REFHYNE 2

CLEAN REFINERY HYDROGEN FOR EUROPE

Deliverable 9.4

GHG emissions avoidance analysis report (pre-construction)

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Executive summary

Hydrogen, with its exceptional potential as a clean energy carrier, has gained substantial attention in recent years as a cornerstone of the transition towards a sustainable and low-carbon energy economy. While hydrogen offers numerous advantages, the environmental sustainability of its production processes is of paramount importance. Greenhouse gas emissions associated with hydrogen production can vary significantly depending on the method employed, feedstock source, and energy inputs. Understanding and quantifying these emissions are essential for informed decision-making in the pursuit of a greener and more efficient hydrogen economy.

This report provides an in-depth analysis of GHG emissions in different hydrogen production processes, aiming to shed light on the environmental impacts associated with each method. Hydrogen production methods, including steam methane reforming, electrolysis (both alkaline and PEM), biomass gasification, and coal gasification, are investigated. The report synthesizes data from a wide range of sources, incorporating recent advancements in technology and updated emissions factors.

This deliverable has been prepared in the framework of the European project REFHYNE 2. REFHYNE 2 is an EU co-funded project that will develop and demonstrate the installation of a 100 MW PEM electrolyser at the Shell Energy and Chemicals Park Rheinland (Germany), using renewable power to produce cost effective and timely green hydrogen. Besides, the project aims at making a viable business case of large-scale electrolysis at refineries by valorising the hydrogen and potentially the by-product stream in the refinery, obtaining Renewable Energy Directive credits for the hydrogen produced and improving efficiency and capital cost.

The above-mentioned performance will be tested in the different work packages of the REFHYNE 2 project and, specifically, in *WP9 – health, safety RCS and environmental analysis,* where one of its objectives is to publish a thorough analysis of the GHG avoidance potential of large-scale electrolysers, taking into account their impact on the energy mix and co-benefits of locating them at industrial / refinery sites. Specifically, the present deliverable 9.4 is the first of a set of reports whose purpose is to study the electrolysis process developed in the project from an environmental point of view and to determine the potential of H_2 to decarbonise different sectors (mainly the industrial and transport sectors). This first deliverable has been elaborated mainly on the basis of estimates of the future performance of the installation, generic data and other information available in the literature. In the upcoming deliverables, the analysis will be refined on the basis of primary data from the project demonstrator. The deliverables considered in the project for this purpose are the following:

- D9.4. GHG emissions avoidance analysis report (pre-construction).
- D9.5. GHG emissions avoidance analysis report (operational).
- D9.6 Report on Life Cycle Analysis of all environmental implications of the deployment.

Document content description

This report is structured as follows: Section 1 corresponds to the introduction and the contextualisation of the analysis, section 2 describes the most common routes currently used to produce hydrogen, section 3 analyses the most common uses of H_2 in different sectors and the GHG emissions avoided in each of these sectors, section 4 presents the recognised methodologies to analyse the emissions generated in the life cycle of H_2 and the methodology selected for this study, section 5 contains a preliminary assessment of the emissions generated by the electrolysis of the REFHYNE 2 project on the basis of data estimated at the pre-construction stage and section 6 contains the most significant conclusions obtained after the analysis.

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Acronyms

ALD: Atomic Layer Deposition.

BEV: Battery Electric Vehicles.

BoL: Begin of Life.

CC: Combined Cycle Power Plants.

CCS: Carbon Capture and Storage.

CVD: Chemical Vapor Deposition.

EFTA: European Free Trade Association.

EoL: End of Life.

EU27: European Union which consists of 27 countries (Belgium, Bulgaria, Czech Republic, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland, Sweden).

FCV: Fuel Cell Vehicles.

GHG: Greenhouse Gases.

GO: Guarantee of Origin.

IPR: Intellectual Property Rights.

LCA: Life Cycle Assessment.

MEP: Mega Electrolyser Platform.

MM: Molten Metal.

PEM: Proton Exchange Membrane.

PGM: Platinum Group Metals.

PSA: Pressure Swing Adsorption.

PSU: Power Supply Unit.

RE: Renewable Energy.

RER: Europe.

RME: Rapeseed Methyl Ester.

SB: System Boundaries.

SMR: Steam Methane Reforming.

TG: Thermal Gas.

WGS: Water-Gas Shift.

WTW: Well to Wheel.

1. Introduction

The 21st century has ushered in a profound global transformation, one where the urgent need to combat climate change has taken centre stage. At the forefront of this transition is the quest for sustainable energy solutions, and hydrogen has emerged as a critical player in this evolving landscape. Hydrogen, with its remarkable potential to decarbonize a wide range of sectors, from transportation to industry and beyond, offers a glimpse into a more sustainable and low-carbon future.

Hydrogen is often touted as the "energy carrier of the future" due to its versatility, high energy density, and environmental benefits when produced using low or zero-emission methods. However, the sustainability of hydrogen as an energy carrier depends significantly on the processes used to produce it. The methods used to produce hydrogen can vary widely in terms of their carbon footprint, depending on factors such as the feedstock used, the energy source powering the production process, and the efficiency of the technology employed.

This report conducts a detailed analysis and quantification of greenhouse gas emissions from different hydrogen production processes. The need for such an investigation is underscored by the pressing global imperative to reduce carbon emissions and mitigate the effects of climate change. Hydrogen, as a potential solution to this challenge, must be produced in a manner that aligns with sustainability goals and emissions reduction targets.

The aim of this report is to help understand the environmental performance of different hydrogen production techniques, ranging from conventional fossil fuel-based methods to innovative, emerging technologies harnessing renewable energy sources. Through analysis and quantification, we will evaluate the carbon footprint and broader environmental consequences of these diverse approaches.

The urgency of this investigation cannot be overstated. Climate change poses a clear and present danger, with rising global temperatures, extreme weather events and other environmental challenges threatening the stability of our planet. Hydrogen, when produced with minimal greenhouse gas emissions, stands as a beacon of hope in mitigating these threats and fostering a sustainable energy ecosystem. However, without a thorough understanding of the emissions associated with hydrogen production, we risk undermining its potential as a key contributor to a carbon-neutral future.

Our analysis encompasses a range of hydrogen production methods, each with its unique set of emissions characteristics. These methods include Steam Methane Reforming (SMR), which relies on natural gas as a feedstock; electrolysis, which utilizes electricity to split water molecules into hydrogen and oxygen; biomass gasification, an approach that transforms organic matter into hydrogen-rich syngas; and coal gasification, which involves the gasification of coal to produce hydrogen.

Within each of these production pathways, we explore the nuances of emissions quantification, taking into account both direct and indirect emissions sources. Direct emissions refer to those produced during the hydrogen production process itself, while indirect emissions encompass the entire lifecycle of the production method, including feedstock extraction, transportation, and energy generation. By adopting a holistic perspective, we aim to provide a comprehensive understanding of the environmental impacts associated with each method.

In conclusion, the quantification of greenhouse gas emissions in the different hydrogen production processes is an important step towards realising the potential of hydrogen as a sustainable energy solution. The future of our planet depends on our ability to transition to cleaner energy sources, and hydrogen has a key role to play in this endeavour. This report is a step forward on that path, offering information, analysis and a call to action for a more sustainable and equitable future.

2. GHG emissions from different H_2 production routes

The global transition to a sustainable and low-carbon energy future necessitates a paradigm shift in the way we produce and utilize energy carriers. Among the emerging solutions, hydrogen stands out as a versatile and clean energy carrier with the potential to significantly reduce greenhouse gas emissions in sectors such as transportation, industry, and power generation. However, the extent to which hydrogen can contribute to decarbonization depends heavily on the emissions associated with its production.

In this regard, the aim of the REFHYNE 2 project is to develop and install a high-capacity electrolyser that uses renewable energy to produce green hydrogen and oxygen, which will be introduced into existing refinery networks to decarbonise refinery operations. Therefore, this report will estimate the GHG emissions that will be generated by the REFHYNE's innovative electrolyser and, in order to quantify the emission reductions achieved, a review of other common H_2 production methods will be carried out to establish a baseline scenario for the analysis.

The production of H_2 can be achieved through various methods, each with its own advantages, disadvantages, and environmental implications. Some of the most common methods to produce hydrogen and its derivates are summarised in the current deliverable.

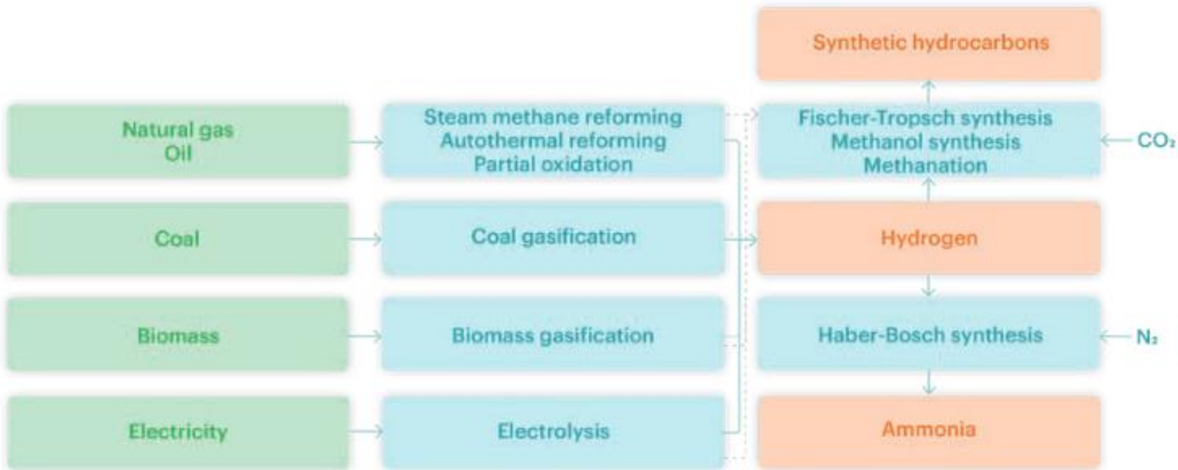

Figure 1. Potential pathways for producing hydrogen and hydrogen-based products [1]

2.1. Steam Methane Reforming

The Steam Methane Reforming (SMR) process is a widely adopted industrial method for producing hydrogen gas from methane, primarily sourced from natural gas. As one of the most prevalent techniques for hydrogen production, SMR is known for its efficiency, cost-effectiveness, and versatility.

SMR process involves a sequence of chemical reactions and physical processes aimed at breaking down methane into hydrogen and carbon monoxide, along with the release of heat. The process can be summarized in the following key steps:

- **Feedstock Preparation:** The primary feedstock for SMR is natural gas, which consists primarily of CH_4. Natural gas is pre-processed to remove impurities, such as sulphur compounds and heavy hydrocarbons, which could damage the catalyst used in the reforming process.

- **Steam Generation:** Water is heated to produce high-temperature steam, which is a critical reactant in the SMR process. Steam generation typically involves heating water in a boiler using external heat sources, such as natural gas combustion or electricity.

- **Reforming Reaction:** The heart of the SMR process takes place in a high-temperature reactor, often containing a nickel-based catalyst. The reforming reaction involves the reaction of CH_4 and steam to produce hydrogen gas and CO in an endothermic reaction:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

This reaction absorbs heat energy, which must be supplied to the reactor to sustain the process. The heat is typically provided by combusting a portion of the incoming natural gas, which is known as the "firing" or "burning" process.

- **Water-Gas Shift Reaction:** To increase the hydrogen yield and reduce the carbon monoxide content in the gas mixture, the produced gases are subjected to a Water-Gas Shift reaction. In this reaction:

$$CO + H_2O \rightarrow CO_2 + H_2$$

The CO is converted into CO_2 while generating additional H_2.

- **Purification:** The gas mixture emerging from the reforming and WGS reactions contains hydrogen, carbon dioxide, carbon monoxide, and traces of other gases. It undergoes purification processes, such as Pressure Swing Adsorption or other separation technologies, to remove impurities, particularly carbon dioxide. The purification step ensures the production of high-purity hydrogen.

- **Hydrogen Recovery:** The final step involves recovering and compressing the purified hydrogen gas, resulting in a high-purity hydrogen stream suitable for various industrial and commercial applications.

A scheme of the described process in plotted in Figure 2.

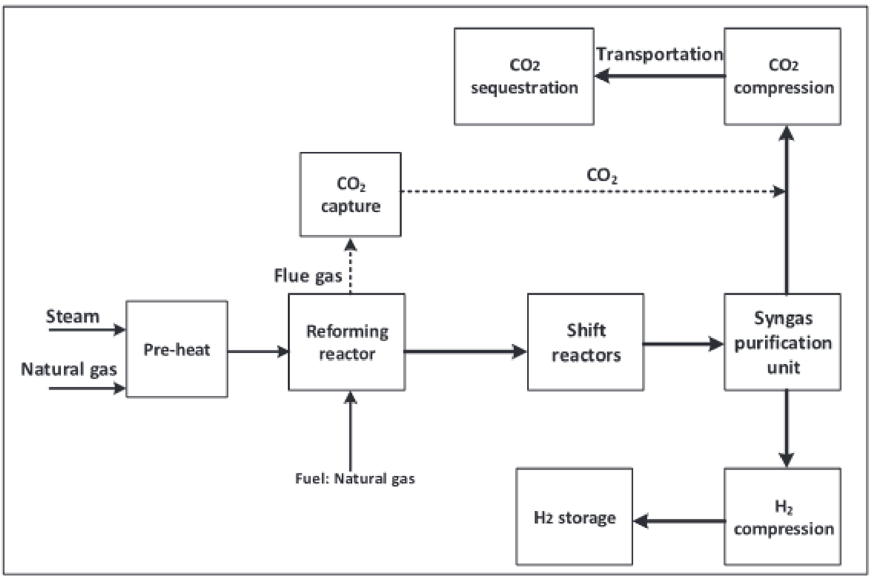

Figure 2. Simplified process flow diagram of steam methane reforming with carbon capture and storage (SMR-CCS) [2]

SMR is a cornerstone of the hydrogen supply chain, serving as a major source of industrial and commercial hydrogen. It finds applications in a variety of sectors, including petroleum refining, ammonia production, chemical manufacturing, and transportation. The high purity and reliability of SMR-produced hydrogen make it a vital component in several processes and technologies, including fuel cells and hydrogenation reactions.

While SMR is an efficient method for hydrogen production, it is not without environmental drawbacks, primarily related to greenhouse gas emissions:

- **CO_2:** The primary greenhouse gas emitted during SMR is CO_2. For every mole of hydrogen produced, about one mole of CO_2 is generated due to the reforming reaction. This carbon dioxide is typically released into the atmosphere unless carbon capture and storage (CCS) technology is applied.
- **CH_4:** While most of the methane is converted into hydrogen in the reforming process, some unconverted methane can escape into the atmosphere, contributing to methane emissions. Methane is a potent greenhouse gas, with a significantly higher global warming potential than carbon dioxide over a shorter timeframe.
- **Other Trace Gases:** SMR can also produce trace amounts of other greenhouse gases, such as NOx and SO_2, depending on the specific conditions and impurities in the natural gas feedstock.

To mitigate the environmental impact of SMR, carbon capture and storage technologies are increasingly being employed. CCS involves capturing the carbon dioxide emissions from the SMR process and then transporting and storing them underground, preventing their release into the atmosphere. This approach can significantly reduce the carbon footprint of hydrogen production via SMR and make it a more environmentally friendly option for hydrogen generation in a low-carbon energy future.

2.2. Electrolysis (Alkaline and PEM)

Electrolysis is an electrochemical process used to produce high-purity hydrogen gas from water by passing an electric current through it. The two most technologically advanced types of electrolysis and with the highest market penetration today are Alkaline Electrolysis and Proton Exchange Membrane (PEM) Electrolysis.

Alkaline Electrolysis:

In alkaline electrolysis, an alkaline electrolyte solution, typically KOH or NaOH, is used to facilitate ion conduction. The electrolyte serves as the medium through which ions can move between the electrodes.

Two electrodes, usually made of nickel or other conductive materials, are immersed in the electrolyte. One electrode is the anode, connected to the positive terminal of the power source, while the other is the cathode, connected to the negative terminal.

When an electric current is applied, water molecules at the cathode are reduced:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

Simultaneously, at the anode, water molecules are oxidized:

$$4OH^- \rightarrow O_2 + 2H_2O + 4e^-$$

The overall result is the production of hydrogen gas at the cathode and oxygen gas at the anode.

PEM Electrolysis:

PEM electrolysis employs a solid polymer electrolyte membrane made of materials like perfluorosulfonic acid. This membrane selectively conducts protons (H^+) while preventing the passage of electrons (e^-).

Similar to alkaline electrolysis, PEM electrolysis utilizes two electrodes, an anode, and a cathode. When an electric current flows through the cell, water molecules undergo electrolysis. At the anode:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

And at the cathode:

$$2H^+ + 2e^- \rightarrow H_2$$

Notably, in PEM electrolysis, the protons migrate through the solid electrolyte membrane, while electrons move through an external circuit.

PEM and alkaline electrolysis differ in both materials and operational characteristics. PEM electrolysis uses a solid polymer electrolyte, typically made of perfluorosulfonic acid (e.g., Nafion), which provides high proton conductivity and allows for compact system design. It requires noble metal catalysts such as platinum and iridium to ensure high efficiency and durability. Operating at higher current densities and responding rapidly to load fluctuations, PEM electrolysis is well-suited for integration with renewable energy sources. In contrast, alkaline electrolysis employs a liquid electrolyte, usually a concentrated KOH solution, and relies on non-precious metal catalysts like nickel or cobalt, reducing material costs. It operates at lower current densities and has slower dynamic response times but benefits from greater technological maturity and lower overall system costs.

Electrolysis, whether alkaline or PEM, is often considered a clean and sustainable method for hydrogen production because it uses water as its feedstock and does not directly produce greenhouse gas emissions during the hydrogen generation process. However, GHG emissions can be associated with the electricity used to power the electrolysis process, depending on the source of that electricity. If the electricity comes from fossil fuels, such as coal or natural gas, GHG emissions will be generated indirectly. In contrast, using renewable energy sources like solar, wind, or hydropower can result in nearly zero GHG emissions, making the hydrogen production process extremely environmentally friendly.

In general terms, electrolysis is considered a sustainable method for hydrogen production when powered by renewable energy, as it aligns with carbon reduction goals and contributes to a greener energy economy. For this reason, it represents a promising avenue for hydrogen production, offering environmental sustainability and versatility. Its ability to integrate with renewable energy sources makes it a crucial component of the transition to a cleaner and more sustainable energy landscape, facilitating the use of hydrogen as a clean energy carrier across various sectors.

2.3. Biomass Gasification

Biomass gasification is a thermochemical process that transforms organic materials, such as wood, agricultural residues and organic waste into hydrogen-rich syngas. In this method, biomass feedstock undergoes pyrolysis and gasification in a high-temperature, oxygen-limited environment, resulting in the production of a gas mixture composed of H_2, CO, CO_2 and other gases.

Biomass gasification begins with the selection and preparation of biomass feedstock. This can include a wide range of organic materials, including wood chips, crop residues, forestry waste, and even dedicated energy crops like switchgrass or miscanthus.

The heart of the biomass gasification process is the gasifier, a high-temperature reactor where the feedstock undergoes several chemical reactions in a controlled environment. The gasifier operates at high temperatures (typically 700 °C to 1,500 °C) and in an oxygen-starved or limited-oxygen environment. In this stage, the biomass undergoes pyrolysis, which is the thermal decomposition of organic materials in the absence of oxygen. This leads to the release of volatiles, which include gases like methane and carbon monoxide, as well as tar and char.

The primary gasification reactions occur in the presence of steam or a combination of O_2 and steam:

1. Steam Gasification: $C + H_2O \rightarrow CO + H_2$
2. Partial Oxidation: $C + 0.5\ O_2 \rightarrow CO$

These reactions generate a mixture of CO, H_2, CO_2, and traces of other gases. The syngas produced is rich in hydrogen and carbon monoxide.

The syngas may contain tar and particulate matter, which can be detrimental to downstream processes and equipment. Therefore, syngas is typically subjected to tar removal and cleaning processes. After cleaning, the hot syngas is cooled and conditioned to the desired temperature and pressure, making it suitable for various applications.

Hydrogen can be separated from the syngas using various methods, such as pressure swing adsorption (PSA), membrane separation, or water-gas shift reactions. These processes increase the hydrogen purity and concentration. The purified hydrogen is compressed to the desired pressure and can be stored for later use or transported to its intended application.

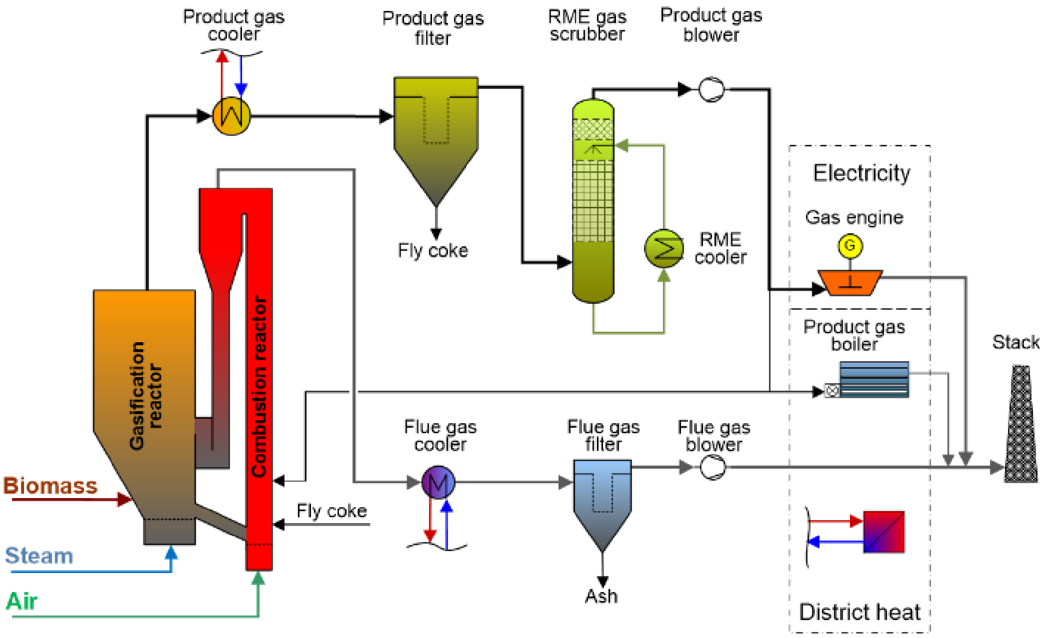

Figure 3. Flowchart of a commercial biomass gasification plant [3]

The environmental impact of biomass gasification is generally considered more favourable than fossil fuel-based processes due to the carbon-neutral nature of biomass feedstocks. However, it's essential to consider the full life cycle of emissions associated with biomass gasification, including both direct and indirect sources:

- **Direct Emissions:** The direct emissions from biomass gasification primarily involve the release of CO_2 and small amounts of CH_4 during the gasification process. While CO_2 is emitted, it is considered carbon-neutral because the carbon dioxide released is part of the natural carbon cycle, as the carbon was initially absorbed by the biomass during its growth. The emissions from methane are typically low in comparison to other methane sources.
- **Indirect Emissions:** Indirect emissions stem from the entire lifecycle of the biomass, including its cultivation, harvesting, transportation, and processing. These emissions depend on factors such as land use practices, energy requirements for biomass production, and the carbon intensity of transportation fuels used. However, these indirect emissions are generally lower than the emissions from fossil fuel-based processes.

Overall, the net greenhouse gas emissions associated with biomass gasification are typically lower than those from fossil fuel-based alternatives. The key to reducing emissions further lies in sustainable biomass management, utilizing efficient gasification technologies, and considering the entire life cycle of the biomass feedstock to ensure a carbon-neutral or even carbon-negative outcome.

2.4. Coal Gasification

Coal gasification is a thermochemical process used to convert coal into a mixture of gases, including H_2, CO, CO_2 and other by-products. Here is an overview of the coal gasification process for hydrogen production:

Before entering the gasification reactor, coal undergoes preparation to remove impurities and reduce its moisture content. This typically involves crushing and sizing the coal. The prepared coal is then introduced into a gasification reactor, which operates at high temperatures (typically between 700°C and 1,600°C) and under controlled conditions. The reactor can take various forms, such as fixed-bed, fluidized-bed, or entrained-flow gasifiers. Inside the gasification reactor, coal is subjected to pyrolysis, a process where it is heated in an oxygen-starved environment, leading to the release of volatile gases, tars, and char. Combustion reactions may also occur simultaneously, providing the necessary heat for gasification reactions.

The char and tars produced during pyrolysis react with steam and, in some cases, O_2 or air (containing O_2) to produce syngas, which is a mixture of hydrogen and carbon monoxide. The primary reactions include:

- Carbon gasification: $C + H_2O \rightarrow CO + H_2$
- Water-gas shift (WGS) reaction: $CO + H_2O \rightarrow CO_2 + H_2$

The raw syngas contains impurities, including particulate matter, sulphur compounds, and trace metals. Various gas clean-up processes, such as tar removal, desulfurization, and particulate removal, are employed to purify the syngas. The purified syngas is cooled to remove excess heat and conditioned to the desired temperature and pressure for downstream processes.

The final step involves the separation of hydrogen from the syngas. This can be achieved using methods like pressure swing adsorption, membrane separation, or water-gas shift reactions to obtain high-purity hydrogen.

The coal gasification process generates GHG emissions, primarily in the form of CO_2 and, to a lesser extent, CH_4. These emissions can be categorized as follows:

- **CO_2:** Coal gasification releases CO_2 as a by-product during both the combustion and gasification stages. While this CO_2 is often considered part of the natural carbon cycle since it was originally absorbed by the coal during its formation, coal gasification can result in higher CO_2 emissions per unit of energy compared to cleaner energy sources.
- **CH_4:** Some methane emissions may occur during coal gasification, particularly if the coal contains methane-bearing formations. Methane is a potent greenhouse gas, and its release can contribute to GHG emissions.
- **CO:** Carbon monoxide is produced during the gasification reactions, and it can be further oxidized to CO_2. While not a major GHG, it plays a role in overall emissions.

The net GHG emissions associated with coal gasification depend on various factors, including the efficiency of the gasification process, the carbon content of the coal, and the extent of CCS technologies applied. To reduce the environmental impact, efforts are focused on improving gasification efficiency and implementing CCS to capture and sequester CO_2 emissions, making coal gasification a potentially cleaner option for hydrogen production in the context of a low-carbon energy future.

2.5. Comparison of the carbon footprint of H_2 produced by different routes

According to the International Energy Agency, hydrogen production in 2024 is still largely dependent on unabated fossil fuels. The unabated natural gas route accounts for around two-thirds of total production continuing the trend of recent years. On the other hand, low-emissions hydrogen production has grown marginally over the past 2 years and remains under 1 Mtpa H_2 – accounting for less than 1% of global production (Figure 4) [4].

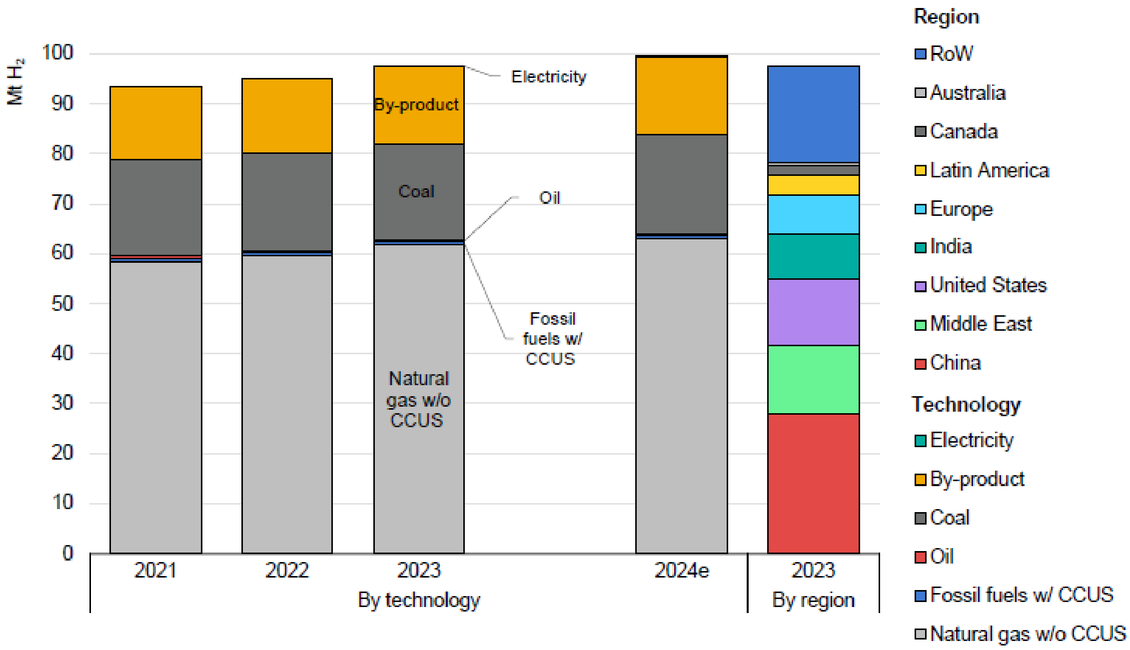

Figure 4. Hydrogen production by technology and by region, 2021-2024 [4]

In this global context, it is important to know the impacts associated with the main H_2 production routes in order to define the benchmarking scenario with which to compare the results of the green H_2 produced in the REFHYNE 2 project. To this end, we have carried out a literature review to study the studies performed by other authors on different H_2 production processes and compare with each other.

In this regard, there are numerous studies in the literature that analyse the emissions generated in natural gas reforming processes (SMR process), which is the most extent production route. In these studies, it has been found that the GHG footprint of each kg of generated fossil H_2 is around 11.5 $kgCO_2$ /kgH_2 [5], [6], [7], [8]. This result, which seems to be widely accepted by the scientific community as an average value, differs from the value available in the EcoInvent database [9], which is also the most common source used by LCA teams. Among others, some authors such as Chen and Lam [10], estimated in their paper the impacts attributable to grey hydrogen from the process named "*Hydrogen, gaseous (GLO) market for*" in the EcoInvent 3.6 database, to which they add the impact of the electricity needed to compress the H_2 and the impacts of transport. The result obtained is that the production of each kg of H_2 generates around 2 kg CO_2 eq, which, for other authors, such as de Kleijne et al. [6], is an erroneous result. In fact, these authors states in their paper that "*The use of this EcoInvent value in LCA studies has led to incorrectly low GHG footprints*". Reliable methane emissions inventories are critical to establish baselines, define targets and track progress. National emission inventories are known to underestimate these emissions, but other efforts in recent years have made progress in closing this gap.

Some authors, such as Timmerberg et al. [11], also compared the GHG emissions associated with different hydrogen production routes in their study (Figure 5). As a conclusion, the highest and the smallest GHG emissions are related to electrolysis, depending on the GHG intensive electricity source. The second lowest GHG emissions arise for hydrogen produced from methane decomposition with renewable electricity in plasma systems and SMR including CO_2 capture and storage. Finally, GHG emissions of hydrogen from SMR and remaining methane decomposition system configurations are in a range between 11 and 14 kg CO_2eq/kg H_2. A similar conclusion can be drawn from the results published by the International Energy Agency in a report published in 2024 [4] (Figure 6). Hydrogen produced by electrolysis can have virtually neutral associated emissions if the electricity mix used is of renewable origin. Due to the conversion efficiency of the electrolysis process, every 100 g CO_2/kWh associated with electricity supply results in nearly 5 kg CO_2-eq/kg H_2 in hydrogen production [4].

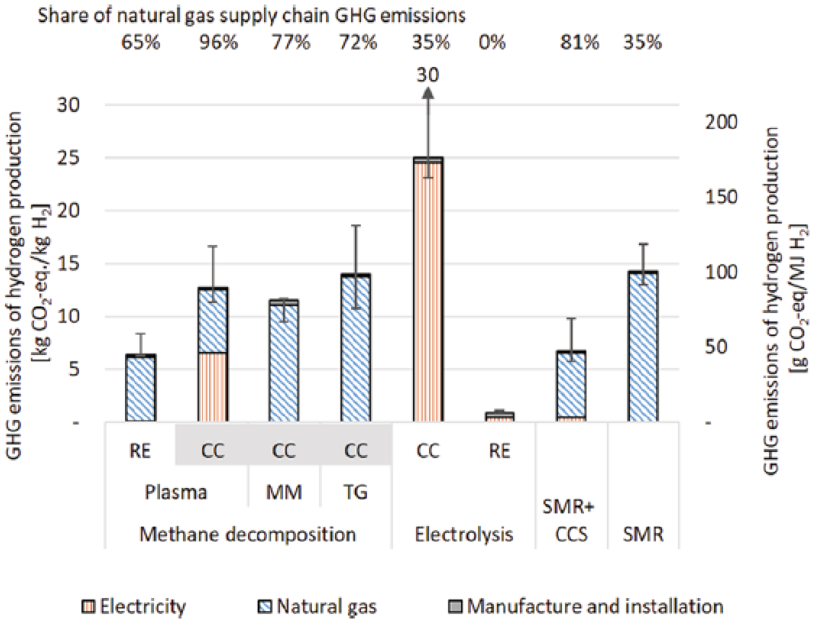

Figure 5. GHG emissions estimation of hydrogen production. Grey background indicates methane decomposition systems using natural gas as basis for process energy; electricity from combined cycle power plants (CC) or renewable energy (RE); methane decomposition in molten metal (MM) and thermal gas (TG) system; steam methane reforming (SMR) without or with CO_2 capture and storage (+CCS)) [11]

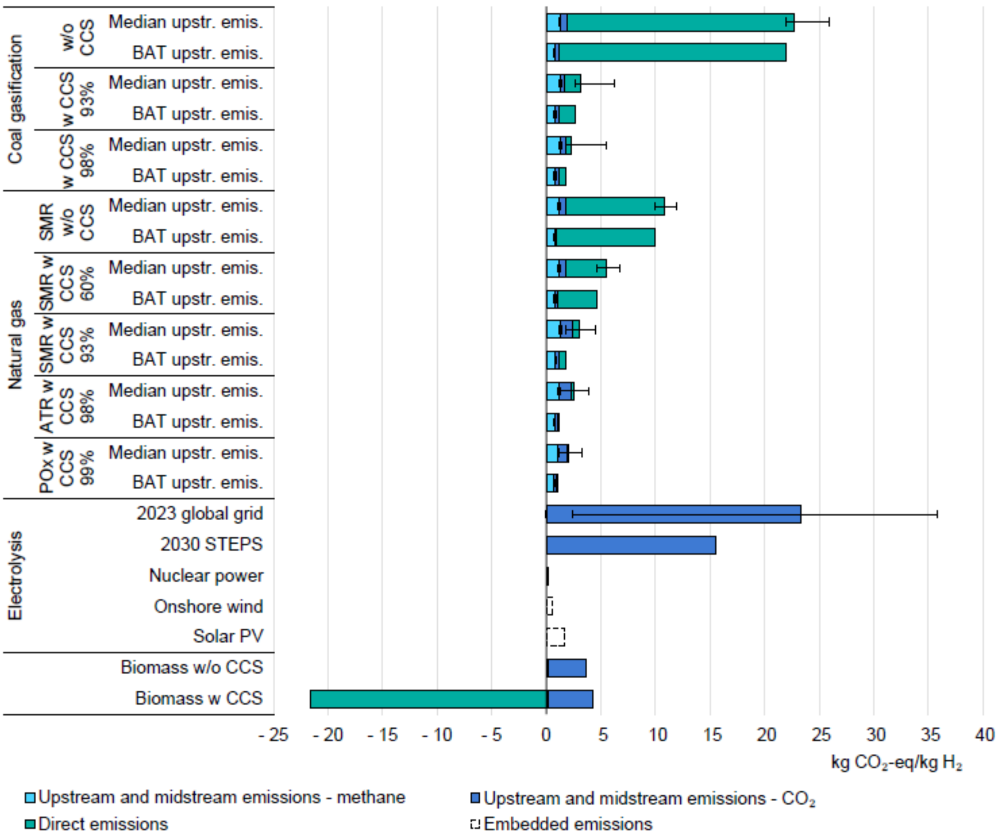

Figure 6. Comparison of the emissions intensity of different hydrogen production routes, 2022 [4]

In the same line, Cho at al. [12] presented in their publication the emissions of the major pollutants emitted from 33 SMR hydrogen production facilities. The average GHG emissions of all these processes were 9.35 kg CO_2eq/kg H_2. They concluded that although the adoption of carbon capture and storage (CCS) to SMR facilities exhibits positive impact reductions by capturing CO_2 from flue gas, additional energy requirement and corresponding operating costs are other factors that need to be considered. However, it has been reported that overall CO_2 emissions from natural gas SMR systems decrease by about 90% when implementing CCS when compared with SMR systems without CCS [13].

For these reasons, and taking into account all of the above, for this project, we have decided to take the value **of 11.5 kgCO_2 / kgH_2 as the reference value for the SMR process for H_2 production**. This data will be used in the future to determine how much emissions have been reduced with the project technology compared to the conventional process currently used at the Shell Energy and Chemicals Park Rheinland.

Regarding the emissions involved in the processes of green H_2 production, it has been found in the literature that the environmental footprint of H_2 can change considerably from one study to another depending on the origin of the electricity used to carry out the electrolysis. Among the many existing studies, the one published by de Kleijne et al. [6] has been selected because it has been published recently and allows an accurate comparison with the results obtained so far in this deliverable. As part of its publication, Figure 7 shows the GHG footprint of green hydrogen produced with different renewables (wind or solar) and current (2020) and future (2030) average grid electricity, based on the life-cycle inventory published in [14]. Besides, different approaches are considered depending on how the oxygen produced is treated. Typically, oxygen that is co-produced in water electrolysis is vented to air and all the process emissions are attributed to the produced H_2. However, the oxygen could also be purified for use in a downstream process. On the one hand, when using a "system scale-up by substitution" approach, it is assumed that the co-produced oxygen replaces conventional oxygen production by air separation elsewhere. On the other hand, the economic approach allocates the process emissions according to the economic value of the hydrogen and oxygen produced.

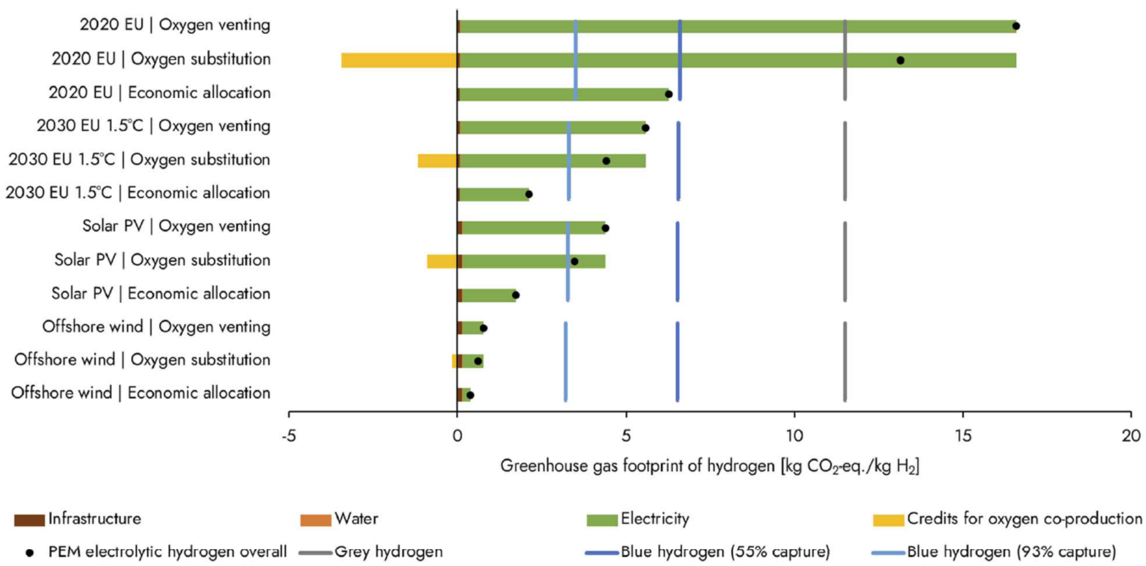

Figure 7. The greenhouse gas footprint of PEM electrolytic hydrogen for different electricity sources and multi-functionality approaches in kg CO_2-eq per kg H_2 [6]

From this study, it was obtained that hydrogen powered by wind energy presents a GHG footprint of 0.4-0.8 kg CO_2eq/kg H_2. On the other hand, using solar PV for hydrogen production generates 1.7-4.4 kgCO_2eq/ kg H_2, which is approximately five times larger compared to wind-based hydrogen. This fact is due to the higher capacity factor of wind turbines, their lower material and manufacturing emissions per kWh and their shorter energy payback time over their operational lifespan.

Finally, using the 2020 EU grid mix, electrolytic hydrogen has a GHG footprint of 6.3–16.6 $kgCO_2$-eq / kg H_2, which is in most cases higher than grey hydrogen. Finally, it is expected that in the future a cleaner 2030 grid mix (compatible with the EU targets for limiting warming to 1.5 ^oC) results in a lower, but still sizable GHG footprint (2.1–5.6 $kgCO_2eq$ / kg H_2) [6]. This study is in line with other results published by different authors [15], [16], [17], [18], [19]. In addition, the general conclusion from these studies is that PEM electrolysis technology generates lower emissions than alkaline electrolysis due to higher efficiencies.

Finally, regarding the remaining routes to produce H_2, production from coal using gasification is specialty relevant in China, although it accounts for a small share of overall production. Hydrogen production using coal produces CO_2 emissions of about 19 $kgCO_2$ /kgH_2, which is twice as much as natural gas [1]. On the other hand, technologies to produce Hydrogen from biomass are not yet fully developed, and they are generally a more expensive way of producing low-carbon hydrogen than solar- or wind-based electrolysis.

As a conclusion to this brief literature review, it has been found that the origin of the electricity used in the electrolysis process can significantly influence the results obtained. Routes like electrolysis with renewable energy or biomass gasification with sustainable feedstocks tend to have lower or even carbon-neutral footprints, while SMR and coal gasification can have higher footprints but can be reduced with carbon capture and storage technologies. The choice of production method and the carbon intensity of the energy source are critical factors in determining the carbon footprint of hydrogen. Furthermore, most authors agree that electrolysis powered by electricity from wind farms is one of the most promising options and that it may generate the greatest environmental benefit in the future decarbonisation.

3. GHG emissions avoidance in H_2 applications

Hydrogen, the lightest and most abundant element in the universe, has captivated scientists, engineers and innovators with its wide range of applications in various industries. From its role as a clean and efficient energy carrier in transportation and power generation to its use in industrial processes, hydrogen's versatility has positioned it at the forefront of efforts to address pressing global challenges, such as reducing carbon emissions, enhancing energy security, and advancing sustainable technologies.

In this sense, the following paragraphs explore the multifaceted and ever-expanding uses of hydrogen across different sectors, highlighting its key role in shaping a more sustainable and technologically advanced future.

3.1. Use of H_2 for transportation

The use of hydrogen for transportation, particularly in the form of fuel cell vehicles (FCVs) and hydrogen-powered vehicles, offers several advantages and has the potential to significantly reduce greenhouse gas emissions and air pollutants. Below are some of the advantages of H_2 as a fuel for different types of vehicles.

Fuel Cell Vehicles: FCVs use hydrogen as a fuel source to generate electricity through a chemical reaction in the fuel cell stack. This electricity is then used to power electric motors, propelling the vehicle. FCVs have the following benefits:

- Zero Emissions. FCVs emit only water vapor and heat as by-products, making them environmentally friendly and reducing greenhouse gas emissions.
- Longer Range. Hydrogen-powered vehicles typically have a longer driving range compared to battery electric vehicles (BEVs), making them suitable for long-distance travel.
- Fast Refuelling. Refuelling a hydrogen vehicle takes only a few minutes, similar to refuelling a gasoline vehicle, as opposed to the longer charging times of BEVs.

Besides, public transit agencies and municipalities have adopted hydrogen fuel cell technology for uses. Hydrogen-powered buses are quiet, produce zero tailpipe emissions and have longer ranges compared to conventional diesel buses.

Hydrogen Trains: Some regions are exploring the use of hydrogen fuel cells to electrify trains. These trains use hydrogen fuel cells to generate electricity for electric motors, eliminating the need for overhead catenary wires. Hydrogen-powered trains offer the advantage of zero emissions, particularly in areas where electrification is challenging.

Hydrogen Aircraft: Researchers and aerospace companies are exploring the potential of hydrogen as a fuel source for aircraft. Hydrogen can be used in fuel cells to power electric propulsion systems, which could lead to quieter and more environmentally friendly air travel.

Marine Transport: Hydrogen can be used in fuel cells to power ship propulsion systems, reducing emissions and pollution in maritime transportation.

Material Handling Vehicles: Hydrogen fuel cells are used in forklifts and material handling equipment in warehouses and industrial settings. These fuel cell-powered forklifts offer longer runtimes and faster refueling compared to battery-powered counterparts.

Bicycles and Scooters: Some prototypes and experimental hydrogen-powered bicycles and scooters have been developed as eco-friendly alternatives for short-distance urban transportation.

Emergency Vehicles: Hydrogen fuel cell technology is being explored for use in emergency vehicles such as fire trucks and ambulances. These vehicles can operate quietly and without emissions, even during critical response situations.

3.2. Use of H_2 for industrial processes

Hydrogen stands as a cornerstone in the field of industrial processes, offering multifaceted applications that span numerous sectors, fundamentally shaping the production of a wide range of materials and chemicals. In the chemical industry, hydrogen serves as a foundational feedstock, underpinning the synthesis of ammonia, a vital component of fertilizers, and methanol, a key precursor to various chemicals and plastics. The versatility of hydrogen is evident in its role as a reducing agent, instrumental in industries such as metallurgy. Here, it contributes to ore reduction and heat treatment processes, aiding in the production of metals like iron and steel, while also enhancing the mechanical properties of various alloys.

Hydrogen's presence extends seamlessly into the high-tech world of electronics manufacturing. Within semiconductor fabrication, hydrogen plays a pivotal role in processes like Chemical Vapor Deposition (CVD) and Atomic Layer Deposition (ALD). By facilitating the deposition of thin films of materials like silicon onto semiconductor substrates, it lays the foundation for the production of microchips and advanced electronic components that power our modern technology-driven world.

Hydrogen is not limited to these sectors alone; it extends its influence into the energy realm as well. Within the field of oil refining, hydrogen is deployed to remove impurities and sulphur compounds from hydrocarbon feedstocks. Moreover, the glass industry benefits from the unique properties of hydrogen. It prevents oxidation during the production of high-quality glass products and can be employed to enhance energy efficiency during the glass-melting process.

Finally, hydrogen finds application in industrial vehicles, particularly forklifts, and material handling equipment. Fuel cell-powered forklifts are gaining popularity in warehouses and industrial settings, offering extended runtimes and faster refuelling compared to their battery-powered counterparts. This enhances efficiency and productivity within industrial operations.

In an era marked by a growing emphasis on sustainability and a reduced environmental footprint, hydrogen emerges as an indispensable asset in optimizing industrial processes. When produced using clean and renewable methods or through carbon capture and utilization technologies, hydrogen offers a pathway to cleaner, more efficient, and environmentally responsible industrial practices, ensuring that industries meet their production needs while simultaneously minimizing their impact on the environment.

3.3. Use of H_2 for Energy Storage

Hydrogen has emerged as a promising energy storage solution that addresses some of the key challenges in our transition towards a more sustainable and renewable energy landscape. Its use as an energy carrier and storage medium is gaining significant attention due to its unique attributes. Hydrogen can store excess energy generated from intermittent renewable sources, such as solar and wind, allowing us to balance supply and demand in the energy grid effectively. This ability to store energy for extended periods is particularly advantageous, as it helps overcome the variability and intermittency associated with renewable energy generation.

One of the key advantages of hydrogen as an energy storage medium lies in its high energy density, making it suitable for both large-scale and long-duration energy storage applications. It can store energy in significant quantities and over extended periods, addressing the challenge of matching energy production with consumption. Furthermore, hydrogen's flexibility extends to various energy conversion pathways. It can be used for power generation through fuel cells, providing clean and efficient electricity, or it can be reconverted into electricity and heat through combustion or gas turbines as needed.

Hydrogen's role in energy storage also contributes to grid stability and resilience. By storing excess renewable energy during periods of low demand and releasing it when demand is high, hydrogen can help mitigate the need for fossil fuel-based peaker plants, reducing emissions and enhancing the reliability of the power grid.

3.4. Potential of H_2 to reduce GHG emissions in different applications

The significance of the clean hydrogen production method, whether it's green (using renewable electricity and water) or blue (utilizing steam methane reforming with carbon capture, utilization, and storage), plays a crucial role in determining the extent of climate advantages, as depicted in Figure 8. While emissions associated with green hydrogen may have a discernible climate impact that is not entirely climate-neutral across all timeframes, the cumulative radiative effect remains lower than that of fossil fuels. This translates to a reduction in global warming when opting for green hydrogen alternatives. Conversely, the climate impact of blue hydrogen can vary, depending on factors such as leakage rates and the time horizon considered.

For instance, over a 100-year timeframe, worst-case scenarios involving high leakage rates result in a doubling of the climate impact of blue hydrogen compared to green hydrogen. Remarkably, the most unfavorable outcomes for green hydrogen are approximately equivalent to the best-case scenarios for blue hydrogen across all timeframes. This equates to approximately a 65% reduction in the warming impact from fossil fuel CO_2 emissions over a 10-year period and an 85% reduction over a 100-year period [20].

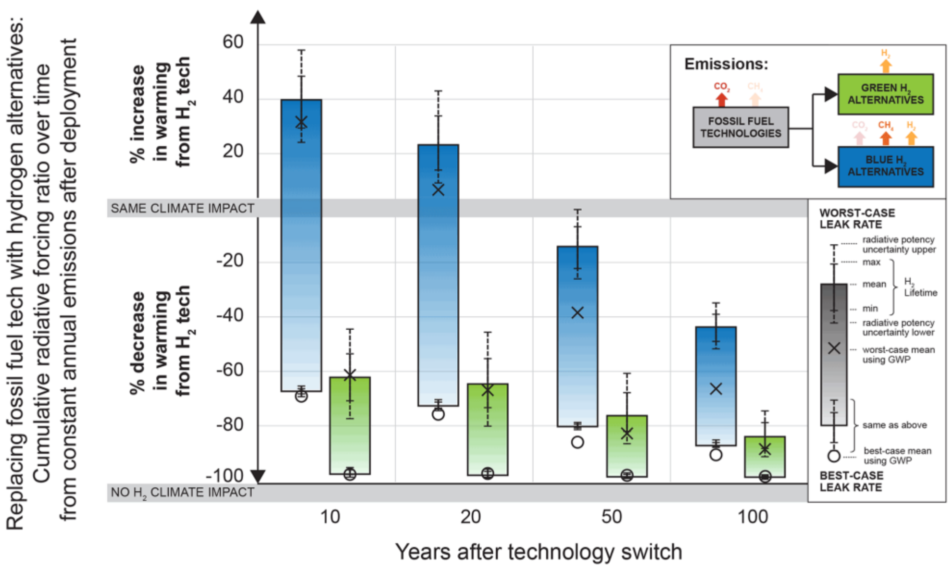

Figure 8. Relative warming impact over time from replacing fossil fuel technologies with green or blue hydrogen alternatives for a generic case [20]

Focusing the study on the transport sector, FCEVs are, together with BEVs, the only vehicles with no exhaust emissions and thus offer the potential to drastically reduce local air pollution, especially in cities. They can also dramatically reduce CO_2 emissions when low-carbon hydrogen is used. Furthermore, hydrogen has some attractive attributes compared to biofuels as it does not generally face resource constraints or competition for land use.

The theoretical potential for future use of hydrogen in road transport is very large. Any road transport mode can technically be powered using hydrogen, either directly using fuel cells or via hydrogen-based fuels in internal combustion engines.

Fossil fuel-powered vehicles burn gasoline or diesel, releasing CO_2, NOx, particulate matter and other pollutants. However, Hydrogen FCVs use a fuel cell to generate electricity from hydrogen, which then powers electric motors. The only tailpipe emissions are water vapor. Regarding the GHG emissions, fossil fuel-powered vehicles are responsible for significant GHG emissions, primarily in the form of CO_2. The exact emissions depend on factors like fuel efficiency, driving habits, and the emissions standards of the vehicle. In the case of the FCV, if hydrogen is produced using renewable energy sources like wind or solar power through electrolysis, the GHG emissions from well to wheel can be very low, approaching zero. Besides in terms of efficiency, internal combustion engines in fossil fuel-powered vehicles are typically less efficient than fuel cell vehicles or electric vehicles, which use hydrogen as an energy source, converting a higher percentage of the energy in hydrogen into vehicle movement.

According to data published by the European Commission in the “JEC Well-To-Wheels report” [21], the use of electricity and hydrogen in the transport sector is determined, in terms of GHG emission savings, by the electricity production pathway. Their use can lead to either an increase or a reduction of emissions compared to the baseline depending on the source of electricity used for this purpose. Therefore, the use of hydrogen fuel cells may not lead to any advantages if the electricity used is not from carbon neutral sources. Among the studies published in the literature on the subject, it is stated that using green hydrogen to power city buses in place of diesel reduces well-to-wheels CO_2 emissions by 33.39 kg per kilogram of hydrogen. When replacing gasoline in cars, the reduction is 28.99 kg per kilogram of hydrogen. Additionally, substituting green hydrogen for grey hydrogen derived from natural gas in refineries lowers CO_2 emissions by 21.74 kg for every kilogram of hydrogen replaced [22].

Greening the EU grid mix indeed helps also in greening the road sector, but not necessary with a proportional correlation. As a result Figure 9 shows the GHG emissions per km travelled by an FCEV depending on the production method of the H_2 consumed. Except in case of electrolysis using coal electricity with downstream hydrogen liquefaction, FCEV show lower GHG emissions than the conventional diesel ICE (100% fossil).

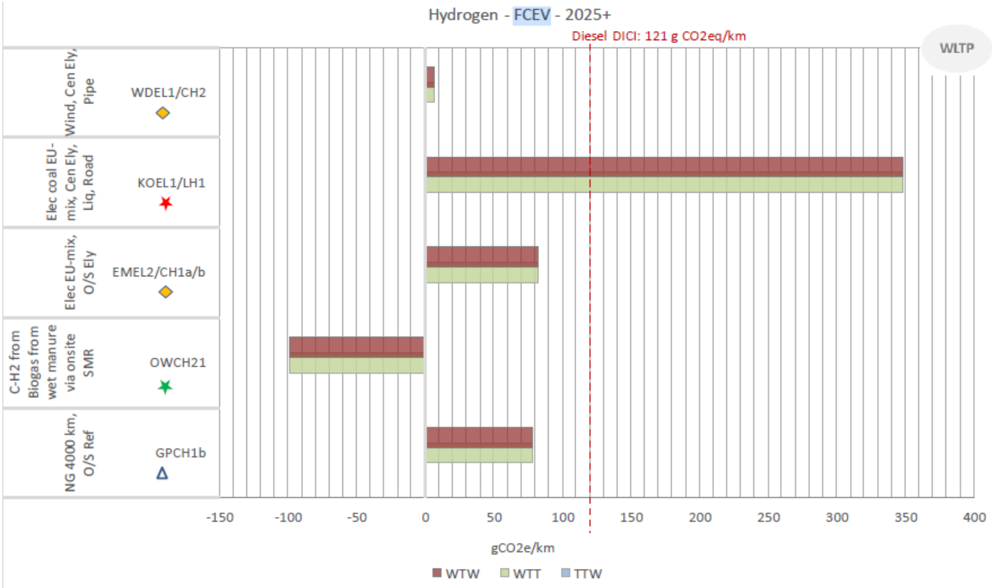

Figure 9. PHEV - GHG emissions (g CO_2eq/km) [[21]

4. Methodology to be applied in this project

4.1. Review of specific methodologies for quantifying GHGs in H_2 production processes

Reviewing existing methodologies for quantifying GHG emissions in H_2 production processes is a crucial step in assessing the environmental impact of different hydrogen production methods and making informed decisions regarding their sustainability.

Over the past three years, numerous certification schemes and regulations have been introduced, each employing different boundaries, production methods, definitions, emissions thresholds, and methodologies for various products (Figure 10). However, the past year has shown promising signs of alignment. The International Organization for Standardization (ISO) recently published a Technical Specification for the hydrogen supply chain, covering the entire process from production to consumption [23]. This serves as a foundation for ISO standards expected to be released within the next two years. On a multilateral level, the COP 28 Declaration of Intent on the mutual recognition of certification schemes reflects a strong commitment to establishing common standards. Similarly, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) Hydrogen Certification Mechanisms (H2CM) Task Force represents another global initiative aimed at analysing existing certification mechanisms and fostering consensus and mutual recognition across different schemes [24].

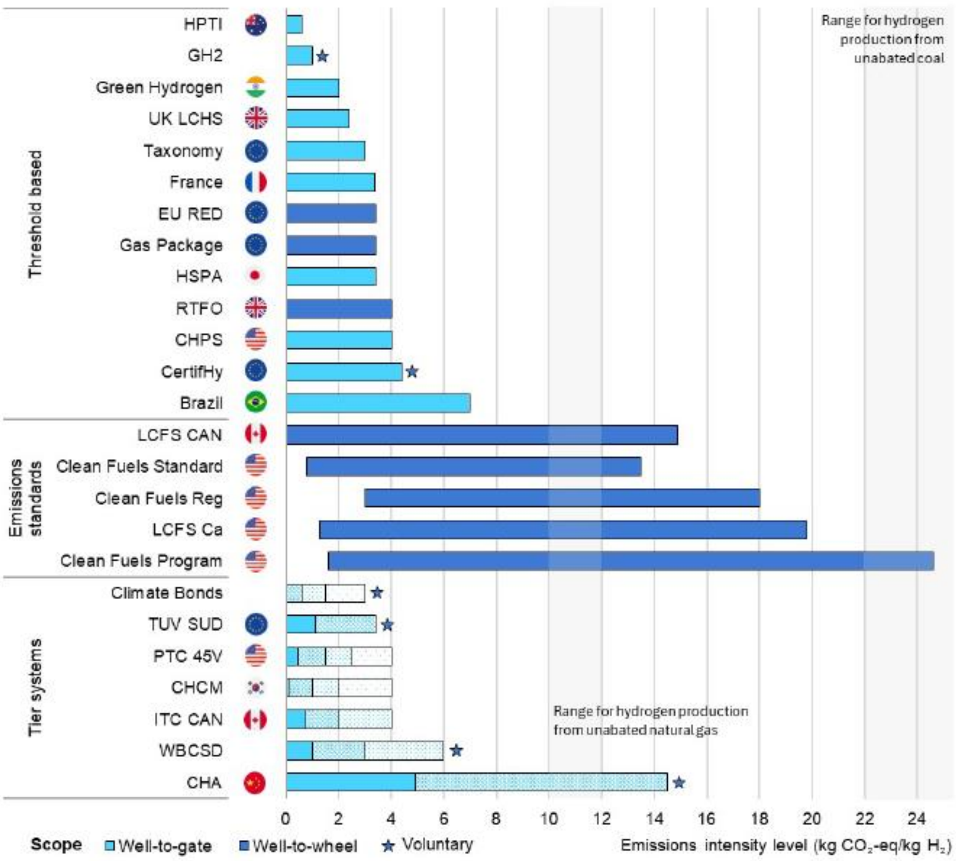

Figure 10. Emissions intensity level of certification schemes and regulatory frameworks for hydrogen and/or derivatives by scope and type of scheme [4]

Here's an overview of some common European methodologies and approaches used for this purpose.

4.1.1. RED II

The Renewable Energy Directive (RED II) [25] is a European Union directive that sets sustainability criteria for bioenergy and renewable energy sources, including hydrogen production. For the H_2 case, the methodology considers the entire life cycle of hydrogen production, including feedstock extraction, transportation, conversion processes, and distribution. It emphasizes the use of renewable energy sources and low-carbon technologies in hydrogen production to minimize carbon emissions. The RED II methodology also encourages the development of hydrogen from renewable sources, such as electrolysis using renewable electricity, and sets criteria for the calculation and reporting of greenhouse gas emissions associated with hydrogen production. Overall, it promotes a more sustainable and environmentally friendly approach to hydrogen production, aligning with the European Union's efforts to reduce carbon emissions and transition towards a greener energy future.

Here's a summary of the most significant aspects of the RED II methodology for evaluating GHG emissions from H_2 production processes:

- The RED II methodology encompasses all stages of the hydrogen production process, from feedstock extraction to distribution. This includes the sourcing of raw materials, transportation, conversion processes, and the distribution of hydrogen.
- RED II, consistent with other sustainability directives and standards, often relies on LCA as a key methodology to evaluate GHG emissions.
- RED II promotes the adoption of low-carbon technologies in hydrogen production, such as electrolysis using renewable electricity or carbon capture and storage to mitigate greenhouse gas emissions.
- It promotes the adoption of low-carbon technologies in hydrogen production, such as electrolysis using renewable electricity or carbon capture and storage (CCS) to mitigate greenhouse gas emissions.
- The methodology encourages the development of renewable hydrogen, produced through electrolysis using renewable electricity. This approach ensures that hydrogen is produced with minimal carbon emissions.
- It aligns with broader sustainability standards and goals, aiming to reduce carbon emissions and transition to a greener energy future in line with the European Union's commitments.
- The methodology establishes reporting requirements for hydrogen producers, ensuring transparency and accountability in tracking carbon emissions throughout the production process.
- RED II may offer incentives or preferential treatment for hydrogen produced using renewable energy and low-carbon technologies, thereby promoting the transition towards greener hydrogen.

As a conclusion, the RED II methodology provides a comprehensive framework for calculating the carbon footprint of hydrogen production processes, prioritizing the use of renewable energy sources, low-carbon technologies, and transparent reporting to reduce the environmental impact of hydrogen production.

4.1.2. ISCC – Certification scheme

The International Sustainability and Carbon Certification (ISCC) [26] is a globally recognized certification scheme designed to ensure the sustainability, traceability, and GHG emissions reduction of biomass, bioenergy, and renewable fuels, including renewable and low-carbon hydrogen. While ISCC covers various feedstocks and production pathways, it provides a robust methodology for assessing and verifying the sustainability attributes and carbon intensity of hydrogen production.

In the context of hydrogen, ISCC certification is aimed at demonstrating compliance with environmental, social, and climate-related criteria, particularly those aligned with the EU Renewable Energy Directive (RED II), voluntary carbon markets, and other emerging regulatory frameworks. ISCC is an approved voluntary scheme for certifying RFNBOs under RED II [27]. The certification process under ISCC ensures that hydrogen producers can validate the renewable origin of the electricity used in electrolysis and accurately quantify the GHG emissions savings compared to conventional fossil-based hydrogen.

The following outlines the general procedure under the ISCC framework for the certification of renewable hydrogen and the evaluation of GHG emissions:

1. Eligibility Assessment: Determination of whether the hydrogen production facility meets ISCC eligibility criteria. This includes the use of renewable energy sources, compliance with sustainability principles (e.g., land use, biodiversity), and a minimum GHG emissions saving threshold compared to the fossil fuel comparator defined in RED II.
2. Engagement with ISCC System: The certification process is initiated through registration with the ISCC system and engagement with an ISCC-recognized certification body.
3. Data Collection and Documentation: Preparation of detailed documentation on the hydrogen production process, including input feedstocks (e.g., water), energy sources (e.g., grid or PPA-based renewable electricity), process emissions, auxiliary energy consumption, and any carbon mitigation measures (e.g., oxygen valorization or waste heat integration).
4. GHG Emissions Calculation: Calculation of the carbon footprint of the hydrogen produced, typically expressed in gCO_2eq/MJ, following the ISCC 205 GHG Emissions Calculation Methodology and LCA-based approaches.
5. Audit and Verification: An independent third-party auditor conducts an on-site audit to verify the accuracy of the reported data, the traceability of the energy and material inputs, and the compliance with ISCC sustainability and GHG criteria.
6. Certification Decision: Upon successful completion of the audit and compliance with all ISCC requirements, the certification body issues an ISCC certificate for the hydrogen production facility. This certificate attests to the sustainability, traceability, and verified GHG performance of the hydrogen produced.
7. Continuous Monitoring and Recertification: Certification is valid for a defined period (typically 12 months), after which the facility must undergo re-auditing to maintain certification status. This ensures continued compliance and accuracy of emissions reporting over time.

For each hydrogen production pathway (e.g., electrolysis, SMR with CCS), ISCC provides tailored guidance for the application of its methodology, including feedstock classification, energy input validation, and GHG allocation procedures. The relevant documentation, such as the ISCC 205 document, outlines the GHG calculation rules and emission factors to be applied [28].

All these specifications, as outlined in the ISCC EU documentation—particularly ISCC 205 and ISCC 205-1—will be taken into consideration in the GHG emission study conducted in this project. This methodology will serve as the basis for evaluating the environmental performance of hydrogen production within the REFHYNE 2 project and to supports future certification of the hydrogen produced as a sustainable, low-carbon fuel under the ISCC EU voluntary scheme.

4.1.3. ISO 19870:2023

ISO/TS 19870:2023, titled "Hydrogen technologies — Methodology for determining the greenhouse gas emissions associated with the production, conditioning and transport of hydrogen to consumption gate," is a technical specification developed by the International Organization for Standardization. This document provides a standardized methodology for assessing the GHG emissions throughout the hydrogen value chain, encompassing stages from raw material extraction to the point of consumption (Figure 11).

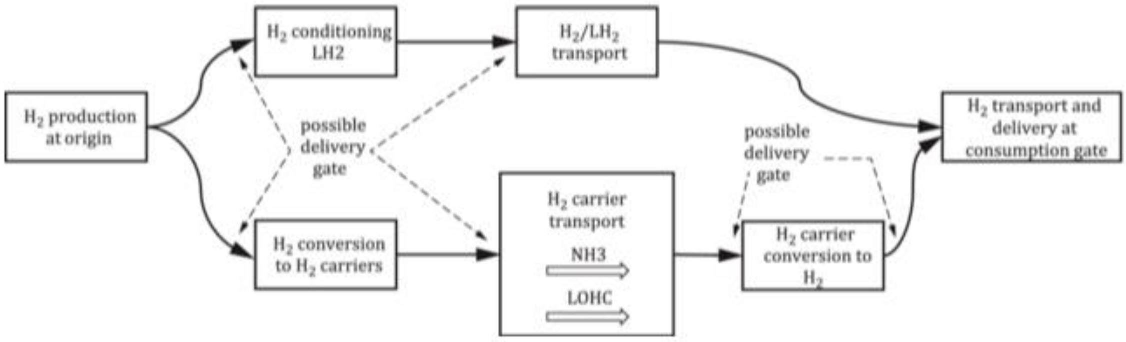

Figure 11. Examples of hydrogen supply chain [23]

The main objective of this international standard is to harmonise the assessment of GHG emissions associated with hydrogen production, conditioning and transport and to establish a common methodological framework to facilitate transparency and comparability between different hydrogen production routes and technologies. Such standardisation is crucial to enable stakeholders to make informed decisions on the environmental impact of hydrogen as an energy carrier.

ISO/TS 19870:2023 outlines a comprehensive LCA approach, covering all stages of the hydrogen supply chain under a cradle-to-gate approach. This approach includes:

- **Feedstock Acquisition:** Covers extraction, harvesting, or collection of raw materials (e.g., natural gas, water, biomass), as well as transportation to the production site.
- **Hydrogen Production:** Emissions from the main production process (e.g., electrolysis, steam methane reforming (SMR), or biomass gasification), as well as energy and materials consumed during production and possible credits for carbon capture, utilization, and storage, if applicable.
- **Hydrogen Conditioning:** Emissions from compression, liquefaction, or purification of hydrogen to make it suitable for transport or storage.
- **Transportation and Storage:** Emissions from transporting hydrogen, including emissions from storage operations, such as energy used for maintaining cryogenic conditions for liquid hydrogen.

Besides, the standard divides emissions into the following categories: direct / indirect emissions, and upstream / downstream emissions, improving the comparability of results and considering the three scopes of a full carbon footprint analysis.

The specification was unveiled during COP28 in Dubai, underscoring its importance in the global effort to harmonize safety, interoperability, and sustainability standards across the hydrogen value chain.

4.2. Goal and scope definition for this project

4.2.1. Objective of this study

The main objective of the environmental assessment carried out in the framework of the task 9.3 of the REFHYNE 2 project is to calculate the carbon footprint associated with a novel electrolysis system designed for hydrogen production and compare the results with other production routes.

Hydrogen is primarily produced through steam methane reforming, which involves the use of natural gas, a fossil fuel, and releases substantial CO_2 emissions. Alternatively, electrolysis, the process of using electricity to split water into hydrogen and oxygen, has been considered a cleaner option when powered by renewable energy sources.

In this sense, the specific objectives of this study are as follows:

- To quantify the carbon footprint of the REFHYNE's electrolysis system for hydrogen production.
- To compare the carbon footprint of this innovative electrolysis system with conventional hydrogen production methods (e.g., steam methane reforming) to assess its environmental performance.
- To identify the key factors influencing the carbon footprint of the innovative electrolysis system, such as electricity source, materials used, and operational parameters.
- To provide recommendations for optimizing the REFHYNE 2 electrolysis system's environmental performance, based on the findings of the carbon footprint analysis.

In this deliverable, results have been obtained from the first data generated in the project (pre-construction) and some assumptions with a degree of uncertainty. Subsequently, in D9.5. the emissions will be calculated from the data obtained in the real tests carried out with this equipment (post-construction + operation).

4.2.2. Reasons for carrying out this study and intended applications

The reasons to undertake a comprehensive study to calculate the carbon footprint of the REFHYNE 2 electrolysis system for H_2 production is motivated by several compelling reasons.

Hydrogen is increasingly recognized as a clean and sustainable energy carrier, particularly for applications in transportation and industrial sectors. However, the environmental impact of hydrogen production methods, particularly in terms of carbon emissions, remains a critical concern. Innovative electrolysis systems under investigation aims to address these concerns by potentially providing a more environmentally friendly approach to H_2 production.

As the global community intensifies its efforts to transition towards sustainable and low-carbon energy sources, understanding the environmental impact of innovative technologies becomes crucial to continue progressing on the path of sustainability. For this reason, this study will demonstrate the environmental benefits of the REFHYNE 2 electrolyser system, and its great potential in the decarbonisation of the industrial sector.

4.2.3. Target audience

The status of this deliverable is public. Therefore, some sensitive input parameters are not revealed. In any case, all groups interested in the progress of the project will find valuable information in this report. This analysis also aims to inform the European Commission about the environmental impacts of technologies developed. Many of the results contained in these reports will be communicated to other interested stakeholders (from hydrogen technology providers, renewable energy providers or research institutes, to hydrogen end-users such as public authorities) through social media posts, research articles, newsletters, etc.

4.2.4. Functional Unit

The functional unit represents the specific quantity or functional output for which the GHG emissions and environmental impacts are assessed, and it must be consistent with the goal and the scope of the study.

In the context of the current study, the functional unit can be defined as the production of a specific amount of hydrogen gas, measured in a standardized unit such as kilograms (kg) or megawatt-hours (MWh) of hydrogen gas.

In this analysis, the study will focus on the 100 MW PEM electrolyser to be installed and operated at the Shell Energy and Chemicals Park Rheinland, (Germany). The electrolyser will be developed as part of the REFHYNE 2 project. Subsequently, once the GHG emissions associated with each kg of H_2 produced have been calculated, the avoided emissions will be analysed in D9.5 according to the different H_2 use cases scenarios addressed in the REFHYNE I case studies: H_2 for transport fuel, H_2 for mobility and H_2 for heating.

The first functional unit used this study is defined as **1 kg of hydrogen produced**.

4.2.5. System boundaries

The system boundaries (SB) define the specific stages and components of the hydrogen production and utilization process that are included in the assessment encompass all the processes necessary to provide the FU of the system. In other words, SB indicate what is and is not included in the analysis. In this case, and in line with the ISO 19870 requirements, the well-to-wheel approach has been applied (or cradle-to-gate approach), taking into account the entire life cycle of hydrogen, from the extraction of raw materials (e.g., water and electricity) to its end use in vehicles or other applications. Here's an explanation of the system boundaries for this study:

- **Well-to-Refinery:** This is the initial stage of the hydrogen production process. It encompasses all activities related to the extraction and transportation of raw materials required for hydrogen production. In the case of electrolysis, this would include the extraction of H_2O and the acquisition of electricity, typically from the grid.
- **Refinery-to-Hydrogen Production:** This stage focuses on the hydrogen production process. It includes all activities related to the operation of the electrolysis system, such as energy consumption, maintenance, and materials used in the system. GHG emissions associated with

the hydrogen production process, including any emissions from the production of materials and components, are accounted for in this stage.

- **Hydrogen Distribution:** After production, hydrogen needs to be transported to its point of use, which can involve compression, liquefaction, or other distribution methods. This stage considers the energy and emissions associated with hydrogen transportation, including compression, storage, and distribution infrastructure.
- **Hydrogen End Use:** This stage examines the emissions associated with the utilization of hydrogen in various applications, such as fuel cell vehicles or industrial processes. It includes the efficiency of the end-use technology and any emissions generated during hydrogen combustion or chemical reactions.
- **End-of-Life Considerations:** The end-of-life stage looks at the disposal or recycling of equipment and infrastructure used in the hydrogen production and distribution process. This includes considerations for the disposal of electrolysis equipment and other components.

Besides, some GHG accounting studies may consider carbon credits or offsets associated with the project. This involves accounting for any actions taken to reduce emissions elsewhere in the supply chain or through other projects.

By clearly defining these system boundaries, the GHG accounting study for the REFHYNE 2 project's electrolysis system provides a holistic assessment of the technology's environmental impact. For this reason, the complete life cycle will be considered in the analysis carried out in the next deliverable 9.5. This comprehensive approach ensures that decision-makers have a complete understanding of the greenhouse gas emissions associated with the technology and its potential contribution to reducing carbon emissions in the transportation and industrial sectors.

4.2.6. Cut-off criteria

The cut-off criteria specify the amount of material, energy flow or level of environmental significance associated with the product system that will be excluded from the study, being negligible to some extent. This must be defined clearly.

The cut-off criteria have been defined in accordance with PEF guidelines [29]. Only material inputs constituting all together less than 5% of the total mass of the components or processes within the scope can be excluded from the system boundaries, as long as the modelled flows account for at least 90% of the overall contribution to each of the environmental impact categories considered.

In this sense, to ensure a comprehensive analysis of the environmental performance of this technology, the material and energy inputs excluded from this analysis do not represent more than 3% of the cumulative mass of the core system. This cut-off criterion is in line with the recommendations given by the EC in the PEF methodology.

4.2.7. Allocation procedures

The allocation rules deal with multifunctionality and the impact categories that must be calculated during the impact evaluation phase later in the study. Allocation is the method used to distribute the environmental burdens and benefits among co-products or processes when multiple products are simultaneously produced within a system. In the context of H_2 production via electrolysis, various co-products may arise, including O_2 and potentially heat.

In the preliminary (and simplified) study carried out in this deliverable, hydrogen is assumed to be the only product of the electrolytic conversion of water, so all the impacts of the process are allocated to this stream. However, it is expected that the O_2 flow generated in the REFHYNE 2 electrolysis process will be also collected and stored. This way, if the co-produced oxygen is also used, the environmental performance of electrolytic hydrogen will improve. For this reason, in the next environmental studies performed in this project, the economic allocation method will be applied between these two co-products. This method considers the market value or price of each co-product to determine the allocation. For instance, if the market value of hydrogen is higher than that of oxygen, a larger share of the environmental impacts would be attributed to hydrogen production.

5. Preliminary analysis of GHG emissions generated by the project technology (pre-construction)

5.1. REFHYNE 2 electrolysis technology description.

The objective of the REFHYNE 2 project is to design and develop a 100 MW electrolysis system based on Proton Exchange Membrane Technology (PEM) that produces hydrogen and oxygen. To this aim, water is fed from the battery limit and is treated to achieve and maintain the required purity within the purification and polishing units. Both are realized as a common unit for 100 MW.

The description of the technology included in this report is based on a simplified description of the envisaged configuration of the final system. However, changes may occur during the implementation of the project. The analysis of the final system configuration will be detailed in deliverable D9.5, which will be published in the last phase of the project.

The electrolysis system is split in 10 x 10 MW parallel units. The produced hydrogen/water mixture is separated, treated in a deoxo-reactor to remove trace oxygen impurities and dried as one common unit before the hydrogen is sent to battery limit. The oxygen/water mixture is separated, and oxygen is vented to atmosphere.

The 10 MW electrolysis unit comprises one oxygen/water separator, one main water pump, one main heat exchanger and five PEM skids. The five sets of PEM skids of 2 MW each operate at the same level of electrical load. The main heat exchanger dissipates the heat generated by the overpotentials in the electrolysis stacks. Depending on the electrical load, water can partially bypass the heat exchanger. The main water pump is frequency controlled and compensates for load-dependent pressure losses within the system. To initiate and sustain the electrolysis reaction, a continuous supply of electrical energy in the form of direct current to the PEM stacks is necessary. For this purpose, the five PEM stack skids share a power supply unit (PSU) consisting of a common transformer and five rectifiers, one per PEM skid.

A hydraulic compression system ensures the tightness of the electrolysis stacks and a good electrical contact within the stacks. A high-pressure hydraulic fluid is applied at two pressure levels, a hydraulic cylinder below the stacks supplies the compression to seal the exterior stack. Several hydraulic pistons inside the stack end plate optimise electrical contact inside the stack. Each PEM skid shares one hydraulic system. Utilities such as cooling water, instrument air, nitrogen and vent unit are also part of the plant.

5.2. Data inventory based on estimates and simulations carried out in this phase of the project.

In order to estimate the GHG emissions associated with the electrolysis technology described above, **an approximation of the results that would be expected to be obtained once it is developed and implemented in an industrial environment** has been made in this report.

At the time of publication of this deliverable, theoretical data from engineering reports and simulations of the technology are being used. Therefore, this study is only a first estimation of the potential of this technology to reduce GHG emissions. This study will be complemented by the analysis that will be carried out during the last period of the project and in which the analysis will be repeated, but using real data extracted from the tests carried out in the electrolyser that will be installed in the Shell Energy and Chemicals Park Rheinland.

In addition, information related to the construction of the electrolyser (drawings, bill of materials, etc.) is considered strictly confidential at this time and therefore will not be detailed in a public deliverable such as this D9.4. The most relevant information related to each stage of the life cycle of the project's electrolyser is detailed in the following paragraphs.

Construction:

- The 100 MW electrolyser is composed by 50 skids using 150 stacks.
    - Weight of one unit of skid without stacks - dry mass = 3857 kg (materials: 90 % carbon steel, 5 % Copper, 5 % stainless steel / plastic / aluminium).
    - Individual stack mass = 488 kg (stack materials: Stainless steel, Titanium, engineering plastics. IPR Proprietary Materials).

Operation:

- At 100 % load:
    - 36 kg hydrogen kg/h/skid.
    - 288 kg oxygen kg/h/skid.
- Nominal consumption 2 MW.
- Nominal 55 kWh/kg.
- Approximately linear turndown.

Maintenance:

- Service life:
    - Skids: 20 years.
    - Stacks: 10 years.

End-of-life:

The electrolyser prototypes developed in the REFHYNE 2 project are considering Eco-design criteria to facilitate the recovery of materials at the end of their useful life and minimize waste generation.

In addition to the above data, further estimates of the consumption and performance of the electrolyser during use are given in Table 1. In this case, the values corresponding to the expected performance during the first years of operation are included in the table, as well as an estimate of the expected values for the last stage of operation, when its energy consumption will possibly be higher if the same rate of H_2 production is to be maintained.

Table 1. Estimation of electrolyser production and consumption

Description	Begin of Life (BoL)	End of Life (EoL)	Average value
Electrical Power (MW)	101.6	111.7	106.6
Hydrogen (kg/h)	1802.6	1802.6	1802.6
Oxygen (vented) (kg/h)	14280.0	14280.0	14280.0

5.3. First results based on pre-construction results

5.3.1. GHG emissions caused by the construction of the electrolyser

To estimate the GHG emissions caused only by the construction of one unit of 100 MW electrolyser, in this deliverable we have applied a simplified approach, considering the total weight of the main components of the electrolyser and the % of materials that make up each piece of equipment, based on the information detailed in the previous section (data inventory). To characterize the emissions generated by the manufacture of each type of material (upstream processes), we have used data from the EcoInvent 3.9 database, which is an internationally recognized database widely used for this type of studies.

Regarding the components that make up the stacks, a detailed description of the materials used by ITM is not available due to confidentiality reasons. Therefore, in this study an approximation has been made based on the data published in the study carried out by Bareiß et al. [30], which shows the average materials that make up the stacks for electrolysers with PEM technology based on the information available in the literature. The main materials (in percentage basis) for the state-of-the-art of a stack from PEM electrolysis is collected in Table 2. Furthermore, considering that the total weight of a stack such as those used in the electrolyser of the REFHYNE 2 project has a weight of 488 kg, an estimation of the weight of the different materials has been made on that basis. The reference of the emission factor used to estimate the GHG emissions generated by each material is shown in the same table.

Table 2. Materials that make up a stack unit and the origin of each emission factor (material references correspond to the datasheets of the Ecoinvent database [9])

	% of each material	Weight (per stack)	Reference
Titanium	77.04%	375.97	Titanium {GLO}| market for titanium | Cut-off, S
Aluminium	3.94%	19.23	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, S
Stainless steel	14.59%	71.21	Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, S
Copper	0.66%	3.20	Copper, cathode {GLO}| market for copper, cathode | Cut-off, S
Nafion	2.33%	11.39	Polyethylene, high density, granulate {RER}| polyethylene production, high density, granulate | Cut-off, S
Activated Carbon	1.31%	6.41	Activated carbon, granular {GLO}| market for activated carbon, granular | Cut-off, S
Iridium	0.11%	0.53	[31]
Platinum	0.01%	0.05	Platinum {GLO}| market for platinum | Cut-off, S

From this information, the results obtained for the GHG emissions caused by the manufacture of the materials contained in each stack are shown in Table 3 and graphically, in Figure 12. In this study, the emissions caused in the transformation processes to manufacture the electrolyser components and assembly operations are not being considered, but its impact is usually much lower than that of raw material manufacturing when it comes to metallic elements.

Table 3. Total GHG emissions generated in the production of the materials that make up a unit of stack

	Global warming (kgCO_2eq)
Titanium	18,570.5
Aluminium	193.1
Steel	359.6
Copper	22.4
Membrane	22.5
Activated carbon	21.8
Iridium	4,454.0
Platinum	3,527.3
TOTAL (per stack)	27,171.2

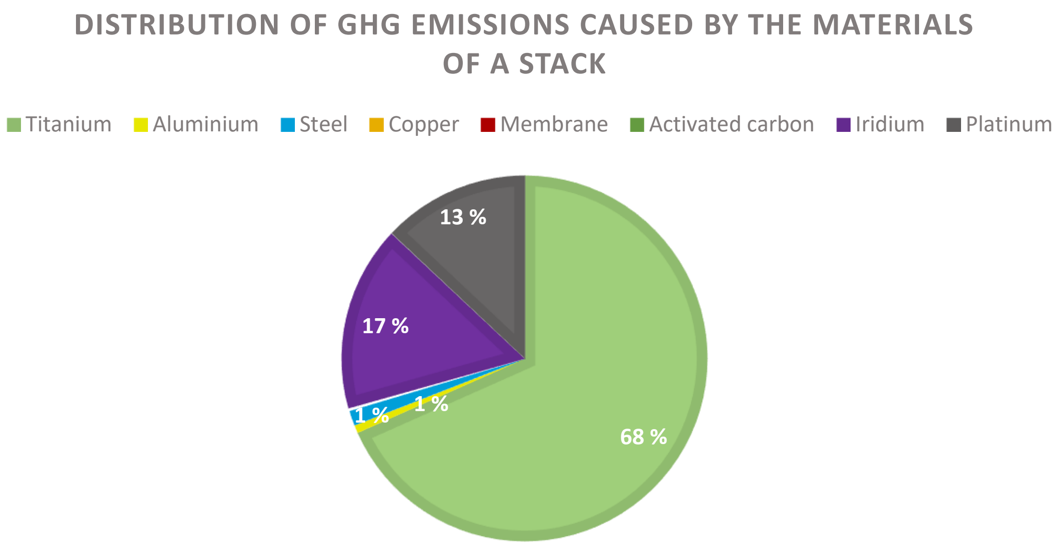

Figure 12. Contribution of each material to the total emissions of a stack unit

In summary, the materials required for the production of one stack unit generate a total of around 27 tons of CO_2eq in their production processes. Of the total emissions, 68 % correspond to the titanium manufacturing process (Figure 12). This material is, by weight, the main component of the stacks. On the other hand, the upstream emissions generated in the production processes of iridium and platinum metals are very relevant, and although they represent a very small share of the stack's weight, between them they account for around 30 % of the emissions generated.

Finally, in total, the 100 MW system proposed in the REFHYNE 2 project will consist of 150 stacks, resulting in total emissions of 4075.5 tons of CO_2eq due to this concept.

In line with the above, the same procedure was followed for the emissions generated in the production of the skid materials. On the one hand, based on the description of the main materials that make up each skid and the weight of each unit, an estimate was made of the weight of each material in each skid. The results are shown in Table 4.

Table 4. Materials that make up a skid unit and the origin of each emission factor

Material	% of each material	Weight (per stack)	Reference
Carbon steel	90%	3471.30	Steel, low-alloyed {Europe without Switzerland and Austria}| steel production, electric, low-alloyed | Cut-off, S
Stainless steel	5%	192.85	Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, S
Copper	5%	192.85	Copper, cathode {GLO}| market for copper, cathode | Cut-off, S

On the other hand, the results obtained in the study of the emissions generated to produce these materials are shown in Table 5 and in Figure 13.

Table 5. Total GHG emissions generated in the production of the materials that make up a unit of skid

Material	Global warming ($kgCO_2eq$)
Carbon steel	1,941.2
Stainless steel	973.9
Copper	1,351.9
TOTAL (per skid)	4,267.0

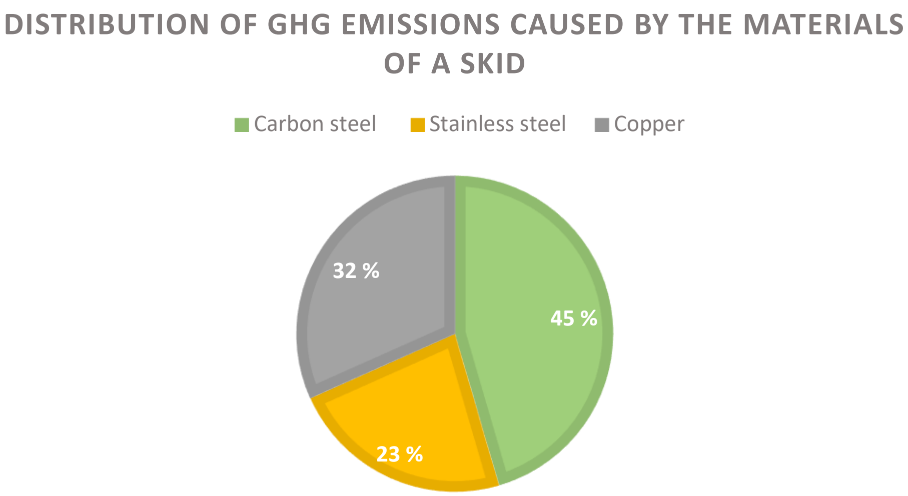

Figure 13. Contribution of each material to the total emissions of a skid unit

In this case, looking at the figure, the three main components of the skids have a significant contribution to the emissions of this equipment. In total, the materials involved in the manufacture of each of these units generate 4.26 tons in their upstream production stages, which is much less than the results obtained for each stack unit. In addition, each skid comprises three electrolysis stacks, so the total assembly of the 100 MW electrolyser would have 50 skids. In this regard, the emissions generated to produce the materials that make up the 50 skids integrated into the REFHYNE 2 electrolyser will generate a total of 213.0 tons.

If the impacts of the total materials that make up the skids and stacks (5x10 skids using 3x5x10stacks) are considered together, the GHG emissions generated in their production processes amount to 4288.5 t CO_2eq. This value, although incomplete since a detailed study of the electrolyser manufacturing would also need to consider the emissions from the assembly processes, as well as the upstream emissions from the auxiliary equipment, allows us to obtain a first approximation of the emissions generated. Furthermore, according to the results of the environmental assessment carried out in the REFHYNE project, the stack represents about 15-20 % of the entire electrolyser system. **In this report, we do not take into account the BoP of the system and the casing/infrastructure, which will be taken into account in future analysis. A more detailed study will be the subject of the next deliverables developed in the framework of task 9.3.**

5.3.2. GHG emissions caused by the EoL of the electrolyser

In a PEM stack, the main components are the polymeric membrane and the anode and cathode compartment. In order to define the possible EoL treatments applied to the different components, Table 6 summarizes common materials used in the manufacturing of a PEM water electrolysis stack, classified according to the type of residue they will generate [32].

Table 6. Common PEM water electrolysis stack materials

Component	Material	Material classification	Material Value
Electrolyte	Perfluorosulphonic acid (Nafion® type)	Non-hazardous	Medium
Anode and cathode -	Thermally sintered Ti	Non-hazardous	Low
	Ti/stainless steel	Non-hazardous	Low
	Graphite/graphite composites (only possible on cathode side)	Non-hazardous	Low
Cathode – catalyst layer	Platinum/Pt-alloys	Non-hazardous	High
Anode – catalyst layer	Iridium/Ir-alloys	Hazardous (irritant, harmful)	High
	Ruthenium/Ru-alloys	Hazardous (irritant, carcinogen)	Medium
Interconnect	Coated Ti/Ti-alloys	Non-hazardous	Low
Sealant	Plastics	Non-hazardous	Low
	Elastomer	Non-hazardous	Low

Of all the end-of-life treatments applicable to the electrolyser components, precious group metals like platinum and iridium are usually designated as the primary focus in End-of-Life technologies due to their significant economic importance. For example, electrodes play a pivotal role in the relatively elevated expenses associated with PEM electrolysers, because of the substantial PGM content. In this regard, hydrometallurgical and pyro-hydrometallurgical processes arise as conventional options for the recovery of PGMs. However, their economic feasibility depends on the recovery efficiency and the initial concentration of precious metals.

In general, the success of many products and components largely hinges on their design, which must consider End-of-Life strategies in alignment with eco-design or design for recycling principles. Nonetheless, not all designs for recycling strategies are always feasible, as they might at times have adverse impacts on the technical performance or the final cost of the product. To address this, recycling compatibility charts can be employed to choose materials that enable practical recovery processes for critical materials or components. These charts are routinely used during the design phase to assess the potential co-recyclability of materials. Other approaches include using materials with varying densities or magnetic properties to facilitate their separation and minimizing the use of painting and coatings to prevent material contamination, particularly in the case of plastics.

ITM, the electrolyser manufacturer of the REFHYNE 2 project consortium, enjoys a leading position with regards to thrifting and reuse of high value stack materials in its products. Components are individually analysed for re-use including, for example, electrode structures, maximising recoverable value (proprietary means). In addition, the stack skid structure considered for the REFHYNE 2 project electrolyser has been designed to be re-used to ensure longevity of life and minimise material disposal. Only where re-use is not an option is recycling or disposal considered. Where components cannot be re-used, they would go through a controlled recycling processes always with regulated environmental practice.

In conclusion, EoL strategies for PEM electrolyser components are vital to the sustainability and environmental impact of hydrogen production. By adopting eco-design principles, selecting recyclable materials and implementing efficient disassembly and separation processes, the green hydrogen industry can reduce waste, conserve resources, and minimize its carbon footprint, contributing to a more sustainable energy future.

At the time of writing this report, it is considered that the vast majority of the components that make up the skids and stacks can be recovered at the end of their useful life to be reused in new equipment or recycled to be incorporated into new value chains. This has been achieved by considering eco-design criteria from the first stages of the equipment design. Therefore, it is considered that at this point, the impacts generated by the end-of-life stages of the REFHYNE 2 electrolyser on the carbon footprint of the produced H_2 will be negligible compared to the impact of the electricity consumed during its use phase (less than 0.5%). For this reason, a more in-depth study has been ruled out in this preliminary study.

A study of the impacts caused by the different end-of-life scenarios will be carried out in the future deliverable D9.6 Report on Life Cycle Assessment of all environmental implications of the deployment.

5.3.3. GHG emissions caused by the operation / maintenance of the electrolyser

With regard to the emissions generated during the operation of the electrolyser, the main cause of GHG emissions is the electricity consumed for electrolysis, and this consumption depends on the number of hours the equipment is operated daily. In this sense, Table 1 shows some estimates made by the REFHYNE 2 project partners of the expected hourly consumption of the electrolyser, as well as the expected H_2 / O_2 production. In addition to electrolysis, other potential stages should be taken into account in a complete study of the system (H_2 compression, storage, transport, etc.). However, the study of these stages is beyond the scope of this preliminary assessment.

In this sense, we have analysed in this section how the impacts associated to each kg of H_2 would change depending on the number of hours of operation of the electrolyser. For this analysis, on the one hand, we have taken into account the energy consumption derived from the operation of the electrolyser. These consumptions are proportional to the number of system operating hours. On the other hand, the total manufacturing GHG emissions of the electrolyser have been allocated to the total kg of H_2 it could produce in its lifetime. For this purpose, a total lifetime of the electrolyser of 20 years has been considered, and it has been assumed that the stacks will have to be replaced after 10 years.

Under these conditions, the GHG emissions associated with the production of one kg of H_2 in the electrolyser considered in the REFHYNE 2 project, assuming an ideal scenario where the electrolyser operates 24 h per day and is powered exclusively by renewable wind energy, are shown in Table 7. As a reference, we have considered the GHG emissions from electricity generation at wind farms in Germany and Spain, using the datasets "*Electricity, high voltage {DE}| electricity production, wind, 1-3 MW turbine, onshore | Cut-off, U*" and "*Electricity, high voltage {ES}| electricity production, wind, 1-3 MW turbine, onshore | Cut-off, U*", available in the EcoInvent v3.9 database.

These datasets model wind farms consisting of 1-3 MW wind turbines (Vestas V80 wind power plant) with a dataset that includes both moving and fixed turbine parts, as well as a network connection. Based on the EcoInvent models, the production of 1 kWh of electricity in such wind farms generates 20.0 g CO_2eq/kWh in Germany and 14.9 g CO_2eq/kWh in Spain. This variation is primarily due to EcoInvent's internal data, which account for differences in the average size of wind farms and the types of turbines commonly installed in each country.

Given these assumptions, each kg of H_2 (classified as green H_2) generates only 1.21 kg CO_2/kg H_2 (using German wind energy) and 0.91 kg CO_2/kg H_2 (using Spanish wind energy) (Table 7).

Table 7. Summary of data used to estimate GHG emissions per kg of H_2 produced at 30 bar, electricity from Spanish and German wind farms

	Concept	**Value**	**Units**
	Daily hours	24	h/day
	Days per year	365	day/year
	Lifetime	20	year
	Electrical Power	106.6	MW
	Hydrogen	1802.6	kg H_2/h
	Total H_2 production	315815520	kg H_2 (20 years)
	E total consumption	18676320	MWh (20 years)
(German wind	FE electricity (German wind energy)	0.020	tCO_2e/MWh
	Total CO_2eq from electricity (operation)	373526.4	t CO_2e (20 years)
	Total CO_2eq from electrolyser manufacturing	8364	t CO_2e (20 years)
	TOTAL:	381890.4	t CO_2e (20 years)
	Emissions: (German wind energy)	**1.21**	**kg CO_2 / kg H_2**
(Spanish wind	FE electricity (Spanish wind energy)	0.015	tCO_2e/MWh
	Total CO_2eq from electricity (operation)	278277.2	t CO_2e (20 years)
	Total CO_2eq from electrolyser manufacturing	8364	t CO_2e (20 years)
	TOTAL:	286641.2	t CO_2e (20 years)
	Emissions: (Spanish wind energy)	**0.91**	**kg CO_2 / kg H_2**

Looking at the results, it is clear that the electricity consumed by the electrolyser generates around 99% or even more of the total environmental impact attributable to each kg of H_2 produced. The impact of the equipment manufacturing is very small in comparison. Therefore, although it is improbable that the electrolyser operates 24/7 all year round, the emissions of the equipment attributable to each kg of H_2 generated are very small, and the real impact comes from electricity consumption, which is proportional to the hours used (no production, no consumption, no emissions).

The origin of the electricity used for electrolysis is a key factor in determining the carbon footprint of the hydrogen produced. For comparison, Table 8 presents the average emission factor of electricity generated in 2022 for selected European countries, along with the emissions of H_2 if produced using different energy mixes [33]. In Germany, a significant share of the total electricity generation in 2022 came from coal and natural gas. Consequently, the emissions associated with producing one kg of H_2 using the average German electricity mix are quite high (22.50 kg CO_2/kg H_2). On one hand, in countries with higher average emission factors—such as the Czech Republic, where electricity has an emission factor of 444 gCO_2/kWh—the GHG emissions of one kg of H_2 produced using the REFHYNE 2 project electrolyser would amount to 26.28 kg CO_2/kg H_2. On the other hand, if grid electricity is sourced from countries with a high share of clean energy (e.g., Sweden, where 70% of electricity comes from renewable sources), emissions per kg of H_2 drop significantly to 1.68 kg CO_2e/kg H_2.

Table 8. Results depending on the origin of the electricity mix

Country	Emission factor Electricity mix 2022 (gCO_2/kWh)	GHG emissions per kg of H_2 produced
Czech Republic	444	26.28
Italy	389	23.03
Germany	380	22.50
Spain	195	11.56
France	73	4.34
Sweden	28	1.68

In conclusion, using renewable energy sources for the future operation of the electrolyser is crucial to achieving a significant reduction in GHG emissions from H_2 use compared to fossil fuel alternatives.

6. Conclusions

The preliminary GHG emissions avoidance analysis carried out in this deliverable for the innovative REFHYNE 2 electrolyser offers valuable insights into the potential of this technology to substantially reduce greenhouse gas emissions in the production of hydrogen. The conclusions drawn from this assessment shed light on several critical aspects that underline the significance of this innovative approach.

On the one hand, this study has demonstrated that an innovative electrolysis technology represents a significant advancement in mitigating greenhouse gas emissions in comparison to other conventional techniques as long as the electricity used comes from renewable sources. The technology's reliance on cleaner energy sources and its inherent efficiency makes it a compelling alternative to conventional hydrogen production methods, representing a substantial reduction in direct emissions associated with hydrogen production. Based on estimates and average data found in the literature, the production of one kg H_2 from the steam methane reforming process, which is the most common production route, generates GHG emissions of 11.5 kg CO_2eq / kg H_2. However, when H_2 is produced through water electrolysis, its generation can be achieved with much lower GHG emissions if clean energy is used to produce the electricity consumed. For example, from the pre-construction data of the REFHYNE 2 project electrolyser, it has been estimated that if electricity from wind power is used, H_2 could be produced with a carbon footprint of only 0.91 kg CO_2 / kg H_2 (cradle-to-gate approach). As a result, the REFHYNE 2 technology could achieve a reduction of more than 90 % of emissions compared to the current most common H_2 production technology.

On the other hand, assessing the entire lifecycle of hydrogen production is vital, and an efficient electrolysis system has shown promise in not only reducing direct emissions but also in facilitating the integration of renewable energy sources. This integration plays a crucial role in avoiding indirect emissions linked to energy production, highlighting the potential for a more sustainable and environmentally friendly energy system.

In addition to the above, the electrolyser's versatility spans multiple industries, including transportation, energy storage, and industrial processes. Its potential for significantly reducing emissions positions it as a pivotal tool in the pursuit of sustainability across various sectors.

However, despite all the advantages in terms of sustainability that have been mentioned above, there is still a clear need for supportive policies and incentives to encourage the widespread adoption and further development of low-carbon technologies like the large-scale electrolysers to produce H_2. Continued research and innovation are essential to enhancing efficiency, reducing costs, and advancing integration with renewable energy sources to maximize the technology's environmental impact and economic feasibility.

In summary, the GHG emissions avoidance analysis indicates that the REFHYNE 2 electrolyser represents a breakthrough technology that holds immense promise in significantly reducing greenhouse gas emissions in hydrogen production. Its adoption and further development will play a crucial role in the global transition towards a more sustainable, low-carbon future.

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