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Decarbonizing Italy’s Energy Sector: The Role of Hydrogen by 2030 and 2050

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Abstract

Moving to a low-carbon economy is crucial for fighting climate change, and hydrogen is becoming an important solution in the global shift to cleaner energy. This research examines how hydrogen can help reduce carbon emissions in Italy's energy sector. It focuses on how hydrogen can support Italy in meeting its 2030 and 2050 climate goals and contributing to the United Nations Sustainable Development Goals (SDGs). The study examines how hydrogen can cut Green House Gas (GHG) emissions and compares Italy’s progress and challenges with other European countries.

The study begins with evaluating the current decarbonization efforts in Italy’s energy sector, highlighting critical areas where hydrogen technologies can drive progress. The analysis explores hydrogen applications across industries, emphasizing their economic feasibility, scalability, and contribution to sustainable development. Technological advancements in hydrogen production, such as Steam Methane Reforming (SMR) with carbon capture, electrolysis powered by renewable energy, and biomass gasification are examined to understand their role in fostering a robust hydrogen economy.

The thesis incorporates advanced modeling using Aspen HYSYS to simulate Steam Methane Reforming (SMR) for hydrogen production and Proton Exchange Membrane Fuel Cells (PEMFCs) for combined heat and power (CHP) systems. These models provide insights into the efficiency and practicality of deploying hydrogen technologies on a scale. The research underscores the transformative potential of PEM fuel cells in decarbonizing urban energy systems by improving energy efficiency and enabling clean energy integration. The role of PEMFCs is particularly vital in achieving Italy’s decarbonization targets by 2030 and 2050, as they offer a sustainable solution for reducing emissions in residential, industrial, and transportation sectors.

Through a comparative analysis with other European countries, the study identifies the best practices and opportunities for international collaboration, emphasizing the importance of strategic investments, innovative policy frameworks, and cross-border partnerships. The conclusions stress that hydrogen technologies, supported by PEM fuel cells for efficient CHP, are integral to achieving a sustainable and decarbonized future for Italy. Policymakers, industry leaders, and researchers are provided with actionable recommendations to accelerate Italy’s progress toward its climate goals, contributing to the broader objectives of the European Green Deal and SDGs.

Table of Contents

List of Abbreviations

CO_2	Carbon dioxide
EU	European Union’s
SMR	Steam Methane Reforming
SDGs	Sustainable Development Goals
GHG	Green House Gas
FCVs	Fuel Cell Vehicles
BAU	Business-As-Usual
ETS	Emissions Trading System
ESGs	Environmental and Sustainable Goals
UN	United Nations
CCS	Carbon Capture System
DRI	Direct Reduced Iron
PEMFC	Proton Exchange Membrane Fuel Cell
SOE	Solid Oxide Electrolysis
AEL	Alkaline Electrolysis
AEI	International Energy Agency
WGS	Water Gas Shift
CHP	Combine Heat and Power

List of Figures

List of Tables

1. Introduction

As climate change continues to accelerate and brings its far-reaching environmental, social, and economic consequences worldwide, countries are accelerating their efforts to shift to a lower carbon economy, cutting carbon dioxide emissions in key sectors. It is crucial to decarbonize, particularly for heavily fossil-fuel-dependent industries like energy, transportation, and manufacturing, where the high carbon outputs significantly contribute to greenhouse gas emissions. As one of the world's major European economies, a member of the European Union, and the country with the world’s largest population of young, Italy needs to rapidly phase out its reliance on fossil fuels and transition to a cleaner path [1].

Carbon neutrality is important to Italy’s contribution to national as well as international climate commitments, including the European Union’s Green Deal, the United Nations Sustainable Development Goals, and the Paris Agreement [2].

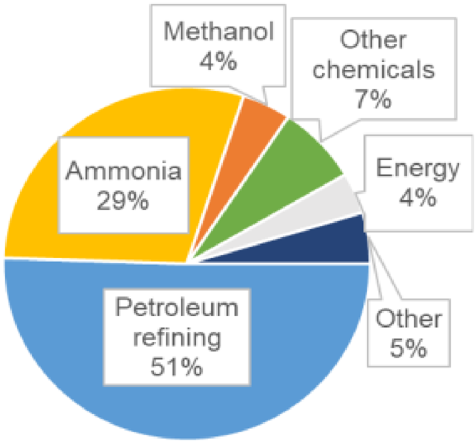


FIGURE 1-1: HYDROGEN CONSUMPTION IN EU COUNTRIES [3]

These frameworks are ambitious targets for reducing emissions, increasing renewable energy use, and promoting sustainable development to prevent, and mitigate the effects of climate change. Innovation, regulatory support, and a shift toward renewable energy sources are required to achieve these targets, and Italy’s energy landscape would need to undergo a major transformation to do it. Hydrogen is one of the many possible solutions to greenhouse gas emissions. The potential for hydrogen as a clean energy carrier to reshape the Italian energy sector through a zero-carbon fuel that can be utilized across many areas is great. Hydrogen, when produced using green methods like electrolysis driven by renewable sources of energy, releases no emissions at all, and only water vapor is produced when used as fuel. This characteristic makes hydrogen a key component of reducing Italy's carbon footprint, supporting the cases for decarbonizing areas that are very challenging to electrify, such as heavy industry and long-haul transportation.

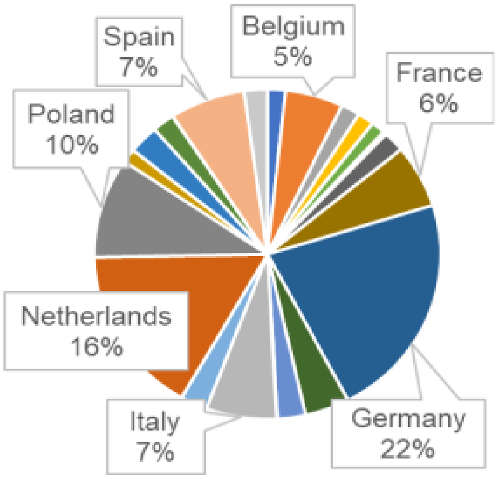


FIGURE 1-2: DEMAND OF HYDROGEN IN EU [3]

Hydrogen is not just about reducing carbon emissions; it has other potential. As a flexible energy resource, it has great promises for integration into existing infrastructure and for scaling across sectors. However, this makes hydrogen a very valuable component for energy storage and grid balancing, as it can compensate for renewable energy power during times of high demand or low production. In addition, hydrogen fuel cells fuel-powered vehicles offer a promising alternative to batteries for electric vehicles, which are particularly attractive in public transportation, and heavy trucking, where battery electrification is constrained by weight, range, and fueling time. By analyzing these benefits, Italy is starting to invest in hydrogen infrastructure as part of its overall national strategy to develop a future based on sustainable energy. In Italy, government and industry stakeholders are doing pilot projects, building partnerships, and crafting policies to speed up hydrogen adoption. It also gives Italy access to support from the European Union – both through funding, as well as with expert advice and new partnerships to bring hydrogen more quickly onto the market in line with European climate goals. But for all that Italy is now attempting to harness hydrogen's potential, the country faces problems, from the high cost of producing green hydrogen to little refueling infrastructure, and the need for supportive policies to make hydrogen an effective part of the energy mix [4]. This thesis report examines the technological, economic, and policy considerations that shape hydrogen's role in Italy's decarbonization strategy and the path to achieving its ambitious targets for 2030 and 2050. As Italy moves toward its decarbonization objectives, hydrogen adoption helps not only achieve these goals but also establish Italy as an energy leader on Europe's sustainable energy path, showing how a hydrogen-based transition can backstop both economic resiliency and environmental stewardship.

1.1. Background on Decarbonization and Hydrogen

Decarbonization represents a fundamental process to reduce global warming, with an emphasis on industries, transportation, electricity, and heating sectors. To achieve the goal of becoming the first carbon-neutral continent, the European Union (EU) has already set ambitious decarbonization goals, these are ambitious but achievable under strong policy frameworks, financial incentives, and technological innovations [5].

Since Italy comes as a member of the EU, it has promised to be a part of these climate targets and has a plan to redesign the destiny of energy in the Italian territory with clean sources of energy, energy efficiency, and the environment. However, for Italy, the decarbonization process is also particularly challenging because the country relies heavily on fossil fuel imports — especially natural gas — for energy. Natural gas imports from Russia accounted for about 40 percent of Italy's total energy consumption in 2021. The reliance of the country on foreign energy resources makes its citizens vulnerable to price volatility while supply disruption occurs during recent geopolitical tensions. As a result, Italy has turned its energy strategy to producing more of its energy domestically through renewable energy and increasing the energy efficiency of its operations or discovering other forms of energy to increase energy security. Hydrogen is one of those options because it can store and discharge energy without the release of carbon dioxide when combusted or run through fuel cells. Yet realization of hydrogen's potential requires solving a host of technical, economic, and environmental challenges. Simply, hydrogen is being taught to be a 'fuel of the future' as it can help to decarbonize a vast swath of sectors on a large scale. If hydrogen is produced using a renewable method, it can be combusted or used in fuel cells, and only water can be produced as a byproduct – which means it is a zero-emission energy source. Hydrogen can be used as an energy carrier in multiple sectors and deployed as a versatile means for decarbonizing Italy. But no matter where hydrogen comes from, there are several ways to generate it and some are more environmentally sustainable than others. Renewable energy-powered electrolysis is what we call green hydrogen, the least polluted, and in line with the Italian decarbonization target. On the other hand, Steam Methane Reforming (SMR), one of the currently widely used processes, tends to provide “gray hydrogen” associated with emissions of CO_2. For this reason, the method employed to produce hydrogen will be of major importance in assessing hydrogen’s contribution to Italy’s carbon reduction goals.

1.2. Importance of Hydrogen in Achieving Sustainable Development Goals (SDGs)

In 2015, the United Nations introduced the Sustainable Development Goals (SDGs), which are 17 global targets from which the world hopes to derive sustainable economic growth, reduce inequalities, and preserve the environment.

The Sustainable Development Goals (SDGs)- 2015

FIGURE 1-1: SUSTAINABLE DEVELOPMENT GOALS [38]

Hydrogen can make a substantial contribution to several of these goals, in terms of clean energy (SDG 7), industry innovation (SDG 9), and climate action (SDG 13). [38]

Hydrogen can play a role in assisting Italy to achieve these sustainability goals while providing employment and socioeconomic benefits in line with broader SDG targets, by being an enabler for the transition to a low-carbon economy. Hydrogen can eventually decarbonize sectors that are difficult to electrify, including heavy industry and long-haul transportation. Hydrogen can replace carbon-intensive fuels in sectors such as steel manufacturing, chemical production, and cement where energy requirements are high and GHG emissions from the total can be reduced. It is important for Italy, where industrial emissions represent an important share of total GHG emissions. While battery technology may not provide the necessary energy density or range, hydrogen also can be a critical part of heavy-duty transportation. Fuel cell vehicles running on hydrogen are particularly good alternatives, particularly for the areas of freight transport and public transport.

In addition, hydrogen production and utilization provide an opportunity to generate economic value through job creation, innovation, and local economic stimulation. While Italian eyes are fixed on the start of its hydrogen journey, if a domestic hydrogen industry is developed it could provide jobs in engineering, manufacturing, and its development. In addition, investment in hydrogen research and development will create conditions for transition in electrolyzer technology, hydrogen storage, and fuel cells. These advances will not only enable Italy to achieve its energy targets but could also make Italy a market leader in the European hydrogen economy. Hydrogen integration enables Italy to achieve the SDGs of economic growth (SDG 8) and sustainable infrastructure (SDG 9) while lowering its carbon footprint (SDG 13).

1.3. Purpose and Scope of the Thesis

This thesis aims to examine the role of hydrogen in Italy’s energy transition to decarbonize 2030 and 2050 targets. In the thesis, the current state of decarbonization in Italy will be analyzed, examining the Italian energy landscape, policies, and progress made thus far. We will use this analysis to establish a basis to examine in greater depth hydrogen production technologies in terms of their feasibility environmental impacts and scalability in Italy. To determine which method for hydrogen production is the most viable in the Italian context, the thesis evaluates methods such as Steam Methane Reforming (SMR), electrolysis, and biomass gasification.

This report has a key element it is highlighting the role hydrogen can play in the reduction of GHG emissions in sectors such as power, industry, and transportation. Various hydrogen applications will be looked at across different use cases such as power generation or fuel cell vehicles, providing perspective on infrastructure and policy needs for widespread hydrogen adoption. Large-scale hydrogen production and distribution will also necessitate capital investment and will be a primary focus on economic feasibility. This report analyzes the costs of different production methods, the potential of investment opportunities, as well as other economic implications, for developing a hydrogen industry in Italy.

Moreover, the report will analyze Italy's hydrogen strategy compared to other European nations and highlight what was learned and best practices to help shape Italy's approach. This has already been done in Germany and the Netherlands, where (amongst other things) already great strides have been made in hydrogen development and they can thus provide valuable insights into the right policy framework, funding mechanisms, and public-private partnerships.

The report aims to benchmark Italy's hydrogen strategy against other EU countries and to show collaborative opportunities that could speed up Italy's hydrogen take-up. Although hydrogen represents a potentially attractive path to decarbonization, the environmental impacts of hydrogen production, storage, and utilization must be fully assessed. Not all hydrogen is produced in suitable ways and some processes producing hydrogen produce CO_2 as a byproduct. As a result, the report will assess the environmental impacts of various hydrogen production methods using a life cycle assessment, calculated for factors such as water consumption, fuel input, and possible emissions. The analysis of this thesis will guarantee that the recommendation of this report is in line with Italy's carbonization goals as well as for sustainable resource use and environmentally friendly. In addition to the ecological aspects, the report will also deal with hydrogen adoption from the economic and social aspects.

The report will examine the potential for the creation of jobs, regional economic development, and community benefits, offering a holistic view of the contribution that hydrogen can play in Italy's energy transition.

1.3.1. Thesis Objectives

1. Analyze the current state of Italy's decarbonization efforts, with a particular focus on the role of hydrogen in achieving national and EU targets.

2. Evaluate different hydrogen production technologies, assessing their environmental impacts, economic feasibility, and potential scalability in the Italian context.
3. Examine hydrogen’s potential across various sectors, including power generation, transportation, and industry, highlighting specific applications and infrastructure needs.
4. Compare Italy’s hydrogen strategy with those of other European nations, identifying best practices and collaborative opportunities.
5. Present policy and strategic recommendations for advancing hydrogen adoption in Italy, focusing on the 2030 and 2050 decarbonization timelines.

Through these objectives, this thesis seeks to provide a comprehensive analysis of hydrogen’s potential to drive Italy’s energy transition and support its decarbonization goals. The thesis will address the technical, economic, and environmental aspects of hydrogen production and use, offering actionable insights for policymakers, industry leaders, and stakeholders involved in Italy’s journey toward a low-carbon economy.

2. Evaluating Hydrogen’s Potential to Reduce GHG Emissions by 2030 & 2050

As countries strive to meet their climate targets and transition to sustainable energy systems, hydrogen emerges as a versatile solution with the potential to minimize greenhouse gas emissions across multiple sectors. This section examines hydrogen's role in reducing emissions by 2030, outlines policy recommendations to achieve 2050 targets, explores the impact of hydrogen on different sectors, and provides case studies and projections to illustrate its effectiveness in contributing to a decarbonized economy.

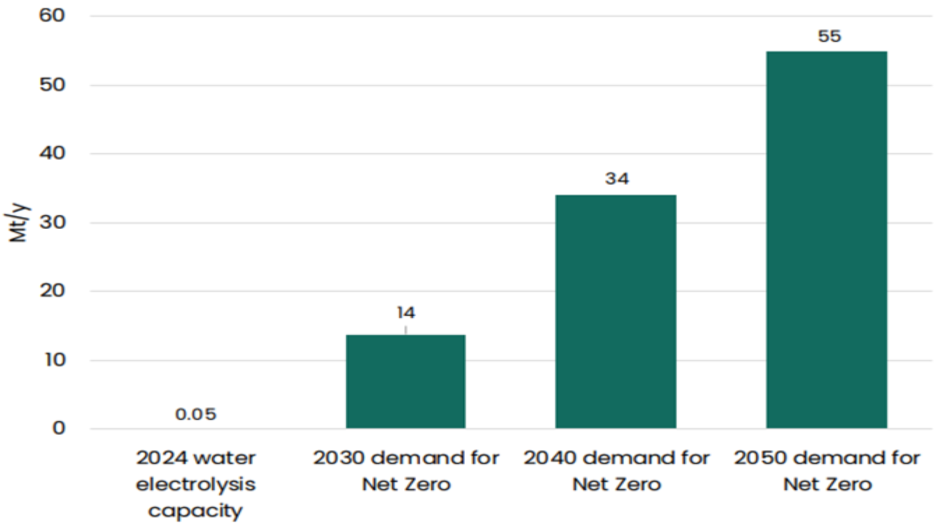


FIGURE 2-1: HYDROGEN CONSUMPTION REQUIRED FOR ITALY AND THE EU TO ACHIEVE NET-ZERO CARBON EMISSIONS BY 2050 [3]

2.1. Hydrogen’s Role to Reduce GHG Emissions by 2030

In the decade ahead, hydrogen can help drive decarbonization across all sectors – transportation, industry, energy – by 2030. The time is now to enable rapid deployment of hydrogen technologies to address climate change while meeting national and international targets such as the Paris Agreement.

Transportation Sector

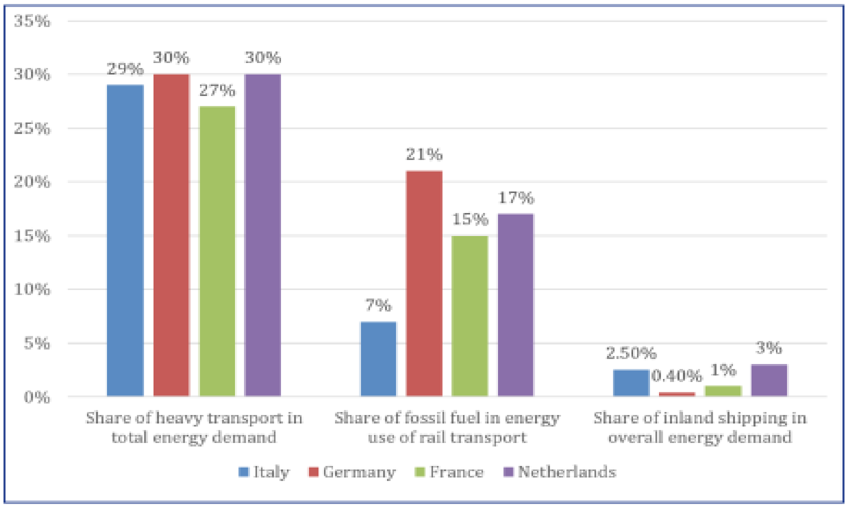


FIGURE 2-2: HYDROGEN LEADS TRANSPORT SECTOR [6]

Transport is among the biggest GHG emitters across the globe. The superior alternative to internal combustion engine-powered vehicles is hydrogen Fuel Cell Vehicles (FCVs), which cut down on emissions. By 2030, the adoption of hydrogen in transportation can lead to substantial emission reductions through:

- **Fuel Cell Buses and Trucks:** Urban areas can be cleaner with hydrogen-powered buses and trucks replacing diesel buses and trucks. For example, studies have shown that fuel cell buses can cut GHG emissions into 50% range or more compared to traditional diesel buses.
- **Passenger Vehicles:** Since regions with limited charging infrastructure are attractive for hydrogen FCVs, they may eventually become mainstream alternatives to BEVs. Wide adoption is presented by a robust hydrogen refueling network combined with government incentives.
- **Maritime and Aviation:** The challenge to electrify maritime and aviation sectors due to energy density requirements makes hydrogen a potential decarbonized for these sectors. Hydrogen can, by 2030, contribute to emissions reduction in shipping and air transport through hydrogen fuel cells and synthetic fuels.

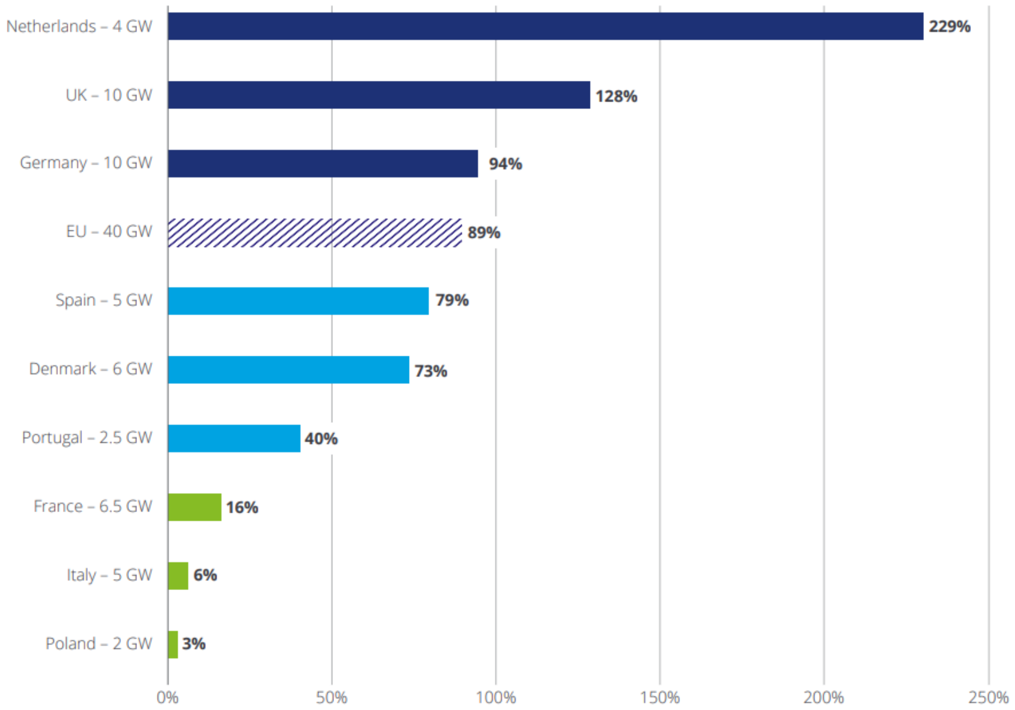


FIGURE 2-3: HYDROGEN CAPACITY TARGET COMPLETION RATE OF ITALY AND OTHER EU COUNTRIES BY YEAR 2030 [7]

2.1.2. Industrial Processes

Hydrogen plays a critical role in reducing the environmental impact of material extraction and industrial processing, primarily by offering a cleaner alternative to carbon-intensive fuels and reducing the need for raw materials. In traditional industrial processes, such as steel and cement production, large quantities of fossil fuels are burned, releasing significant carbon dioxide emissions. Hydrogen, particularly "green hydrogen" produced through electrolysis using renewable energy sources, provides a zero-emission alternative. When used in processes like direct reduction of iron (DRI) in steelmaking, hydrogen reacts with iron ore to produce pure iron and water vapor, replacing the need for carbon-intensive coke. This substitution not only curtails greenhouse gas emissions but also reduces reliance on coal and coke mining, thus diminishing extraction activities that have environmental and social costs, such as habitat destruction and air pollution.

Moreover, hydrogen can enhance efficiency in chemical industries, where it can be used as a feedstock in a more sustainable production of chemicals and fuels. As hydrogen becomes increasingly integrated, industries can rely less on traditional extractive resources and instead leverage circular and renewable inputs, leading to reduced demand for mined materials and a smaller overall environmental footprint. The adoption of hydrogen across sectors also stimulates the development of a sustainable infrastructure, paving the way for reduced reliance on finite resources and facilitating the transition to a low-carbon economy.

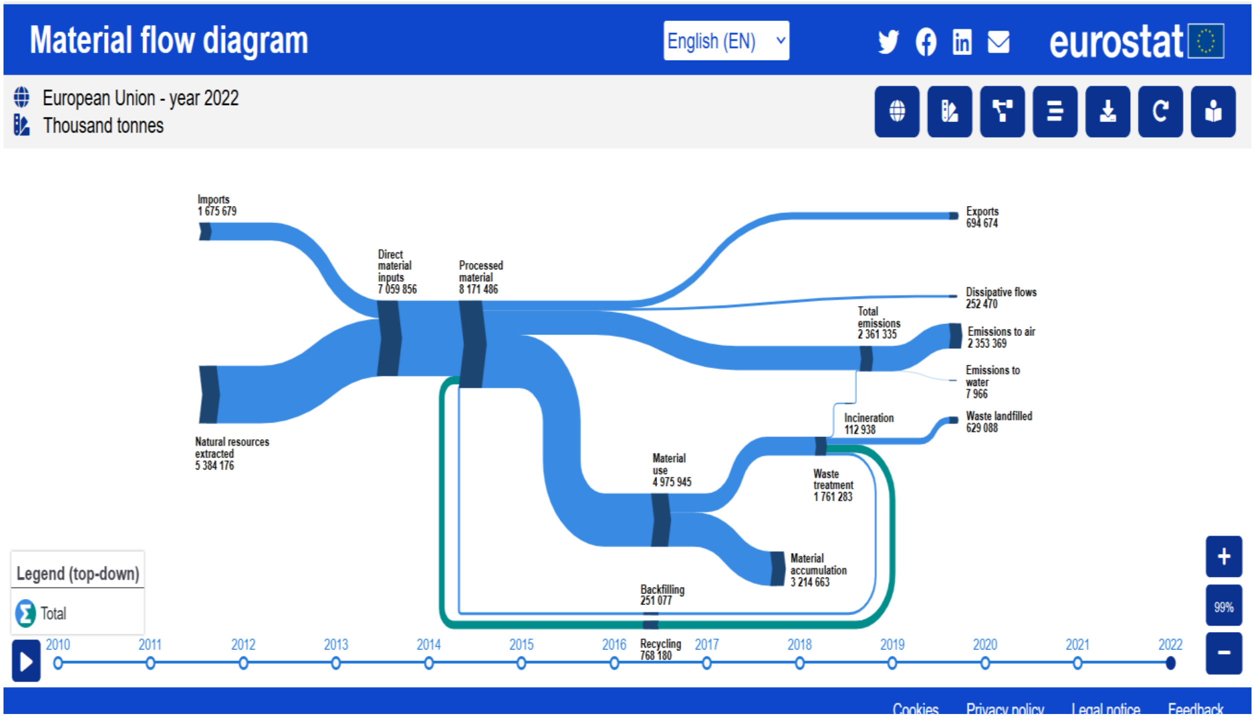


Figure 2-4: Material Flow diagram EU [46]

Hydrogen is key for decarbonizing hard-to-abate industrial processes like steel, cement, and chemical making. Hydrogen can be an alternative in cleaner fuels to these fossil fuels which make up a huge portion of the global emissions.

- **Steel Production:** Steel production is almost entirely dependent on coking coal, which causes high emissions. Using a hydrogen-based direct reduction process may cut emissions by as much as 95%. Several pilot projects are already underway, and scaling up these technologies to 2030 will result in considerable emission reductions.
- **Cement Manufacturing:** Another major source of emissions is cement production. Hydrogen as a fuel in kilns or as a reducing agent in lime production can contribute to the

sector's decarbonization. Hydrogen integrated into existing processes can substantially cut emissions while continuing near sacred productivity goals.

- **Chemical Production:** Ammonia is an important product and key feedstock for fertilizers and from ammonia, hydrogen. Electrolysis of green hydrogen could dramatically cut the carbon footprint of the ammonia industry. A pathway to achieve major reductions in emissions through hydrogen use in chemical processes can start already by 2030.

By replacing fossil fuels, enhancing recycling, and enabling more sustainable resource processing, hydrogen can drastically reduce the environmental impact and volume of material extraction in industrial sectors. This shift not only curbs emissions but also promotes a more resource-efficient, sustainable industrial landscape.

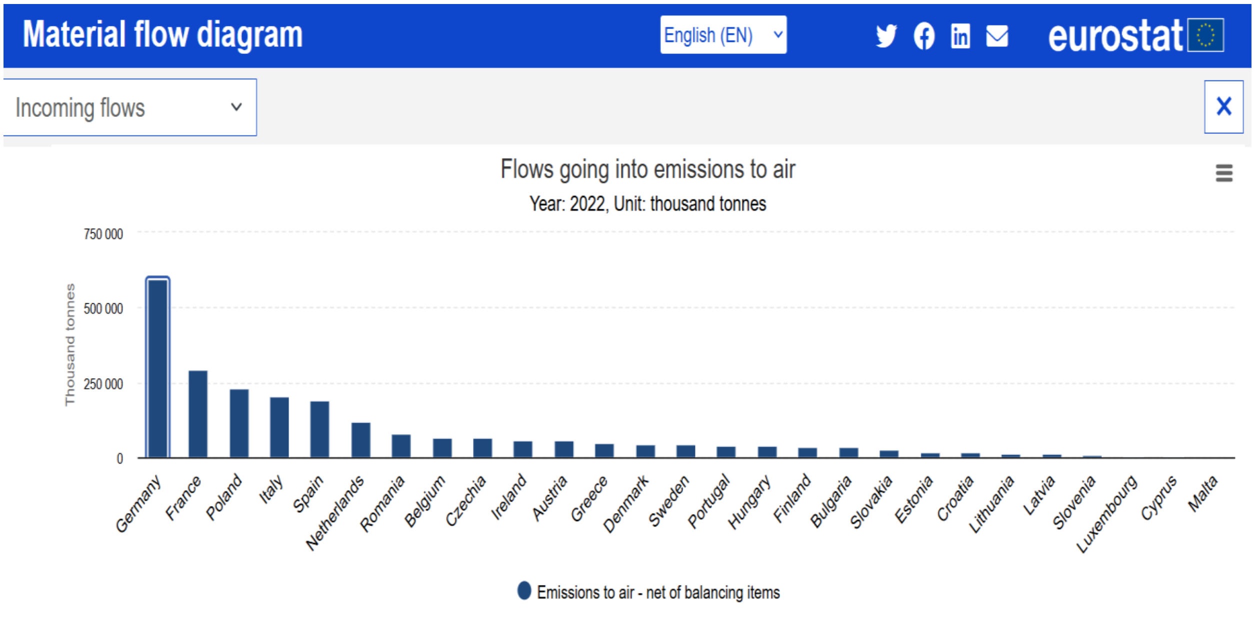


FIGURE 2-5: EMISSIONS INTO THE AIR IN EUROPE – NET BALANCING ITEMS [SOURCE: EUROSTAT]

2.1.3. Energy Sector

The energy sector can use hydrogen to increase energy storage capacity, facilitate the integration of renewables, and decarbonize power generation.

- **Energy Storage:** Hydrogen could be stored for a long-term energy storage solution to balance intermittent renewable energy sources like wind and solar. By 2030, developing hydrogen storage technologies can allow excess renewable energy to be converted into hydrogen and stored for later use, thus structural buffering the energy supply.

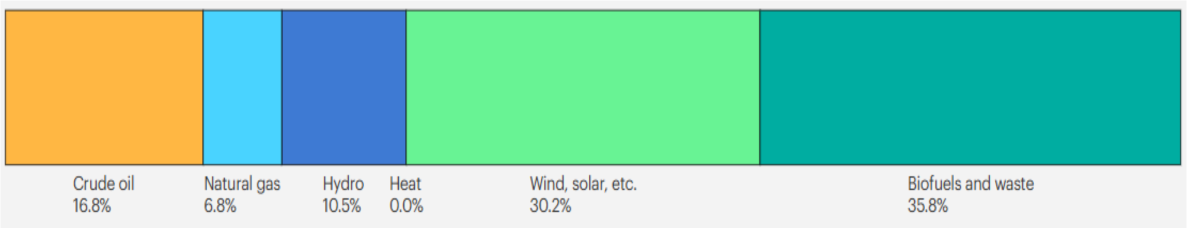


FIGURE 2-6: ENERGY PRODUCTION IN ITALY FROM DIFFERENT RESOURCES [8]

- **Power Generation:** Mixing hydrogen in with natural gas already used by power plants, however, could reduce emissions while keeping existing power infrastructure intact. In addition, hydrogen could be used in new hydrogen-fired turbines for zero-carbon power generation. Increased use of hydrogen in an energy mix can result in substantial GHG reductions by 2030.
- **Grid Stability:** Hydrogen production thus allows one to provide a controllable energy source, which complements variable renewable energy generation, and that can help increase grid stability. Hydrogen's integration into the energy system can provide a safe electricity supply, that does not rely on fossil energy more than other means.

2.2. Policy Recommendations for 2050 Targets

To attain substantial GHG emissions reductions by 2050, such a comprehensive policy framework is needed. To make hydrogen technologies adaptable, policymakers must first create an enabling environment for hydrogen technologies, secondly, remove barriers to adoption, and finally encourage investment in research and development.

TABLE 2-1: SHARE OF HYDROGEN ENERGY IN ITALY [47]

Category	Current Status	2050 Target
Total Energy Consumption	1,436 TWh	-
Current Hydrogen Consumption	~16 TWh (1% of total energy)	-
Hydrogen Production	480,000 t/year	2.3 million tones
Hydrogen Imports	~8,500 t/year in cylinders/pipes	~1 million tones
Total Hydrogen Consumption	480,000 t/year	

2.2.1. Long-Term Strategic Planning

1. Aligning the national goals with international climate commitments requires a long-term hydrogen strategy. This will provide a vision for the future where stakeholders can develop a clear roadmap for hydrogen deployments, from production through distribution, storage, and end use [9].
2. Policymakers should set long-term targets for hydrogen production as well as utilization for the year 2050 and short-term objectives to measure the companies' performance of the switched targets [10]. Targets should provide differentiation by sector to encourage targeted emission reductions.
3. Several of these strategies should incorporate hydrogen strategies in more aligned and consistent ways to broaden climate and energy policies that have applications toward achieving decarbonization goals.

2.2.2. Financial Incentives and Funding Mechanisms

There will be a strong reliance on governments for the increased industry demand for hydrogen. Monetary rewards and other capital-providing instruments encourage the use of HYDROGEN, research of its applications, and development of the necessary facilities and equipment.

1. Provide financial support for hydrogen research projects, pilot programs, and large-scale deployment initiatives to lower upfront costs for private investors.

2. Implement a carbon price that correctly provides the market with the correct cost for carbon emissions. This can incentivize industries to adopt low-carbon technologies, including hydrogen, by making fossil fuel alternatives less economically attractive [11].

2.2.3. Research and Innovation Support

Like all disruptive commercial technologies, investing in research and innovation is key to furthering hydrogen technologies, to developing higher efficiency, more affordable products and services.

1. Funding research institutions and industry partnerships working on hydrogen production, storage, and utilization technology. It can even accelerate the development of the next generation of technologies.
2. Sponsor collaboration among academia, industry, and government agencies that will drive the exchange of knowledge by enabling it to be shared, innovated, and commercialized into hydrogen solutions.

2.2.4. Infrastructure Development

Building a robust hydrogen infrastructure is essential for enabling widespread hydrogen adoption.

1. Put the investment in hydrogen production facilities, storage, and distribution networks as a priority and integrate hydrogen into the energy system.
2. To support fuel cell vehicle adoption, it should develop hydrogen refueling stations for transportation applications in urban and densely traveled regions such as major transportation corridors.

2.3 Impact of Hydrogen on Various Sectors

Hydrogen can have a potential impact on many sectors from transportation, industry, energy, and beyond. Extracting the hydrogen from other sectors and converting it into an energy carrier that can deliver power to either directly mitigate emissions or further help provide for more sustainable energy is uniquely beneficial for each sector.

TABLE 2-2: SHARE OF CO2 EMISSIONS IN THE EU [39]

Category	Share
Global CO_2 Emissions Share	0.9% of combustible fuels
CO_2 Emissions per Capita	5.258 tones
Oil (Fuel Combustion)	48% of CO_2 emissions
Transport (Energy-Related)	33% of CO_2 emissions
Electricity & Heat Producers	30% of CO_2 emissions

2.3.1. Transportation

Earlier we showed that hydrogen plays an important part in decarbonizing the transportation sector. Substantial GHG emission reductions can be achieved by integrating hydrogen fuel cells into buses, trucks, and passenger vehicles. Because hydrogen FCV, emissions consist of only water vapor, they alleviate significantly the air quality problems in urban areas and diminish air pollution-related health risks from fossil fuel vehicles. Hydrogen fuel cells have higher energy efficiency than internal combustion engines, better mileage, and consume less overall energy. Hydrogen is an especially good case for heavy-duty vehicles due to longer ranges and faster refueling times than battery electric vehicles.

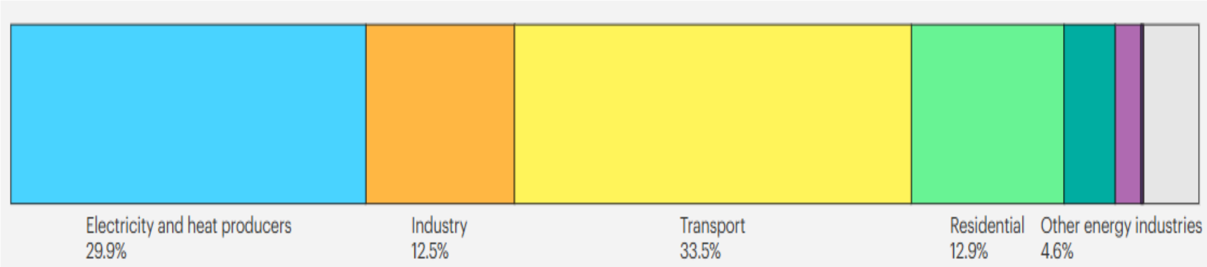


FIGURE 2-7: CO_2 EMISSIONS BY DIFFERENT SECTORS IN ITALY [8]

2.3.2. Industry

The decarbonization of a range of industrial processes can be encouraged by the use of hydrogen, resulting in substantial emissions reductions. Hydrogen can also help industries, including steel and cement, transition out of carbon-intensive processes which will lower their carbon footprint significantly. The application of green hydrogen to chemical manufacturing would make chemical production processes cleaner and provide the ability to innovate and encourage sustainability in the chemical industry. Hydrogen technologies and infrastructure development will bring new manufacturing, research, and energy sector job opportunities.

2.3.3. Energy Sector

Hydrogen can be used by the energy sector to further integrate renewables, increase energy security, and cut emissions. By storing excess renewable energy, such as wind and solar, in hydrogen, such systems can make greater use of wind and solar and require less dependence on fossil fuels. This local production of hydrogen allows the community to develop local decentralized energy systems, which attempt to increase energy security and resilience. Hydrogen can as a viable solution for long-term energy storage, making short-term storage such as batteries necessary.

2.3.4. Agriculture and Other Sectors

Beyond transportation, industry, and energy, hydrogen can impact other sectors such as agriculture and waste management. The optimization of the utilization of green hydrogen in ammonia production results in sustainable fertilizer solutions to the emission issue. We can find several factors linked to the conventional production of fertilizer. Hydrogen can also be generated from the gasification of organic waste, helping at the same time, disposal of waste and offering a renewable energy source.

2.4 Case Studies and Projections

Several case studies and projections illustrate hydrogen's potential in reducing GHG emissions and contributing to a sustainable energy future. These examples provide insights into successful hydrogen initiatives and their impacts on emissions reduction.

2.4.1. Case Study: Germany’s Hydrogen Strategy

Germany has seen itself as a world leader in the development and deployment of hydrogen technology. In 2020, the German government introduced the National Hydrogen Strategy to become a global front-runner in hydrogen technologies by 2030. Germany wants to invest €9 billion into hydrogen production and aims to produce 'green hydrogen' from renewable sources [12]. Working with major industrial players such as Siemens and ThyssenKrupp, they want to develop and scale hydrogen technology for use in, among other things, steel production. With green hydrogen replacing fossil fuels, the hydrogen strategy in Germany could reduce GHG emissions accordingly, especially in the industrial sector, according to projections.

2.4.2. Case Study: Japan’s Hydrogen Economy

Hydrogen uptake has remained high in Japan where leadership has focused on hydrogen's contribution to energy security and emission mitigation. Ambitious targets of hydrogen use by 2030 and 2050 were set recently with the Hydrogen Roadmap in 2017 from the Japanese government. The National FCV plan calls for 800,000 FCVs on the road by 2030, supported by an extensive network of hydrogen refueling stations. The government is also in the business of investing in hydrogen production technologies like electrolysis and steam methane reforming to diversify the supply of hydrogen. In International Hydrogen Initiatives Japan actively engaged in partnerships with Australia for hydrogen exports. According to projections, Japan’s eventual transition toward an economy based on hydrogen could cut emissions in the transportation and energy sectors and help the beleaguered country meet its climate targets.

2.4.3. Projections for Italy

In terms of Italy, hydrogen could play a major role in its decarbonization. Some studies even saw hydrogen becoming a major part of Italy’s energy mix by 2030 and playing a major role in its emissions reductions in key sectors. Adoption of hydrogen in transportation could reduce emissions by 30–40% relative to Business-As-Usual (BAU) scenarios in the heavy-duty and public transport sectors by 2030. If hydrogen is implemented in steel and chemical production, the industrial sector could reduce emissions by up to 50 % by 2030. According to projections, hydrogen could contribute up to 15% to the total energy consumption in Italy by 2030, increasing energy security, and reducing the use of fossil fuels. Overall, hydrogen has the potential to reduce GHG emissions from the different sectors over both the 2030- and 2050-time frames. The versatility of that energy carrier, and the complementary evolution of strategic policy frameworks and investments, can support the transition towards a sustainable energy future. To reach ambitious climate targets in Italy and elsewhere, it will be essential to get on board with hydrogen tech to reach carbon neutrality and address the real challenges of climate change [13]. With enhanced efforts and new approaches, the fuel of the future, hydrogen, can play a pivotal part in building a carbon-neutral economy.

3. Understanding the Current State of Decarbonization in Italy's Energy Sector

Currently, Italy’s energy sector is in a transforming phase; with its intention to reduce its GHG emissions and facilitate the transition to a low-carbon economy, it is at a pivotal time. The transformation presented here is consistent with both national and international climate commitments, and it is critical in contributing to Italy’s carbon neutrality by 2050. Because it relies so heavily on imported fossil fuels and ambitious renewable energy targets, Italy’s decarbonization approach is conditioned by a complex combination of policy, technology, and economic factors. Foreseeing the role hydrogen may play in this transition requires looking beyond the program — that means understanding the current Italian energy landscape, the policies and regulations driving the energy market forward, and the steps taken to date to lower emissions.

3.1. Overview of Italy's Energy Landscape

A main feature of Italy’s Energy landscape is the strong dependence on imports of fossil fuels, specifically natural gas, oil, and coal representing significant fractions of the country’s energy mix. However, Italy has progressed in increasing its contribution to renewable energy, and in this case especially in terms of the power sector. Italy’s renewable energy profile includes hydropower, solar, wind, and biomass, making for a rich portfolio of energy sources. Italy has few domestic fossil fuel resources, so these renewables are important, given energy security is the central consideration for Italy's energy policy. In Italy, the largest source of energy supply (about 40%) is still natural gas. Natural gas, imported largely from Algeria, Russia, and Libya, is used extensively for electricity generation, heating, and process applications. Oil is mainly imported and is used in the transportation sector in addition Italy is a major refiner country. Coal energy is still an input to electricity generation, though the government is committing resources to ensure the total elimination of its usage in electricity generation by 2025 [14].

In Italy, on the other hand, renewable energy has become increasingly important within the country’s energy topology. Italy is home to a great amount of river systems and mountainous terrain therefore hydropower has historically served as Italy’s leading source of renewable energy. However, because of government incentives and favorable geographical conditions, solar and wind power have grown tremendously in the last few years. With a sunny climate and ambitious solar deployment targets, Italy is now one of Europe's leaders in solar energy. While wind energy is less common than in other European countries, it is gradually increasing, especially in southern regions and offshore areas. Italy's renewable energy mix is also made up of biomass and waste-to-energy facilities in the countryside and rural areas. Renewables are starting to play a major role in Italy's electricity generation. Recent successes in increasing the share of renewables in electricity production have led the country to boast that renewables contribute nearly 40% of the total electricity consumption. Integration of renewables into Italy's electricity grid has helped reduce its dependency on fossil fuel-fired power plants though efforts are needed to balance intermittent renewable sources with demand.

3.2. Current Policies and Regulations

Policies and regulations promoting decarbonization in Italy are in line with European Union (EU) directives and international climate agreements. These policies cover diverse areas in the energy sector including policies to encourage the use of renewable energy, policies regarding emission reductions, and policies that focus on energy efficiency. There is also an ideological strategic map of the Italian government for decarbonization, and the EU's Green Deal as well as the recent Fit for 55 package offers additional support. The National Energy and Climate Plan is one of the key policies Italy must implement on the path to decarbonization: it provides and elaborates Italy's energy and climate targets for the 2030 horizon. The NECP provides specific goals on renewable energy, energy efficiency, and emissions cuts. It wants to ensure the contribution of renewables in gross final energy consumption of about 30% by the year 2030 and a reduction in GHG emissions from the non-ETS sectors by 43% from the 2005 level. Further, it paves the way for green hydrogen to ensure the delivery of a carbon-free economy to segments, where the direct application of electricity is feasible. Along with the NECP, Italy has introduced incentive schemes to promote the development of renewable energy. The Conto Energia was one of the first feed-in tariff schemes in Europe and helped boost the take up of solar PV and make Italy one of the leaders in solar energy. While Conto Energia has been discontinued, new programs including feed-in tariffs through competitive bidding for renewable power projects and incentives for energy-efficient buildings are still in the process of encouraging the expansion of renewables.

Italy is also consistent with the objectives of the EU Fit for 55 package that targets a reduction of net greenhouse gas emissions in the EU by at least 55% by the year 2030 compared to 1990 levels.

Fit for 55 engines several pieces of legislation instruments of energy, transport, and industrial sectors. That is why measures have been taken to adhere to the decarbonization goals and respond to climate change in Italy. The Italian government has paid attention, especially in the future related policies in hydrogen as an impulse of the hydrogen strategy in the EU to form the European hydrogen market and infrastructure. The other key part of the decarbonization policy mix in Italy is carbon pricing. As a member of the ETS, Italy obeys a cap-and-trade structure that makes carbon emissions for power plants, industrial factories, and other heavy polluters cost-effective. This system provides an economic signal to firms to either cut their emissions or utilize fewer polluting technologies. In the most recent years, the price of carbon under the ETS has increased significantly placing a higher cost on the emission of CO_2 and therefore has encouraged the use of renewable and low-carbon choices. Other policies that exist in Italy comprise regulatory policies that enhance the energy efficiency of the different sectors. The Efficient Italian Energy Consumption Directive establishes efficiency objectives for energy use and promotes energy savings in construction, industrial, and transport facilities. Italy has also employed policies on green transport that entice the use of electric and hybrid cars as well as public transport. The push for efficiency aligns well with Italy's decarbonization drive because it lowers the overall energy requirement to meet, thus making the move to cleaner energy lighter. Although these policies and regulations are useful in the way to energy transition happens in Italy, more policy support is necessary to advance the hydrogen production system and hydrogen market. The high costs of green hydrogen production, the establishment of the hydrogen infrastructure, and the regulatory norms for using hydrogen in Italy are important to start incorporating hydrogen into the country's energy mix. Despite the strong policy foundation of Italy's participation in the EU's Hydrogen Strategy and its commitment to increase green hydrogen production, investment and policy development remain important for hydrogen adoption to become widespread.

3.3. Progress Towards Decarbonization Goals

In terms of decreasing its share of emissions, Italy has made important progress, especially in having raised the share of renewable power in its electricity production, as well as improving energy efficiency. GHG emissions, mainly driven by the growing share of renewable energy, enhanced energy efficiency, and lessening of the use of coal, have been reduced by 33% compared with 1990 levels. This progress sets Italy on a favorable path to achieve its 2030 and 2050 climate goals but more effort will be needed to continue along this path.

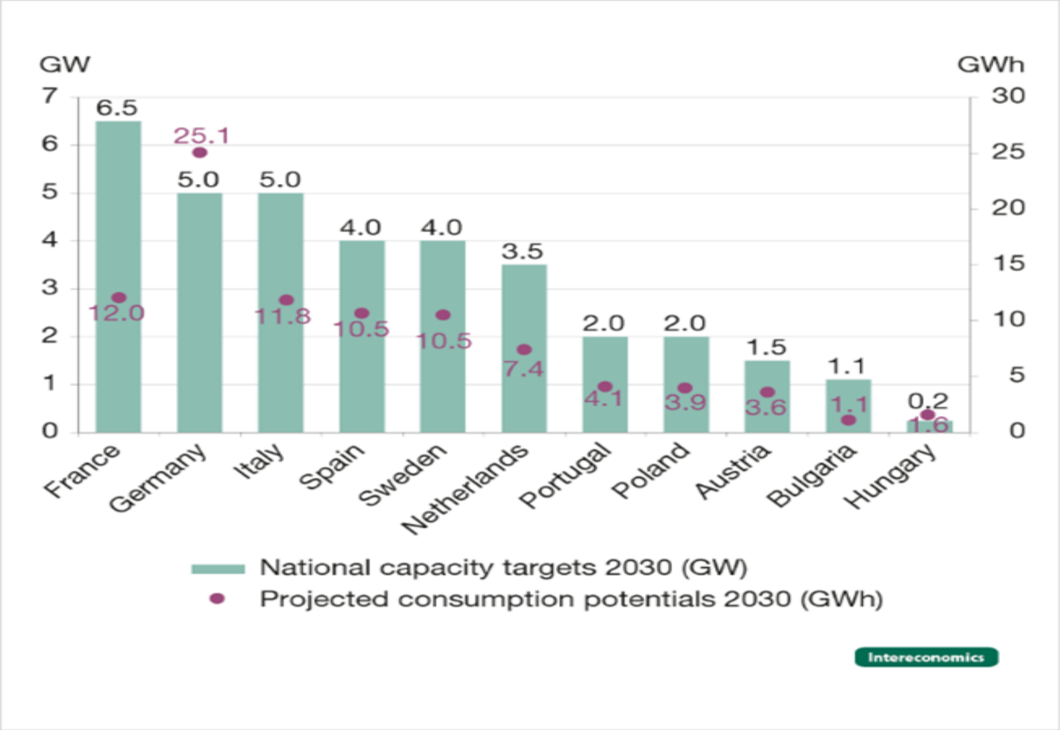


FIGURE 3-1: GREEN HYDROGEN CAPACITY TARGETS AND CONSUMPTION POTENTIAL IN ITALY AND OTHER EU COUNTRIES [3]

The growth of Italy’s renewable energy capacity is one of Italy’s most notable achievements. In recent years, renewables have supplied about 40 percent of Italy’s electricity consumption, driven by solar, wind, and hydropower. Solar power has been growing rapidly and Italy is now one of Europe's leaders in solar PV capacity. Indeed, wind energy has grown as well, particularly in southern Italy and offshore areas, helping spread Italy’s renewable energy sources. Reducing Italy's energy demand and emissions has also turned to energy efficiency improvements. Italy has reduced its overall energy use while maintaining economic growth by pursuing policies to increase building efficiency, industrial process, and transport energy efficiency. Energy-efficient building renovation incentives, as well as incentives for the adoption of energy-efficient technologies in the industry, have allowed lower emissions and reduced energy costs. Full decarbonization of electricity generation and heating in Italy is restricted by its reliance on natural gas, coal, and oil.

To achieve long-term decarbonization in Italy, it will be necessary to transition away from natural gas to renewables, or low-carbon alternatives such as hydrogen.

The Italian government along with its industry partners has identified that hydrogen can be an equally effective solution as renewable in the decarbonization process. Field trials are currently being conducted to test the usage of hydrogen across the transportation, industrialization, and energy storage sectors. For example, Italy has set programs to develop green hydrogen via electrolysis supported by renewable energies since the hydrogen will serve as a zero-emission solution for hard-to-abate sectors. In addition, Italy's membership in the European Clean Hydrogen Alliance plus others shows its intent to increase the use of hydrogen technologies as it transitions to a low-carbon economy.

One is the slow but sure move toward eliminating coal-fired power stations as sources of electrical energy. Closing its remaining coal plants before 2025 will similarly materially reduce emissions from the power sector in Italy. The phase-out of conventional energy sources during this transition is in line with Italy's broader energy transition strategy and consistent with the country's aim to lower its dependence on high-emitting fuels. Switching from coal to renewables and other low-carbon technologies is not only good for Italy's climate targets but it will also boost air quality and public health. Finally, the current and future trends of Italy have revealed that the Italian state is transforming steadily on the way to achieving decarbonization with the help of a favorable policy environment, growth of RES share in the electricity generation, and increase of energy efficiency. But it will still take some more effort to get fully de-carbonized. Italy's current policies and progress for hydrogen are reasonably well set to advance the adoption of hydrogen although more capital, installation, and especially legislation will be required to enhance the establishment of this energy source in Italy. While Italy works its way toward the 2030 and 2050 goals, it will need to expand further renewables share and effectively integrate hydrogen.

4. The Role of Hydrogen in Italy’s Energy Transition, Application, Economic Feasibility & Sustainable Development

On the one hand, hydrogen responds to Italy’s Environmental and Sustainable Goals (ESGs) as an energy and decarbonization source for the most energy-intensive sectors. Hydrogen is in line with ESG principles and serves to reduce Italy’s carbon footprint, reduce pollution, and strengthen energy security. Looking at things from a more long-term perspective it aligns itself with the ESG framework’s core pillars of environmental stewardship, social equity, and governance through its opening up channels for clean energy options, pushing industry innovation, and helping foster sustainable economic growth.

Hydrogen’s greatest advantage in terms of the environment is that it can produce energy without emission. Renewed sources for carbon-free hydrogen production, along with decreased environmental impact and the emission of water vapor when used in its carbon-free phase, can mitigate air pollution and limit GHG. It therefore turns out to be very compatible with Italy's ambitious targets for reducing GHG by 55% by 2030 and carbon neutrality by 2050. Hence, a lot of potential for hydrogen to fulfill Italy’s energy needs and drastically cut emissions in sectors like transportation, heavy industry, and household heating that are difficult to electrify. In addition, hydrogen meets Italy’s goals for sustainable innovation. Investing in hydrogen promotes the creation of a domestic market for new technologies (electrolyzers and fuel cells) to be exported worldwide. These investments not only highlight Italy’s role in sustainable energy but also motivate the promotion of clean energy industries that are in line with international ESG benchmarks.

4.1. Hydrogen’s Role in Achieving Environmental and Sustainable Goals (ESGs)

4.1.1. ESG Alignment

Hydrogen technology and its applications are naturally aligned with specific goals in the ESG framework. Particularly relevant to hydrogen’s promise is the UN Sustainable Development Goals (SDG) Goals 7 (Affordable and Clean Energy) and 13 (Climate Action). Reducing fossil fuel reliance and enabling decarbonization of hard-to-abate sectors, green hydrogen production from renewables can power an affordable, sustainable energy supply. Hydrogen can replace the use of carbon-intensive fuels like steel, cement, chemicals, and other sectors. This also provides further opportunities for hydrogen to contribute to Goal 9 (Industry, Innovation, and Infrastructure) by contributing to sustainable and resilient infrastructure. Not only do these activities enable Italy's industrial development, but they also facilitate the integration of hydrogen storage technologies, fueling production facilities, and establishing hydrogen refueling networks, supporting hydrogen-based industries across Europe. In line with Goal 12 (Responsible Consumption and Production), Italy's green hydrogen advances sustainable production cycles and materials recycling by aligning to the generation of green hydrogen to rely more on renewable inputs. The growth of the hydrogen sector means high-value employment in engineering, manufacturing, and research and development. If Italy is to accelerate its energy transition and create growth that is exclusive, sustainable, and anchored in long-term prosperity, it needs to establish a skilled workforce focused on hydrogen production, production, and infrastructure.

4.1.2. Hydrogen Adoption: Socioeconomic Benefits

The adoption of hydrogen in Italy's energy mix brings a range of socioeconomic advantages to a resilient, inclusive green economy. First, the large-scale deployment of hydrogen technologies is a powerful source of employment generation for the production, distribution, and maintenance of hydrogen systems. Based on Italy's post-COVID-19 economic revivification, hydrogen investments can provide a potential base of robust employment opportunities, particularly those affected by industrial transition or the declining fossil fuel sector in those regions. Italy can create hydrogen hubs and an innovation cluster with the support of government and private investments which can help create employment and help Italy stay strong in Europe's energy market for example with clean energy. In addition, hydrogen helps make Italy's energy independent from imported fossil fuels. Locally sourced, reliable energy alternative to imported gas and oil, which can also be hydrogen produced domestically using renewable sources is a positive. This diversification anchors Italy's energy security by providing Italy with less dependence on international market fluctuations resulting in lower and more stable energy costs for consumers. Aside from this, hydrogen adoption could have health benefits as it will limit greenhouse gases, particularly air pollution in urban areas. It means less reliance on carbon-intensive fuels, less pollution (pollutants like nitrogen oxides – NOx and particulate matter), improved air quality, and reduced health-related expenditures. When coupled with shifts, this can improve the quality of life of citizens and decrease the cost of the medical situation of air purity.

4.1.3. Challenges and Considerations

The transition towards hydrogen has many advantages, but there are many challenges in the process of the adoption of green hydrogen energy. Besides Technical and financial barriers to hydrogen production, Hydrogen storage, and distribution are also the main challenges. At present, the cost of green hydrogen production is high, resulting primarily from high energy inputs to electrolysis and from the limited scale of renewable energy sources. The costs of hydrogen production are so high compared to conventional fuels that hydrogen cannot do well in the market without the support of policies and preferential treatment. However, unlike natural gas, hydrogen is highly flammable, has a low energy density, and thus requires the specialized pipelines, storage, and transportation systems it utilizes. Opening such infrastructure is expensive, time-consuming, and may require reusing existing infrastructure, for example, natural gas pipelines. The conversion of Italy's extensive natural gas infrastructure to hydrogen-compatible systems, however, could prove advantageous for Italy, though it would almost surely require complex regulatory and technical adaptations. It is also important to scale Hydrogen solutions with the establishment of a coherent regulatory framework.

However, hydrogen policies and standards at the regional level (EU level, NACE division, or National) currently vary both among regions and across countries, limiting hydrogen’s integration in the broader European energy market. To facilitate cross-border trade, create safety standards, and support private sector investment, Italy faces the difficult task of working with EU policymakers to create harmonized regulations. For hydrogen adoption to take off, and for Italy to compete within Europe’s evolving hydrogen economy, clear, consistent policies will be crucial. As the world moves to hydrogen, public trust is needed - most especially in the safety of hydrogen storage, possession, and use.

4.2. Power Generation / Fuel Cell Vehicles Using Hydrogen

In Italy’s energy transition, where improvements in air quality will rely on increased use of cleaner energy sources, hydrogen is providing itself as a multi-purpose energy carrier with great potential in the production and use of power in FCVs. Hydrogen makes an attractive alternative fuel for power generation compared with traditional fossil fuels. For Italy, hydrogen has huge implications for the energy landscape helping balance the intermittency of renewable sources such as wind and solar on the grid. Life support can be provided to Italy’s energy infrastructure during peak demand periods or when renewables do not produce as expected, through hydrogen fuel cells supporting power generation [15]. Additionally, hydrogen-fueled generation plants can be scaled down to operate at a smaller scale also serving as an energy system decentralization that will enhance local energy independence primarily in areas where electricity access is not certain. Another promising application of hydrogen is fuel cell vehicles and Italy, to reduce greenhouse gas emissions from its transportation sector, can specifically benefit from them. FCVs powered on hydrogen are different from regular internal combustion engines as they do not produce any polluting gases and do not emit any carbon into the air as they do. Having air quality issues in urban areas, FCVs represent an interesting alternative to diesel and gasoline vehicles for public and commercial transport networks in Italy. Hydrogen is an excellent choice for heavy-duty vehicles like trucks, buses, and trains because of the high energy density, which matches the range and power that battery electricity cannot provide today. It could foster the idea of hydrogen-powered fleets for public transportation, freight, and logistics, cutting Italy's transport environmental footprint.

4.2.1. Hydrogen Mobility Infrastructure Development

This shift towards hydrogen mobility requires significant infrastructure development that both challenges and opens opportunities. Unlike fuel stations selling other fuels, hydrogen refueling stations demand special equipment, and very strict safety regulations, due to hydrogen being a highly flammable gas, and must be stored under considerable pressure. To make FCVs viable for long-range travel and urban mobility it will be essential that such a widespread network of these stations be established across Italy. Already, though, Italy is on course to make a start in this direction, using pilot projects and partnerships that will bring about hydrogen corridors across major highways and urban regions. For hydrogen mobility to grow, it is also necessary in Italy to take account of the wider logistics of hydrogen production, storage, and distribution. Domestic hydrogen production through renewable electrolysis will expand, providing a sustainable supply chain, and investment in the production of hydrogen-compatible pipelines will hasten transport and enhance economies. Such infrastructure must be developed for collaboration between public and private sectors and regulatory frameworks around safety and quality.

4.3. Economic Feasibility of Large-Scale Hydrogen Production

Italy is tackling its challenging climate targets and large-scale hydrogen production is emerging as a cornerstone for Italy’s shift to a low-carbon economy. The economic viability of large-scale hydrogen production, however, depends on a wide range of factors, from production costs to infrastructure investment and market dynamics that support it. However, green hydrogen, produced via electrolysis using renewable energy, is one of the most promising pathways but is currently more expensive than hydrogen produced from fossil fuels, such as Steam Methane Reforming (SMR) and carbon capture and storage. Renewable-based hydrogen fits with Italy's decarbonization goals but without bulk investments, governmental incentives, and scale-dependent strategies to reduce production, the economic viability is challenging. To increase the adoption of hydrogen production, most notably green hydrogen, costs need to come down through economies of scale, technological advancements, and policy in all cases. The reduction of electrolyzer costs, which make up a big part of green hydrogen production expenses, is mostly driven by improvements in technology and increased production. In addition, as Italy's renewable energy industry develops, it could use surplus solar and wind energy to electrolyze the hydrogen, thereby making it a more competitively priced fuel in the future. However, to meet the economic feasibility for large-scale production of hydrogen, further reductions in renewable energy costs are necessary, increased electrolyzer efficiency is required, and an integrated hydrogen infrastructure comprising pipelines and storage facilities must be created. In the end, the investment to establish a hydrogen infrastructure can create an economic ecosystem for hydrogen by leveraging scaling technology and building regional hydrogen markets.

4.3.1. Cost Analysis of Hydrogen Production Methods

There exist different ways of generating hydrogen and each has different cost structures, energy demands, and carbon footprints. Different cost profiles exist for the primary methods: green hydrogen (from renewable electrolysis), blue hydrogen (from SMR with carbon capture), and gray hydrogen (from SMR without carbon capture). Now, gray hydrogen is the cheapest form of hydrogen, which is anywhere from \$1 to \$2 per kilogram based on natural gas without any carbon mitigation. But as Italy aims to reduce emissions, the appeal of gray hydrogen diminishes because it has so high a carbon footprint. SMR combined with Carbon Capture System (CCS) to produce blue (CO_2 captured and stored) hydrogen costs approximately \$2–\$3 per kilogram, or slightly more [16]. This solution presents itself as a means by which the existing natural gas infrastructure of Italy can be adapted for hydrogen with CCS. Blue hydrogen emits less CO_2 than gray hydrogen, but it still takes fossil fuels, and it was highlighted that there are concerns about the viability of long-term carbon capture, the possibility of methane emissions, and energy consumption for the

CCS process. But the most expensive option, to produce green hydrogen, is currently around $4 to $6 per kilogram, and research shows that aligned most closely with Italy’s sustainability goals. However, this cost could drop substantially compared to a renewable energy source, an electrolyzer with increasing efficiency, and an expanding production base.

4.3.2. Investment Opportunities and Market Dynamics

Investment opportunities of significant size exist in the production of hydrogen and its associated infrastructure in renewable energy, electrolyzer manufacturing, hydrogen storage, and distribution networks. To capitalize on the investment potential of hydrogen, Italy’s government has recognized its potential and passed policies such as subsidies for renewable hydrogen projects, tax credits, and grants to do research and development. But they send out a signal of a determination to create a domestic hydrogen economy and reassure investors that project risks are being lowered. Italy’s potential as a European hydrogen hub also makes sense given the ambition set by the European Union about hydrogen targets and the funds available for hydrogen projects within the European Union. Domestic and international companies are investing in hydrogen production, distribution, and applications in Italy’s hydrogen sector [17].

Energy giants, technology companies, and industrial companies are joining forces to establish joint ventures to accelerate hydrogen adoption, taking on expertise. For example, oil and gas companies in Italy are learning to engineer the hydrogen economy and are pushing for investment into blue and green hydrogen projects. Given their experience in energy systems, they are well placed to be a leader in renewables infrastructure, pipeline adaptation, and storage. The demand in Italy for hydrogen is also evolving across several market segments such as transportation, industry, and power generation, and impacts the dynamics of the market for hydrogen there. This means that, as demand grows, costs will be driven down by market competition so that hydrogen becomes easier to access across sectors. Hydrogen fuel is already employed in substantial amounts in transportation, particularly in heavy duty and public transit because it provides a longer range and therefore shorter refueling times as alternatives to battery electric vehicles. In addition, long-term demand for hydrogen in industrial applications such as steel, cement, and chemicals is also expected to drive a steady market environment over the long term and enable large-scale production investment. Green hydrogen production, however, is the closest thing to Italy's sustainability goals, but is currently the most expensive way of producing, costing from $4 to $6 per kilogram. But as renewable energy base loading capacity grows and electrolyzer, energy conversion efficiency increases, this cost may come to drop significantly. The dependence of green hydrogen's future competitiveness from the increasing reduction of costs in renewable energy sources and advanced electrolyzer technologies.

4.3.3. Economic Impact on Local Communities

The hydrogen economy would bring a positive contribution to the local communities in Italy. Hydrogen production facilities, distribution networks, and refueling stations are expected to provide job opportunities, mostly leading to local economies, and promoting and aiding a just transition for those workers affected by the decline of fossil fuel industries. The range of these opportunities includes technical operations and maintenance plant positions to research and development positions [18].

Hydrogen production can be a way to use local resources to generate renewable energy in rural areas, where the potential for renewables is strong, to create new revenue streams and reduce reliance on imports. Reductions in environmental impacts also mean that hydrogen deployment can lead to improved quality of life and lower healthcare costs for residents, as well as building on benefits for local economies. The shift to hydrogen can reduce pollution-related health problems experienced by urban centers and industrial zone communities and ultimately bring communities benefits and a healthier workforce over the long term. Large-scale hydrogen production is, therefore, the opportunity to promote the sustainability and resilience of Italy, not only economically, but especially in terms of environmental impact, also supporting clean energy jobs.

4.4. Industrial Applications of Hydrogen in Italy

Hydrogen plays an important role in energy production and transport as it is used in several industrial processes. As the nation aims to reduce its carbon footprint, hydrogen is proving to be a critical part of decarbonizing heavy industries that have traditionally relied on fossil fuels. Industrial like steel, cement, and chemicals account for a large portion of Italy's greenhouse gas emissions and hydrogen provides a clear path to cut those emissions with innovative applications. Natural gas, oil, and coal are potential sources of hydrogen, especially when they are brought to the industrial scale as a cleaner alternative to electricity generated by burning these sources of fuels. Natural gas and oil are turned into hydrogen specifically to generate industrial heat or to support other processes that require the use of high temperatures or specific chemical reactions. In line with the main goals of the EU for industrial decarbonization, Italy's choice of following the path of hydrogen adoption in its industrial applications also speaks loudly about the role the element can play in its energy transition strategy [19].

One of Italy's most carbon-intensive sectors, the steel industry, has a potential solution in hydrogen. To produce steel, traditionally the process of steel production has relied on carbon-rich fuels and materials and CO_2 is a huge part of the process. But in Italy, in the world's most carbon-intensive steel production process, steelmakers can use Direct Reduced Iron (DRI) technology to save on carbon, avoiding the use of coke or coal. The ability to produce 'green steel' thereby eliminating CO_2 emissions during reduction, means that Italy can emerge as a competitive supplier in the European steel market of increasing importance where green credentials matter. Italian steel-making companies are starting pilot projects on hydrogen-based DRI and other green technologies to pave the way for wider industrial adoption. Such integration of hydrogen into Italy's steel industry could provide a model for other industries, as well as promote technological innovation and new infrastructure development across the country.

4.4.1. Hydrogen in Industrial Processes

Hydrogen has versatile applications in many other industrial processes in Italy. Hydrogen could replace conventional fuels for firing kilns in the cement industry, where such extremely high temperatures are needed to produce clinker, the key ingredient of cement. Italian cement manufacturers can use the high-temperature processes without sacrificing lowering their carbon emissions by replacing their fuel supply with hydrogen [20].

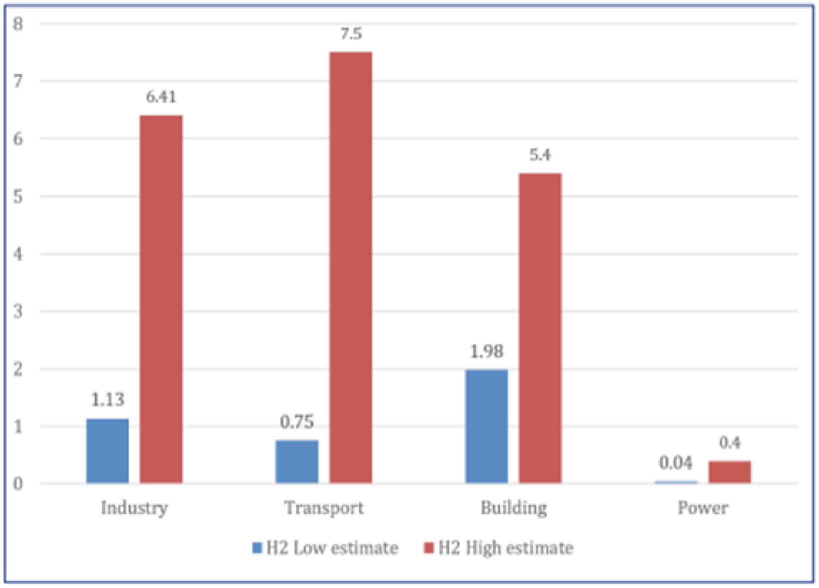


FIGURE 4-1: ESTIMATION OF HYDROGEN DEMAND IN ITALY IN TWhH$_2$ [6]

Furthermore, hydrogen also provides a safer and more flexible means of energy for industries with fluctuating energy demands or where renewable energy is unavailable. Adopting hydrogen could also help Italy’s cement sector, one of the country’s key industrial polluters, adopt low-carbon building materials in support of green building standards and sustainable urban development right across the country. Additionally, there is potential to increase clean hydrogen production and increase the use of hydrogen in the petrochemical and refining industries whose processes rely on the use of hydrogen for hydrocracking and other refining operations. Currently, conventional hydrogen production in these sectors has come from fossil fuel-based sources, but the production of hydrogen from renewable sources, or using carbon capture in SMR production, would greatly reduce the environmental footprint of petrochemical refining. Italian refineries could by shifting to green hydrogen, reduce emissions from their production processes, as well as minimize the environmental impact of their final product. In the meantime, as industries are searching for further sustainable alternatives to conventional feedstock, green hydrogen is taking on a critical role as a base material for synthetic fuels, an eco-friendly solution for the hard-to-decarbonize sectors of aviation and shipping [21]. Such applications offer big opportunities to Italy’s robust petrochemical industry, pursuing green practices and ensuring there is enough clean fuel to match the growing need.

4.4.2. Chemical Manufacturing Opportunities

Hydrogen is both a vital feedstock and a necessary energy source in chemical manufacturing. Hydrogen is needed for many chemical processes, including for ammonia and methanol production, and green hydrogen provides a promising avenue for emissions reduction. Green hydrogen can be used by Italy's chemical industry, a key player in the European market, to make ammonia with low or no carbon emissions that help feed the planet via greener fertilizers. Ammonia, as one of the key ingredients in fertilizer production, could be made green by the addition of green hydrogen and can help Italy's agricultural input industry reduce the environmental impacts of being further downstream. Like, a favorite compounding material, methanol which is used in a broad range of products, such as plastics and pharmaceuticals, can be produced with hydrogen, offering the chemical industry a chance to decrease rather than increase their reliance on fossil fuels. Green hydrogen therefore ensures the supply of chemicals to emerging markets dedicated to sustainable materials by Italian chemical manufacturers that are committed to environmental responsibility.

Apart from creating cleaner products, the use of hydrogen in chemical manufacturing promises cost-saving advantages. As renewable energy prices continue to decrease, green hydrogen becomes increasingly economically feasible and manufacturers reduce their reliance on natural gas, gaining long-term savings from energy. This shift is closely coordinated with Italy's investment in renewable energy infrastructure specifically, solar and wind, which together support the integration of hydrogen through chemicals more economically over time. In addition, the European Union policies and incentives for green hydrogen uptake improve the profitability of the use of hydrogen in chemicals for companies of all sizes, both in large-scale productions and more dedicated supply markets.

5. Comparative Analysis of Hydrogen’s Role: Italy vs. Other European Nations

Across Europe, hydrogen is emerging as a leading game changer in energy transition, climate, and industrial decarbonization. With the European Union's 'Green Deal' gathering momentum, there is an ever-increasing focus on how hydrogen can be used in reducing carbon emissions and securing energy supply. Within the scope of this broader effort, Italy is focusing on employing hydrogen applications in the industry, mobility, and power sectors. But when we compare Italy’s approach to hydrogen to the rest of Europe, we find very different levels of investment, progress, and strategic direction.

5.1. Benchmarking Against Other EU Countries

Germany is a leader in hydrogen development when compared with the other EU countries. In November 2020, Germany launched one of the EU’s most ambitious and comprehensive National Hydrogen Strategies. Germany has made over €9 billion in investment in domestic and international hydrogen projects and has been focusing on setting up a hydrogen production and distribution network. Germany also wants to become a European champion when it comes to green hydrogen production, using wind and solar as renewable energy sources, among others. While Germany has invested heavily in large projects in the blue and green hydrogen sector, Italy's strategy remains blurry, with a mix of blue and green hydrogen and little when compared to Germany. However, if Italy hopes to close the gap, it will need to concentrate on building hydrogen infrastructure, obtaining funding, and expanding renewable capacity.

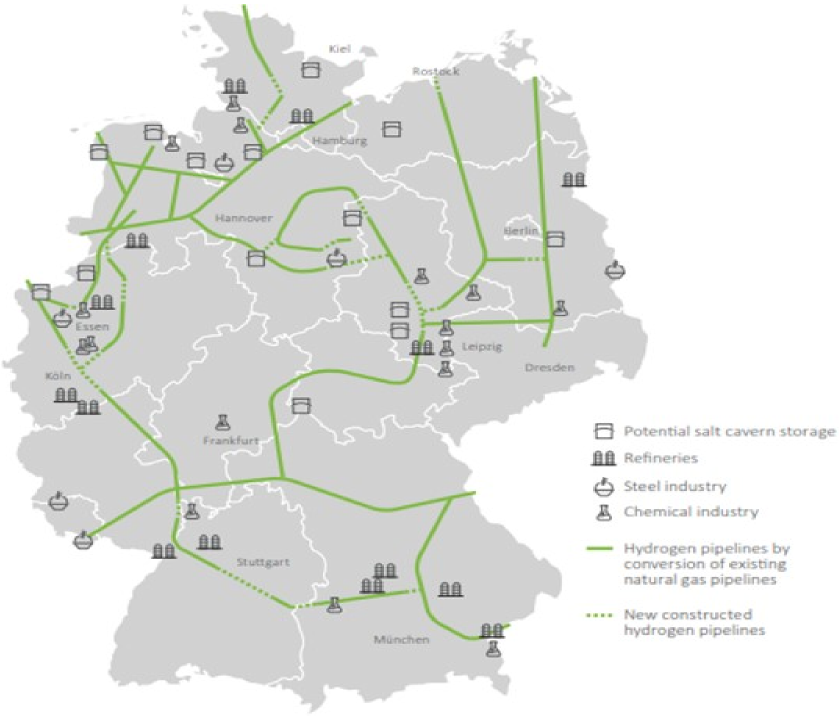


FIGURE 5-1: HYDROGEN BACKBONE IN GERMANY [19]

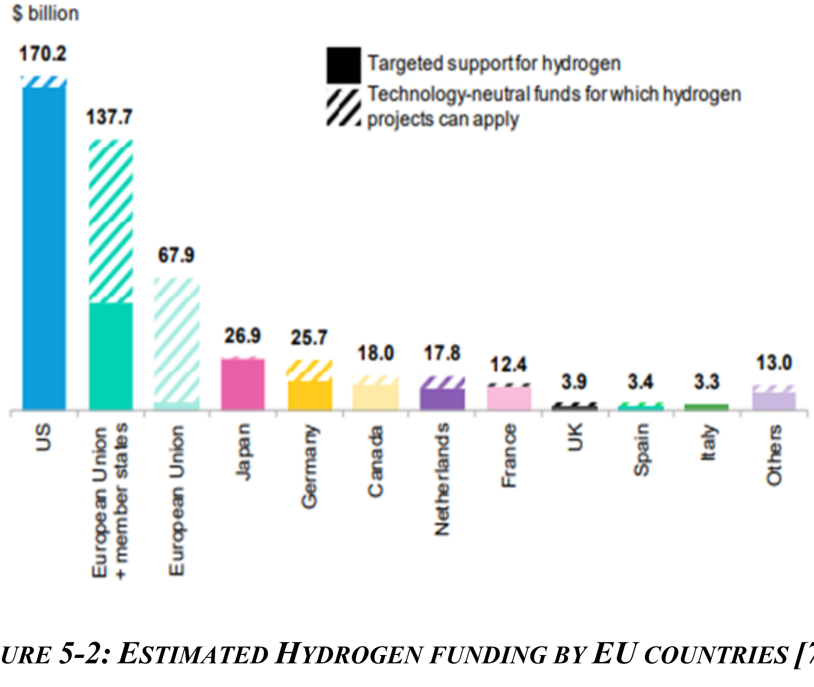


FIGURE 5-2: ESTIMATED HYDROGEN FUNDING BY EU COUNTRIES [7]

Netherlands is such a country, in which its industrial sectors and port facilities have strong hydrogen commitments. The Netherlands is quickly becoming a leader in hydrogen technology and logistics, with a particular focus on hydrogen's integration into that country's well-developed natural gas infrastructure. One aspect of the Dutch strategy is to use the country’s extensive gas infrastructure to transport hydrogen, while also using it for transportation in chemicals and manufacturing, among other sectors. By thinking about Italy’s gas infrastructure and figuring out how to reuse it for hydrogen distribution, Italy can learn from the Netherlands. Italy has also developed the concept of Hydrogen Import and Export through port facilities and is working to expand its extensive coastline to provide opportunities for hydrogen import and export through port facilities a concept already being developed by the Netherlands and the Port of Rotterdam.

Two southern European countries, Spain and Portugal have strong renewable energy sectors that are using natural resources to produce green hydrogen. Spain has set out to be a major player on the green hydrogen scene: it is aiming to become a world leader in its production by 2030 and has singled out solar energy as its preferred source of energy for making it. Meanwhile, Portugal has also created one of the most comprehensive hydrogen development plans across Europe, focused on green hydrogen for export. But both countries are well placed to be competitive in green hydrogen production, by using abundant solar and wind resources. Like Italy, which has identical climatic advantages, the country could increase the production of green hydrogen, particularly in the southern areas where solar irradiance is high. Italy could benefit from collaboration with Spain and Portugal which would provide practical information on how to maximize renewable hydrogen production.

France has also reached further with its hydrogen strategy, with a focus on developing green hydrogen to help decarbonize industrial activities and lower carbon mobility. France's approach is impacted by its high concentration of nuclear energy in providing a low-carbon electricity source for electrolysis, which the country needs to produce green hydrogen. France, meanwhile, has set aside about €7 billion for hydrogen projects that include local production and a reduction in imports of hydrogen. Meanwhile, Italian nuclear power capacity is more limited than that of France and depends mainly on natural gas. For Italy’s hydrogen strategy, alternatives to green hydrogen production will therefore need to be considered, like scaling up solar and wind power to feed electrolysis plants.

Another EU country that is well advanced in hydrogen development is Denmark, where there is particular emphasis on integrating hydrogen into existing renewable energy subsystems. Denmark is the world leader in wind power and has an enormous capacity to produce large amounts of renewable energy itself to produce green hydrogen. Denmark is focusing on integrating its wind energy resources with green hydrogen and this is the key component of Denmark's strategy. Similar strategies could be adopted in other regions, such as Sardinia and Sicily, blessed by wind resources. Furthermore, knowledge-sharing partnerships with Denmark could be something, particularly offshore wind and the integration of hydrogen production.

5.2. Lessons Learned and Best Practices

Italian hydrogen strategy could benefit from several best practices from other European countries. Germany has laid a solid foundation of Research & Development investment in hydrogen innovation leading to advanced hydrogen production, storage, and distribution methods. Financing hydrogen R&D would be facilitated by Italy through cooperation with German research bodies. Furthermore, collaborative partnerships with neighboring countries for the construction of cross-border hydrogen infrastructure, as is happening with Germany, are important for regional cooperation trends that can be capitalized on by Italy in the form of expanding hydrogen infrastructures trading within the broader Mediterranean region [22-23].

As a reminder, low-carbon electricity is essential for hydrogen generation, as France’s nuclear-powered green hydrogen production shows. France's integration of hydrogen into its industrial base, particularly in hard-to-abate sectors such as cement and steel could be a model for Italy. In addition, France has stimulated hydrogen mobility by setting targets for fuel cell vehicles and a hydrogen refueling network [24].

The EU has ultimately envisioned carbon-neutral transportation, and Italy could apply similar policies to speed up hydrogen mobility relatively within the country. Spain and Portugal’s investment in green hydrogen shows the opportunities renewable resources in southern Europe have for the generation of the fuel. Italy could exploit the same environmental conditions as Spain and Portugal and implement their use of solar and wind energy in large-scale hydrogen projects [25]. The southern Italy region could also become a green hydrogen hub, and it could become a great exporter of green hydrogen as has happened in Spain and Portugal. Cooperation with these neighboring countries on the way to producing hydrogen could, in turn, help Italy to strengthen its hydrogen green sector and reduce production costs. It is found that the experience of the Netherlands will be assessed to be feasible for implementing hydrogen infrastructure since the extensive natural gas connection is available in Italy as well. Italy can easily integrate new hydrogen solutions in the existing gas pipeline system thus reducing the cost as it expands the distribution network [26].

Furthermore, the support of industrial players in designing hydrogen-ready infrastructure in the Netherlands may help Italy consider the role of the private sector in its hydrogen strategy. Another model that Italy can follow is the method used by Denmark in the integration of hydrogen with the renewable energy system. The production of green hydrogen through wind farms in Denmark is a classic example of resource complementarity. Offshore and onshore wind resources of Italy, especially the coastal and mountain terrains could have similar hydrogen prospects raising the possibility of increasing renewable hydrogen production along with energy security.

5.3. Collaborative Opportunities in Hydrogen Development

Both Italy and its European neighbors share the goals of reducing carbon emissions and energy independence, the potential for partnership between the two and the rest of Europe in the hydrogen field is enormous. Due to its geographical situation, Italy could realize a hydrogen corridor in the Mediterranean. Spain, France, and Portugal could form partnerships for a Mediterranean hydrogen supply chain, trade hydrogen, share knowledge, and make mutual investments in hydrogen infrastructure. A collaboration to co-develop a hydrogen export and import network, enabling southern Europe to play a key role in the EU hydrogen economy.

Collaborative projects with Germany, Denmark, and the Netherlands would be of benefit to Italy in research and development. Shared hydrogen R&D efforts could move the needle in electrolysis efficiency storage technology, and fuel cell applications to make a quicker hydrogen transition in Italy. Italian researchers would be greatly helped by Germany’s strong innovation network and Denmark’s expertise in wind-powered hydrogen production. These would not only help to improve technical knowledge but also help to obtain EU funding for joint projects, supplying finance as Italy scales up its hydrogen sector.

Moreover, Italy can join the French effort to promote the use of hydrogen in mobility. A Franco-Italian network of hydrogen refueling stations along major transportation routes would allow cross-border travel by hydrogen vehicles, thus encouraging adoption. The initiative fits within the EU's objective to develop a seamless hydrogen infrastructure across member states and would support Italy's objective of decarbonizing its transportation sector. Moreover, these two countries can learn from each other from their experiences to adopt green hydrogen in different sectors such as the chemical industry, power sector, transportation, etc.

Italy could benefit from collaborations with Spain and Portugal about the production of green hydrogen and raising renewable hydrogen capacity. Because these southern European countries have similar renewable energy profiles, they can collaborate on joint projects using the solar and wind potential of the region. The study proposes joint initiatives in the production, storage, and export of green hydrogen as an opportunity to reinforce southern Europe's role in the EU's hydrogen network. Shared production standards and certification systems would also enable the realization of cross-border trade in a consistent Mediterranean hydrogen supply chain.

But Italy and Denmark’s cooperation in offshore wind hydrogen production is the one that could unlock the most potential for renewable hydrogen. Due to the large stretches of Italy’s coastline, there are ideal locations for offshore wind farms, and Denmark’s experience with offshore wind energy could bring to Italy the expertise to build large offshore wind energy projects. Denmark's partnerships can include technology transfer, workforce training, and best practices in environmental management which will build Italy’s capacity for its use of offshore wind for hydrogen production. In addition to being part of Italy’s hydrogen economy, the collaboration would help to advance the EU’s renewable energy and decarbonization efforts.

6. Hydrogen Production Technologies and Advancements

Hydrogen is considered one of the important potential energy carriers of the future and can play a large role in the conversion to the use of clean energy. While countries like Italy strive to meet their goals of decarbonization and greenhouse gas emissions cut, hydrogen serves as a unique, solution-driven technology that can address the decarbonization of sectors that are difficult to electrify such as industrial processes, mobility, and long-term storage and supply of energy. Hydrogen production, thus, depends on the economic, environmental, and technological feasibility of the methods that are followed. This section gives details on the main hydrogen production technologies, the processes involved, their strengths, and some of their limitations with a focus on the technologies that would support the decarbonization of Italy.

6.1. Overview of Hydrogen Production Methods

Hydrogen can be produced through various methods, which are broadly categorized based on the feedstock and energy source used in the production process. The primary hydrogen production technologies include:

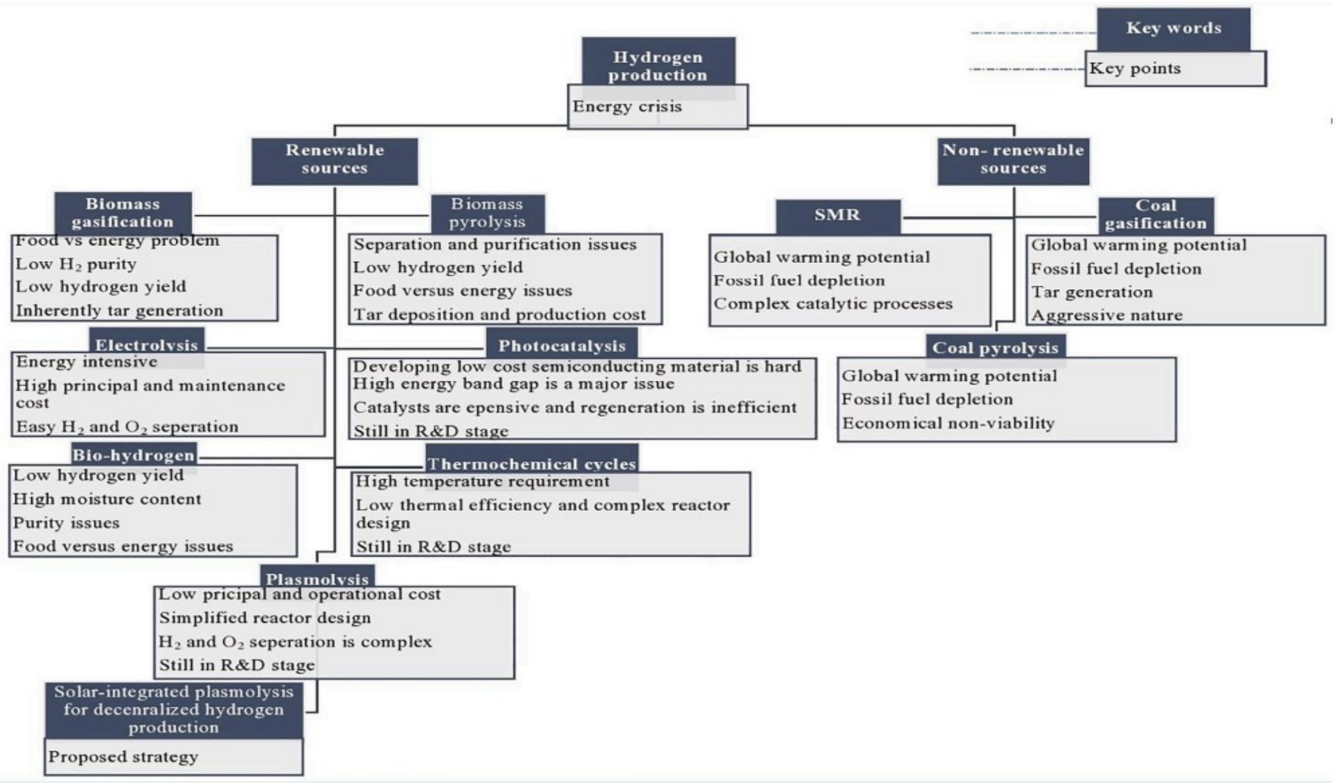


FIGURE 6-1-A: SCHEMATIC REPRESENTATION OF HYDROGEN PRODUCTION PATHWAYS. [40]

- **Steam Methane Reforming:** This is the cheapest method for mass production of hydrogen and is used extensively around the world [39,40]. It is extracting hydrogen from natural gas or methane, although in the presence of steam at high temperatures. However, the general utilization of SMR is tied to massively increasing carbon dioxide emissions, making it unfit for sustainable and long-term energy plans unless accompanied by CCS technology.[40]
- **Electrolysis:** Electrolysis is the splitting of water using an electric current into hydrogen, and oxygen. If it is powered with renewable electricity, electrolysis produces green hydrogen. With the ever-falling cost of renewable energy, the use of electrolysis for the sustainable production of hydrogen is gaining attention as a viable technology.
- **Biomass Gasification:** Biomass gasification is the process of using heat to convert organic materials such as agricultural waste or wood in the presence of little oxygen, then releasing hydrogen. It produces both hydrogen and carbon monoxide and carbon dioxide. Biomass gasification is a renewable approach; if biomass is sourced sustainably emissions can be vigorously and effectively controlled.
- **Other Methods:** Besides the thermochemical water splitting and microbial production, there are other means of hydrogen production, including hydrogen production which are scarcely used, for instance, these less commonly used methods of hydrogen production are in an earlier stage of development and less for large scale deployment at present.

It is important to note that each of these methods has advantages and challenges, and thus depends on context, as the choice of technology. Electrolysis using solar and wind power has great potential when renewable energy potential is strong, in Italy, for example. However, a combination of methods with SMR coupled with CCS, and electrolysis, might be necessary to produce hydrogen on an affordable scale as renewable energy infrastructure grows.

6.2. Steam Methane Reforming (SMR)

SMR is the most widely used approach to produce hydrogen because it is compatible with existing infrastructure [39, 40]. Currently, about 95% of hydrogen produced in the world is realized through SMR. Despite the high efficiency of the industrial method of production for hydrogen, SMR, it remains environmentally unfriendly because of the CO_2 generated during the production [27].

During SMR, natural gas (methane) is reacted with high-temperature steam (700–1,000°C) in the presence of a catalyst producing hydrogen, CO, and a little CO_2. The process typically occurs in two main steps. Methane reacts with steam under 3-25 bar pressure (1 bar) in the presence of a catalyst to produce hydrogen, CO, and a relatively small amount of CO_2 through the following reaction:

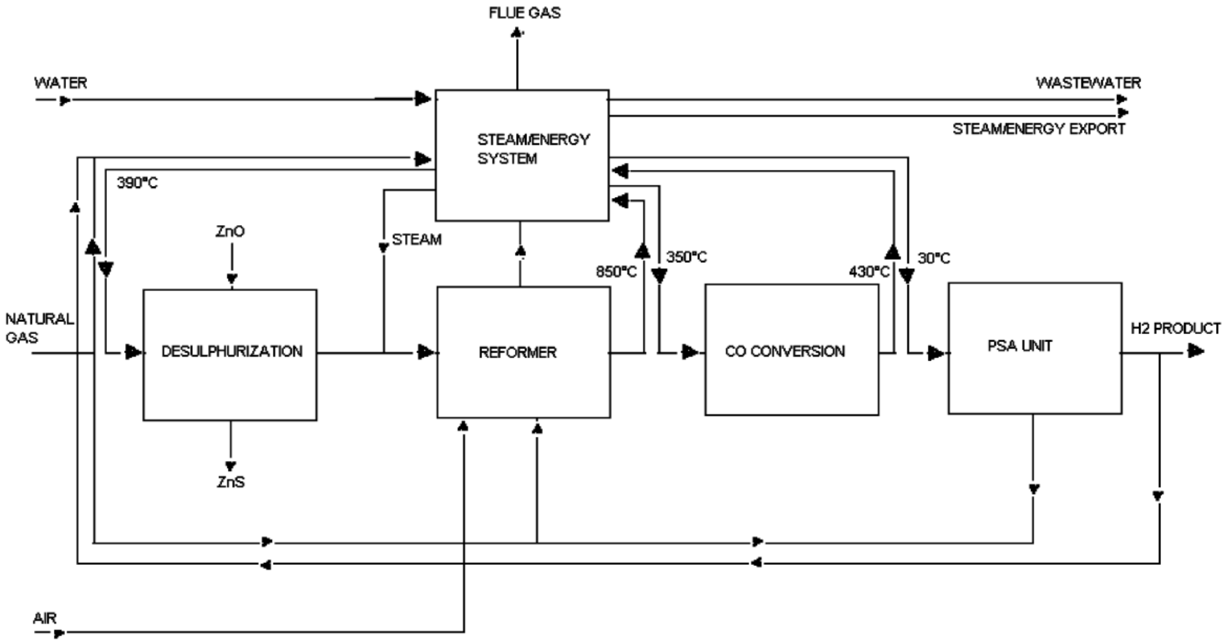


Figure 6-2-b: SMR Process for producing Hydrogen [41]

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad [6.1]$$

In this reaction, one molecule of methane is reacted with one molecule of steam to produce one molecule of CO and 3 molecules of hydrogen. Steam reforming reaction is endothermic because heat must be supplied to the process for the reaction to proceed. This endothermic reaction requires a significant amount of energy. The high temperature required for the reaction is provided by combusting a portion of the natural gas feedstock in the reformer. The reformer usually uses a catalyst, typically a nickel-based catalyst supported on alumina, to increase the reaction rate and increase the production of hydrogen. Because of such high temperature and harsh reaction environment the catalyst degrades and thus needs to be replaced or regenerated periodically [29,30].

The water–gas shift reaction is secondary for the syngas to maximize hydrogen production. In this reaction, CO reacts with additional steam to produce more hydrogen and CO_2:

$$CO + H_2O \rightarrow CO_2 + 2H_2 \qquad [6.2]$$

The water–gas shift reaction is exothermic in conventional catalytic situations, releasing energy, and it usually proceeds in two steps at distinct temperatures. In the first stage, CO is converted to CO_2 at higher temperatures (350°C) using a high-temperature shift catalyst (e.g. iron oxide with chromium) to optimize CO conversion. After this, the gas mixture is cooled and passed over a low-temperature shift catalyst to obtain the maximum hydrogen production at lower temperatures (around 200°C). The exothermic reaction also increases the overall yield of hydrogen, as well as CO_2. Though efficient and well-developed, SMR is considered a 'gray hydrogen' production method due to its resulting carbon dioxide emissions. To reduce these emissions, recent progress has involved coupling SMR with CCS technology, which turns SMR into “blue hydrogen.” Blue hydrogen reduces the total carbon emission from SMR, though it does not eliminate it. The connection of SMR with natural gas as feedstock also has economic and environmental implications since natural gas prices are volatile and the world is moving towards achieving decarbonization goals. One possible solution to this problem is to use biomethane as an alternative feedstock of renewable methane produced from organic waste sources. Like conventional natural gas, biomethane can participate in the SMR process and can produce an equivalent amount of hydrogen but it emits less CO_2 as compared to natural gas.

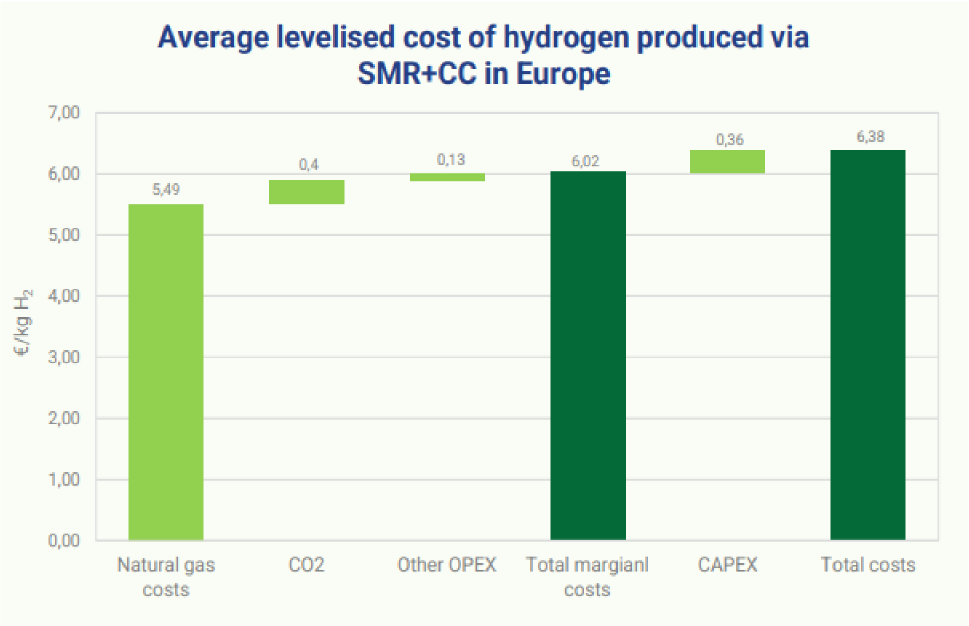


Figure 6-3: Average levelized cost of hydrogen produced via SMR+CC in Europe (€/kg H_2) [42]

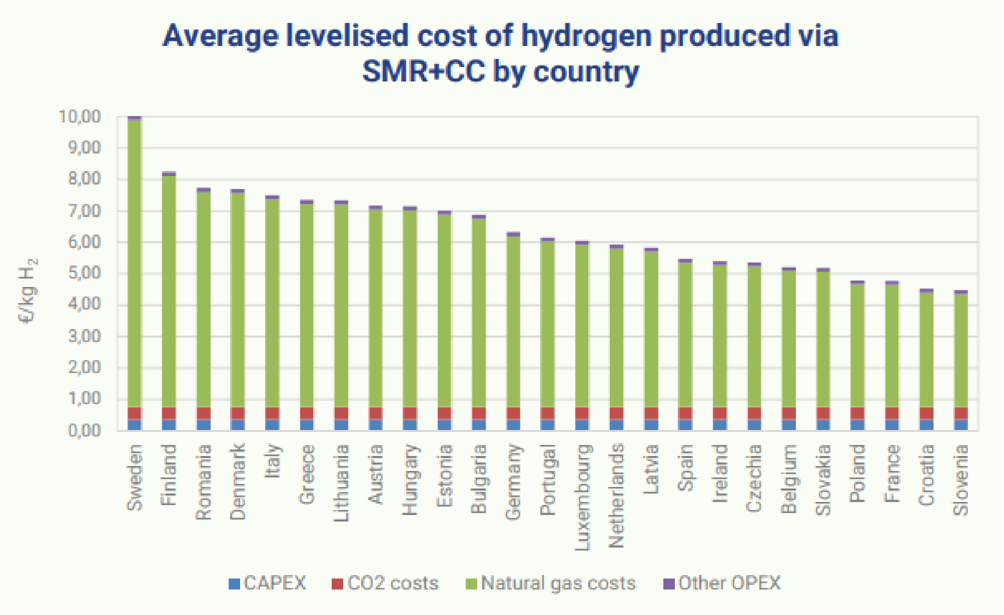


Figure 6-4: Average levelized cost of hydrogen produced via SMR+CC (in €/kg H_2) by country in 2022 [42]

Costs of producing hydrogen via SMR with Carbon Capture (SMR+CC) differ dramatically across European countries depending on natural gas prices, CO_2 costs, and operating costs. Its production cost is currently the highest at around €9.5/kgCO_2, while largely a result of high natural gas costs and CO_2 costs. At the opposite extreme, Slovenia and Croatia have the lowest costs of €4.0 to €4.2/kgCO_2 on account of the lower cost of natural gas and possibly lower CO_2 emission costs. Despite that, the product of hydrogen gas production through this process is relatively affordable compared to electrolysis using the grid electricity, but it is not environmentally friendly as it still depends on fossil fuels.

6.2.1. Advantages of SMR

1. Electricity is the most favorable (economic) hydrogen production method. It is also attractive for large-scale hydrogen production in regions where natural gas is affordable.
2. SMR technology is well established, already proven, and present with infrastructure ready for scale production and quick deployment.
3. SMR is well suited for industrial applications and hydrogen-consuming sectors which require more energy to fulfill their energy requirements, with high hydrogen yield.

6.2.2. Challenges of SMR

1. SMR is essentially carbon-intensive because it uses natural gas as feedstock and produces large amounts of CO_2 as a form of waste. While CCS means emissions still occur, CCS is not as sustainable as green hydrogen.
2. The problem with SMR is that it runs on natural gas – a fossil fuel with volatile prices, and subject to geopolitical risks. The dependence puts a cap on the sustainability and energy security benefits that underlie hydrogen produced by SMR.
3. Though SMR requires high temperatures for its process, this can reduce overall process energy efficiency.

6.2.3. Biomethane for hydrogen production

Anaerobic digestion of organic materials provides a renewable pathway for hydrogen production. Biomethane is made from agricultural wastes, food scraps, or sewage sludge and has far lower emissions than fossil fuels. By serving as a feedstock for hydrogen production via SMR, biomethane helps make the hydrogen cycle possible, especially when combined with CCS technology. The ability to run off existing natural gas infrastructure is one of the key advantages of using biomethane. Many European nations already have natural gas networks that can be used for biomethane, and immediate hydrogen solutions, and Italy is among them. This approach helps to reduce energy security from imports while keeping fuel production local and sustainable. But scaling hydrogen production comes with a challenge. The organic waste supply is limited in availability, and not expected to provide a sufficient supply of biomethane to hydrogen demand over the longer term. In addition, availabilities and pricing of biomethane may be influenced by competition with alternative uses, such as direct injection into gas networks. Despite these limitations, biomethane is a useful, intermediate solution to Italy's energy transition. However, it can be a bridge technology to green hydrogen when other proven hydrogen production technologies are lacking in viability. Italy can offset emissions, diversify its energy vector, and support local economic development if it includes biomethane, leading to immediate and long-term sustainability objectives.

6.3. Renewably produced hydrogen and electrolysis

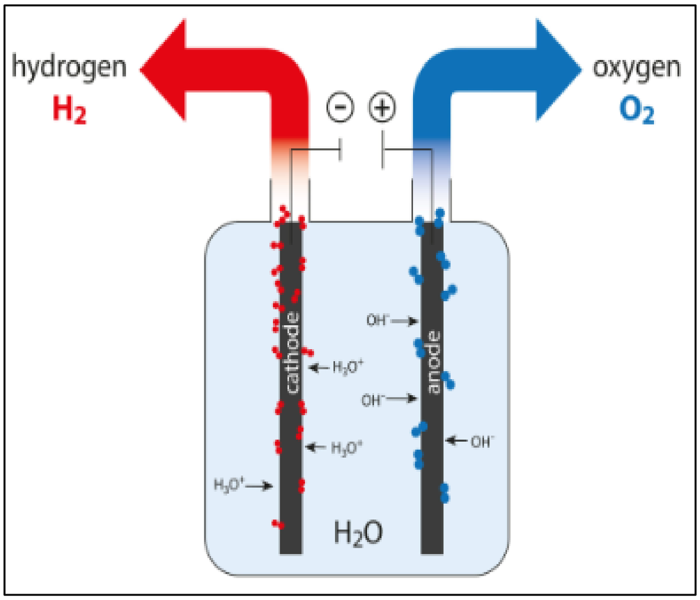


FIGURE 6-5: PROCESS OF ELECTROLYSIS [31]

The process of splitting the water molecules into hydrogen and oxygen gases through electrolyzes to produce green hydrogen is called the process of electrolysis. If the electricity to be used is from renewable sources, such as wind, solar, or hydropower, the hydrogen produced in this process is considered 'green hydrogen', hence it is a zero-emission fuel. Hydrogen produced by electrolysis does not require any fossil fuels and electrolysis produces only oxygen as a byproduct, making it a cleaner route to hydrogen production compared with traditional methods, such as SMR. When powered by renewable energy, the technology of electrolysis is a promising route to producing hydrogen with zero emissions as compared to the SMR and other methods of producing green hydrogen [32, 33].

An electrolyzer is an electrolytic cell that produces an electrolyte in between its anode and cathode to conduct the process of electrolysis. The three main types of electrolysis technologies are:

1. **Alkaline Electrolysis (AEL):** The most established form of electrolysis is AEL, a liquid alkaline electrolyte. Although less expensive than other methods, it is less efficient.
2. **Proton Exchange Membrane (PEM) Electrolysis:** Because they operate at higher current densities and are more efficient, PEM electrolysis is better for applications where it's necessary to respond quickly, for example on the grid. However, the precious metal in the catalysts used in PEM electrolyzers made it more expensive.
3. **Solid Oxide Electrolysis (SOE):** The high-temperature operation (700–800°C) of SOE increases efficiency but requires high heat input. The SOE is still in its developmental stage and is not yet commercially available for wide-scale hydrogen production.

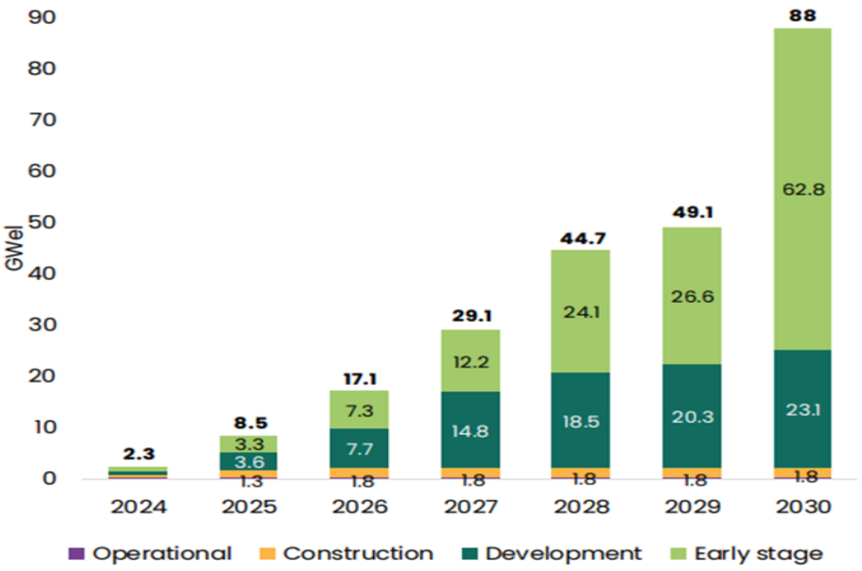


FIGURE 6-6: WATER ELECTROLYSIS PROJECTS FOR PRODUCING HYDROGEN IN ITALY AND OTHER EU COUNTRIES BY YEAR 2024-2030 [7]

The overall reaction for water electrolysis can be expressed as:

$$H_2O(l) \rightarrow H_2(g) + 1/2O_2(g) \qquad [6.3]$$

This reaction shows that one molecule of water produces one molecule of hydrogen and half a molecule of oxygen. At the anode, water is oxidized to form oxygen gas, releasing protons (H^+) and electrons (e^-). This reaction is expressed as:

$$2H_2O(l) \rightarrow O_2(g) + 4H^+ + \ 4e^- \qquad [6.4]$$

At the cathode, hydrogen ions (H^+) are reduced as they gain electrons to form hydrogen gas. This reaction is expressed as:

$$4H^+ + \ 4e^- \rightarrow 2H_2(g) \qquad [6.5]$$

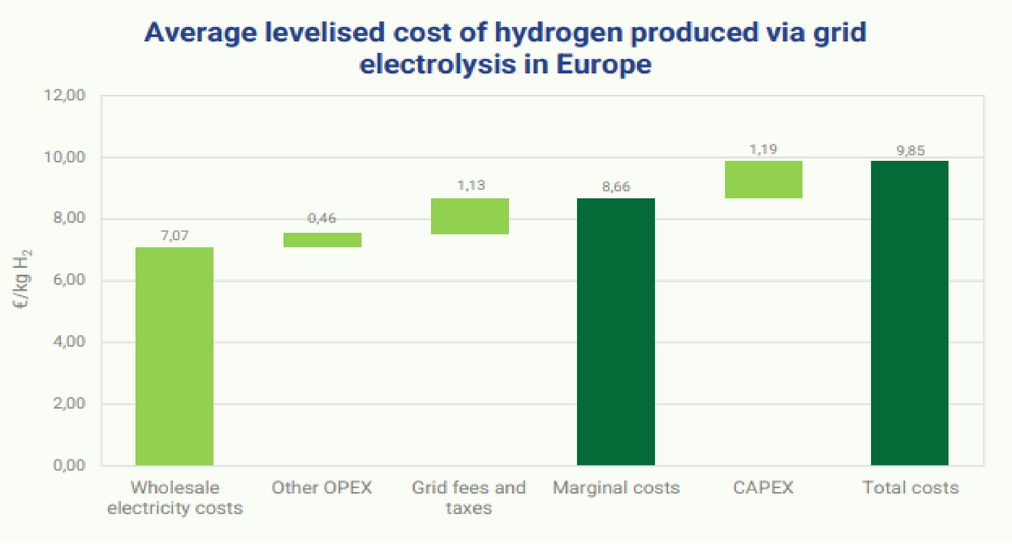


Figure 6-7: Average levelized cost of hydrogen produced via grid electrolysis (€/kg H_2) in Europe in 2022 [42]

The advantage of electrolysis is that it can be driven with renewables powering it, so it has zero emissions. Storage and use of this green hydrogen as a clean energy supply is possible and is a promising way to decarbonize harder-to-electrify sectors, like industrial processes and long-haul transportation.

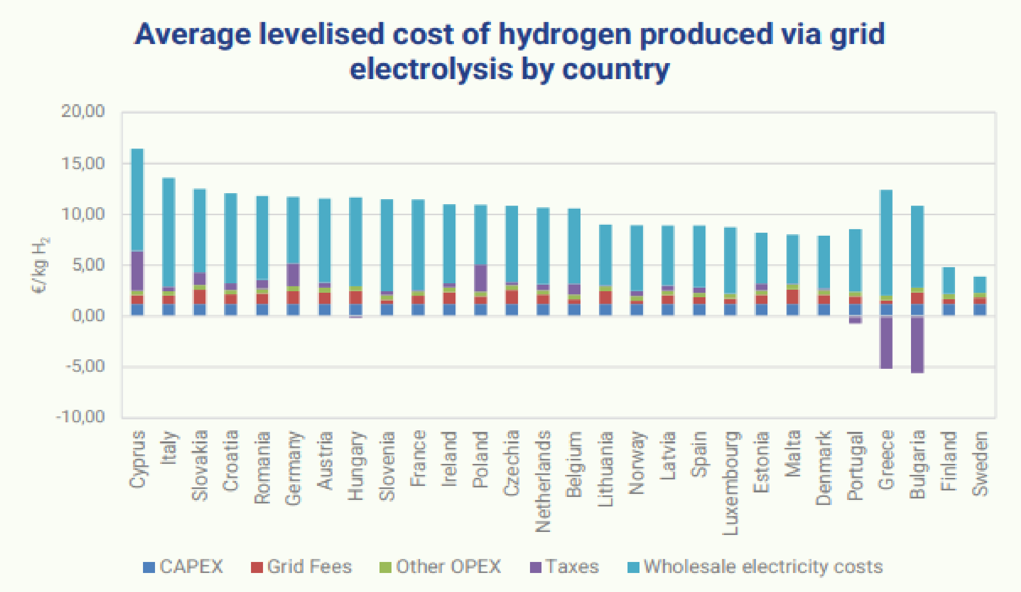


Figure 6-8: Average Levelized cost of hydrogen produced via grid electrolysis by country [43]

The countries that rely on grid electricity for hydrogen production are much higher. That is mostly due to wholesale electricity costs and grid fees being high. For instance, the very high production costs in Cyprus and Italy (up to €17.5/kgH_2) are mainly related to high electricity prices and other grid costs.

Table 6-1: Cost of Hydrogen per kg produced by the Electrolysis process connected with the grid in different EU Countries

. Country	**Total Cost (€/kgH_2)**
Luxembourg	8.5
Slovakia	8.3
Croatia	8
Slovenia	7.8
Hungary	7.5
Italy	7.2
Latvia	7
Romania	6.8
Lithuania	6.5
Germany	6.2
Denmark	6
Finland	5.8
Poland	5.6
Norway	5.3
France	5.1

Portugal	4.8
Estonia	4.6
Austria	4.3
Netherlands	4.2
Sweden	4
Malta	3.8
Spain	3.5
United Kingdom	3.3
Ireland	3.1
Belgium	2.9

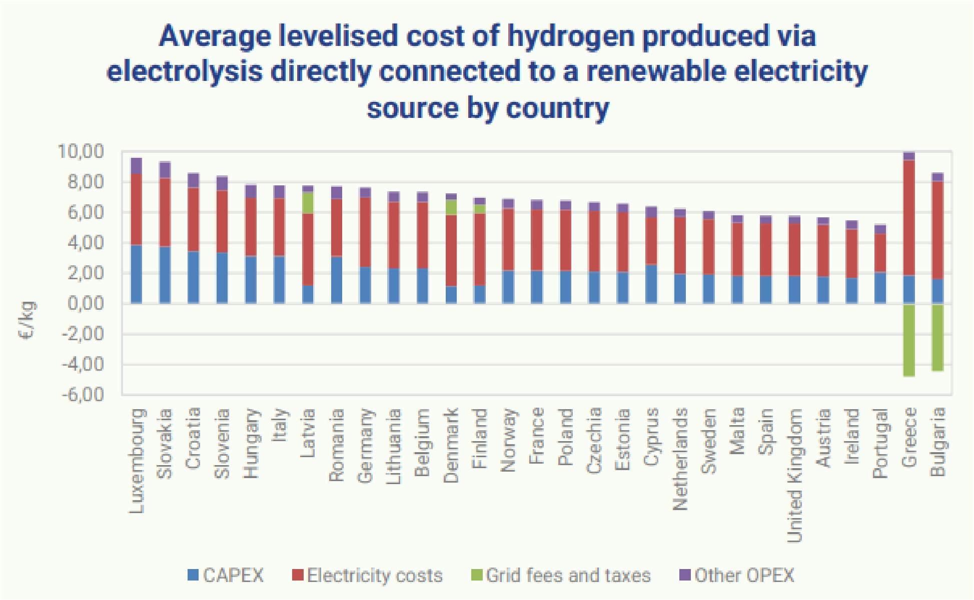


FIGURE 6-9: AVERAGE LEVELIZED COST OF HYDROGEN PRODUCED VIA ELECTROLYSIS DIRECTLY CONNECTED TO RENEWABLE ELECTRICITY [42]

On the other hand, countries that generate hydrogen from renewable sources have a large cost reduction. For example, the production costs for Luxembourg and Slovakia, though relatively high due to CAPEX and electricity expenses, remain well below grid-based costs. Such countries, such as Greece and Bulgaria, even claim negative numbers, that show that it is possible to produce hydrogen from a combination of subsidies and cheap renewable energy.

Table 6-2: Cost of Hydrogen per kg produced by Electrolysis process connected with renewable resources in different EU Countries.

Country	**Total Cost (€/kg H_2)**
Cyprus	17.5
Italy	14.5
Slovakia	13.5
Croatia	13.2
Romania	12.7
Germany	12.5
Austria	12.2
Hungary	12
Slovenia	11.8
Greece	11.5
Spain	11
Finland	10.7
France	10.5
Ireland	10.3

Poland	10
Netherlands	9.5
Belgium	9.2
Lithuania	8.9
Norway	8.7
Latvia	8.5
Estonia	8.3
Malta	8.1
Denmark	7.8
Portugal	7.5
Bulgaria	7.2

6.3.1. Advantages of Electrolysis

1. Electrolysis can make hydrogen without any direct emissions — the most sustainable form of hydrogen production.
2. RES through Electrolysis can be accommodated with renewable systems to provide templates for surplus electricity as hydrogen to be converted back into electricity as required, balancing supply and demand [34].
3. Because of the large number of applications, Electrolysis can be scaled from small on-site systems to large, centralized plants and can thus be adapted to a wide variety of hydrogen demand scenarios.

6.3.2. Challenges of Electrolysis

1. Currently, the costs of renewable electricity and the capital needed to build electrolyzers make electrolysis more expensive than SMR.

2. It has all the requirements for a high-power density source; however, it requires large amounts of electricity which prohibits it from operating.
3. Most investments and regulatory support will be necessary to develop infrastructure for the production and distribution of green hydrogen.

The favorable environment for electrolysis in Italy arises from abundant solar and wind resources. There will be some additional cost reductions in renewable energy and electrolyzer technology, as well as government incentives (such as tax incentives) to encourage investment in green hydrogen infrastructure required to scale up electrolysis to produce large quantities of hydrogen.

6.4. Biomass Gasification

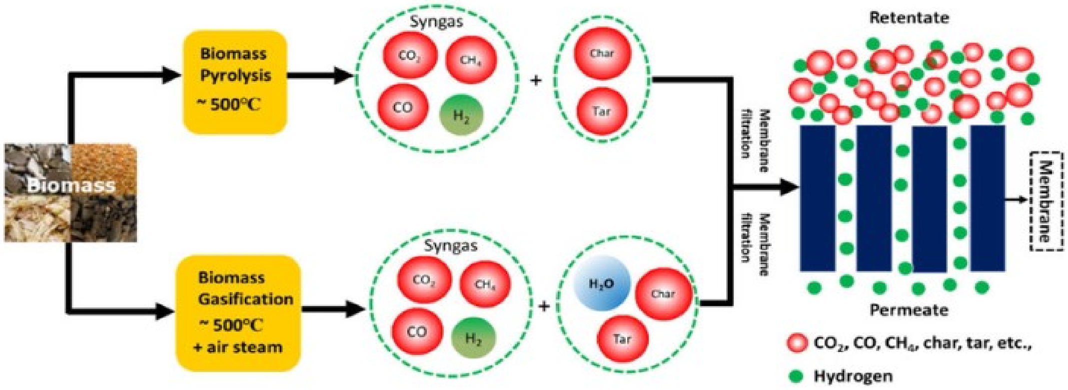


FIGURE 6-10: BIOMASS GASIFICATION FOR PRODUCING HYDROGEN [35]

Biomass gasification is a production method for hydrogen in which a biomass feedstock, including agricultural residues, forestry waste, and dedicated energy crops, is gasified. It consists of heating the biomass in a controlled environment with oxygen production of syngas, a mixture of hydrogen, CO, and CO_2 [36].

Biomass gasification can produce hydrogen in a renewable way, depending on the CO2 produced being captured and stored, or utilized in other ways. Biomass gasification involves the following steps:

- **Feedstock Preparation:** Also, the feasibility of gasification of biomass feedstock is improved when the feedstock is dried and prepared to enhance the efficiency and energy content in the gasifier.

- **Gasification Process:** Syngas are generated by heating biomass in a controlled environment, such as a gasifier, to form syngas, which further processing can increase the syngas' hydrogen content [37].
- **Hydrogen Separation:** The separation of hydrogen from other gases in the syngas is achieved through membrane separation and/or pressure swing adsorption.

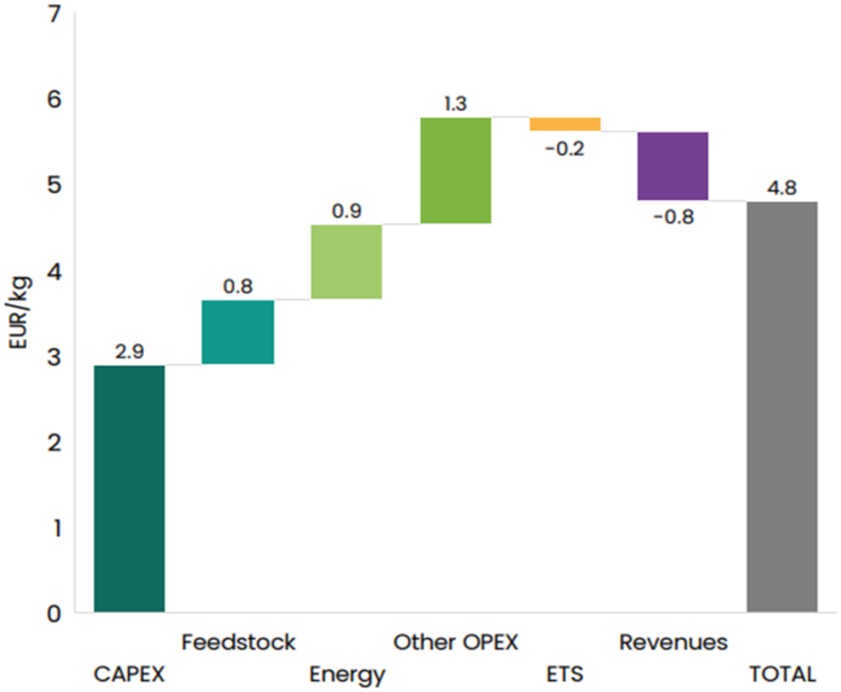


FIGURE 6-11: LEVELIZED COST OF BIOMASS GASIFICATION TO HYDROGEN PER KG [45]

Economically hydrogen can be produced from biomass gasification at Levelized costs between \$1.48 and \$3 per kilogram. At a cost of around \$3.15 to \$3.60 per kilogram when CCS technology is included. The CCS costs come in \$3.37/kg on average and \$2.24/kg without it. Hydrogen from biomass should be able to be completely priced with a potential selling price as low as 2.7 EUR/kgH_2 [44], according to techno-economic studies. The process brings a sustainable pathway toward hydrogen production using renewable biomass feedstock for a low-carbon energy transition.

6.4.1. Advantages of Biomass Gasification

1. Organic waste materials are used as feedstock in biomass gasification, a renewable source of hydrogen.

2. Biomass gasification can be used in waste management strategy, converting agricultural or forestry residue into a useful energy resource.
3. Together, biomass gasification and CCS can deliver negative emissions, because carbon dioxide from the gas can be captured and stored.

6.4.2. Challenges of Biomass Gasification

1. Finally, a legitimate challenge of sustainable biomass supply is to manage the land use and resources such that it does not cause environmental impacts.
2. Biomass gasification is less efficient than SMR biomass gasification and is therefore less suitable for hydrogen production.
3. The sustainability benefits of biomass gasification can be diminished, if not managed properly, by deforestation or other environmental concerns that result.

Biomass gasification provides a very rare opportunity to produce hydrogen locally from the agriculture and forestry sectors of Italy, an important sector of the Italian economy. Scaling this technology will however require a sustainable feedstock management practice, investment in infrastructure, and policies that promote the integration of biomass gasification into the energy sector.

6.5. Steam Methane Reforming Process and Proton Exchange Membrane Fuel Cell (PEMFC) Modelling by Aspen HYSYS

A process model for hydrogen production was developed using Aspen HYSYS, focusing on SMR as the primary method. The model utilizes a conversion reactor to simulate reforming reactions, where methane reacts with steam to produce hydrogen and carbon monoxide. Following the reforming stage, an equilibrium reactor is employed for the Water-Gas Shift (WGS) reaction, which converts carbon monoxide and water into additional hydrogen and carbon dioxide. To enhance hydrogen purity, a CO_2 absorption column was designed and integrated into the process to capture and remove CO_2 from the reformate stream. Additionally, the hydrogen output was integrated into a PEMFC model to simulate CHP generation. This approach provides a comprehensive model of hydrogen production with CO_2 capture and energy co-generation, supporting sustainable and efficient hydrogen-based energy systems.

6.5.1. SMR Model for Hydrogen Production by Aspen HYSYS

Hydrogen production through SMR is a widely implemented industrial method due to its high efficiency, cost-effectiveness, and scalability. This SMR model utilizes methane, commonly from natural gas, and reacts it with steam in a high-temperature environment to produce a hydrogen-rich synthesis gas (syngas) composed primarily of hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2).

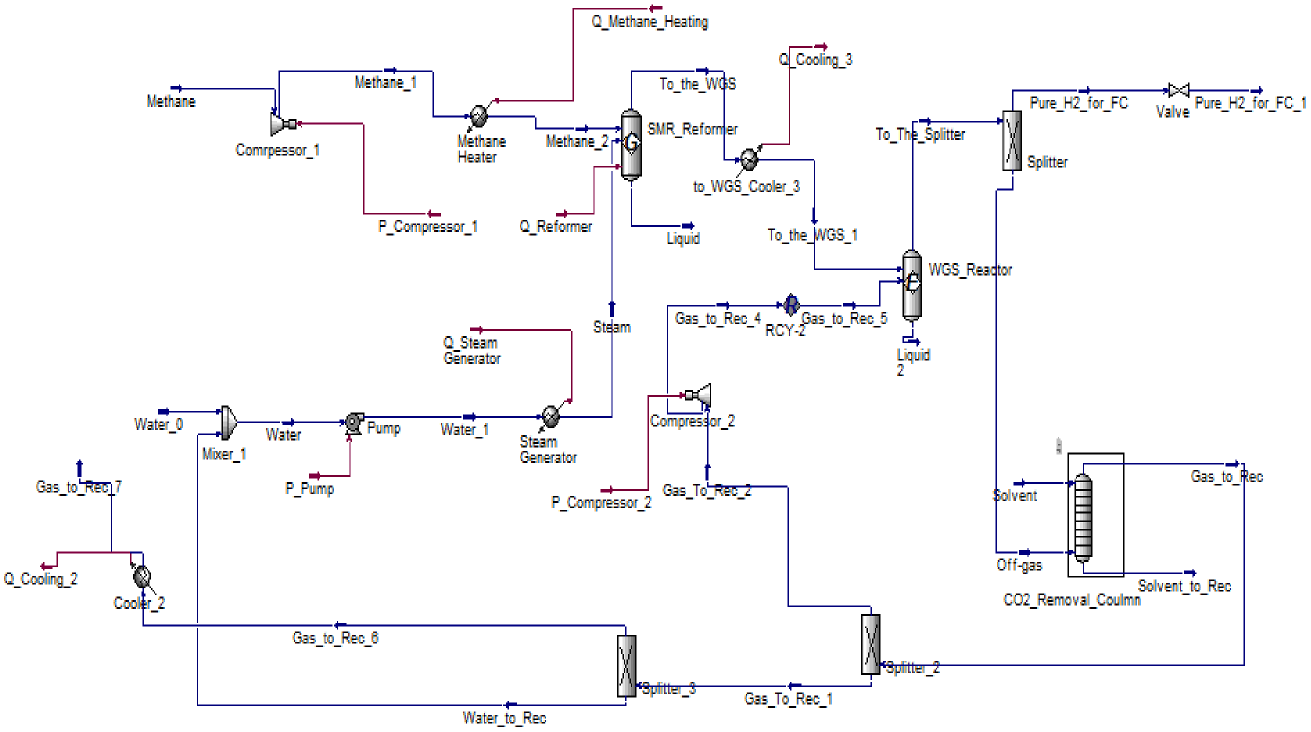


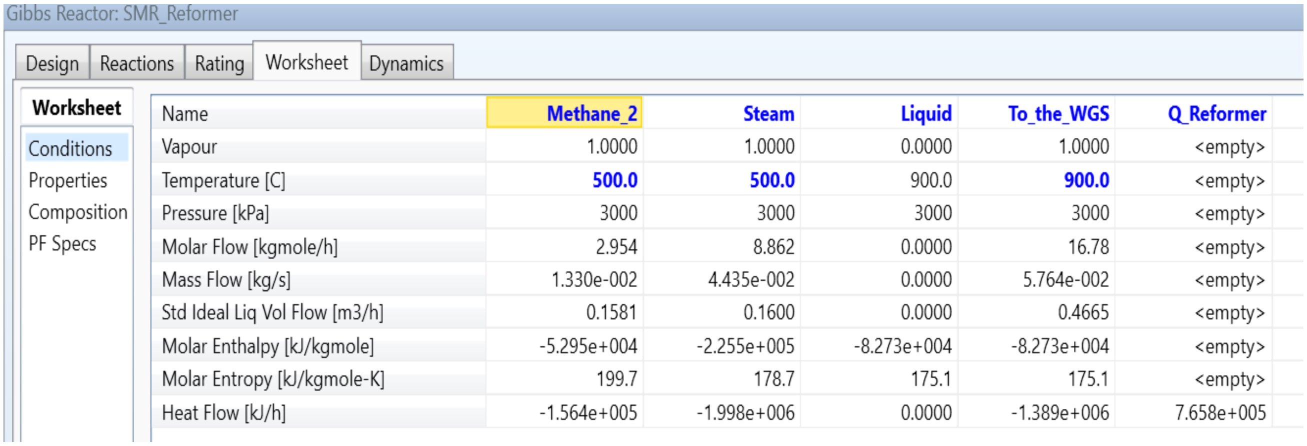
FIGURE 6-12: STEAM METHANE REFORMING PROCESS FOR HYDROGEN PRODUCTION BY ASPEN HYSYS

The process involves two main reactions: the reforming reaction and the water-gas shift (WGS) reaction. In the reforming step, methane and steam were at 500°C and a pressure of 3000 kPa. The main reaction can be described as follows:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad [6.6]$$

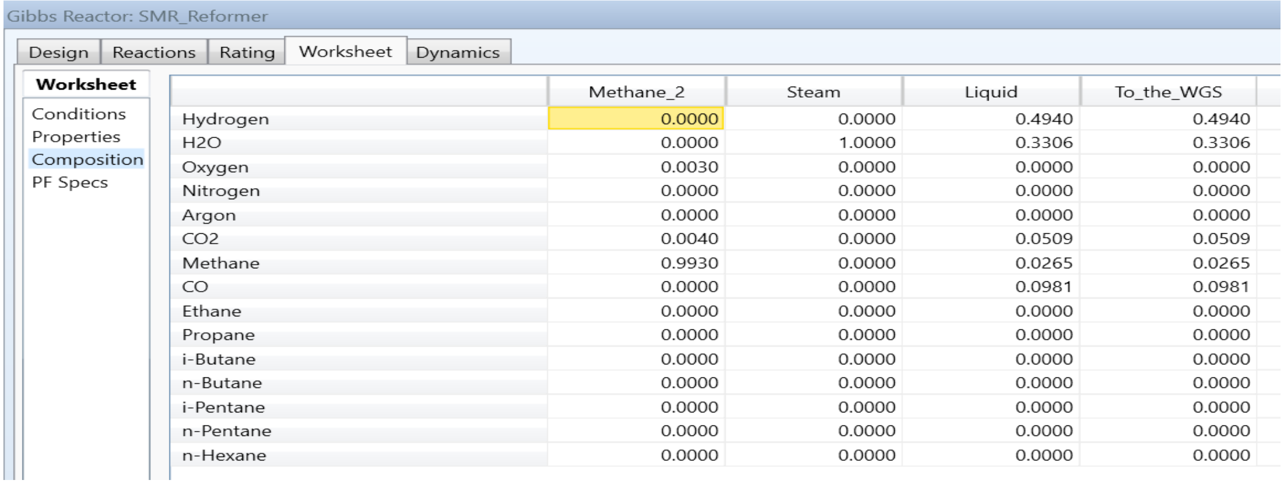
This endothermic reaction requires significant energy input, and thus, an efficient heat integration strategy is vital for economic feasibility. In this model, a Gibbs reactor is utilized within Aspen

HYSYS to simulate the reforming process, allowing for the detailed control of methane conversion rates and thermodynamic conditions.



Name	Methane_2	Steam	Liquid	To_the_WGS	Q_Reformer
Vapour	1.0000	1.0000	0.0000	1.0000	<empty>
Temperature [C]	500.0	500.0	900.0	900.0	<empty>
Pressure [kPa]	3000	3000	3000	3000	<empty>
Molar Flow [kgmole/h]	2.954	8.862	0.0000	16.78	<empty>
Mass Flow [kg/s]	1.330e-002	4.435e-002	0.0000	5.764e-002	<empty>
Std Ideal Liq Vol Flow [m3/h]	0.1581	0.1600	0.0000	0.4665	<empty>
Molar Enthalpy [kJ/kgmole]	-5.295e+004	-2.255e+005	-8.273e+004	-8.273e+004	<empty>
Molar Entropy [kJ/kgmole-K]	199.7	178.7	175.1	175.1	<empty>
Heat Flow [kJ/h]	-1.564e+005	-1.998e+006	0.0000	-1.389e+006	7.658e+005

Figure 6-13: Reformer reactor (Gibbs) conditions



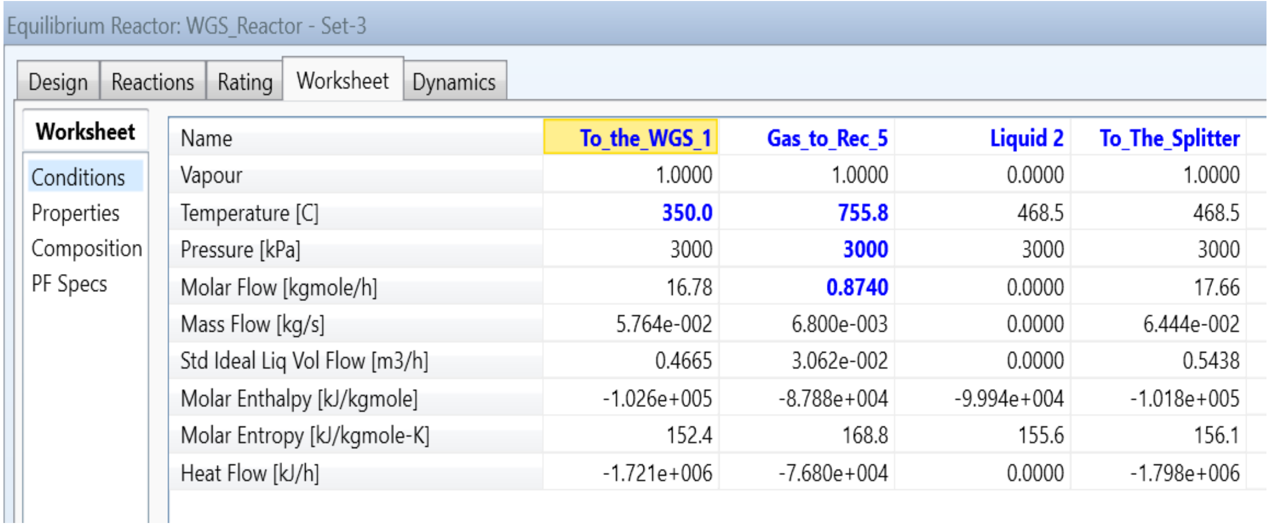
	Methane_2	Steam	Liquid	To_the_WGS
Hydrogen	0.0000	0.0000	0.4940	0.4940
H2O	0.0000	1.0000	0.3306	0.3306
Oxygen	0.0030	0.0000	0.0000	0.0000
Nitrogen	0.0000	0.0000	0.0000	0.0000
Argon	0.0000	0.0000	0.0000	0.0000
CO2	0.0040	0.0000	0.0509	0.0509
Methane	0.9930	0.0000	0.0265	0.0265
CO	0.0000	0.0000	0.0981	0.0981
Ethane	0.0000	0.0000	0.0000	0.0000
Propane	0.0000	0.0000	0.0000	0.0000
i-Butane	0.0000	0.0000	0.0000	0.0000
n-Butane	0.0000	0.0000	0.0000	0.0000
i-Pentane	0.0000	0.0000	0.0000	0.0000
n-Pentane	0.0000	0.0000	0.0000	0.0000
n-Hexane	0.0000	0.0000	0.0000	0.0000

Figure 6-14: Reformer reactor composition

Following the reforming reaction, the syngas undergoes a WGS reaction (using an Equilibrium Reactor), where carbon monoxide and steam further react to produce additional hydrogen and CO_2:

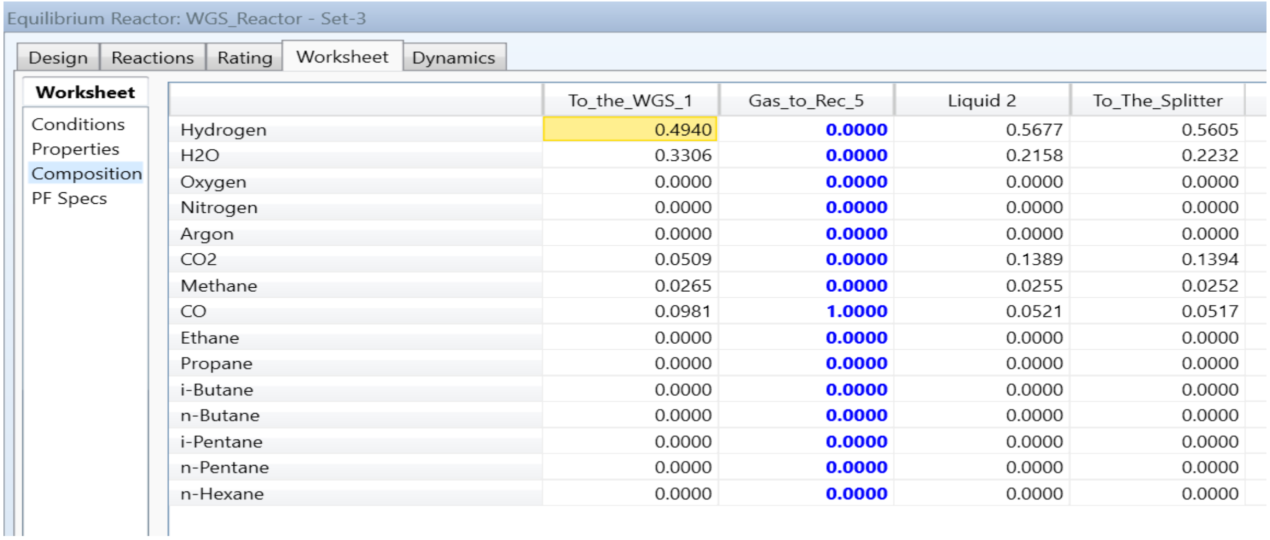
$$CO + H_2O \rightarrow CO_2 + 2H_2 \qquad [6.7]$$

In Aspen HYSYS, the WGS reaction is modeled using an equilibrium reactor, which calculates the thermodynamic equilibrium composition based on reaction conditions, maximizing hydrogen production while reducing CO content in the syngas.



Name	To_the_WGS_1	Gas_to_Rec_5	Liquid 2	To_The_Splitter
Vapour	1.0000	1.0000	0.0000	1.0000
Temperature [C]	350.0	755.8	468.5	468.5
Pressure [kPa]	3000	3000	3000	3000
Molar Flow [kgmole/h]	16.78	0.8740	0.0000	17.66
Mass Flow [kg/s]	5.764e-002	6.800e-003	0.0000	6.444e-002
Std Ideal Liq Vol Flow [m3/h]	0.4665	3.062e-002	0.0000	0.5438
Molar Enthalpy [kJ/kgmole]	-1.026e+005	-8.788e+004	-9.994e+004	-1.018e+005
Molar Entropy [kJ/kgmole-K]	152.4	168.8	155.6	156.1
Heat Flow [kJ/h]	-1.721e+006	-7.680e+004	0.0000	-1.798e+006

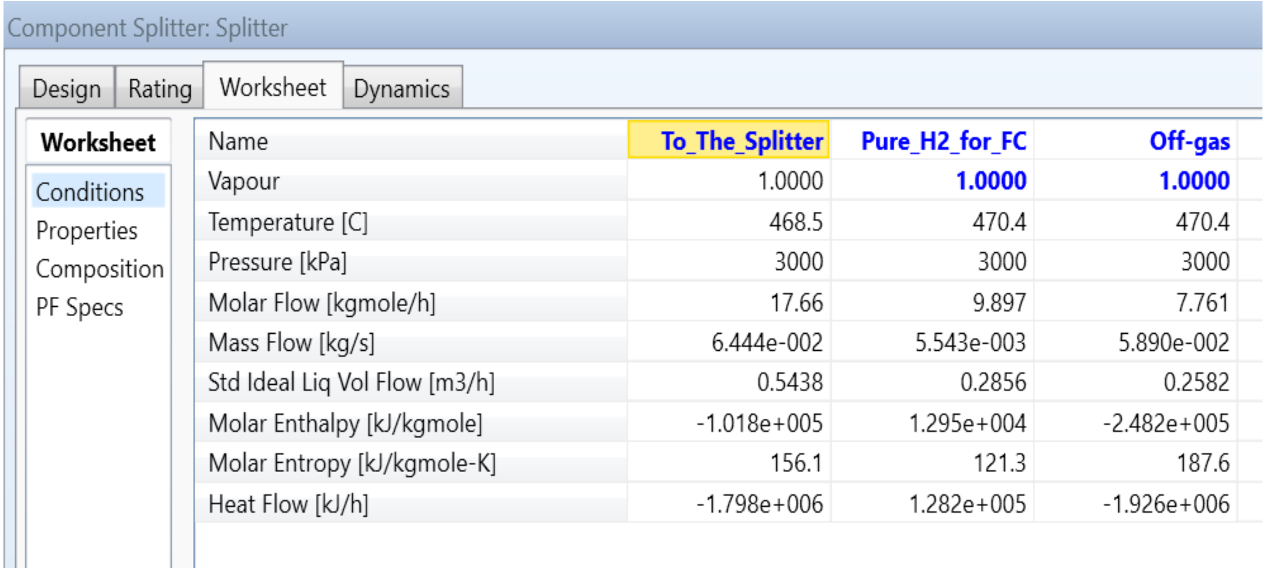
FIGURE 6-15: WATER GAS SHIFT REACTOR CONDITIONS



	To_the_WGS_1	Gas_to_Rec_5	Liquid 2	To_The_Splitter
Hydrogen	0.4940	0.0000	0.5677	0.5605
H2O	0.3306	0.0000	0.2158	0.2232
Oxygen	0.0000	0.0000	0.0000	0.0000
Nitrogen	0.0000	0.0000	0.0000	0.0000
Argon	0.0000	0.0000	0.0000	0.0000
CO2	0.0509	0.0000	0.1389	0.1394
Methane	0.0265	0.0000	0.0255	0.0252
CO	0.0981	1.0000	0.0521	0.0517
Ethane	0.0000	0.0000	0.0000	0.0000
Propane	0.0000	0.0000	0.0000	0.0000
i-Butane	0.0000	0.0000	0.0000	0.0000
n-Butane	0.0000	0.0000	0.0000	0.0000
i-Pentane	0.0000	0.0000	0.0000	0.0000
n-Pentane	0.0000	0.0000	0.0000	0.0000
n-Hexane	0.0000	0.0000	0.0000	0.0000

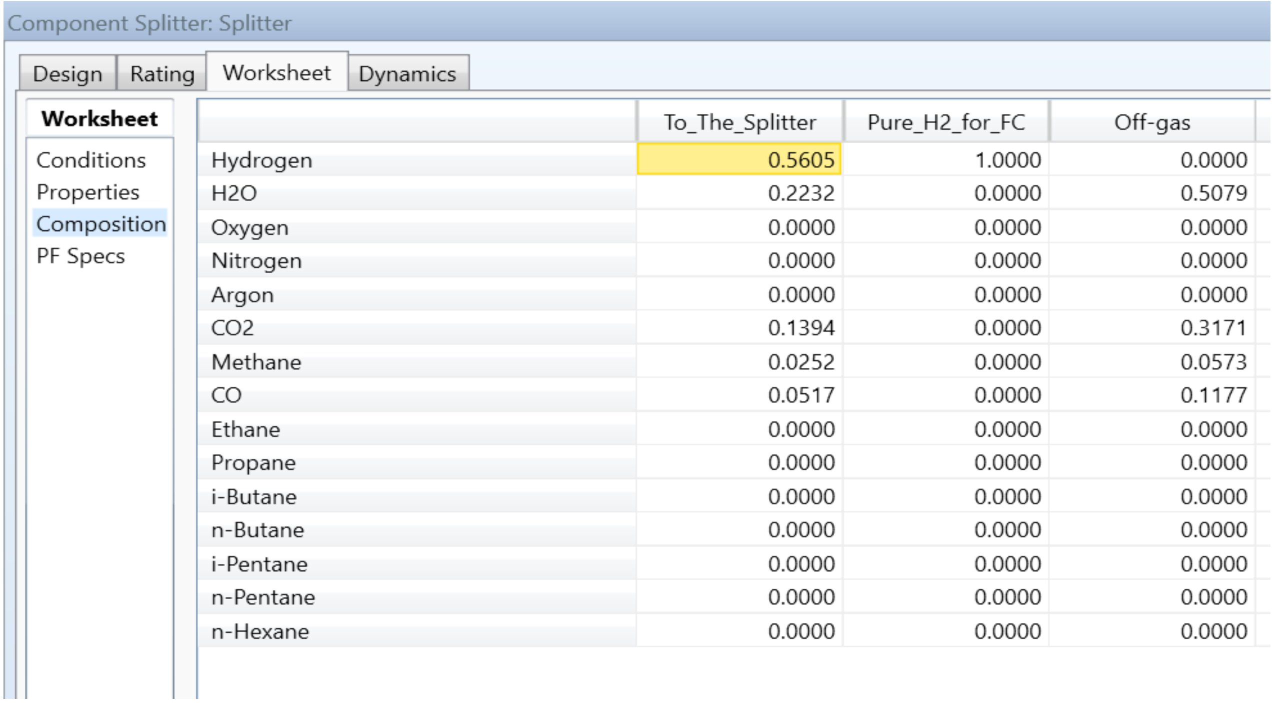
FIGURE 6-16: WATER GAS SHIFT REACTOR COMPOSITION

After the water gas shift reaction, a splitter for the separation of hydrogen from off-gases is incorporated. Below are reported figures from the software related to the condition and composition of the splitter.



Name	To_The_Splitter	Pure_H2_for_FC	Off-gas
Vapour	1.0000	1.0000	1.0000
Temperature [C]	468.5	470.4	470.4
Pressure [kPa]	3000	3000	3000
Molar Flow [kgmole/h]	17.66	9.897	7.761
Mass Flow [kg/s]	6.444e-002	5.543e-003	5.890e-002
Std Ideal Liq Vol Flow [m3/h]	0.5438	0.2856	0.2582
Molar Enthalpy [kJ/kgmole]	-1.018e+005	1.295e+004	-2.482e+005
Molar Entropy [kJ/kgmole-K]	156.1	121.3	187.6
Heat Flow [kJ/h]	-1.798e+006	1.282e+005	-1.926e+006

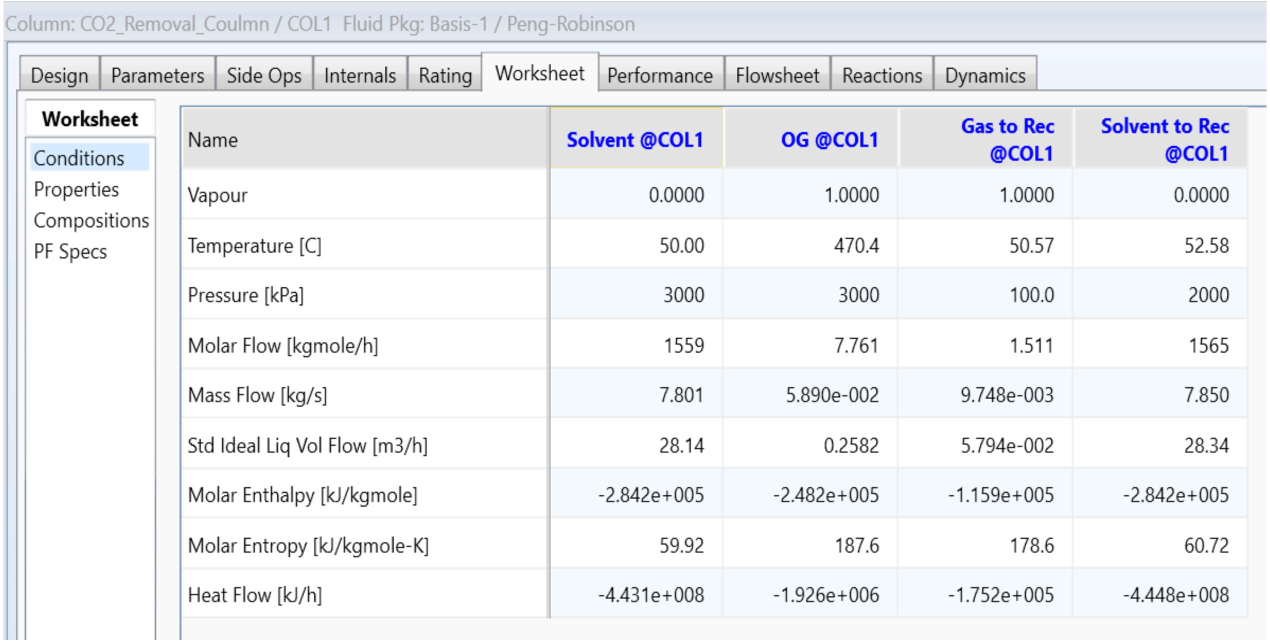
FIGURE 6-17: COMPONENT SPLITTER CONDITIONS



	To_The_Splitter	Pure_H2_for_FC	Off-gas
Hydrogen	0.5605	1.0000	0.0000
H2O	0.2232	0.0000	0.5079
Oxygen	0.0000	0.0000	0.0000
Nitrogen	0.0000	0.0000	0.0000
Argon	0.0000	0.0000	0.0000
CO2	0.1394	0.0000	0.3171
Methane	0.0252	0.0000	0.0573
CO	0.0517	0.0000	0.1177
Ethane	0.0000	0.0000	0.0000
Propane	0.0000	0.0000	0.0000
i-Butane	0.0000	0.0000	0.0000
n-Butane	0.0000	0.0000	0.0000
i-Pentane	0.0000	0.0000	0.0000
n-Pentane	0.0000	0.0000	0.0000
n-Hexane	0.0000	0.0000	0.0000

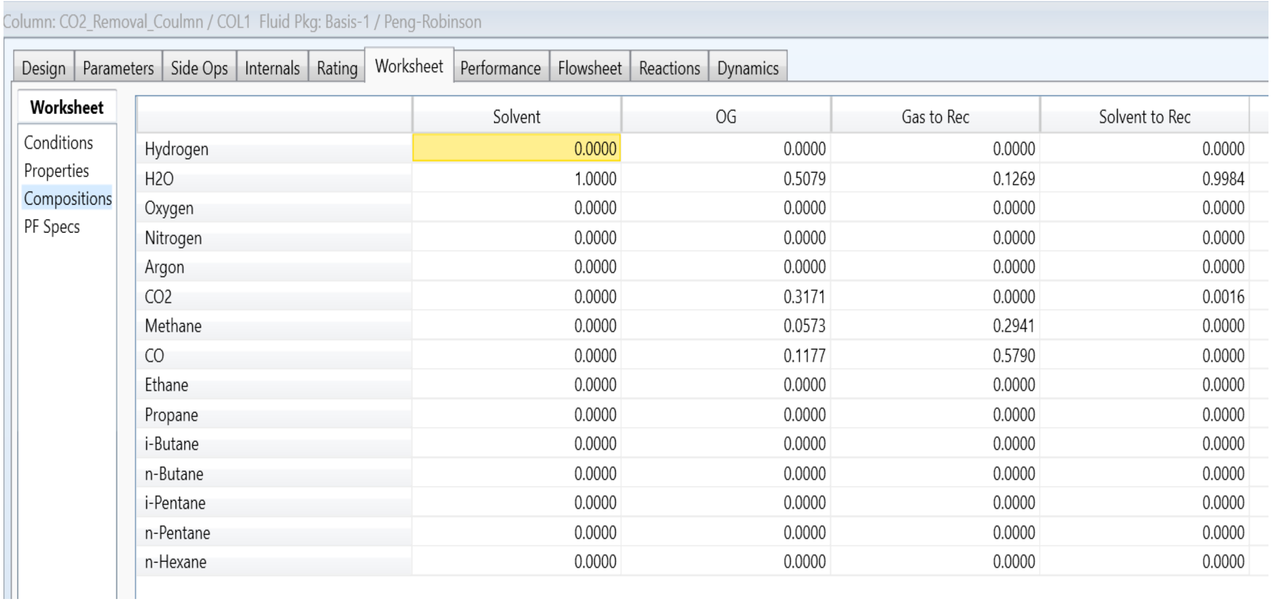
FIGURE 6-18: COMPONENT SPLITTER COMPOSITIONS

To capture and remove CO_2 from the syngas, a CO_2 absorption unit is modeled using an absorption column. In this step, CO_2 is selectively absorbed from the gas stream, often using solvents such as amines. This reduces the greenhouse gas footprint of the SMR process and results in a more purified hydrogen stream, which can then be conditioned for end-use applications.



Name	Solvent @COL1	OG @COL1	Gas to Rec @COL1	Solvent to Rec @COL1
Vapour	0.0000	1.0000	1.0000	0.0000
Temperature [C]	50.00	470.4	50.57	52.58
Pressure [kPa]	3000	3000	100.0	2000
Molar Flow [kgmole/h]	1559	7.761	1.511	1565
Mass Flow [kg/s]	7.801	5.890e-002	9.748e-003	7.850
Std Ideal Liq Vol Flow [m3/h]	28.14	0.2582	5.794e-002	28.34
Molar Enthalpy [kJ/kgmole]	-2.842e+005	-2.482e+005	-1.159e+005	-2.842e+005
Molar Entropy [kJ/kgmole-K]	59.92	187.6	178.6	60.72
Heat Flow [kJ/h]	-4.431e+008	-1.926e+006	-1.752e+005	-4.448e+008

Figure 6-19: CO2 removal column conditions



	Solvent	OG	Gas to Rec	Solvent to Rec
Hydrogen	0.0000	0.0000	0.0000	0.0000
H2O	1.0000	0.5079	0.1269	0.9984
Oxygen	0.0000	0.0000	0.0000	0.0000
Nitrogen	0.0000	0.0000	0.0000	0.0000
Argon	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.3171	0.0000	0.0016
Methane	0.0000	0.0573	0.2941	0.0000
CO	0.0000	0.1177	0.5790	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000
Propane	0.0000	0.0000	0.0000	0.0000
i-Butane	0.0000	0.0000	0.0000	0.0000
n-Butane	0.0000	0.0000	0.0000	0.0000
i-Pentane	0.0000	0.0000	0.0000	0.0000
n-Pentane	0.0000	0.0000	0.0000	0.0000
n-Hexane	0.0000	0.0000	0.0000	0.0000

Figure 6-19: CO2 removal Colmn composition

6.5.2. PEMFC Modelling by Aspen HYSYS for Combine Heat and Power (CHP)

PEMFCs are an attractive technology for CHP systems, particularly in hydrogen-based energy solutions. PEMFCs convert the chemical energy in hydrogen directly into electricity with high efficiency and low emissions. The process involves the electrochemical reaction of hydrogen with oxygen, producing water as the only by-product along with heat and electricity.

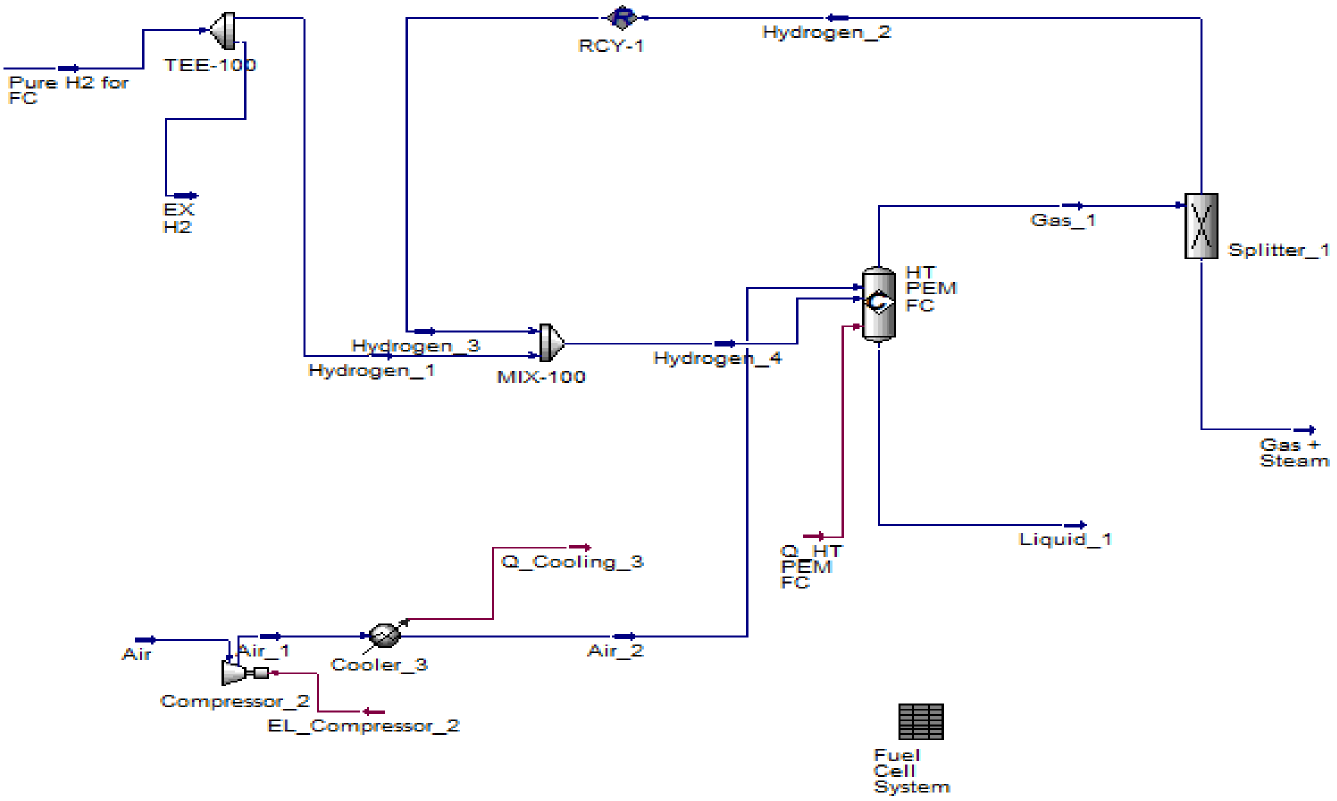
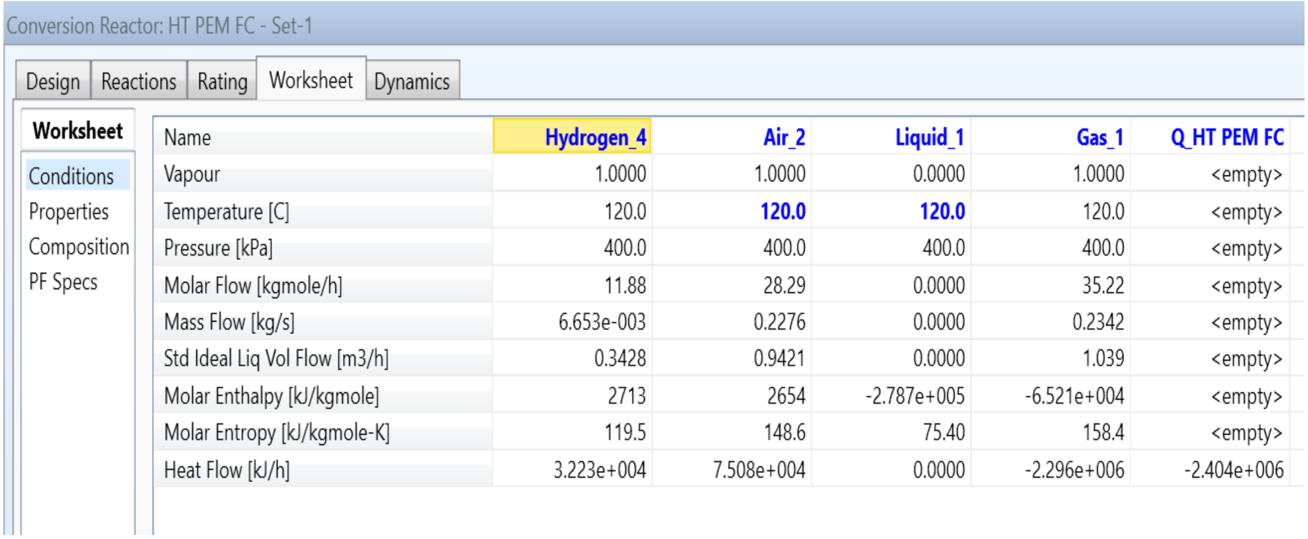
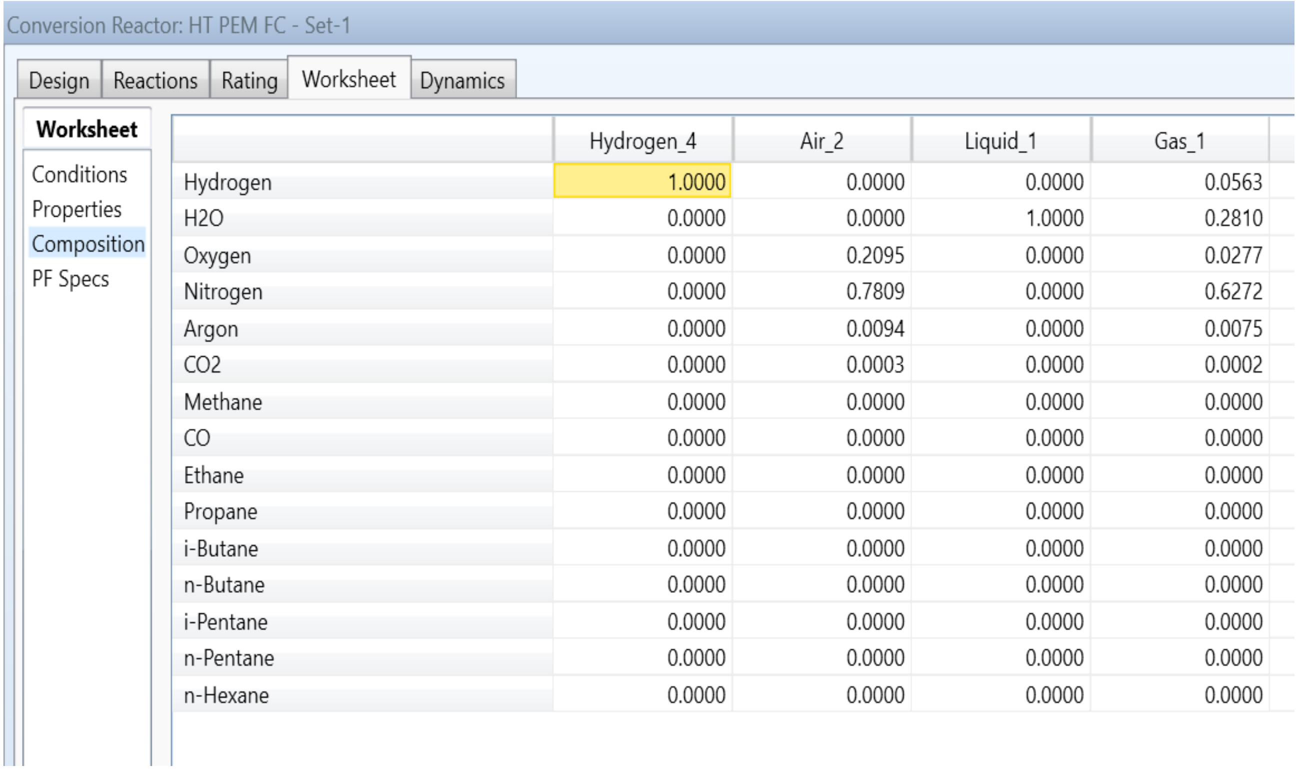


FIGURE 6-20: PROTON EXCHANGE MEMBRANE FUEL CELL (PEMFC) MODEL BY ASPEN HYSYS FOR CHP



Name	Hydrogen_4	Air_2	Liquid_1	Gas_1	Q_HT PEM FC
Vapour	1.0000	1.0000	0.0000	1.0000	<empty>
Temperature [C]	120.0	120.0	120.0	120.0	<empty>
Pressure [kPa]	400.0	400.0	400.0	400.0	<empty>
Molar Flow [kgmole/h]	11.88	28.29	0.0000	35.22	<empty>
Mass Flow [kg/s]	6.653e-003	0.2276	0.0000	0.2342	<empty>
Std Ideal Liq Vol Flow [m3/h]	0.3428	0.9421	0.0000	1.039	<empty>
Molar Enthalpy [kJ/kgmole]	2713	2654	-2.787e+005	-6.521e+004	<empty>
Molar Entropy [kJ/kgmole-K]	119.5	148.6	75.40	158.4	<empty>
Heat Flow [kJ/h]	3.223e+004	7.508e+004	0.0000	-2.296e+006	-2.404e+006

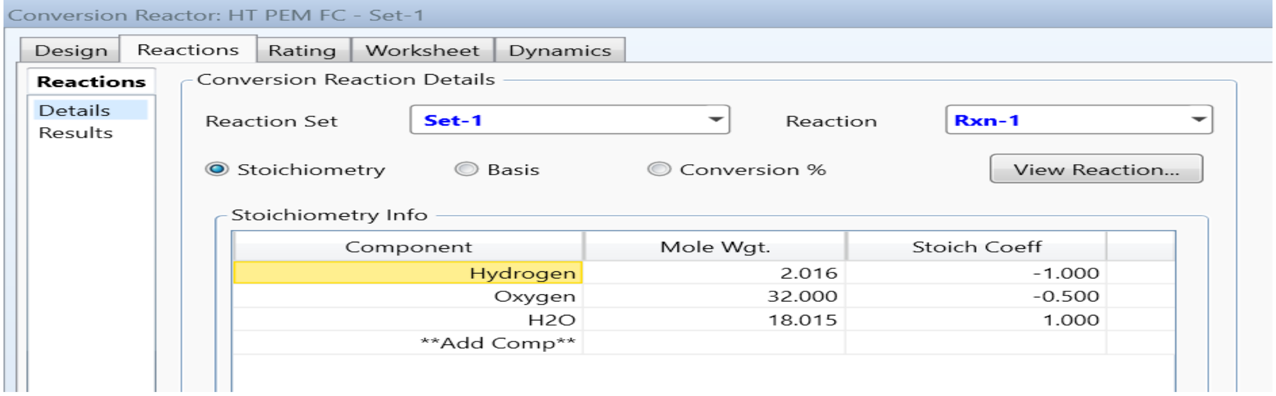
FIGURE 6-20: FUEL CELL REACTOR CONDITIONS



	Hydrogen_4	Air_2	Liquid_1	Gas_1
Hydrogen	1.0000	0.0000	0.0000	0.0563
H2O	0.0000	0.0000	1.0000	0.2810
Oxygen	0.0000	0.2095	0.0000	0.0277
Nitrogen	0.0000	0.7809	0.0000	0.6272
Argon	0.0000	0.0094	0.0000	0.0075
CO2	0.0000	0.0003	0.0000	0.0002
Methane	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000
Propane	0.0000	0.0000	0.0000	0.0000
i-Butane	0.0000	0.0000	0.0000	0.0000
n-Butane	0.0000	0.0000	0.0000	0.0000
i-Pentane	0.0000	0.0000	0.0000	0.0000
n-Pentane	0.0000	0.0000	0.0000	0.0000
n-Hexane	0.0000	0.0000	0.0000	0.0000

FIGURE 6-21: FUEL CELL REACTOR COMPOSITIONS

The reaction at the anode and cathode of the PEMFC can be summarized as:



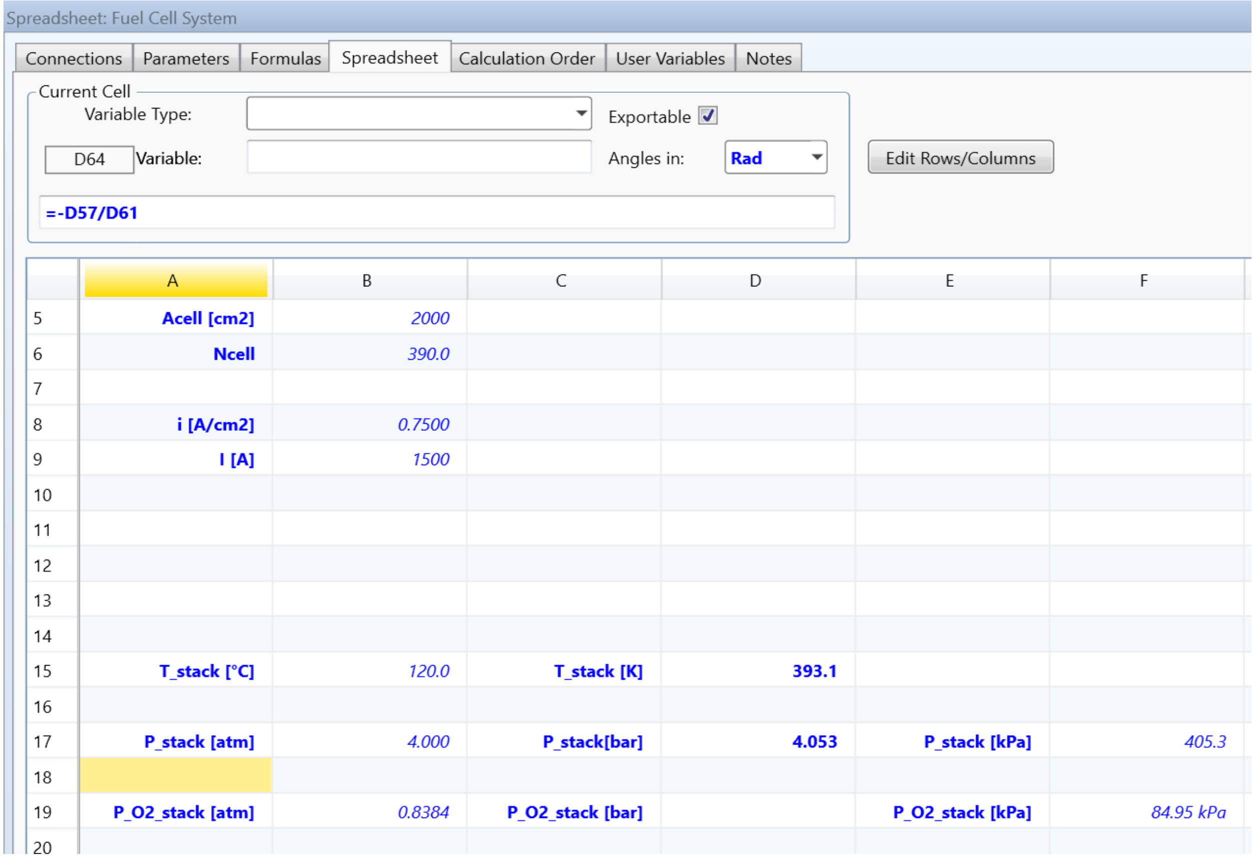
Reaction Set: Set-1

Reaction: Rxn-1

● Stoichiometry ○ Basis ○ Conversion %

Component	Mole Wgt.	Stoich Coeff
Hydrogen	2.016	-1.000
Oxygen	32.000	-0.500
H2O	18.015	1.000
Add Comp		

FIGURE 6-22: FUEL CELL REACTOR REACTION



Variable Type:

Exportable ☑

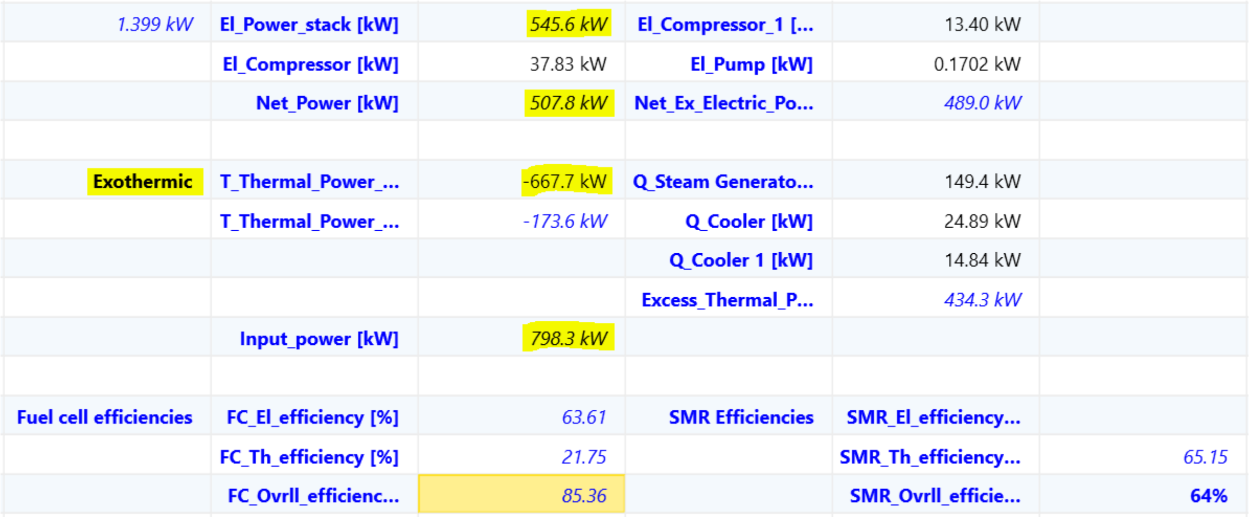
D64 Variable:

Angles in: Rad

=-D57/D61

	A	B	C	D	E	F
5	Acell [cm2]	2000				
6	Ncell	390.0				
7						
8	i [A/cm2]	0.7500				
9	I [A]	1500				
10						
11						
12						
13						
14						
15	T_stack [°C]	120.0	T_stack [K]	393.1		
16						
17	P_stack [atm]	4.000	P_stack[bar]	4.053	P_stack [kPa]	405.3
18						
19	P_O2_stack [atm]	0.8384	P_O2_stack [bar]		P_O2_stack [kPa]	84.95 kPa
20						

FIGURE 6-23:STACK SYSTEM CONDITIONS



1.399 kW	**El_Power_stack [kW]**	545.6 kW	**El_Compressor_1 [...**	13.40 kW	
	El_Compressor [kW]	37.83 kW	**El_Pump [kW]**	0.1702 kW	
	Net_Power [kW]	507.8 kW	**Net_Ex_Electric_Po...**	489.0 kW	
Exothermic	**T_Thermal_Power_...**	-667.7 kW	**Q_Steam Generato...**	149.4 kW	
	T_Thermal_Power_...	-173.6 kW	**Q_Cooler [kW]**	24.89 kW	
			Q_Cooler 1 [kW]	14.84 kW	
			Excess_Thermal_P...	434.3 kW	
	Input_power [kW]	798.3 kW			
Fuel cell efficiencies	**FC_El_efficiency [%]**	63.61	**SMR Efficiencies**	**SMR_El_efficiency...**	
	FC_Th_efficiency [%]	21.75		**SMR_Th_efficiency...**	65.15
	FC_Ovrll_efficienc...	85.36		**SMR_Ovrll_efficie...**	**64%**

Figure 6-24: Fuel cell and SMR results of CHP with efficiencies

The negative value of thermal heat in a fuel cell reactor indicates that the system is releasing heat, a characteristic of an exothermic process.

6.5.3: Efficiencies calculation

$$\eta = \frac{Total\ output\ energy}{Total\ input\ energy} \qquad [6.8]$$

FOR SMR:

$$\eta_{\mathrm{Thermal}} = \frac{\text{Energy Output as H2 }(Q_{H2})}{\text{Energy input as fuel+Qadditional heat}} * 100 \qquad [6.9]$$

or

$$\eta_{Thermal} = \frac{Q_{H2}}{Q_{Input}} * 100 \qquad [6.10]$$

Q_{H2}Useful Energy Output from Hydrogen in SMR, kWh

$$Q_{H2} = Mass\ of\ hydrogen\ produced * \text{LHV of Hydrogen}$$

$$Q_{H2} = \frac{9.897\ kmol}{h} * \frac{241.9\ MJ}{kmol} = 2394.1\ MJ/hr$$

Or

$$Q_{H2} = 665\ kWh$$

Q_{Input}= CH_4 rate * LHV of CH_4

CH_4 molar flow rate = 2.95 kmol/h

LHV = HHV – Latent heat of vaporization of H_2O

LHV = 797.1 MJ/kmol

Eq.1 becomes

$Q_{Input\ as\ fuel}$ = 2.95 kmol/h * 797.1 MJ/kmol = 2351.4 MJ/h = 653.2 kWh

From the entire SMR process heat required, $Q_{\text{additional heat}}$ = 212.7 (reformer) + 149.4 (steam generation) + 5.5 (methane pre-heating) = 367.6 kWh

$$\eta_{Thermal} = 65.1\%$$

Electric energy Input Auxiliary system = 18.8 kWh, lowering the SMR's overall efficiency to 64%.

FOR HT PEM FC:

$$\eta_{Electrical} = \frac{\textbf{Electrical Energy Output by the fuel cell}}{\textbf{Useful Energy Input from Hydrogen}} \qquad [6.11]$$

$$\eta_{Thermal} = \frac{\textbf{Thermal Energy Output by the fuel cell}}{\textbf{Useful Energy Input from Hydrogen}} \qquad [6.12]$$

$$\eta_{Overall} = \eta_{Electrical} + \eta_{Thermal} \qquad [6.13]$$

Q_{H2}, Useful Energy Input from Hydrogen, kWh

$$Q_{H2} = Mass\ of\ hydrogen\ produced * \frac{\text{LHV of Hydrogen}}{\text{kmol}}$$

$$Q_{H2} = \frac{11.88\ kmol}{hr} * \frac{241.9\ MJ}{kmol} = 2873.8\ MJ/hr$$

Or

$$Q_{H2} = 798.3\ kW$$

Electrical Net Energy Output by the fuel cell = 507.8 kW

Thermal Net Energy Output by the fuel cell = 173.6 kW

Useful Energy Input from Hydrogen = 798.3 kWh

$$\eta_{Electrical} = 63.6\%$$

$$\eta_{Thermal} = 21.8\%$$

$$\eta_{Overall} = 85.4\%$$

6.6. Key Role of PEMFC with SMR Aspen Model

The key role of this Aspen HYSYS model is to contribute toward decarbonization, by modeling PEMFCs, fueled by green hydrogen, are highly efficient technology for CHP generation, enabling substantial reductions in greenhouse gas emissions while enhancing energy security and efficiency. By leveraging hydrogen in PEMFC-based systems, Italy can transition away from fossil fuels in industrial, residential, and transportation applications. The potential for co-generating electricity and thermal energy with high efficiency aligns closely with the decarbonization priorities outlined in the European Green Deal, such as cutting emissions by at least 55% by 2030 and achieving net-zero by 2050.

In terms of the UN SDGs, deploying PEMFCs supports Goal 7 (Affordable and Clean Energy) by promoting access to clean and modern energy services and Goal 13 (Climate Action) by reducing reliance on carbon-intensive energy sources. Additionally, it contributes to Goal 9 (Industry, Innovation, and Infrastructure) by fostering clean energy technologies and Goal 11 (Sustainable Cities and Communities) by enabling greener urban energy systems.

Modeling PEMFCs for CHP using Aspen HYSYS underscores their feasibility and effectiveness in real-world scenarios, demonstrating the potential to optimize hydrogen use for energy production while addressing Italy's unique energy demands. By 2030, scaling up hydrogen-based solutions such as PEMFCs can drive decarbonization in hard-to-abate sectors. By 2050, with advancements in hydrogen infrastructure and electrolysis, PEMFCs could become a key enabler of a fully renewable energy system, ensuring that Italy meets its climate commitments while fostering innovation and sustainable development.

In conclusion, PEMFC technology exemplifies the transformative power of hydrogen in Italy's energy transition. By integrating this clean energy solution into its roadmap, Italy can lead in achieving its 2030 and 2050 decarbonization goals, contributing meaningfully to a sustainable future in alignment with European and global frameworks.

7. Conclusions and Recommendations

This report examined the role of hydrogen in Italy's carbon emission reduction effort and comparison, to other European countries, evaluated its economic viability, and assessed its potential effects in different sectors. Several key findings and insights emerged from this analysis to highlight where Italy can be positioned in the hydrogen economy through policy recommendations and indications for further research.

7.1. Summary of Key Findings

The hydrogen strategy for Italy is still not advanced as compared to countries like Germany and France, but Italy has significant potential. The country has established comprehensive targets and objectives to integrate hydrogen in each sector, particularly in hard-to-decarbonized sectors such as transportation, industrial, and energy sectors. Italy possesses natural advantages such as large solar resources and well-developed gas infrastructure that present a favorable operational environment for hydrogen production and distribution. But there are several gaps in Italy's hydrogen strategy, as compared to its European competitors. Italy has a strong potential for wind and solar energy so Italy can utilize these resources to produce green hydrogen, which is necessary for sustainable decarbonization. Further, the country's potential for scaling its hydrogen economy is limited by the availability of limited policy frameworks, funding, and infrastructure for hydrogen mobility and industrial applications. Countries such as Germany and the Netherlands are moving swiftly, backed by existing hydrogen infrastructure, and are heavily investing in green hydrogen, while others, like Spain and Portugal, are taking advantage of renewable resources to become green hydrogen production leaders. These insights can be used by Italy. Another important finding is that Italy needs to create collaborative hydrogen activities in the EU. Aligning with other nations in terms of cross-border infrastructure, hydrogen trade, and technology sharing could help both cut costs and accelerate learning in Italy.

7.2. Policy And Strategic Recommendations

Strengthen Renewable Energy Infrastructure: The only way for Italy to produce green hydrogen on a large scale is by increasing its renewable capacity, particularly in solar and wind energy. Several things could elevate the level of incentives offered, such as fast-tracking renewable energy projects, simplifying regulatory processes for new installations, offering incentives for renewable energy investments, or some combination of all of these.

- **Increase Funding for Research and Development (R&D):** Italy's capacity to innovate and compete in the European hydrogen economy depends on R&D funding. Research into hydrogen technology, including advanced electrolysis, fuel cell development, and hydrogen storage can help bring down production costs while making the process more efficient.
- **Establish Hydrogen Mobility Policies and Infrastructure:** Hydrogen can be easily adopted in Italy's transportation network. Therefore, the government should specify targets for how many hydrogen-powered vehicles will be used in heavy-duty vehicles such as buses, trucks, and trains. To create such an ecosystem for hydrogen mobility, policies should incentivize the purchase of vehicles and investments in hydrogen refueling stations.
- **Leverage Existing Natural Gas Infrastructure:** With a broad natural gas program, Italy can adapt its gas network from natural gas to hydrogen distribution. Recycling pieces of this network for hydrogen transport would speed up the deployment of hydrogen infrastructure. The Netherlands has already begun converting sections of its gas network so it can accommodate hydrogen, and Italy could do the same. Italy could consider joint projects also with neighboring countries toward the realization of a Mediterranean hydrogen corridor connecting Italy's infrastructure with broader European networks.
- **Encourage Regional Collaboration in Hydrogen Development:** Due to such a geographic position and an excellent set of trading relations in Europe, Italy is in the condition to be involved in the regional hydrogen projects. Italy should cooperate with other European countries, such as Spain, Portugal, and France, on developing cross-border hydrogen projects. Such options could be shared with hydrogen pipelines, common agreements on hydrogen, common investments, or infrastructure in hydrogen. Such initiatives would also include collaborative research with hydrogen R&D leading countries like Germany and Denmark to strengthen the knowledge base and improve the culture of innovation as well.

7.3. Directions for Future Research

There are several future research paths into hydrogen development to help Italy reach its goals for energy transition and sustainability. Efficiency of hydrogen production is one of the key elements.

Green hydrogen is still expensive and thus, the more affordable one is making this a viable energy source. The cost of Electrolyzes is very high and Electrolysis is one of the main components in the process of producing green hydrogen. Through its collaboration with leading research institutes throughout Europe, Italy can make more efficient and cheaper systems to produce more reliable and inexpensive green hydrogen. Italy's vast gas infrastructure can also be a transitional one for hydrogen. The research on combining hydrogen with natural gas allows Italy to benefit from its existing networks by providing hydrogen distribution while bypassing the long-term requirement for dedicated hydrogen pipelines. Therefore, this approach is a method to bring hydrogen to the market in an efficient manner without the initial costs of infrastructure, and in the meantime create momentum of hydrogen usage in different sectors.

The proper development of hydrogen projects can lead to job creation, stimulate local economies, and support the development of energy security, particularly in regions dependent on traditional industries and transitioning from them. Studies analyzing the regional impact of hydrogen projects in Italy, including input and value added to the regional economy and job creation, economic revitalization, and long-term energy stability could benefit Italy. Such studies would provide policymakers with insights to develop strategies that maximize social and economic benefits, support communities suffering from the renewable energy transition, and aid in creating local support for future hydrogen initiatives. By progressively increasing its dependence on renewable energy sources, Italy will require grid stability. Importantly, hydrogen is a valuable energy storage and grid balancing medium because it can store excess renewable energy and release it when there is high demand. Research into hydrogen's role in grid stabilization could provide Italy with a reliable solution to the problem of grid stabilization due to fluctuations generated by renewable energy production, one that would enable Italy to provide a stable and regular energy supply as renewable energy sources grow.

Furthermore, we require a framework for sustainable choices and research into the environmental impacts of various hydrogen production methods. While hydrogen is often seen as clean energy, hydrogen produced through natural gas is not always so. The research of carbon capture and storage technology CCS for blue hydrogen can help Italy understand which pathways are most congruent with sustainability goals, enabling cleaner hydrogen production. Finally, Europe's demand for green hydrogen is on the rise, and Italy can consider becoming an exporter of this energy, above all to countries with limited renewables. Studying logistics, costs, and feasibility will allow Italy to be a major supplier in Europe, contributing its share in covering the continent's hydrogen needs and strengthening its role as Europe's hydrogen leader in the energy transition. These research areas will help Italy to gain the understanding and resources necessary to develop a full hydrogen strategy that can assist the transition towards a cleaner, economical, and reliable energy transition.

8. References

[1] A. Bosisio, A. Morotti, S. Penati, A. Berizzi, C. Pasetti, and G. Iannarelli, “A feasibility study of using renewable-based hydrogen in off-grid domestic energy systems: a case study in Italy,” in *2022 Second International Conference on Sustainable Mobility Applications, Renewables and Technology (SMART)*, IEEE, Nov. 2022, pp. 1–7. doi: 10.1109/SMART55236.2022.9990178.

[2] L. Jansons, L. Zemite, N. Zeltins, I. Geipele, and A. Backurs, “Green and Sustainable Hydrogen in Emerging European Smart Energy Framework,” *Latvian Journal of Physics and Technical Sciences*, vol. 60, no. 1, pp. 24–38, Feb. 2023, doi: 10.2478/lpts-2023-0003.

[3] M. M. (Ch. 2), G. P. (Ch. 3), I. P. Y. (Ch. 4), N. B. (Ch. 5), K. M. I. P. Y. M. K. D. F. K. W. M. A. C. B. I. A. M. I. Joana Fonseca (Ch. 1), “CLEAN HYDROGEN MONITOR 2024,” *Hydrogen Europe*, 2023.

[4] “Green Hydrogen – The Missing Piece in The European Energy Mix,” *Yearbook of UNWE*, vol. 60, no. 2, pp. 87–93, Dec. 2022, doi: 10.37075/YB.2022.2.07.

[5] D. Grecea, T. Csaszar, G. Pupazan, and A. Nicola, “Hydrogen, the new green energy resource,” *MATEC Web of Conferences*, vol. 389, p. 00027, Jan. 2024, doi: 10.1051/matecconf/202438900027.

[6] Marco Giuli, “Italy in the International Hydrogen Economy,” *iai*, 2022.

[7] Monitore deloitte, “The European hydrogen economy – taking stock and looking ahead An outlook until 2030,” 2022.

[8] https://www.iea.org/countries/italy/emissions, “Italy,” *IEA*.

[9] P. Brusiło, “The EU Green Industrial Policy for Hydrogen Economy Development,” *Ekonomia XXI Wieku*, vol. 2023, no. 26, pp. 17–26, 2023, doi: 10.15611/e21.2023.02.

[10] A. Prontera, “Italian Hydrogen Policy: Drivers, Constraints and Recent Developments,” 2024, pp. 149–163. doi: 10.1007/978-3-031-59515-8_8.

[11] A. Ajanovic, M. Sayer, and R. Haas, “On the future relevance of green hydrogen in Europe,” *Appl Energy*, vol. 358, p. 122586, Mar. 2024, doi: 10.1016/j.apenergy.2023.122586.

[12] Alex Scott, “Europe to fund new wave of hydrogen projects,” *C&EN Global Enterprise*, vol. 100, no. 35, pp. 12–12, Oct. 2022, doi: 10.1021/cen-10035-buscon6.

[13] F. Arpino *et al.*, “Green hydrogen for energy storage and natural gas system decarbonization: An Italian case study,” *Int J Hydrogen Energy*, vol. 49, pp. 586–600, Jan. 2024, doi: 10.1016/j.ijhydene.2023.09.299.

[14] S. Macagno, L. Degiorgis, and M. Santarelli, “H2 &#38; RENEWABLE ENERGY: A CASE STUDY IN NORTH-WESTERN ITALIAN ALPS,” in *Proceeding of World Congress of Young Scientists on Hydrogen Energy Systems*, Connecticut: Begellhouse, 2023, pp. 341–351. doi: 10.1615/HYSYDAYS2005.510.

[15] M. Conte, F. Di Mario, A. Iacobazzi, A. Mattucci, A. Moreno, and M. Ronchetti, “Hydrogen as Future Energy Carrier: The ENEA Point of View on Technology and Application Prospects,” *Energies (Basel)*, vol. 2, no. 1, pp. 150–179, Mar. 2009, doi: 10.3390/en20100150.

[16] E. Barison, F. Donda, B. Merson, Y. Le Gallo, and A. Réveillère, “An Insight into Underground Hydrogen Storage in Italy,” *Sustainability*, vol. 15, no. 8, p. 6886, Apr. 2023, doi: 10.3390/su15086886.

[17] G. Spazzafumo and G. Raimondi, “Economic assessment of hydrogen production in a Renewable Energy Community in Italy,” *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 4, p. 100131, Jun. 2023, doi: 10.1016/j.prime.2023.100131.

[18] M. Conte *et al.*, “Investigating the economic and environmental impacts of a technological shift towards hydrogen-based solutions for steel manufacture in high-renewable electricity mix scenarios for Italy,” *IOP Conf Ser Earth Environ Sci*, vol. 1106, no. 1, p. 012008, Nov. 2022, doi: 10.1088/1755-1315/1106/1/012008.

[19] R. Quitzow and Y. Zabanova, “The Geopolitics of Hydrogen in Europe: The Interplay between EU and Member State Policies,” 2024, pp. 233–249. doi: 10.1007/978-3-031-59515-8_12.

[20] M. Coveri, M. Ferraro, F. Massaro, E. R. Sanseverino, and S. Ruffino, “The sustainable energy development in Southern Italy through green hydrogen: a cost analysis,” in *2023 IEEE International Conference on Environment and Electrical Engineering and 2023 IEEE Industrial*

and Commercial Power Systems Europe (EEEIC / I&CPS Europe), IEEE, Jun. 2023, pp. 1–6. doi: 10.1109/EEEIC/ICPSEurope57605.2023.10194682.

[21] M. Gandiglio and P. Marocco, “Mapping Hydrogen Initiatives in Italy: An Overview of Funding and Projects,” *Energies (Basel)*, vol. 17, no. 11, p. 2614, May 2024, doi: 10.3390/en17112614.

[22] B. Vivanco-Martín and A. Iranzo, “Analysis of the European Strategy for Hydrogen: A Comprehensive Review,” *Energies (Basel)*, vol. 16, no. 9, p. 3866, May 2023, doi: 10.3390/en16093866.

[23] D. Vergara, P. Fernández-Arias, G. Lampropoulos, and Á. Antón-Sancho, “Hydrogen Revolution in Europe: Bibliometric Review of Industrial Hydrogen Applications for a Sustainable Future,” *Energies (Basel)*, vol. 17, no. 15, p. 3658, Jul. 2024, doi: 10.3390/en17153658.

[24] B. Trincone, “Hydrogen corridors in Europe: strategies and countries involved,” *European Transport/Trasporti Europei*, no. 98, pp. 1–14, Jun. 2024, doi: 10.48295/ET.2024.98.11.

[25] G. Ficco, F. Arpino, M. Dell’Isola, M. Grimaldi, and S. Lisi, “Development of a Hydrogen Valley for Exploitation of Green Hydrogen in Central Italy,” *Energies (Basel)*, vol. 15, no. 21, p. 8072, Oct. 2022, doi: 10.3390/en15218072.

[26] L. Zemite *et al.*, “A Comprehensive Overview of the Europen and Baltic Landscape for Hydrogen Applications and Innovations,” *Latvian Journal of Physics and Technical Sciences*, vol. 60, no. 3, pp. 33–53, Jun. 2023, doi: 10.2478/lpts-2023-0016.

[27] E. Shagdar, B. G. Lougou, Y. Shuai, E. Ganbold, O. P. Chinonso, and H. Tan, “Process analysis of solar steam reforming of methane for producing low-carbon hydrogen,” *RSC Adv*, vol. 10, no. 21, pp. 12582–12597, 2020, doi: 10.1039/C9RA09835F.

[28] V. Fetisov, “Analysis of numerical modeling of steady-state modes of methane–hydrogen mixture transportation through a compressor station to reduce CO2 emissions,” *Sci Rep*, vol. 14, no. 1, p. 10605, May 2024, doi: 10.1038/s41598-024-61361-3.

[29] T. Younus, A. Anwer, Z. Asim, and M. S. Surahio, “Production of Hydrogen by Steam Methane Reformation Process,” *E3S Web of Conferences*, vol. 51, p. 03003, Aug. 2018, doi: 10.1051/e3sconf/20185103003.

[30] A. Ganguli and V. Bhatt, “Hydrogen production using advanced reactors by steam methane reforming: A review,” *Frontiers in Thermal Engineering*, vol. 3, Apr. 2023, doi: 10.3389/fther.2023.1143987.

[31] Georgia Pratt, “Hydrogen Electrolysis,” 2022.

[32] H. Mabrak, S. Elmazouzi, D. Takky, Y. Naimi, and I. Colak, “Hydrogen Production by Water Electrolysis: Review,” in *2023 12th International Conference on Renewable Energy Research and Applications (ICRERA)*, IEEE, Aug. 2023, pp. 372–380. doi: 10.1109/ICRERA59003.2023.10269356.

[33] L. P. Afisna, P. A. Kolala, G. Meha, F. W. Pasaribu, and I. G. P. N. Sindhu, “A COMPARISON OF HYDROGEN PRODUCTION BY ELECTROLYSIS METHOD USING WATER ELECTROLYTE WITH STAINLESS STEEL AND COPPER ELECTRODES,” *Jurnal Dinamika Vokasional Teknik Mesin*, vol. 9, no. 1, Apr. 2024, doi: 10.21831/dinamika.v9i1.73126.

[34] A. Pozio and S. Galli, “The role of hydrogen from electrolysis in the overproduction of energy fromrenewable sources,” *IOP Conf Ser Mater Sci Eng*, vol. 1265, no. 1, p. 012001, Nov. 2022, doi: 10.1088/1757-899X/1265/1/012001.

[35] A. T. Besha, M. T. Tsehaye, G. A. Tiruye, A. Y. Gebreyohannes, A. Awoke, and R. A. Tufa, “Deployable Membrane-Based Energy Technologies: the Ethiopian Prospect,” *Sustainability*, vol. 12, no. 21, p. 8792, Oct. 2020, doi: 10.3390/su12218792.

[36] Afor Avwioroko, “BIOMASS GASIFICATION FOR HYDROGEN PRODUCTION,” *Engineering Science & Technology Journal*, vol. 4, no. 2, pp. 56–70, Jun. 2023, doi: 10.51594/estj.v4i2.1289.

[37] A. Ghasemi, H. Nikafshan Rad, and M. Akrami, “Biomass-to-Green Hydrogen: A Review of Techno-Economic-Enviro Assessment of Various Production Methods,” *Hydrogen*, vol. 5, no. 3, pp. 474–493, Aug. 2024, doi: 10.3390/hydrogen5030027.

[38] United nation – Sustainable development goals

[39] International Energy Agency (IEA)

[40] Younas, M., Shafique, S., Hafeez, A., Javed, F., & Rehman, F. (2022). An Overview of Hydrogen Production: Current Status, Potential, and Challenges. *Fuel*, *316*, 123317. https://doi.org/10.1016/j.fuel.2022.123317

[41] Kothari, R., Buddhi, D., & Sawhney, R. L. (2008). Comparison of environmental and economic aspects of various hydrogen production methods. Renewable and Sustainable Energy Reviews, 12(2), 553–563. https://doi.org/10.1016/j.rser.2006.07.012

[42] European Hydrogen Observatory. (2024, March 20). Observatory.clean-Hydrogen.europa.eu. https://observatory.clean-hydrogen.europa.eu/

[43] Watson Farley & Williams, "The Italian Hydrogen Strategy ," 2021.

[44] ieabioenergy.com/wp-content/uploads/2019/01/Wasserstoffstudie_IEA-final.pdf

[45] *Introduction to the Hydrogen Market in California, Introduction to the Hydrogen Market in California DRAFT for comment]*

[46] Eurostat.

[47] Strockl, R. (2021, April 14). The Italian Hydrogen strategy. *Watson Farley & Williams*. https://www.wfw.com/articles/the-italian-hydrogen-strategy/