

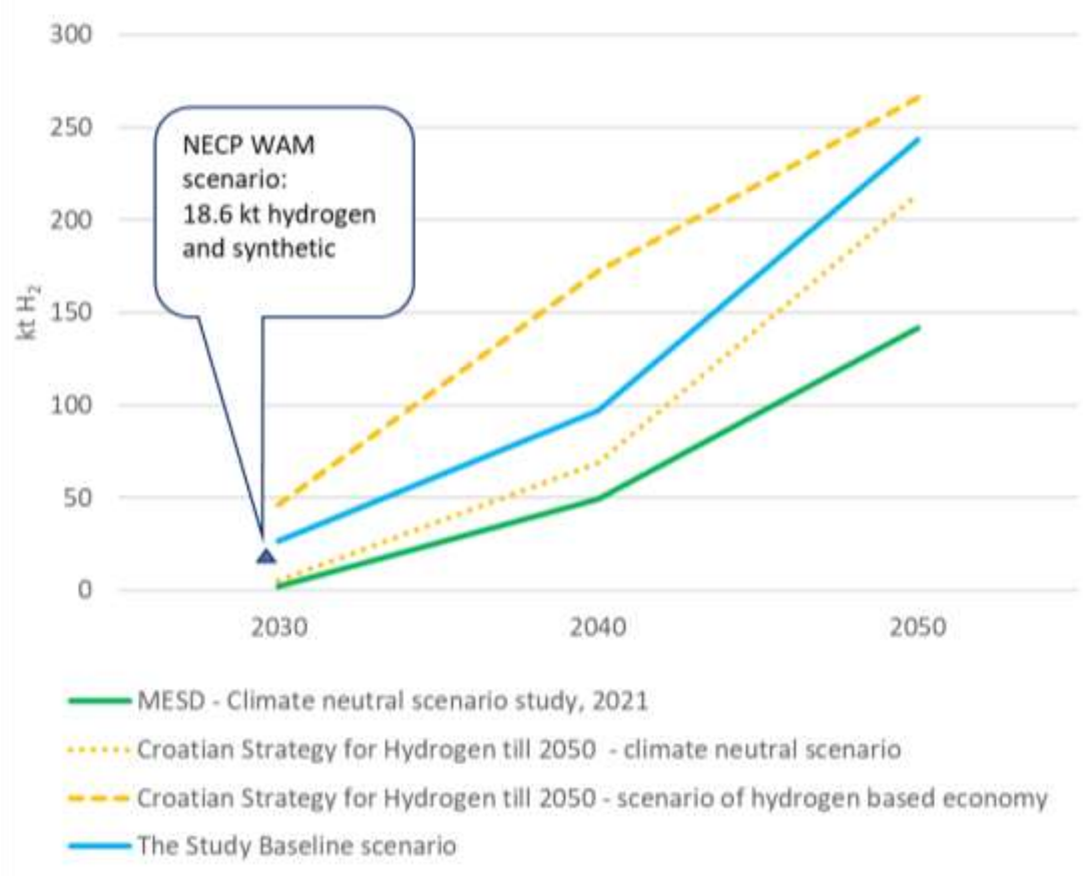


Figure 13: Expected Hydrogen Consumption in Croatia in 2030, 2040, and 2050

Compared to neighbouring countries, based on their NECP projections, Croatia's hydrogen consumption of 6.5 kg per capita in 2030 exceeds the range of 2.8 – 5.6 kg per capita observed in Slovenia, Hungary, Italy, and Austria.

3.6. The Possibility of Using the Existing Infrastructure and the Need to Expand it

Croatia boasts a robust natural gas infrastructure comprising transport and distribution networks, underground storage, and an LNG terminal, supported by domestic gas fields in the northern continental and Adriatic regions. The gas transport system, managed by PLINACRO d.o.o., comprises international and main pipelines that transport gas from domestic production, the LNG terminal on the island of Krk, and imports from Slovenia and Hungary, feeding into distribution networks and industrial consumers.

Integrating hydrogen into this network requires significant adaptations due to hydrogen's lower energy density (12.1 MJ/m³ compared to methane's 37.8 MJ/m³) and its higher diffusivity. Evaluations for compatibility are necessary, potentially involving material changes to prevent leakage and ensure safety. The potential for hydrogen blending was assessed based on the average gas consumption from 2016 to 2021 (approximately 2,874 million m³ per year), indicating significant opportunities for decarbonising the gas supply and reducing CO_2 emissions (Table 24).

Table 24: Different Scenarios for Gas Blending and Decarbonizing Gas Supply

H_2 blending scenario [%]	Blending potential		CO_2 emission reduction potential
	[1,000,000 m^3_{H2}]	[kt_{H2}]	[kt_{CO2}]
3	86	7.2	166
5	144	12.0	276
10	287	24.1	552
100*	9,784 eq.	819.9 eq.	5,520

*Total natural gas consumption expressed in tones of H_2 equivalent.

Retrofitting and upgrades involve thorough assessment and pressure testing to determine necessary modifications. Advanced monitoring technologies and safety valves designed for hydrogen's properties are crucial. Compliance with EU and international standards is necessary for safety and efficiency. Strategic enhancements include developing new pipelines and hydrogen refuelling stations, particularly at strategic locations. Cooperation between government, regulatory bodies, and private stakeholders is key for efficient planning and implementation. Despite these challenges, due to lower space and construction costs, it is still more practical and cost-effective to produce hydrogen near renewable energy sources and transport it via pipeline rather than transporting electricity and producing hydrogen at the consumption site.

Croatia's strategic position at the crossroads of Central, Eastern, and Southeastern Europe, coupled with its deep-water harbours, makes it an ideal hydrogen hub. Rijeka Bay, with its industrial heritage and existing LNG terminal, is particularly suitable for new hydrogen infrastructure. The LNG terminal at Krk could be converted to handle hydrogen imports, enabling Croatia to distribute hydrogen across Central and Southeastern Europe. Alternatively constructing a new hydrogen-specific terminal could foster Croatia's position as a significant hydrogen hub for both imports and (near-distance) exports.

In addition, Plinacro has already submitted five projects to ENTSOG's TYNDP, included in the EHB development plans. Therefore, hydrogen transport system in Croatia will consist of Hydrogen Supply Systems Croatia - North and Croatia - South. The Croatia - North project involves repurposing the 75-bar system north of Karlovac and the 50-bar pipeline in continental Croatia towards the main consumption centres. The Croatia - South project involves repurposing the 75-bar system south of Karlovac. This system will transport hydrogen from coastal areas, where green hydrogen production is expected to be high, to the main consumption centres in northern Croatia and international interconnections with Slovenia and Hungary, linking to the international hydrogen network.

Building the necessary hydrogen infrastructure is complex and time consuming, but Croatia's recent experience with the LNG terminal positions it well for such projects. Prompt planning and development are essential to harness this potential sustainably. Utilising existing infrastructure involves the extensive pipeline network that could be adapted for hydrogen transport. Evaluations are also needed for hydrogen compatibility of the various installations, as hydrogen can cause embrittlement in certain metals. Upgrades may be required to adapt to hydrogen's properties, including improved seals and joints to prevent leakage.

3.7. Development Plan for Future Hydrogen Refuelling Stations

Croatia's development plan for hydrogen refuelling stations is strategically designed to integrate hydrogen fuel infrastructure within the national framework and the broader EU transport network, aligning with the EU's Trans-European Transport Network (TEN-T). Europe aims at establishing a network of hydrogen refuelling stations along the TEN-T corridors by 2030, with each station having a minimum capacity of 1 tonne/day and equipped with a 700 bar refuelling nozzle. By 2030, each city node along the TEN-T core network should have at least one publicly available hydrogen refuelling station. Furthermore, it should be ensured that this infrastructure supports various transport modes, including road, rail, and inland water transport, and meets cross-border alignment requirements to promote seamless hydrogen supply along the TEN-T corridors.

The stations in Croatia's plan will be placed to meet the EU's stipulated maximum distances, ensuring continuous travel for hydrogen-powered vehicles without range anxiety. In urban areas, hydrogen refuelling stations will be near major traffic nodes and public transport depots to support fleets transitioning to hydrogen fuel. By 2030, cities like Zagreb, Split, Osijek, Rijeka, Varaždin, and Dubrovnik will have at least one publicly accessible hydrogen refuelling station. Additional hydrogen refuelling stations will be built along TEN-T corridors and outside of them ensuring connectivity among regions (see Figure 14). This infrastructure is crucial for the steady growth of hydrogen-powered transport and for ensuring a reliable hydrogen supply. Additionally, placing stations near ports, airports, and railway stations enhances multimodal connectivity, promoting and supporting hydrogen adoption across maritime, rail, and aviation sectors.

Figure 14: Potential Locations of HRS in Croatia

Each station will feature advanced hydrogen storage and compression technologies to handle high throughput and ensure rapid refuelling, similar to conventional refuelling stations. Technologies for both 350 bar and 700 bar refuelling pressure will accommodate various vehicles from light passenger cars to heavy-duty trucks. Initial stations will have scalable capacities to expand as hydrogen vehicle adoption increases, allowing for easy growth in storage and dispensing capabilities.

The development aligns with stringent EU safety and environmental regulations, ensuring efficient infrastructure with minimised impact on environment and society. Compliance with the EU's Alternative Fuels Infrastructure Regulation (AFIR) is essential for the hydrogen refuelling station roll-out. The implementation benefits from EU financial instruments such as the Connecting Europe Facility (CEF) and Horizon Europe, providing important funding and support for clean energy transport initiatives.

Croatia's national policies support hydrogen infrastructure implementation through incentives like tax reductions, subsidies, and financial support for research and development. Active engagement with vehicle manufacturers, energy companies, and technology providers ensures that infrastructure meets market needs and benefits from technological advancements. The overarching goal is to establish a comprehensive network of hydrogen refuelling stations that supports upcoming demand and accommodates future expansions. This network aims at making hydrogen a central component of Croatia's decarbonisation efforts in the transport sector, aligning with broader EU environmental and energy policies.

3.8. Hydrogen Hubs

Hydrogen hubs are centralised complexes that co-locate hydrogen production, storage, distribution, and application activities, aiming at optimising the hydrogen supply chain. By reducing transportation costs and energy losses, these hubs enhance the efficiency of hydrogen utilisation across various sectors. Serving multiple functions, hydrogen hubs focus on producing hydrogen (primarily through electrolysis), storing it in (large-scale) facilities, and distributing it via local pipelines or transporting it per truck to hydrogen refuelling stations and industrial consumers.

Croatia's strategic positioning for hydrogen hubs leverages its geographic features and access to renewable energy resources like hydro, wind, and solar power, which are abundant in coastal and/or highland regions. These areas are ideal for hydrogen production facilities powered by locally generated renewable energy. Additionally, the proximity to existing infrastructure, such as repurposable natural gas pipelines and major transport routes, is crucial for the effective distribution of hydrogen to end-users.

Envisioned as central nodes in Croatia's future energy network, hydrogen hubs link renewable energy production with hydrogen-based energy consumption, acting as the backbone of the hydrogen economy. They facilitate the transition of various sectors, including transport and industry, to hydrogen fuel. Economically, these hubs stimulate local economies by creating jobs and attracting investments in technology and infrastructure development. Environmentally, they play a significant role in reducing GHG emissions by promoting the use of green hydrogen.

The following suggested hydrogen hubs in Croatia highlight their strategic importance (see Figure 15):

- **Energy Hub 1:** Covering Northern Croatia, the City of Zagreb, and the western part of the Pannonian Croatia region, this area holds the highest potential for hydrogen applications, particularly in public transport in Zagreb and in the Petrokemija Kutina industry complex by 2030.
- **Energy Hub 2:** Encompassing the northern part of the Adriatic Croatia region, specifically the Rijeka Bay area, known for its strategic importance in the traffic of goods and energy products. By 2030, significant potential lies in the public transport of Rijeka, maritime transport, and oil refining, with considerations for constructing a hydrogen import terminal. Due to its advantageous location, this Hub can potentially be developed to be a central energetic connection point between South-Eastern and Central Europe for the transport of liquid (LNG) and gaseous (hydrogen) energy carriers by ship and by pipeline.
- **Energy Hub 3:** Spanning the eastern part of the Pannonian Croatia region, home to key industries like the pulp & paper and non-metal minerals industries. By 2030, the transport sector shows the greatest potential for hydrogen use, with potential applications in the above mentioned industries expected in subsequent years.
- **Energy Hub 4:** Covering the central part of the Adriatic Croatia region, this area includes the non-metallic minerals industry and public transport in major cities. By 2030, transport offers the highest potential for hydrogen application, with possible future use in the mentioned industry.

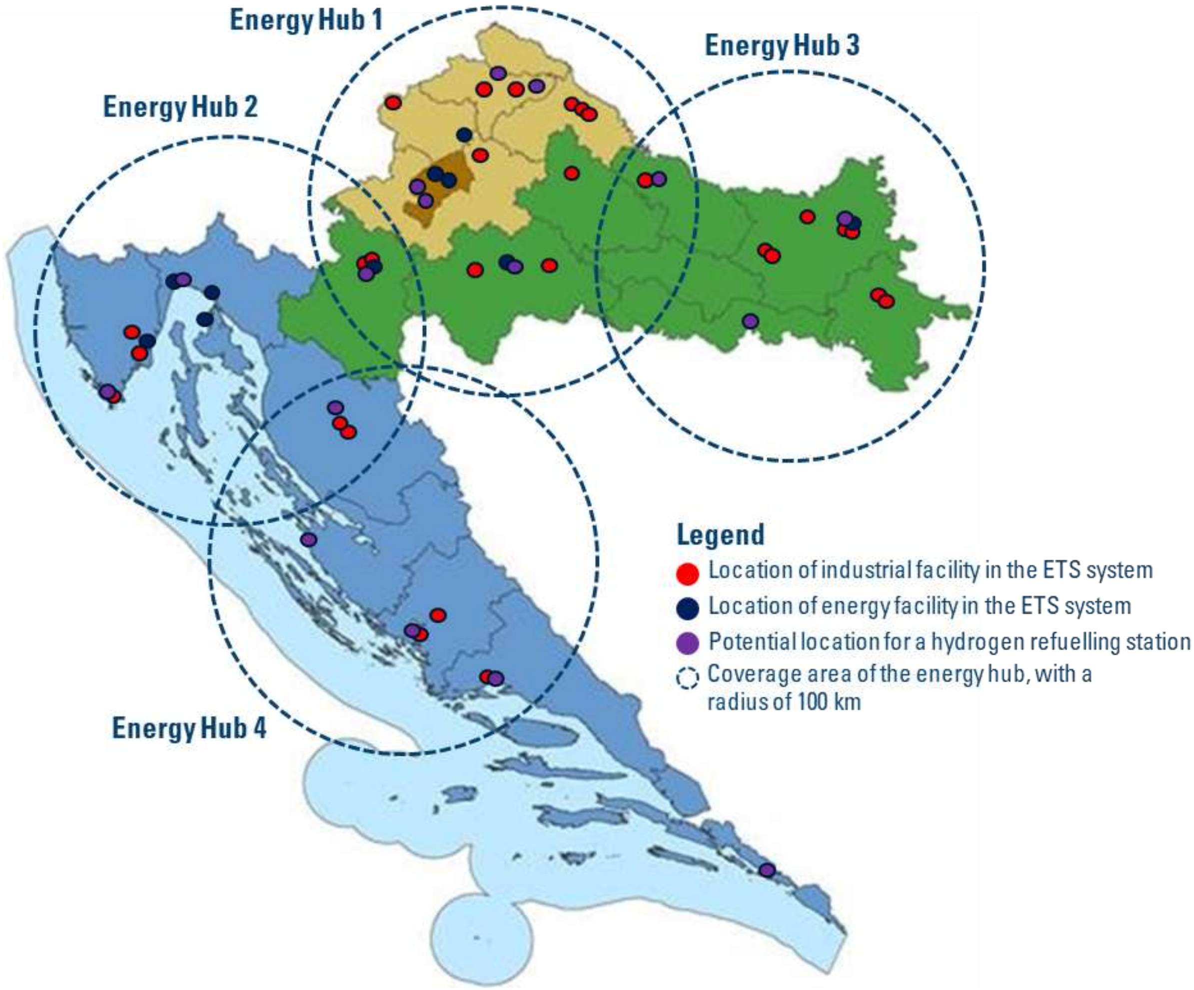


Figure 15: Potential Hydrogen Energy Hubs in the Republic of Croatia

The development of hydrogen hubs in Croatia is strongly supported by national policies and aligned with EU directives related to clean energy and carbon reduction. This support includes financial incentives, regulatory frameworks, and technical assistance from the EU. Collaborations with other EU countries, energy companies, and technology providers are vital for a successful implementation of hydrogen hubs, ensuring access to advanced technologies and best practices in hydrogen production, storage, distribution, and end-use applications.

The initial development of hydrogen hubs utilises current technology and infrastructure, with plans for scalability and technological upgrades as new innovations in hydrogen technology become commercially viable. This approach ensures that hydrogen hubs can adapt to future energy needs and market developments, maintaining their relevance and effectiveness in the evolving energy landscape.

3.9. Hydrogen Import Infrastructure

Strategically located at the crossroad leading to Central Eastern and Southeastern Europe, as well as the region, Croatia, thanks to the natural depth of its sea, has the conditions to build infrastructure for accommodating large vessels without difficulties associated with sea changes (tides). Its position, which extends deep into the European continent, represents a key advantage in reducing the distance of transport routes, thereby significantly contributing to the reduction of transportation costs, making it even more attractive for trade flows.

Rijeka Bay is a particularly attractive location for development of infrastructure for hydrogen import (see Figure 16). It is an area which already has a long tradition of industrial development. Numerous industrial ports for importing necessary raw materials, as well as for container traffic, are located there. Among the existing ports, it is important to highlight the LNG terminal on the Island of Krk and Rijeka Oil Refinery.

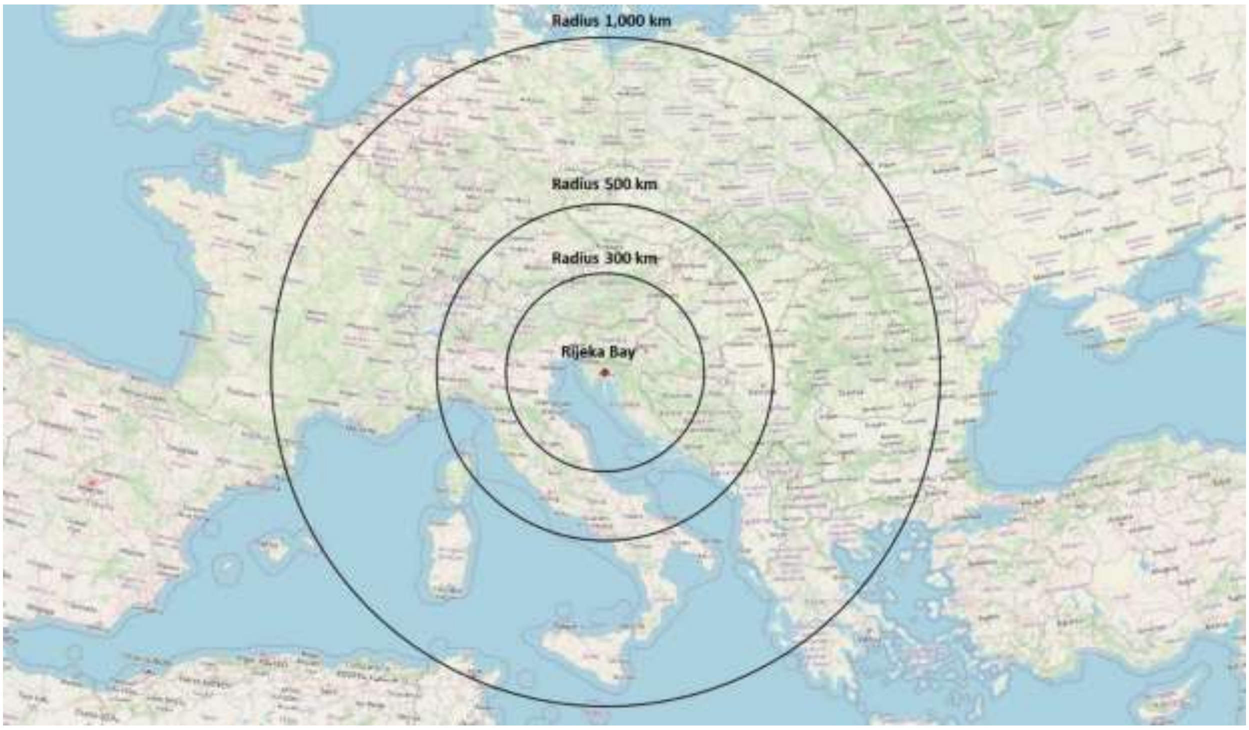


Figure 16: Geostrategic Position of Rijeka Bay (© OpenStreetMap)

Previously mentioned oil refinery, which is conveniently located at Rijeka Bay, represents a potential nearby consumer for renewable hydrogen. On the other hand, due to the recent commissioning of the LNG terminal, Rijeka Bay is connected to the high-pressure gas transmission network which constitutes a part of the future hydrogen backbone network. LNG terminal location is also recognized by the national hydrogen Strategy as suitable for converting for future import of renewable hydrogen.

4. STATE OF HYDROGEN PROJECTS IN CROATIA

This chapter on the one hand provides a quick overview of actual hydrogen projects in Croatia and their current status. On the other hand, it elaborates on the challenges, basic considerations and the implementation of hydrogen projects in general. Finally, it explains briefly the mechanisms for granting financial assistance to hydrogen projects.

4.1. Current Status of Hydrogen Projects in Croatia

In total, 32 hydrogen projects are currently in progress in Croatia at different stages of maturity. Out of these, 6 projects are covered in the North Adriatic Hydrogen Valley. Figure 17 provides an overview of the maturity of the various projects.

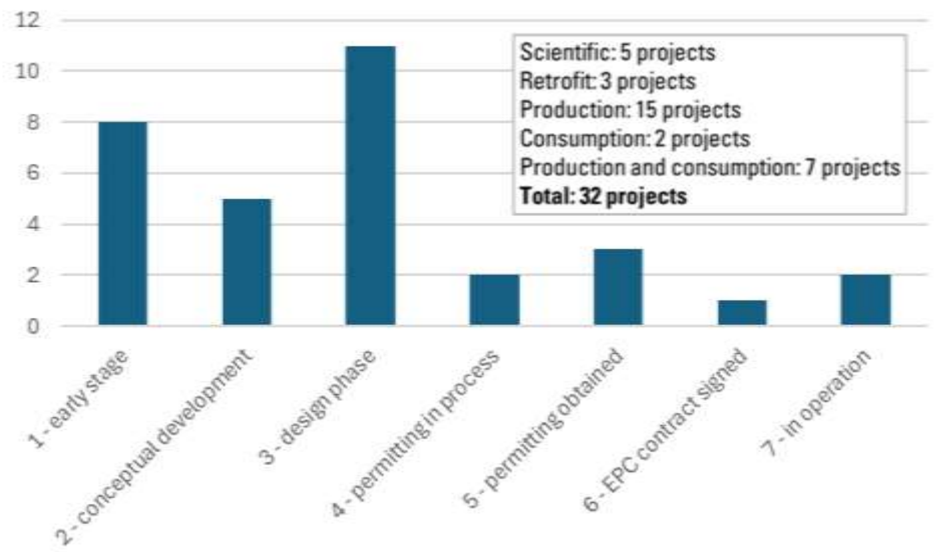


Figure 17: Maturity of Hydrogen Projects in Croatia

After reviewing the existing projects, it appears that most of them do not form integrated hydrogen ecosystems. Only seven projects, estimated to produce approximately 975 tonnes of hydrogen per annum, are designed to produce and consume hydrogen simultaneously, thereby mitigating the risk associated with an absent hydrogen market. On the other hand, currently there is a clear oversupply in hydrogen production projects, estimated at approximately 33,750 tonnes of hydrogen per annum, which lack clear indications of potential buyers. Projects focused on hydrogen consumption are estimated at approximately 382 tonnes of hydrogen per annum. However, estimated hydrogen demand in the following years easily supports even higher hydrogen production intentions.

4.2. Pilot Projects of National Importance for Croatia

This chapter defines the concept for the implementation of first hydrogen pilot projects in Croatia.

4.2.1. Challenges of Implementing Hydrogen Projects

Initial hydrogen pilot projects must overcome numerous challenges that have already been solved for other energy carriers from both fossil and renewable sources. These challenges specifically include the lack of a functional renewable hydrogen market, limited experience regarding hydrogen technology, and an ambiguous or absent regulatory framework.

Although renewable hydrogen projects are pursued, the absence of a functional hydrogen market puts project promoters in a difficult position, resulting in uncertainty about revenue generation and financial viability. Due to the lack of a mature hydrogen market, which would be characterised by widespread hydrogen use across various sectors, hydrogen projects need to be designed and implemented as self-sufficient, closed ecosystems. Only this approach ensures that all necessary components along the hydrogen value chain for a specific project are available and can be integrated into a fully functioning, self-sustaining activity. Depending on the project, this integration may involve hydrogen production, storage, distribution to the consumer site, and ultimately the usage of the hydrogen itself. After implementing several of such independent projects, the consolidation of the hydrogen market can commence, allowing elements of the previously established value chain to evolve independently and compete in the market, thereby establishing a fair hydrogen price for end-users. Thereby the European Commission's idea of implementing so called Hydrogen Valleys should be taken into account.

Table 25: Characteristics of the Challenges of the Use of Hydrogen in Various End-Use Sectors

	Demand for hydrogen in the near future	Hydrogen consumption location	Costs and barriers to switching to hydrogen	Long-term contracts for hydrogen supply
Transport	Small hydrogen consumption. The retail price of hydrogen, without subsidies, is likely to be very high.	Consumption locations are spread throughout the country. Adequate hydrogen distribution needs to be ensured.	Hydrogen filling stations have yet to be built. Hydrogen vehicles are more expensive than conventional vehicles.	Long-term contracts are possible but depend on market development.
Industry	High demand for hydrogen could stimulate the development of hydrogen production projects.	Hydrogen consumption needs to be concentrated close to the infrastructure for transport and storage.	Investment cost and plant downtime for existing methane users. Using both fuels is not practical in most cases.	Given that plants can close or change their mode of operation, there is reluctance to sign long-term contracts.
Energy	The main role of hydrogen will likely be in peak power plants.	Relatively flexible.	Investment cost for switching to hydrogen. The storage capacity for hydrogen can be large.	Long-term contracts are possible but depend on market development.
Mixing with natural gas (heating)	Heating represents stable demand, but injecting hydrogen into the gas network is not sufficiently researched.	Hydrogen consumption is possible where there is a consumer connected to the gas network.	Regulatory constraints on injecting hydrogen into the gas network. Additional safety tests are required.	Long-term contracts are likely possible. Possible restrictions on the acceptance of hydrogen by end consumers.

To successfully realise hydrogen projects at this early stage of market development, it is crucial to focus on commercially viable technologies, including their efficient implementation, maintenance, and spare part replacement. Furthermore, installation, commissioning and operation require adequately trained personnel. Finally, the total cost of ownership for these technologies should be competitive with alternative solutions, particularly those dependent on fossil fuels.

Overall, each hydrogen end-use sector faces individual challenges as listed in Table 25.

Moreover, a clear and predictable regulatory framework is critical for the success of first hydrogen pilot projects. Such a framework provides the foundation for creating market conditions required for the initiation, the growth, and the expansion of hydrogen initiatives.

4.2.2. Basic Considerations for Hydrogen Projects

The concept of implementing successful hydrogen pilot projects covers all elements from the initial project idea to regular project operation. It includes number of key elements that ensure the successful implementation of the project including defining goals, selecting technologies, resource planning, and risk management.

Goals: The objectives to which hydrogen pilot projects should contribute should be measurable and realistic. One of these objectives certainly relates to those from the RED, which include the application of renewable fuels of non-biological origin in transport, including a separate target for maritime transport and for domestic air transport, and the objective of the application of renewable fuels of non-biological origin in industry, which is already using hydrogen as a feedstock in certain technological processes. It is also necessary to define goals that will contribute to future developments such as the construction of a number of hydrogen refuelling stations on all important transport corridors as well as the adaptation of the existing gas infrastructure for hydrogen transport and distribution.

Technology: Given that the targets are set for the use of renewable fuel of non-biological origin, the focus should be directed to those hydrogen technologies that are at the highest stages of maturity, i.e. which are commercially available. For hydrogen production, this is electrolysis. It is also possible to implement new technologies in dedicated demonstration projects if deemed appropriate e.g. to advance technology for specific applications or to support local stakeholders.

Resources: Hydrogen pilot projects must provide a clear business plan, which includes all essential elements of the activity such as sources of financing, initial investments, operating costs, income recovery plan, return on investment plan, project management plan, human resources, maintenance, equipment procurement plan, raw material procurement plan, plan for obtaining necessary permits and approvals, etc.

Risks: Hydrogen pilot projects, as the market has not yet been fully developed, must provide a good risk management plan. A variety of risks must be managed, encompassing technical, financial, operational, environmental, regulatory, market, and personnel-related challenges. In order to successfully deal with all the above-mentioned risks, it is necessary to develop an adequate response plan regarding the avoidance, the reduction, or eventually the acceptance of the various risks.

4.2.3. Hydrogen Supply Cost

Each element of hydrogen value chain has its own utilisation costs. **Total cost of hydrogen supply is highly dependent on case-by-case scenario**. In some cases, it is possible to omit certain elements of hydrogen value chain, such as distribution and storage, if hydrogen is produced on consumption site. In other cases, all elements of hydrogen value chain, such as production, transport, distribution and storage will be utilized and thus result with highest overall hydrogen supply cost.

If not subsidized, hydrogen production constitutes the largest share of supply costs, typically ranging from 60 to 70%. Recent estimates for the cost of hydrogen production using a PEM electrolyser are approximately **8 EUR/kg$_{H2}$**. The cost of renewable electricity used in hydrogen production is a critical factor that significantly influences the production costs and requires special attention.

Logistic costs, which include transportation, distribution, and storage, depend on multiple factors such as the mode of transportation (ship, train, truck, pipeline), the distance covered, and the total storage capacity installed. These costs are usually added to the hydrogen production cost, thereby increasing the overall cost of hydrogen supply. Their share in total supply costs could range from 15 to 20%.

Specifically referring to the transport sector, hydrogen refuelling stations represent an additional element of the hydrogen value chain. The construction and operation of these stations entail certain costs that are factored into the overall supply cost, which could also range from 15 to 20% of the total.

Without financial support or additional tax to fossil alternatives utilisation of renewable hydrogen, and particularly RFNBO, is not yet cost competitive. Financial backing would lower the initial capital investments required for setting up production facilities, such as electrolysers, and other hydrogen infrastructure. It could also stimulate research and development into more efficient and cost-effective hydrogen production methods. Ultimately, robust financial support could make hydrogen a more competitive alternative in the energy market, potentially leading to greater energy security and diversification.

The total average cost of renewable hydrogen, which includes the cost of all elements of the hydrogen value chain, was estimated at 14 EUR/kg (see Figure 18). It should be emphasized that this is only a rough estimate of costs that are subject to change depending on the specifics of the investment project such as location, specifics of technology, conditions for connection to external infrastructure (electricity, water) and the overall complexity of the project itself.

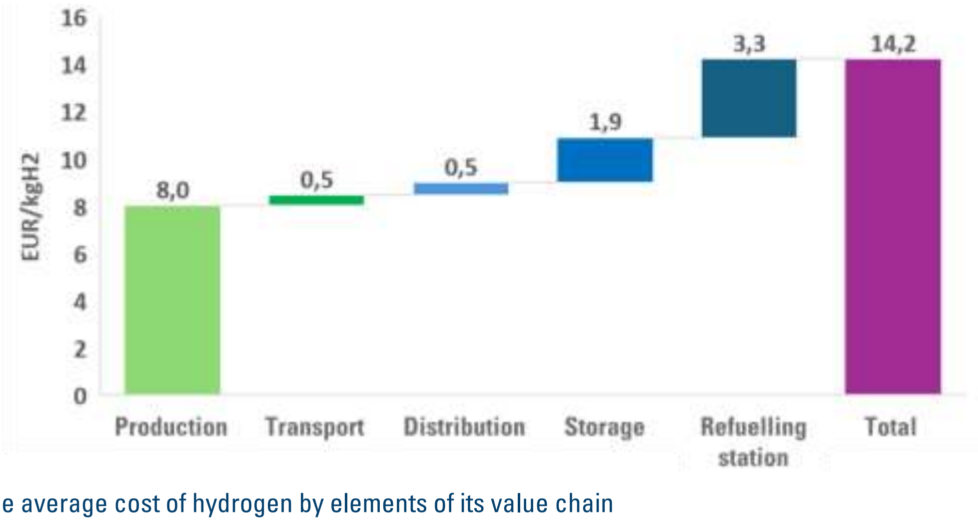


Figure 18 The average cost of hydrogen by elements of its value chain

4.2.4. Implementation of Hydrogen Projects

Preparation and implementation of each of the previously identified elements of the hydrogen value chain is an administratively and technically demanding exercise. Given the complexity of a pilot project, it is recommendable to foresee the role of an overall project supervisor that will keep the overview of all the aforementioned elements of the project, and who will orchestrate the activities of all individual stakeholders involved in the project. The implementation of such comprehensive projects also requires a thorough time planning that can be grouped in the following phases:

1) Preparatory phase

2) Obtaining the necessary permits and approvals

3) Agreement on the financial structure

4) Procurement of equipment

5) Construction of infrastructure

6) Procurement of hydrogen-powered vehicles

7) Commissioning.

A time plan, for the example of a hydrogen vehicle and refuelling station project, is depicted in Figure 19.

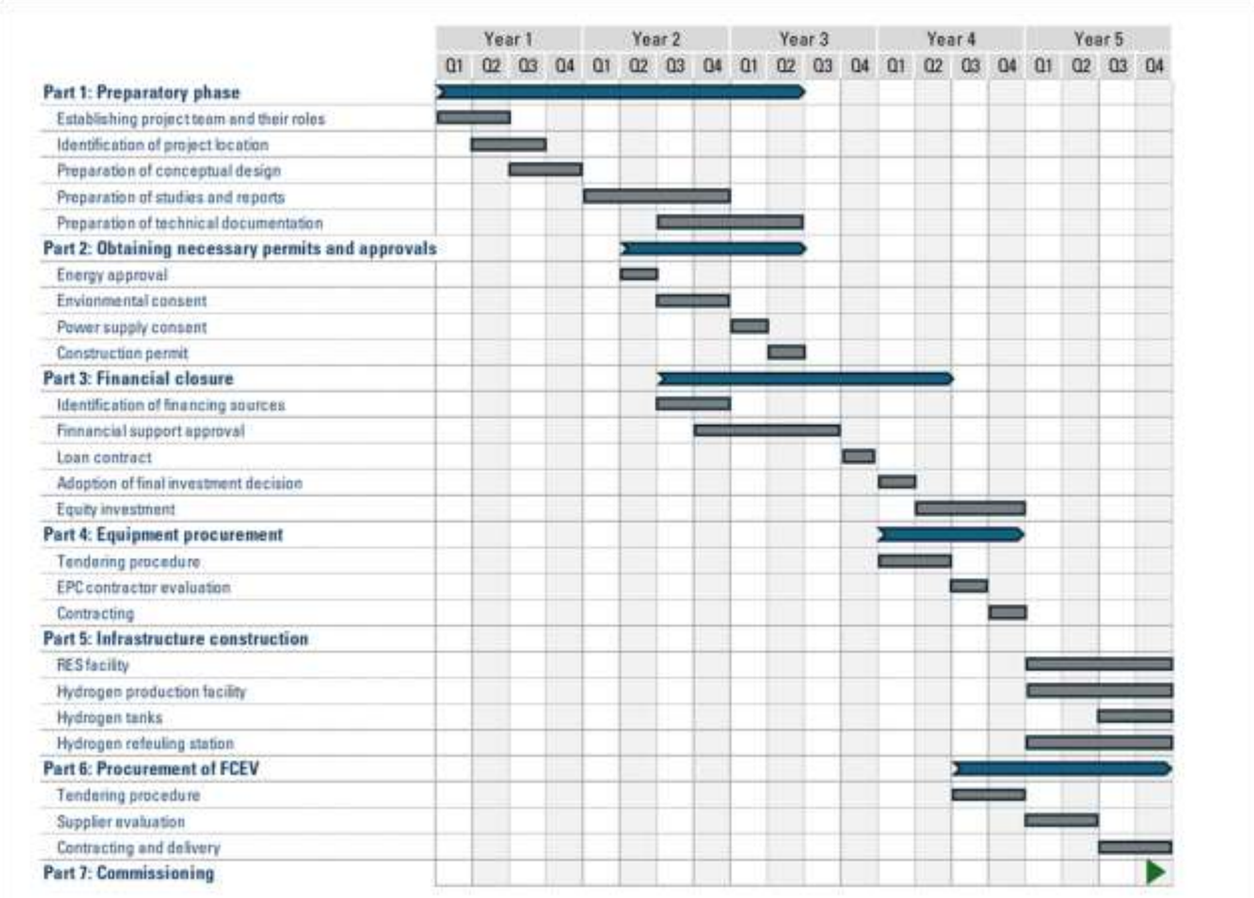


Figure 19: Potential Timeline for a Hydrogen Pilot Project in the Transport Sector

4.2.5. Pilot Project Framework

Based on the analyses carried out within this Study, the transport sector offers the most suitable preconditions for initiating hydrogen pilot projects in Croatia. This primarily includes road transport, more precisely public transport, and possibly maritime and rail transport. At the earliest stage of the development of the hydrogen market it can be expected that public transport in the largest urban centres of the Republic of Croatia, Zagreb, Split, Osijek, and Rijeka, will be amid the first adopters of hydrogen technology.

It should be noted that such applications require the implementation of the entire hydrogen value chain, from its production, distribution, storage to the end use. The implementation of all elements of the hydrogen value chain must take place simultaneously because only all elements together form a self-sustaining project as shown in Figure 20 for the public transport value chain.

The following list of criteria is proposed for the selection of first pilot projects:

- Project must be complete (i.e., from hydrogen production to hydrogen end-use application)
- Project must be realistic and (technically and economically) feasible
- Project must have serious / credible / committed partners
- Priority for those projects that have already secured (some) financing
- Project should have good visibility.

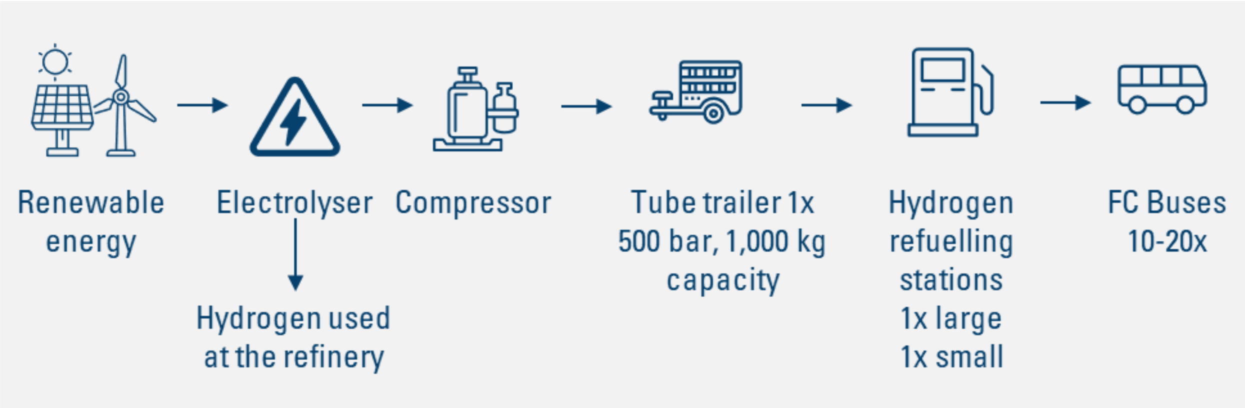


Figure 20: Example of a Self-Sustaining Hydrogen Supply Chain for Pilot Projects in the Transport Sector

A hydrogen fuel cell bus project for public transport involving the overall supply chain may involve 1-2 hydrogen refuelling stations supplied by 500 bar hydrogen trailers and 10-20 hydrogen fuel cell buses as depicted in Figure 20.

Due to the high prices of renewable hydrogen, maintaining the same affordability level in public transport might pose a challenge. In later stages, the affordability of clean public transport will be achieved by imposing CO_2 taxes on fossil fuel counterparts. However, in the early stages of pilot project roll-out, reducing the price of renewable hydrogen might be a more straightforward solution. This, however, requires the introduction of a new national model for incentivizing renewable hydrogen production, as described in the following chapter.

4.3. Financial Assistance Mechanisms

National and European plans envisage significant investments that will boost projects of large production and utilisation of renewable hydrogen. This chapter provides descriptions of the financing instruments available to support hydrogen-related projects, covering the development of new and improved technologies and the entire value chain of production, distribution, storage, and the end-use of hydrogen.

The *Croatian Hydrogen Strategy 2050* stipulates that the establishment of a hydrogen-based economy should be financed by EU funds, allocated at the EU level and EU funds allocated on the basis of national programs.

Of the EU fund programmes that do not have national allocations, the most important are the **Innovation Fund** (grants and auctions) and **Horizon Europe**.

Innovation Fund (grants): Demonstration of innovative low-carbon technologies in EU ETS sections

Innovation Fund (auctions): Auctions for the cost-efficient roll-out of low-carbon technologies, starting with EU RFNBO production

Horizon Europe: Research and innovation funding programme for R&D and demos (Clean Hydrogen JU, SPIRE)

With the aim of building digital, transport, and energy trans-European infrastructures that emphasise decarbonisation and contribute to long-term sustainability, the EU has set up the **Connecting Europe Facility** (CEF) wherein priority thematic areas **CEF-Transport** and **CEF-Energy** cover hydrogen projects.

CEF-Transport: Focus on financing key projects on the Trans-European Transport Network (TEN-T) that promote smart, sustainable, affordable, and safe mobility

CEF-Energy: Support of the implementation of the Trans-European Energy Networks Regulation (TEN-E), a regulatory framework aimed at connecting the energy infrastructure of EU countries

Also, EU funds are available as national programs financed by EU funds: **European Regional Development Fund**, **Cohesion Fund**, **Modernization Fund**, **National Recovery and Resilience Plan**.

European Regional Development Fund (ERDF): Contribution to increasing cohesion within the EU by reducing economic, social, and territorial disparities between regions and supporting the integration of less developed regions with the EU internal market through grants and financial instruments

Cohesion Fund: Financing of capital-intensive investments in the environment and transport. It provides support to EU member states with gross national income per capita below 90% of the European average

Modernization Fund: Financing programme intended for 10 lower developed EU countries in their transition towards climate neutrality, contributing to the modernization of their energy systems and improving energy efficiency

National Recovery and Resilience Plan (NRRP/NPOO): Financing electrolysers, hydrogen refuelling stations and the procurement of hydrogen-powered vehicles

Social Climate Fund: Supports structural measures and investments in energy efficiency and renovation of buildings, clean heating and cooling and integration of renewable energy, as well as in zero- and low-emission mobility solutions.

Further financial assistance mechanisms assistance are the following:

Just Transition Fund: Focus on supporting the regions mostly affected by the fossil fuel transition by providing financial support to transition plans

LIFE: Only EU fund dedicated exclusively to environmental, climate and energy targets consisting of four sub-programmes: Nature and Diversity, Circular Economy and Quality of Life, Adaptation and Mitigation of Climate Change and Clean Energy Transition

InvestEU: Supporting investments by financial partners such as the European Investment Bank (EIB) and other financial institutions

National funds, which can finance projects involving hydrogen, are tied to the state budget and the revenue generated from the sale of allowances.

New national model for incentivizing renewable hydrogen production, which can be based on well-established models for incentivizing renewable electricity production, i.e. contracts for difference. “The difference” or “the premium” would be calculated as the difference between the production cost of renewable hydrogen and the reference market price of hydrogen. The reference market price represents the price at which renewable hydrogen is competitive with its fossil alternatives. Assuming the prices of CO_2 emissions to increase over time, a reduction in the required amount of premium can be expected. Day to day operations of the financing model would be governed by the Croatian Energy Market Operator. The premium amount is expected to be in the range of 3.5 - 5 €/kg of renewable hydrogen produced. Consequently, annual funds in 2030 necessary to incentivize the use of renewable hydrogen in the transport sector would amount to approx. €20 million.

5. INSTITUTIONAL AND REGULATORY FRAMEWORK FOR CROATIA

This chapter elaborates how Croatia's legislation should be further developed to be aligned with the EU's "Fit for 55" package and to enable and encourage the integration of renewable hydrogen across various sectors such as transport and industry, ensuring full compliance and facilitating the transition to a sustainable, low-carbon economy. Furthermore, it takes into account the role of research centres and discusses forms of cooperation with the scientific community. Finally, it contributes to defining the role of the Hydrocarbon Agency and other relevant bodies.

5.1. Guidelines for the Regulatory Framework

In line with the adoption of the "Fit for 55" package and the associated hydrogen regulation (see section 2.1), the Republic of Croatia must adapt its legislation to integrate renewable hydrogen as a key element in the transition to a sustainable and low-carbon economy. This package represents a comprehensive set of legislative measures introduced by the European Commission in the field of climate and energy, including various directives and regulations, as well as the new "hydrogen and decarbonised gas package".

Although Croatian legislation is already highly aligned with EU regulations, certain revisions of existing laws and by-laws are necessary to ensure full compliance with the directives and regulations from the "Fit for 55" package. Such adjustments will enable the efficient integration of renewable hydrogen into various sectors, including transport and industry. The guidelines for structuring the regulatory framework are primarily focused on the area of energy legislation and transportation, as these are key areas for hydrogen production and use. Other administrative areas applicable to the hydrogen value chain, which are otherwise very broad, currently do not require immediate changes and are therefore not included in the scope of the presentation and analysis of this regulatory framework. The regulatory framework covered by the guidelines includes:

Table 26: Croatian Regulatory Framework Related to Hydrogen[4]

Hydrogen value chain	Sectors for hydrogen use	Regulatory framework (laws and by-laws)
Hydrogen production	All sectors (transport, industry etc)	Energy Act • Rules on Permits for Performing Energy Activities and Maintaining the Register of Issued and Revoked Permits for Performing Energy Activities • Regulation on the System of Guarantees of Origin for Energy RES and High-efficiency CHP Plants Act • Regulation on the Use of RES and High-efficiency CHP Plant • Regulation on Guarantees of Origin for Electricity Electricity Market Act Act on Biofuels for Transport

[4] All references mentioned in this table are listed in the List of References at the end of this document.

Hydrogen value chain	Sectors for hydrogen use	Regulatory framework (laws and by-laws)
		• Rulebook on Terms and Conditions of Applying Sustainability Requirements in the Production and Use of Biofuels
Infrastructure for transport, distribution and storage of hydrogen	All sectors (transport, industry etc)	Energy Act • Rules on Permits for Performing Energy Activities and Maintaining the Register of Issued and Revoked Permits for Performing Energy Activities Gas Market Act • General Conditions for Gas Supply • Network Rules for the Gas Distribution System • Network Rules for the Gas Transmission System • Rules for the Use of the Gas Storage System • Rules for the Use of the Liquefied Natural Gas Terminal • Rules on the Organization of the Gas Market • Criteria for Issuing Approvals for the Construction and Operation of a Direct Gas Pipeline
Hydrogen use	All sectors (transport, industry etc)	Act on Biofuels for Transport • Rules on Measures to Encourage the Use of Biofuels in Transport • Rules on Determining the Average Energy Values of Fuels • Regulation on the Special Environmental Fee for Not Placing Biofuels on the Market and for Not Reducing Greenhouse Gas Emissions • Rules on Terms and Conditions of Applying Sustainability Requirements in the Production and Use of Biofuels
Hydrogen refuelling stations	Transport	Act on Implementation of Alternative Fuels Infrastructure • Rules on Identification Code Registry and Infrastructure for Alternative Fuels • Rules on the Comparison of Unit Prices of Alternative and Conventional Fuels
Hydrogen vehicles	Transport	Act on the Promotion of Clean Vehicles in Road Transport

With the adoption of the RED III Directive, compared to the previously adopted RED II Directive, the targets for the use of hydrogen as a renewable fuel of non-biological origin have been expanded to include the industrial sector, in addition to the already included transport sector. Considering that the Croatian regulatory framework, particularly the Act on Biofuels for Transport and its associated by-laws, currently emphasises the use of hydrogen exclusively in transport, it is necessary to amend it in accordance with the

RED III Directive. This includes extending the law's application to the industrial sector and possibly revising the titles of the law and by-laws to clearly encompass both the transport and industrial sectors.

To effectively regulate **renewable hydrogen production,** the existing regulatory framework must be revised to include renewable hydrogen as a form of energy. Since energy production requires a permit, it is essential to establish clear protocols for obtaining the appropriate permit for renewable hydrogen production. In renewable electricity production, the regulatory framework must include specific conditions for its use in renewable hydrogen production, as well as for issuing corresponding guarantees of origin. Additionally, the regulatory framework for the sustainability of biofuel production needs to be expanded to include hydrogen as a renewable fuel of non-biological origin in the industrial sector. Finally, it is crucial to establish a system that incentivizes renewable hydrogen production, including the collection and disbursement of incentives. This will contribute to its greater application and integration into the energy system, enabling the creation of a robust and flexible regulatory framework that supports the transition towards a sustainable and low-carbon economy.

The regulatory framework for managing the **infrastructure for hydrogen transport, distribution, and storage** needs to be updated according to the new "hydrogen and decarbonised gas package" This package extends guidelines for regulating the natural gas market to include gases from renewable sources, including hydrogen. In this regulatory segment, it is necessary to revise the technical rules for the existing gas infrastructure to enable its adaptation for hydrogen use. This will ensure compliance with the latest requirements and standards for the safe and efficient management of hydrogen infrastructure.

The regulatory framework for **hydrogen use** needs to be thoroughly revised to include not only the transport sector but also the industrial sector and potentially other sectors such as the energy sector and the production of energy for heating. Considering the new provisions adopted by the RED III Directive, it is necessary to define 'renewable hydrogen' more precisely, distinguishing renewable fuels of non-biological origin from other forms of renewable hydrogen based on bioenergy. Additionally, within the regulatory framework related to promoting the use of biofuels in transport, specific measures for promoting the use of renewable hydrogen need to be introduced. This approach should also be extended to the industrial sector, where it is necessary to align the sustainability rules for the use of biofuels with those to be applied to renewable hydrogen.

The existing regulatory framework for constructing **hydrogen refuelling stations** needs to adopt Regulation (EU) 2023/1804 on deploying alternative fuels infrastructure.

General guidelines for revising the existing regulatory framework to enable the implementation of the hydrogen value chain, particularly renewable hydrogen, with a focus on its use in the transport and industrial sectors, have been previously outlined. It is important that the content of the directives from the "Fit for 55" package is adequately transposed into national legislation. Legislation from the mentioned package that have not yet been fully incorporated into national legislation need to be adopted through implementation laws. This specifically refers to Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport and Regulation (EU) 2023/2405 on ensuring fair competition conditions for sustainable air transport.

5.2. Mapping of Areas for RES Projects

According to Article 15.b of RED III, Croatia must carry out a coordinated mapping by May 21st, 2025, to identify areas necessary for deploying renewable energy projects to meet its national contributions toward the overall Union renewable energy target for 2030. This involves considering the availability of renewable energy sources, projected energy demand, and relevant energy infrastructure. Multiple uses of these areas should be favoured, ensuring compatibility with pre-existing uses.

Article 15.c of RED III requires Croatia to designate specific land and sea or inland water areas as areas for the acceleration of renewable energy sources that are suitable for the development of renewable energy projects if they will not have a significant impact on the environment and excluding sensitive areas such as Natura 2000. This designation should facilitate quicker permit-granting procedures by pre-solving spatial planning documents for the planned projects within these areas.

Designating areas along TEN-T corridors for hydrogen production for transport would reduce the need for hydrogen distribution. The major transport corridors passing through Croatia are: the Mediterranean Corridor, the Rhine-Danube Corridor, the Baltic-Adriatic Corridor and the Western Balkan-Eastern Mediterranean Corridor (see Figure 14). The above-mentioned corridors with hydrogen refuelling stations and locations for hydrogen production, key to the integration of the infrastructure of renewable energy sources, must be clearly defined in spatial planning documents, so that the procedures for issuing permits can take place within the deadlines specified in Articles 16.a to f of RED III.

5.3. The Role of Research Centres and the Form of Cooperation with the Scientific Community

The primary role of research centres is to create new value through the development of new technologies, services, and products. Through interaction with the scientific community, centres not only utilise scientific discoveries and technological achievements but also actively participate in shaping scientific research. They identify practical problems that require solutions. This collaboration enables the creation of synergy between theoretical research and practical application, resulting in accelerated innovations and increased market competitiveness.

At the national level, one form of collaboration can be joint research projects that enable the sharing of resources and knowledge between different institutions to achieve tangible results. Furthermore, technology transfer is another form of collaboration that allows the transfer of knowledge from research institutions to the private sector, thereby promoting the commercialisation of innovations. A crucial role in ensuring the continuity of expert development in the field of hydrogen technologies is played by scholarships, which enable young experts to finance and further develop their knowledge. Another form of collaboration can be the establishment of joint research laboratories that provide an environment for conducting advanced research, testing, and developing new technologies.

The formation of a research centre can be carried out in various ways, each with its specific advantages and challenges. One approach involves forming the centre as an independent body separate from other institutions, where the centre would have autonomy in decision-making and conducting research activities. This would allow the centre to focus on its goals and strategies and to develop its identity and expertise in the field of hydrogen and related technologies. Another approach is to form the centre within an existing institutional structure, such as a macro-regional centre for competence within the North Adriatic Hydrogen

Valley, which fosters collaboration between different stakeholders and allows for resource sharing. Both approaches require a clear vision, goals, and strategies, as well as the establishment of cooperation with relevant stakeholders, including industry, the academic community, and political entities.

The main role in establishing the centre will be played by the industry and the state. The role of the industry is to provide expertise in areas such as hydrogen technology, engineering, production processes, and application. It can also provide infrastructure, laboratory capacities, and access to technological innovations, and should dictate its needs and directions for further research. On the other hand, the state needs to provide the regulatory and financial framework for establishing the centre. State support may include the establishment of policies and strategies aimed at promoting hydrogen research and development, funding research projects through public funds and incentives, ensuring cooperation between industry, academia, and politics, and supporting the commercialisation of research results.

5.4. Defining the Role of the Croatian Hydrocarbon Agency

The existing tasks of the Croatian Hydrocarbon Agency (CHA) are defined by Article 58.a of the RES and High-efficiency CHP Plants Act[5]. These tasks include programming and implementing strategic plans as technical assistance to the Ministry and other state bodies responsible for hydrogen-related issues. They also involve preparing complex and innovative projects of national interest, stakeholder mapping, technically verifying capacity, potential, and the seriousness of project proposals, implementing projects in relevant funds, coordinating the implementation process in complex and innovative projects of national interest, and communicating with other member states regarding project positioning and negotiating project complementarity. Identifying and activating financial resources and reporting through the Ministry and the European Commission on the implementation of the hydrogen Strategy are also among the existing tasks of the Agency.

The Study proposes that the coordination role of CHA should be expanded to cover all renewable fuels in transport. Under this new role, CHA will assume additional operational tasks and specific responsibilities aimed at contributing to the implementation of energy and climate policy. As part of technical support, CHA will assist in achieving renewable energy (RES) targets in transport, support the sustainability certification process for renewable hydrogen, and enhance support for hydrogen value chain projects (see Figure 21).

[5] [OG138/21 2023]

Figure 21: New Tasks of CHA and Some Specific Tasks within Existing Competencies to Contribute to the Implementation of Energy and Climate Policy

Technical support in promotion of RES in transport

The Study proposes that the Croatian Hydrocarbon Agency, as the national coordinator for the promotion of hydrogen use, develops a system for monitoring the achievement of hydrogen use targets, through appropriate key performance indicators. Among the indicators, the most important is to monitor the quantities of renewable hydrogen throughout the entire value chain, the quantities of achieved CO_2 emission reductions and evidence of sustainability for renewable hydrogen and other renewable fuels. The proposal is to extend the coordination role to the use of other renewable energy sources in transport (biofuels, electrical energy, synthetic fuels, e-fuels). By the end of 2024, in accordance with the requirements of the RED III directive, "The Union database" will be established, which will enable the monitoring of liquid and gaseous renewable fuels and fuels from recycled carbon. This will require business entities to enter data on transactions and fuel sustainability properties directly into the "Union database" or via the established national database. Therefore, it is proposed to expand the coordination role of CHA with access to the "Union database" as a national „Lead User“ and the national database in order to monitor goals achievement and reporting.

Establishment and maintenance of a national register of sustainability of hydrogen in transport

The establishment of a sustainability certification system for renewable fuels of non-biological origin (RFNBO) in transport ensures that energy from renewable fuels of non-biological origin contributes to the reduction of greenhouse gas emissions by at least 70%, as required by the RED III directive.

Sustainability certification can be implemented using ''voluntary schemes'' by the European Commission or by establishing a national certification scheme. The advantages of the national scheme are, for example: a simpler certification process for the economic operators, as certain elements of the hydrogen value chain can be certified together in the same review/report, which can have a favourable impact on reducing certification costs. A coordinating role of CHA is proposed in the process of establishment and later implementation of hydrogen sustainability certification. This would enable continuous monitoring of the amount of RFNBO in transport and its contribution to the achievement of decarbonization goals.

Promoting and monitoring hydrogen value chain projects

The preparation and implementation of hydrogen projects in the Republic of Croatia is currently based on the innovation of individual economic entities. Therefore, it is necessary to establish an updated database of hydrogen value chain projects in order to coordinate the production, distribution and consumption of hydrogen. Such a base can enable systematic planning and preparation of investment projects, which can also contribute to effective programming of resources.

With its activities, CHA can contribute to the faster implementation of projects that have an integrative approach (hydrogen valleys, energy hubs, smart cities, CCUS solutions, etc.). It is recommended to include representatives of CHA in the work of various technical committees that support development of intersectoral policies. At the international level, there are numerous associations and initiatives, especially for regional cooperation, which provide an opportunity for the development of common infrastructure and greater opportunities for the realization of more financially demanding projects.

In conclusion, expanding the role of CHA will improve the efficiency of energy and climate policy implementation and contribute to transition towards a sustainable, low-carbon economy. CHA will assist in monitoring of the fulfilled goals of renewable energy sources and the reduction of greenhouse gas emissions through technical support, upgrading the legislative framework, developing an operational monitoring and reporting system, and supporting the sustainability certification process.

6. PRIORITY ACTIVITIES UNTIL 2030

The Study proposes actions throughout the hydrogen value chain to achieve the defined goals by implementing the baseline scenario proposed here. Below is a summary of the priority actions for implementation:

- **Using Study Results for NECP Revision and Spatial Planning:** In the revision of the NECP, it is necessary to include the results of the Study, which helps to increase ambitions regarding RES in the transport sector and industry and consequently reduce greenhouse gas emissions.
- **Construction of Hydrogen Refuelling Stations:** The highest priority is the construction of hydrogen refuelling stations. The network of refuelling stations should be established by the end of 2026.
- **Co-financing of FCEV Vehicles:** Funds that have allocated resources for financing zero CO_2 emission vehicles (electric and hydrogen vehicles) should announce calls specifically for financing the procurement of hydrogen vehicles.
- **Defining the Premium for RFNBO in Transport:** The Study clearly indicates that a subsidy system for the price of renewable hydrogen will be needed for a longer time. The model should be flexible and guarantee the justification of investment in the long term.
- **Defining RFNBO Target in Industry:** The existing major producer and consumer of hydrogen is the ammonia production plant in Kutina. The national goal is to achieve 42% renewable hydrogen by 2030, replacing the current production method using natural gas thermal reforming. This is extremely challenging. Croatia is in a specific situation as it has only one factory, so the national goal directly applies to one economic entity. This issue should be discussed with the European Commission in the process of transposing the RED III directive.
- **Adjusting Legislative Framework and Implementing RED III Directive:** It is necessary to start the transposition of the RED III directive and make other legal adjustments through this process. The procedure also includes possible negotiations with the European Commission regarding possible flexibilities.
- **Establishment of National RFNBO Sustainability Certification Approach:** It is necessary to take a decision on whether to establish a National RFNBO Sustainability Certification Approach.
- **Strengthening the Implementation of Clean Vehicle Regulations:** It is urgently necessary to operationally establish a system for monitoring the implementation of clean vehicle regulations and strengthen enforcement.
- **Inclusion of Hydrogen Transport Projects in Social Climate Fund:** It is important to get involved in the process of programming EU Social Climate Fund resources, which will start to be implemented from 2027 and will be funded by the emissions trading system in the building and transport sectors (ETS II).
- **Analysis of Role of Hydrogen for National Security:** The responsible ministry should initiate an analysis of hydrogen use to contribute to national security from an energy perspective, maintaining production and services critical for functioning in crisis situations.
- **Information Exchange:** The results of this Study should be shared with stakeholders, including business banks, potential investors, regional and local governments, development agencies, etc. Cooperation with associations should be strengthened.

7. CONCLUSIONS

In alignment with the EU hydrogen strategy and policy, Croatia adopted the **Croatian Hydrogen Strategy** for 2050 in 2022, outlining a national framework for hydrogen production and use, focusing on renewable hydrogen as an alternative to fossil fuels.

The Strategy's **development plan** devised in the present Study **strategically positions Croatia** by leveraging its unique strengths in the hydrogen value chain.

The Study guides Croatia towards a hydrogen Strategy implementation that is coherent with European objectives and developments, facilitates EU and international cooperation, and puts Croatia in a position to fully exploit the benefits of hydrogen for the national economy and the climate.

The **European strategy and legislative framework for hydrogen** developed over the past five years allows Croatia to tap its specific potentials and opportunities while aligning with other EU Member States in a joint development of the hydrogen economy. While the **regulatory and institutional framework** for hydrogen has not yet been fully developed **in Croatia**, the existing framework provides for a good basis to build upon and allows for making fast progress.

The total hydrogen consumption in the Baseline scenario proposed by this Study of the hydrogen value chain development falls between the two scenarios of the Croatian Hydrogen Strategy: the neutral climate scenario and the hydrogen-based economy scenario.

By 2030, the Baseline scenario complies with the targets defined in the Renewable Energy Directive and in ReFuelEU Aviation by achieving:

- >1.0 % of renewable fuel of non-biological origin (RFNBO) in the transport sector
- >1.2 % of RFNBO in maritime transport
- >0.7% of synthetic fuel based on hydrogen in aviation
- 42% of RFNBO in energy and non-energy consumption of hydrogen in industry.

The total amount of renewable hydrogen, produced and consumed in Croatia, for the transport, industry, residential and commercial sectors as well as for the production of power and heat by blending with natural gas, is 26.4 kt in 2030, 97.1 kt in 2040 and 243.2 kt in 2050. Implementation of hydrogen will reduce CO_2-eq emissions by 0.9% in 2030, 3.6% in 2040 and 9.8% in 2050 of total national emissions compared to the year 2021.

Croatia has **four NUTS-2 regions**: Pannonian Croatia, Adriatic Croatia, the City of Zagreb, and Northern Croatia. Each region's strengths and challenges provide for the basis of individual foci, e.g. the use of hydrogen in maritime transport in Adriatic Croatia as the most obvious one. Industrial consumption of hydrogen has strong potential in Pannonian Croatia and less pronounced in Adriatic Croatia. In Zagreb and in Northern Croatia, public transport and blending hydrogen into the gas distribution network are foci. Renewable power generation for hydrogen production has strong potential in Adriatic Croatia for solar and wind including offshore, and in the other regions notably for solar except Zagreb with only rooftop solar potential.

The regional approaches developed here combine well towards the national development plan.

Croatia's **potential for green hydrogen production** is underpinned by a series of strategic initiatives. Croatia's geographical location at the crossroads of Central, Eastern, and Southeastern Europe provides for a strategic advantage for the development and distribution of hydrogen in alignment with the European Hydrogen Backbone (EHB) initiative for a pan-European hydrogen network. The country's extensive coastline and access to deep-water ports makes it a viable hub for the import and export of hydrogen. Croatia has great potential in solar power and wind for producing renewable electricity. The raw material for electrolysis is only water, which is not challenging in Croatia as relatively rich in water resources.

The focus of **hydrogen use** will be on the strategic deployment of hydrogen in the transport sector and in key industries as well as in the power generation and heating sectors in the mid- to long-term perspective to ensure a sustainable and resilient energy future.

The **transport sector** in Croatia shows considerable promise for hydrogen applications, particularly for reducing GHG emissions and dependence on fossil fuels. Hydrogen fuel cell electric vehicles (FCEVs) are suitable for heavy-duty road transport, buses, and vehicles covering long distances. In public transport, hydrogen is a viable option for buses, especially in urban areas where reducing emissions is crucial, with concrete projects already under development. Regional trains, particularly in regions where electrification of rail lines is not feasible or economically viable, are also considered together with coaches for intercity travel.

For **aviation**, hydrogen is considered a longer-term alternative for reducing aviation's carbon footprint.

The extensive Adriatic coastline and the numerous islands of Croatia are a prominent tourist destination, but also host significant transport infrastructures, notably **ports** such as Rijeka, and **industrial facilities** such as refineries, cement plants, etc. Croatia thus lends itself to the use of **hydrogen in the maritime sector**, including ferries, small ships, and boats, which would synergistically support **green tourism**.

In Croatia, hydrogen is presently used in **industry** predominantly within the Rijeka Oil Refinery and for ammonia production at Petrokemija Kutina. The fossil energy for the production of hydrogen used in industry can be replaced over time by renewable sources. Furthermore, cement production and production of lime and lime products are important industry sectors in Croatia that could use hydrogen in the mid- to long-term perspective. Since a relevant part of its CO_2 emissions are difficult-to-avoid process emissions, the cement industry currently focuses on carbon capture and permanent geological storage (CCS), while energy-related emissions can be avoided by using hydrogen in the longer-term.

Hydrogen is set to play an important role in the future **electricity generation and heating sectors** for reducing GHG emissions, enhancing energy security, and integrating renewable energy sources. Its use in electricity generation, energy storage, and heating systems is being actively explored at present. Hydrogen can thus complement other sources of renewable heating, including significant geothermal potentials in the Pannonian basin.

Currently, a total of **32 hydrogen projects** are on their way in Croatia at different stages of maturity. For the future, it is of high relevance to perform the next step in combining alone-standing technology projects to larger **pilot projects** which can be developed further to **self-sustaining hydrogen ecosystems** such as **hydrogen hubs** or **hydrogen valleys**. Thereby, scarce financial resources can be used wisely and efficiently in a steadily growing hydrogen economy.

The Study proposes the hydrogen coordination role of the Croatian Hydrocarbon Agency (CHA) to be expanded to cover all renewable fuels in transport. Under this new role, CHA would assume additional operational tasks and specific responsibilities aimed at contributing to the implementation of energy and climate policy. As part of technical support, CHA will assist in achieving renewable energy (RES) targets in transport, enhance support for hydrogen value chain projects, and could support the sustainability certification process for renewable hydrogen.

Croatia is in a good position and has key strengths for establishing hydrogen production and use. A stringent implementation of the development plan presented in this Study would allow Croatia achieving the benefits of hydrogen for the national economy and the climate.

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