EPHYRA

Establishing European Production of Hydrogen from RenewAble energy and integration into an industrial environment

D1.1 Technology validation

WP1 – Detailed technology and integration concept

Co-funded by the European Union

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BACKGROUND AND DISCLAIMER

Project Background

EPHYRA project with the full title: “Establishing European Production of Hydrogen from RenewAble energy and integration into an industrial environment” was submitted in the call HORIZON-JTI-CLEANH2-2022-2, under the topic HORIZON-JTI-CLEANH2-2022-01-08 “Integration of multi-MW electrolyzers in industrial applications”. The project receives support by the Clean Hydrogen Partnership and its members Hydrogen Europe and Hydrogen Europe Research through the Grant Agreement No. 101112220.

Objective of Deliverable

The deliverable titled "D1.1 Technology Validation" marks the initiation of activities within Work Package 1 (WP1) - "Detailed Technology and Integration Concept." Its primary goal is to provide a comprehensive overview of the work conducted during the initial phase of the project. This includes a thorough assessment of various hydrogen production technologies, laying the groundwork for subsequent evaluations. Following the technology assessment, the deliverable outlines a detailed methodology for the evaluation process of various electrolysis technology vendors. This methodology serves as a structured approach to assess and compare different vendors based on predefined criteria and objectives. Furthermore, the deliverable encompasses an assessment of the technical requirements essential for the successful integration of an industrial green hydrogen production system. This assessment aims to identify the necessary components, specifications, and operational considerations needed to achieve project objectives effectively.

Overall, "D1.1 Technology Validation" serves as a foundational document within WP1, providing crucial insights and guidelines for decision-making and project planning moving forward.

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Executive Summary

The deliverable presents a comprehensive overview of the initial steps undertaken within Task 1.1 of WP1 of the EPHYRA project, which focuses on the detailed technology and integration concept for industrial-scale green hydrogen production. The primary objectives of Task 1.1 include conducting a technology assessment, defining system boundaries, and procuring necessary equipment through a best-value tender process. The technology assessment phase involves evaluating various hydrogen production technologies to identify the most suitable option for achieving project goals. This assessment considers factors such as efficiency, scalability, environmental impact, fitness with MOH industrial site and cost-effectiveness, aligning with the Clean Hydrogen Partnership's Strategic Research & Innovation Agenda (SRIA) KPIs for 2024. Additionally, the deliverable highlights the best-value tender process for procuring electrolyzer systems and equipment. Through a competitive tender process, the project seeks to select suppliers who can deliver the necessary equipment and materials at competitive prices without compromising on performance or sustainability. Furthermore, the deliverable outlines the key technical requirements for the integration of the industrial-scale green hydrogen production system. These requirements encompass various aspects, including the provision of green electricity, utilization of waste heat, non-freshwater usage, and utilization of produced oxygen within the industrial facility. These elements are vital for optimizing the efficiency, sustainability, and cost-effectiveness of the green hydrogen production process.

The deliverable is organized as follows:

Section 2 provides a comprehensive evaluation of various hydrogen production technologies as part of the EPHYRA project's initial assessment phase. The evaluation process considers factors such as efficiency, scalability, environmental impact, and cost-effectiveness. Different technologies, including Alkaline Electrolysis (AEL), Proton Exchange Membrane (PEM) electrolysis, Solid Oxide Electrolysis (SOE), Anion Exchange Membrane (AEM) electrolysis, and others, are analyzed to identify the most suitable option for achieving project objectives.

Section 3 outlines the vendor evaluation process undertaken as part of the EPHYRA project to procure the necessary electrolysis system and equipment. The Section describes the methodologies used to assess potential vendors and select the most suitable supplier based on predefined criteria. The vendor evaluation process begins with the identification of key criteria for rejection and ranking of the vendors, such as cost, quality, reliability, compliance, and innovation. These criteria are verified against the technical requirements of the project and weighted according to their importance in the decision-making process. Potential vendors submit proposals, which are then evaluated based on the established criteria, technical compliance, and their respective weights.

Furthermore, the Section presents the outcomes of the vendor evaluation process conducted to select the most suitable supplier for the EPHYRA project's electrolyzer system. Through a rigorous evaluation process utilizing two distinct methodologies, that complement each other, one from CERTH and one from MOH, multiple vendors were assessed based on their proposals, and their performance was measured against the predetermined criteria. Each vendor's strengths, weaknesses, produced Levelized Cost of Hydrogen (LCOH) and overall suitability for the project were thoroughly analyzed. Ultimately, both evaluation methodologies converged to the same conclusion, identifying the same vendor as the optimal choice for the EPHYRA project. This vendor demonstrated excellence in meeting the criteria outlined in the evaluation process, offered the most competitive solution in terms of cost, quality, and reliability and contributes to achieving the overarching objectives of the EPHYRA project in terms of realizing the most competitive renewable hydrogen production in Europe. This alignment reinforced the confidence in the vendor selection, validating the thoroughness and reliability of the evaluation process. The Section concludes with the announcement of the selected vendor, METACON AB, marking an important milestone in the project's procurement process. This decision sets the stage for the next phases of the project, as the selected vendor will play a crucial role in supplying the electrolyzer system needed for the industrial-scale green hydrogen production facility.

Section 4 provides a summary of the technical requirements necessary for the successful integration of an industrial-scale green hydrogen production system within the EPHYRA project. These technical requirements are crucial for ensuring the efficient operation and performance of the integrated system. The chapter begins by outlining the various components and specifications essential for the green hydrogen production system. This includes the provision of green electricity, utilization of waste heat, non-freshwater usage, and the utilization of produced oxygen within the MOH Refinery. Additionally, the Section presents the technology validation for the SoluForce pipelinesand the gap analysis in respect to the Refinery regulations and the national and international standards. In more detail, for the Ephyra project it is considered to use SoluForce pipe for the transport of the produced hydrogen and, where possible, other process streams like any water stream for production of hydrogen or energy recovery. In order to have approval from the local regulators to build and operate a pipeline of SoluForce pipe a GAP analyses is made to see if there are already issues which need to be addressed before discussions for approval are started. Both the transport of hydrogen and using the non-metallic SoluForce pipe will need extra attention and support for engineers and the local regulators. The GAP analyses was started by creating a list of standards typically used for Greece and the Motor oil refinery. The search for specific standards resulted in a short list. This list was extended by standards which were already listed in other EU projects. The listed standards were screened for content which would deviate from the possibilities of the SoluForce system or will need extra attention. The points for extra attention are more elaborated, the points of attention are listed. From the GAP analyses it becomes clear that many standards are related to the engineering of the pipeline itself and the safety measures to be made, independent of which pipeline material is used, but more in relation the fluid risk level. When the regulations are followed and the recommendations taken into account the SoluForce pipe can be used. The attention points for using the SoluForce pipe are fire resistance, earthquake resistance and permeation. The earthquake resistance and permeation are taken care of in the design of the SoluForce pipe. For every project the local specifications for these two items need to be checked against the specification of the SoluForce pipe. Fire resistance will need steps to protect the SoluForce pipe in case of heavy fires. Overall, the Section emphasizes the importance of aligning these technical requirements with project objectives and ensuring compatibility with existing infrastructure and processes.

Section 5 serves as a comprehensive summary of the conclusions drawn from the document, synthesizing the key findings and outcomes derived from the technology validation, vendor evaluation, and assessment of technical requirements for the green hydrogen production system.

Finally, Annexes are included with supplementary information on the SRIA targets, the KPIs for electrolyzer based on the tender and fundamentals for water electrolysis.

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ABBREVIATIONS

Abbreviation	Explanation
AEM	Anion Exchange Membrane
AOP	Advanced Oxidation Process
AWE	Alkaline Water Electrolysis
BoP	Balance of Plant
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCSU	Carbon Capture, Storage, and Utilization
CHJU	Clean Hydrogen Joint Undertaking
DI	De-ionized
EDI	ElectroDIalysis
EPC	Engineering, Procurement and Construction
EU	European Union
FAT	Factory Acceptance Test
FEED	Front-End Engineering Design
GDL	Gas Diffusion Layers
GHG	Greenhouse Gas
HER	Hydrogen Evolution Reaction
HTE	High Temperature Electrolyzer
KPI	Key Performance Indicator
LCOH	Levelized Cost Of Hydrogen
LTE	Low Temperature Electrolyzers
LTSA	Long Term Service Agreement
LV	Low Voltage
MCP	Market Clearing Price
MEA	Membrane Electrode Assembly
NTP	Non-Thermal Plasma
O&M	Operation & Maintenance
OER	Oxygen Evolution Reaction
OES	Optical Emission Spectroscopy
OPEX	Operating Expenses
ORC	Organic Rankine Cycle
ORF	Oxygen Recovery Facility
PEM	Proton Exchange Membrane
PPA	Power Purchase Agreement
PWW	Process Wastewater
RES	Renewable Energy Sources
RfQ	Request for Quotation
RO	Reverse Osmosis
SAT	Site Acceptance Test
SHE	Standard Hydrogen Electrode
SMR	Steam Methane Reforming

Abbreviation	Explanation
SoA	State of the Art
SOE	Solid Oxide Electrolysis
SOEC	solid oxide electrolysis cells
SRIA	Strategic Research & Innovation Agenda
TCO	Total Cost of Ownership
TIC	Total Investment Cost
tpa	tons per annum
TrOC	Trace Organic Chemicals
UCP	Unit Control Panel
UV	Ultraviolet
VPP	Virtual Power Plant
WACC	Weighted Average Cost of Capital

1. Introduction

The transition towards a sustainable, low-carbon economy has placed renewable hydrogen at the forefront of efforts to decarbonize various sectors, including industry, transportation, and energy. As the European Union (EU) strives to achieve its ambitious climate goals and transition towards a carbon-neutral future, initiatives like the EPHYRA project play a pivotal role in advancing the development and deployment of renewable hydrogen technologies. EPHYRA represents a groundbreaking endeavor aimed at establishing a large-scale renewable hydrogen production facility in South-Eastern Europe. This introductory section provides an overview of the project's objectives, its significance in the context of the EU's clean energy transition, and the key elements that define its approach.

Background and Context

The global imperative to mitigate climate change and reduce greenhouse gas emissions has underscored the importance of transitioning to renewable energy sources. Hydrogen, particularly when produced from renewable sources through electrolysis, offers a promising pathway towards decarbonizing various sectors that are challenging to electrify directly. Within the EU, renewable hydrogen has emerged as a key priority under the European Green Deal and the EU Hydrogen Strategy. By leveraging renewable energy sources such as wind and solar power, hydrogen production can be decoupled from fossil fuels, offering a sustainable alternative with minimal environmental impact.

Objectives of the EPHYRA Project

The primary objective of the EPHYRA project is to demonstrate the viability and scalability of renewable hydrogen production at an industrial scale. Specifically, the project aims to:

- Establish a 30 MW renewable hydrogen production facility integrated with MOH's Corinth Refinery.
- Operate the facility under commercial conditions for a minimum of two years.
- Supply renewable hydrogen to both refinery processes and external end-users.
- Implement a circular economy and industrial symbiotic approach to enhance efficiency and sustainability.
- Contribute to the achievement of key performance indicators outlined in the Clean Hydrogen Partnership's Strategic Research & Innovation Agenda (SRIA).

Significance and Impact

EPHYRA holds significant implications for the EU's energy transition and broader sustainability objectives. By showcasing the feasibility of large-scale renewable hydrogen production within an industrial context, the project aims to:

- Accelerate the development and deployment of renewable hydrogen technologies.
- Support the decarbonization of industrial processes and contribute to meeting EU emissions reduction targets.
- Foster innovation and collaboration across industries to unlock the full potential of renewable hydrogen.
- Position Europe as a global leader in the transition to a hydrogen-based economy, driving economic growth and competitiveness.

For the successful implementation of the EPHYRA project, a thorough technology assessment for green hydrogen production is essential. This assessment serves as the foundation for selecting the most suitable electrolysis system through a tender process aimed at securing the best value for procurement of electrolyzer and associated equipment.

The subsequent sections of this report detail the research conducted and the actions taken to fulfill the objectives of Task 1.1 within WP1. Task 1.1 focuses on conducting a comprehensive technology assessment for green hydrogen production, laying the groundwork for subsequent procurement activities. This assessment involves evaluating various hydrogen production technologies, considering factors such as efficiency, scalability, environmental impact, and cost-effectiveness. Furthermore, the report outlines the methodologies employed for the procurement process, emphasizing the importance of selecting vendors who can provide the best value in terms of quality, performance, and cost. The tender process is designed to ensure transparency, fairness, and efficiency in selecting the electrolyzer system and related equipment necessary for the successful implementation of the project.

Overall, this report provides insights into the critical steps taken to assess technology options, initiate the procurement process, and advance the objectives of the EPHYRA project. It underscores the project's commitment to achieving its goals of establishing a large-scale renewable hydrogen production facility that produces hydrogen at competitive cost, while contributing to the EU's clean energy transition.

1.1 Scope of Work Package 1 – Detailed technology and integration concept

Work Package 1 aims to establish the foundation for the implementation of the EPHYRA project. This includes conducting technologies assessment, outlining technical requirements, and initiating key activities such as licensing and safety planning. Additionally, WP1 involves evaluating different electrolyzer technologies, assessing their suitability for integration into the project, and identifying the necessary materials and equipment for the industrial green hydrogen production system. Furthermore, this package encompasses decision-making processes such as go/no-go assessment to ensure project viability and safety planning to mitigate potential risks.

The objectives outlined for WP1 of the EPHYRA project encompass three key areas:

1. **Technology Assessment for Green Hydrogen Production:** Conducting a comprehensive technology assessment involves evaluating various methods and technologies for producing green hydrogen. This assessment includes considering factors such as efficiency, scalability, environmental impact, and cost-effectiveness. By aligning with the Clean Hydrogen Partnership's SRIA KPIs for 2024, the project aims to identify the most suitable technology that meets both short-term and long-term objectives for green hydrogen production.
2. **Definition of System Boundaries:** Defining the boundaries of the integrated industrial green hydrogen production system is crucial for ensuring clarity and precision in project planning and execution. This involves specifying the components, processes, and interfaces of the production system to ensure seamless integration and optimal performance. By accurately delineating the system boundaries, the project can effectively identify material requirements and avoid ambiguities during implementation.
3. **Best Value Tender for Electrolyzer and Equipment Procurement:** The tender process for procuring the electrolyzer system, is focused on obtaining the best value for money while ensuring that the selected suppliers meet the project's requirements and standards. This involves evaluating proposals from potential vendors based on criteria such as cost, performance, quality, reliability, and compliance with SRIA targets. Through a competitive tender process, realized in WP1, the project aims to select suppliers who can deliver the necessary Electrolyzer equipment and materials at competitive prices without compromising on performance or sustainability.

By pursuing these objectives, EPHYRA project aims to establish a robust and efficient industrial green hydrogen production system in the EU that not only meets the immediate needs of the project but also aligns with broader industry goals for sustainability and competitiveness. This strategic approach ensures that the project maximizes its impact and value while contributing to the advancement of EU green hydrogen technologies and practices.

1.2 Scope of Deliverable 1.1 – Technology validation

Deliverable 1.1 entails a comprehensive report detailing the assessment of electrolyzer technology and outlining the technical requirements for the integrated industrial green hydrogen production system. Beginning with an evaluation and technology validation conducted by CERTH, the report will assess the novelty, competitiveness, and fitness of the electrolyzer technology for optimal integration into the MOH Refinery, aiming to achieve project performance beyond the state-of-the-art in order to enhance competitiveness of renewable hydrogen production.

Additionally, the tender process for procuring the electrolyzer system and the vendor evaluation methodology are detailed in this deliverable. This involves defining the criteria for vendor selection, such as cost, technology suitability, and past performance/ experience, conducting the tender process, and evaluating vendor proposals based on the predefined criteria. The vendor evaluation methodology ensures a systematic and objective assessment of vendor proposals to identify the most suitable supplier for the project's requirements. By documenting the tender process and vendor evaluation methodology, the project ensures transparency, fairness, and accountability in the procurement process.

Finally, various technical requirements for the integrated system will be defined, including the provision of green electricity and power management by ITA, the utilization of waste heat to support electrolyzer operation by ENER, the non-freshwater usage by CERTH, and utilizing produced oxygen within the MOH Refinery by MOH. Furthermore, SF will offer full support for technology validation related to these requirements.

This deliverable will serve as a foundation for subsequent project activities and guide the implementation of the integrated industrial green hydrogen production system.

2 Water Electrolysis systems – An overview of technologies

In this section, an in-depth assessment of various hydrogen production methods is conducted, presenting a comprehensive overview of the available technologies. The assessment begins by examining traditional methods of hydrogen production, such as Steam Methane Reforming (SMR) and coal gasification, highlighting their drawbacks in terms of carbon emissions and environmental impact. It then delves into emerging technologies like electrolysis, including both Alkaline Electrolysis (AEL) and Proton Exchange Membrane electrolysis (PEM), which offer the potential for cleaner and more sustainable hydrogen production. Furthermore, novel approaches such as Solid Oxide Electrolysis (SOE) and Anion Exchange Membrane electrolysis (AEM) are also explored, highlighting their unique characteristics and potential applications in green hydrogen production.

2.1 Introduction - Hydrogen production methods

The increasing global energy demand, coupled with finite reserves of fossil fuels and growing concerns about sustainability and environmental impact, necessitates the development of new energy approaches with zero carbon emissions. Environmental-friendly energy strategies, aimed at replacing current fossil fuel-based production methods, have garnered attention in recent years.

Hydrogen emerges as a promising and environmentally friendly energy carrier, generating only water as a byproduct with zero carbon emissions. Its high energy density (142 MJ/kg), makes it particularly attractive, since it is more than two times higher than that of typical solid fuels (40-50 MJ/kg). Global hydrogen production currently stands at around 120 million tons per year, predominantly serving industrial applications such as fertilizers, petroleum refining, and chemical processes. Various methods are employed for hydrogen production, utilizing both renewable energy sources, like biomass and water electrolysis and non-renewable energy sources, including fossil fuels like methane steam reforming, oil/naphtha reforming, and coal gasification. Figure 1 shows these hydrogen production methods [1] [2] [3] [4] and Table 1 summarizes their advantages and disadvantages [5] [6] [7].

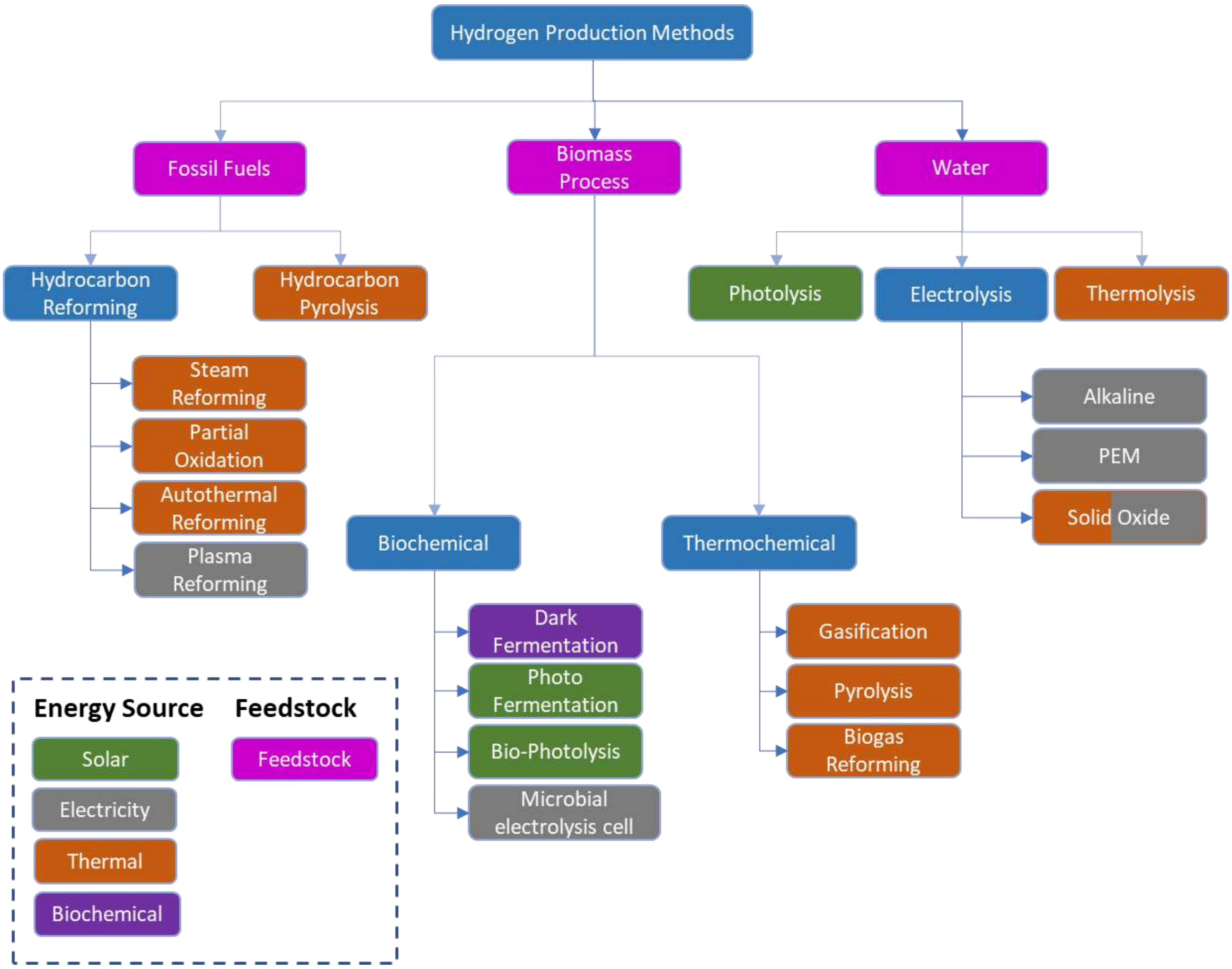


Figure 1 Various Hydrogen production methods [1] [2] [3] [4]

Table 1 Advantages – Disadvantages of Hydrogen production methods [2] [5] [6]

Technology	Advantages	Disadvantages	Efficiency %
Steam Reforming	Developed technology & existing infrastructure	Produced CO, CO_2, unstable supply	74–85
Partial Oxidation	Established technology	Along with H_2 production, produced heavy oils and petroleum coke	60–75
Auto thermal Reforming	Well established technology & existing infrastructure	Produce CO_2 as a byproduct, use of fossil fuels	60–75
Bio-photolysis	Consumed CO_2, produced O_2 as a byproduct, working under mild conditions	Low yields of H_2, sunlight needed, large reactor required, O_2 sensitivity, high cost of material.	10–11
Dark Fermentation	Simple method, H_2 produced without light, no limitation O_2, CO_2-neutral, involves to waste recycling	Fatty acids elimination, low yields of H_2, low efficiency, necessity of huge volume of reactor	60–80
Photo Fermentation	Involves to waste water recycling, used different organic waste waters, CO_2-neutral	Low efficiency, low H_2 production rate, sunlight required, necessity of huge volume of reactor, O_2-sensitivity	0.1
Gasification	Abundant, cheap feedstock and neutral CO_2	Fluctuating H_2 because of feedstock impurities, seasonal availability and formation of tar	30–40

Technology	Advantages	Disadvantages	Efficiency %
Pyrolysis	Abundant, cheap feedstock and CO_2-neutral	Tar formation, fluctuating H_2 amount because of feedstock impurities and seasonal availability	35–50
Thermolysis	Clean and sustainable, O_2-byproduct, copious feedstock	High capital costs, elements toxicity, corrosion problems	20–45
Photolysis	O_2 as byproduct, abundant feedstock, No emissions.	Low efficiency, non-effective photocatalytic material, requires sunlight	0.06
Electrolysis	Established technology, zero emission, existing infrastructure, O_2 as byproduct	High capital costs, integration with renewable energy sources	60–80

Hydrogen production processes, despite their potential benefits, come with environmental implications. Throughout the entire lifecycle of hydrogen, including feedstock acquisition, energy inputs, and waste emissions, its environmental cleanliness is determined. To categorize hydrogen, based on its environmental impact, it is classified into eleven colors, as shown in Table 2.

Green hydrogen is deemed the cleanest as it relies predominantly on renewable energy sources and water electrolysis for production, resulting in zero CO_2 emissions. Yellow hydrogen refers to hydrogen that is made using electrolysis powered by a mix of renewables and fossil fuel power. Pink hydrogen utilizes electricity from nuclear plants for water electrolysis. Purple hydrogen is produced through chemo-thermal electrolysis of water using nuclear power and heat. Red hydrogen is derived from high-temperature catalytic water splitting using nuclear thermal energy. Turquoise hydrogen, generated by thermal methane splitting, via methane pyrolysis. The process, though at the experimental stage, removes the carbon in a solid form instead of CO_2 gas. Blue hydrogen, derived from fossil fuels, incorporates Carbon Capture and Storage (CCS) or Carbon Capture, Storage, and Utilization (CCSU) technologies to mitigate CO_2 emissions, rendering it carbon neutral. Gray hydrogen, produced via Steam Methane Reforming (SMR), emits CO_2 directly into the atmosphere. Black or brown hydrogen, sourced from coal through gasification, is highly polluting, releasing CO_2 and carbon monoxide. Black and brown colors refer to the type bituminous (black) and lignite (brown) coal. White hydrogen refers to naturally occurring hydrogen.

Table 2 Color classification of produced hydrogen

Production from	Terminology	Process	Fuel Source	GHG Intensity (relative)
Water	Green	Electrolysis	Renewable electricity	▏
	Yellow		Renewable + Grid Electricity	██████
	Pink		Nuclear Electricity	█
	Purple		Nuclear Electricity +Heat	█
	Red	Catalytic Splitting	Nuclear Heat	█
Fossil Fuels	Turquoise	Pyrolysis	Natural Gas	Solid Carbon
	Blue	Steam Reforming	Natural Gas	████
	Gray		Natural Gas	████████
	brown	Gasification	Brown coal (lignite)	██████████
	Black		Black coal (bituminous)	██████████
Nature	White	Naturally occurring		

Currently, as shown in Figure 2, the majority of hydrogen production (96%) stems from fossil fuel, notably from natural gas or from coal, using carbon-intensive methods like steam reforming of methane and coal gasification [8] [9]. However, reliance on fossil fuels results in lower hydrogen purity and increased greenhouse gas emissions. For hydrogen to be environmentally sustainable, it must be produced using low-carbon energy sources such as solar, wind, or low-carbon grid electricity, known as green hydrogen. Currently, only 4% of global hydrogen production comes from water electrolysis.

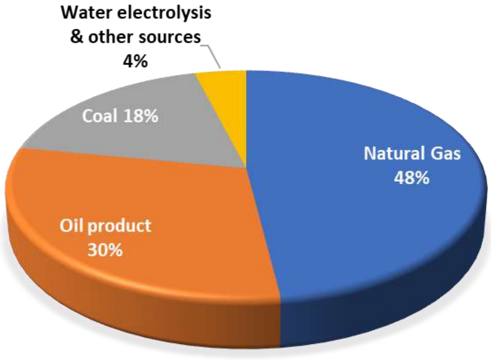


Figure 2 Hydrogen origin sources distribution

However, producing hydrogen from renewable water sources, offers a promising solution. Among the other hydrogen production methods, water electrolysis when uses renewable energy sources, stands out as an eco-friendly method with near zero carbon emissions, capable of yielding high-purity hydrogen (99.8%), that needs less additional refining steps.

The EU's vision for climate neutrality and zero pollution is focusing on renewable hydrogen. The roadmap for renewable hydrogen development sets clear milestones for 2024 and 2030, with long-term ambitions extending to 2050 [8]. It outlines the phased deployment of renewable hydrogen technologies up to 2050. The strategic objective of phase 1 (2020-2024) is to install at least 6 GW of renewable hydrogen electrolyzers in the EU to produce up to 1 million tons of renewable hydrogen. At phase 2 (2025-2030) the objective is to integrate hydrogen as a key component of the energy system by installing at least 40 GW of renewable hydrogen electrolyzers to produce up to 10 million tons of renewable hydrogen in the EU. As long-term vision (2031-2050) for climate neutrality and zero pollution, EU targets on deploying renewable hydrogen technologies at a large scale.

2.2 Water electrolysis technologies

Water electrolysis is a fundamental process for producing hydrogen gas. This process involves splitting water molecules into hydrogen and oxygen gases using an electrical current. It is a sustainable method as it utilizes water as the raw material, which is abundant and renewable. This basic reaction is described by the following equation:

$$H_2O\ (l)\ \rightarrow\ H_2(g) + \frac{1}{2}O_2(g)$$

Electrolysis typically occurs in an electrolyzer, which consists of an anode and a cathode separated by an electrolyte. When an electric current is passed through the electrolyte, water molecules at the anode undergo oxidation, releasing oxygen gas, while hydrogen ions are reduced at the cathode to form hydrogen gas. The rate of gas production per unit time is directly correlated to the current flowing through the electrochemical cell. The generated hydrogen gas can be stored and used as a clean fuel for various applications, including fuel cells, transportation, and industrial processes.

Water electrolysis offers a scalable and efficient means of producing hydrogen, with the potential for integration with renewable energy sources such as solar, wind and water power. One of the key advantages of water electrolysis is its ability to provide a pathway for renewable energy storage and utilization, enabling grid stabilization and energy balancing. Moreover, water electrolysis produces high-purity hydrogen gas without generating harmful emissions or by-products. It can also be integrated with carbon capture and utilization technologies to produce hydrogen from carbon-neutral sources.

However, challenges such as high energy consumption and cost need to be addressed to enhance the commercial viability of water electrolysis. Research efforts are underway to develop advanced electrolyzer technologies with improved efficiency, durability, and cost-effectiveness. These advancements include the development of novel electrode materials, innovative electrolyte compositions, and efficient system designs. Furthermore, ongoing research aims to optimize operating conditions and electrolysis processes to minimize energy consumption and increase overall efficiency.

Water electrolysis holds promise as a key technology for achieving a sustainable hydrogen economy and mitigating climate change. Its role in enabling the widespread adoption of hydrogen as a clean energy vector is increasingly recognized by governments, industries, and research institutions worldwide. Investments in research and development are driving innovation in electrolysis technology, paving the way for cost-effective and scalable hydrogen production. As water electrolysis continues to mature and evolve, it has the potential to play a pivotal role in the transition to a low-carbon energy future.

Water electrolysis categories

Water electrolysis can be categorized into three main types based on their electrolyte, operating conditions, and ionic agents (OH-, H+, O^{2-}). These methods include Alkaline Water Electrolysis (AWE), Solid Oxide Electrolysis (SOE) and Proton Exchange Membrane (PEM) water electrolysis. Despite the variations in electrolyte and operating principles, the goal of producing hydrogen from water remains consistent across these methods. The fundamentals of water electrolysis and the water electrolysis thermodynamics can be found in Annex 3.

2.2.1 Alkaline electrolyzers (AEL)

Hydrogen production through alkaline water electrolysis has become a well-established technology, due to its advanced maturity and broader commercial adoption. Commercially, it is implemented up to the megawatt scale worldwide. The phenomenon was first introduced by Troostwijk and Diemann in 1789.

Alkaline electrolysis typically operates at lower temperatures, such as 30–80°C, using an aqueous solution (KOH/NaOH) as the electrolyte, with concentrations ranging from 20% to 30%. The liquid electrolyte is not consumed during the reaction, but it needs replenishing over time due to system losses, particularly during hydrogen recovery. The system comprises a pair of electrodes submerged in this alkaline solution separated by a microporous diaphragm, typically asbestos. For cathode electrode, the material commonly used is nickel with catalytic coating like platinum, while for anode, metals such as nickel or copper coated with metal oxides like manganese, tungsten, or ruthenium are employed. The diaphragm, positioned in the middle of the cell, serves to separate the cathode and anode, as well as the produced gases, thereby preventing the mixing of gases during the electrolysis process.

The electrolysis process initiates at the cathode side, where water is introduced and decomposed into hydrogen (H_2) and hydroxyl ions (OH^-). The produced H_2 is released from the cathode surface and recombines in a gaseous form, while the hydroxyl ions (OH^-) migrate under the influence of the electrical circuit between the anode and cathode through the porous diaphragm to the anode. Here, they discharge to form oxygen (O_2) and water (H_2O). The O_2 recombines at the surface of the electrode, while hydrogen remains in the alkaline solution and is subsequently separated from the water in a gas-liquid separation unit external to the electrolyzer and escapes as hydrogen. This mechanism is illustrated in Figure 3.

$$\textbf{Cathode:} \quad 2H_2O + 2e^- \longrightarrow H_2 + 2OH^-$$

$$\textbf{Anode:}\quad 2OH^- \longrightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

$$\textbf{Overall cell:}\quad H_2O \longrightarrow H_2 + \frac{1}{2}O_2$$

Despite the maturity and widespread usage of alkaline electrolysis, the process does have some drawbacks, including limited current densities (typically below 400 mA/cm^2), relatively low operating pressure, and relatively low energy efficiency in the range of 50-60%.

A new approach in alkaline electrolysis involves the development of Anion Exchange Membranes (AEM) made from polymers with anionic conductivity, replacing asbestos diaphragms. This innovative technology shows promise in the field of alkaline water electrolysis and is presented in a later section.

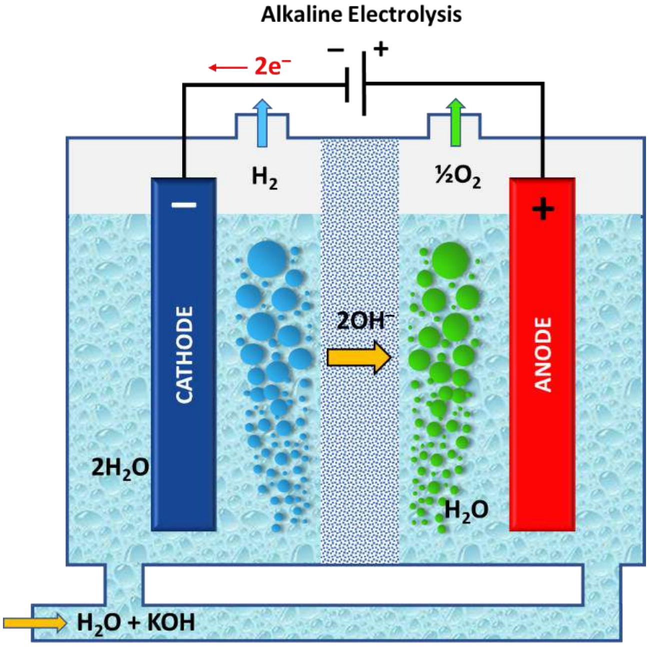


Figure 3 Schematic illustration of alkaline water electrolysis

2.2.2 Proton exchange membrane (PEM) electrolyzers

The concept of PEM water electrolysis was first conceptualized by Grubb in the early 1950s, with subsequent development by General Electric Co. in 1966 aimed at addressing the limitations of alkaline water electrolysis. PEM water electrolysis technology closely resembles PEM fuel cell technology, typically employing electrode catalysts such as Pt carbon, iridium, ruthenium, and rhodium and utilizing solid polysulfonated membranes like Nafion and fumapem as the electrolyte (proton conductor). These proton exchange membranes serve to both separate the electrodes and act as a gas separator and offer several advantages, including lower gas permeability, high proton conductivity (0.1 ± 0.02 S/cm), reduced thickness (R20–300 mm), and compatibility with high-pressure operations.

Principle of PEM water electrolysis

In PEM water electrolysis, the process involves the electrochemical splitting of water into hydrogen and oxygen at their respective electrodes: hydrogen forms at the cathode, and oxygen forms at the anode. This process begins with water being pumped to the anode, where it undergoes electrolysis to yield oxygen (O_2), protons (H^+), and electrons (e^-). The protons then migrate through a proton-conducting membrane to reach the cathode. Meanwhile, the electrons exit the anode through an external power circuit, providing the necessary driving force or cell voltage for the reaction. At the cathode, the protons and electrons combine to produce hydrogen, while oxygen gas and unreacted water remain as illustrated in Figure 4. Unlike other electrolyzer types, there's no need for a separate gas-liquid separation unit in PEM electrolyzers. Depending on purity requirements, a drier may be employed to eliminate residual water after the gas-liquid separation process. The reactions at the anode and cathode proceed as follows:

Anode: $$H_2O \longrightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$$

Cathode: $$2H^+ + 2e^- \longrightarrow H_2$$

Overall cell: $$H_2O \longrightarrow H_2 + \frac{1}{2}O_2$$

From a sustainability and environmental standpoint, PEM water electrolysis emerges as a favorable method for converting renewable energy into high-purity hydrogen. Notably, PEM water electrolysis has a compact design, offer low ionic resistances, allowing for high current density (above 2 A/cm^2), high efficiency ranging from 55% to 70%, rapid response, small footprint, operation at lower temperatures (20–80°C), and production of ultrapure hydrogen along with oxygen as a byproduct. Additionally, the simplicity of balancing PEM electrolysis plants adds to their appeal for industrial applications.

State-of-the-art electrocatalysts for PEM electrolysis typically involve high-activity noble metals like Pt/Pd for the hydrogen evolution reaction (HER) at the cathode and IrO2/RuO2 for the oxygen evolution reaction (OER) at the anode. However, the reliance on these noble metals contributes to the higher cost of PEM water electrolysis compared to alkaline water electrolysis. Consequently, one of the primary challenges in PEM water electrolysis lies in reducing production costs while maintaining high efficiency. Extensive research efforts have been directed towards enhancing PEM water electrolysis components, bringing this technology closer to commercial viability.

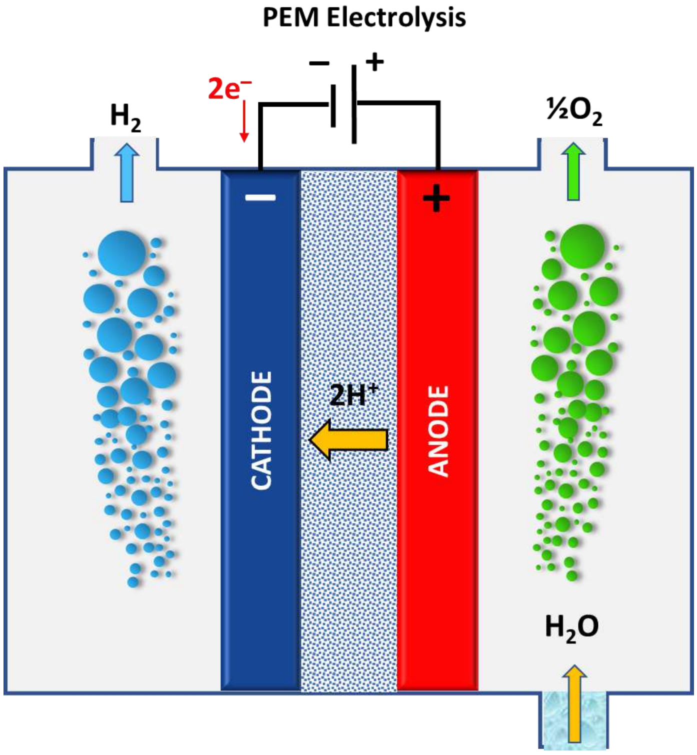


Figure 4 Schematic illustration of PEM water electrolysis

2.2.3 Solid Oxide Electrolysis Cell (SOEC) electrolyzers

Both AEL and PEM electrolyzers belong to the category of Low Temperature Electrolyzers (LTE), whereas the Solid Oxide Electrolyzer (SOE) is categorized as a High Temperature Electrolyzer (HTE). While LTE technologies like AEL and PEM have achieved widespread adoption, HTE, represented by SOE, stands out for its ability to perform water vapor electrolysis at elevated temperatures, resulting in superior efficiencies compared to LTE options. Additionally, HTE offers the potential to harness waste heat alongside electricity, further boosting its efficiency. However, durability issues stemming from harsh operating conditions, have delayed the commercialization of HTE technologies.

The concept of SOE was introduced by Donitz and Erdle in the 1980s. Since then, SOE has attracted significant attention due to its capability to convert electrical energy into chemical energy while producing ultra-pure hydrogen efficiently. Operating at high pressures and temperatures ranging from 500°C to 850°C, SOE utilizes steam as the water source.

Solid Oxide Electrolysis Cells (SOEC) function in reverse compared to solid oxide fuel cells, utilizing thermal energy alongside electrical energy to split water molecules. This approach enhances efficiency by reducing anode and cathode overpotentials, major contributors to power loss during electrolysis. Operating at higher temperatures, can significantly decrease combined thermal and electrical energy requirements. In SOEC operation, oxygen ions migrate through the electrolyte, leaving hydrogen in the unreacted steam stream, as shown in Figure 5. The reactions at the anode and cathode proceed as follows:

Anode: $H_2O + 2e^- \longrightarrow H_2 + O^{2-}$

Cathode: $O^{2-} \longrightarrow \frac{1}{2}O_2 + 2e^-$

Overall cell: $H_2O \longrightarrow H_2 + \frac{1}{2}O_2$

While similar to AEL systems, SOECs utilize a non-corrosive solid electrolyte, traditionally O_2 conductors, eliminating issues related to liquid handling or flow distribution. Recently, there has been growing interest in ceramic proton conducting materials for SOE, offering higher efficiency and superior ionic conductivity at temperatures between 500°C and 700°C. However, high-temperature operation requires specialized materials and fabrication methods, including yttria-stabilized zirconia (YSZ) electrolytes, nickel-containing YSZ anodes, and metal-doped lanthanum metal oxides. Despite its higher operating temperature, which presents advantages over low-temperature electrolysis methods, SOE faces challenges related to stability and degradation that must be addressed before large-scale commercialization can be achieved. Sealing also remains a challenge in SOEC systems and is subject to ongoing investigation.

Efficiency in high-temperature electrolysis depends on temperature and the thermal energy source. While efficiencies can be high, ranging from 85% to 90% with electrical input alone, incorporating the thermal source may reduce overall efficiency. For example, SOECs operating with advanced high-temperature nuclear reactors may achieve up to 60% efficiency. Efforts to explore alternative energy sources, such as solar energy, aim to further enhance efficiency and sustainability in high-temperature electrolysis processes.

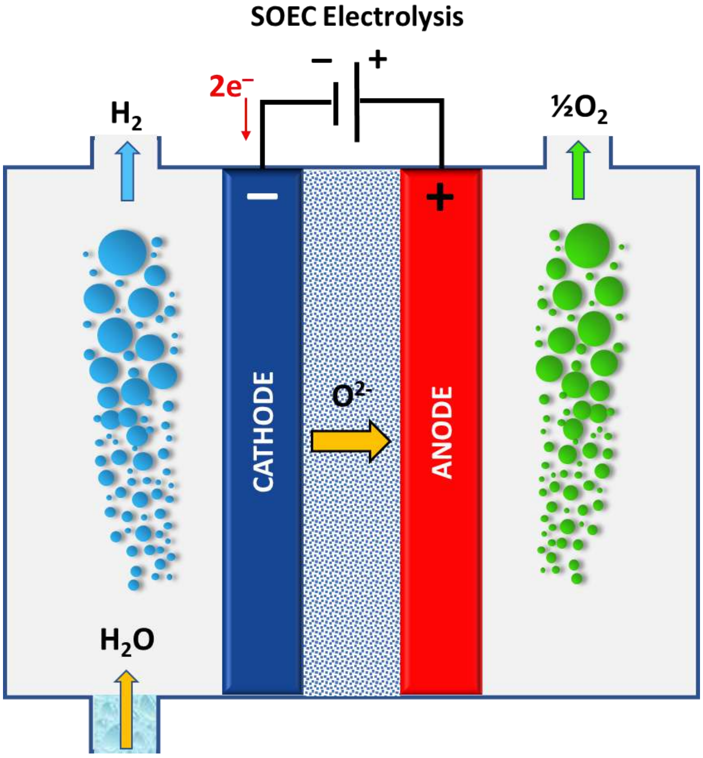


Figure 5 Schematic illustration of SOEC water electrolysis

2.2.4 Anion Exchange Membrane (AEM) electrolyzers

Anion Exchange Membrane water electrolysis (AEM) represents a cutting-edge technology that combines the strengths of both PEM and traditional AEL electrolysis for efficient and economical hydrogen production. Similar to AEL, the AEM cell transport anions (OH^-) instead of protons (H^+), resulting in distinct operational characteristics and benefits and adopts a "zero gap" design, which reduces cell resistance by narrowing the space between electrodes. This configuration optimizes performance and enhances conductivity, leading to improved efficiency in hydrogen generation.

At the heart of the AEM cell lies the Membrane Electrode Assembly (MEA), which is a system composed from an AEM and catalytic layers deposited either directly onto the membrane or the Gas Diffusion Layers (GDLs). This design allows for the seamless movement of hydroxide ions (OH^-) across the cell, facilitating the conversion of water into hydrogen and oxygen at the cathode and anode, respectively. The integration of anion exchange ionomers (AEI) further enhances ion conduction, paving the way for optimized performance and durability.

The water electrolyte in the AEM electrolyzer, typically containing only 1% potassium hydroxide (KOH), is primarily confined to the anode half-cell, moistening the membrane while leaving the cathode side dry. Consequently, hydrogen produced at the cathode possesses low moisture content, as no KOH is present in this half-cell. Water molecules traverse the membrane and undergo reduction at the cathode to yield hydrogen. An external power source establishes an electrical potential difference at the electrolyte-electrode interface, driving the hydrogen evolution reaction (HER) through electron transfer:

$$\textbf{Cathode:}\quad 2H_2O + 2e^- \longrightarrow H_2 + 2OH^-$$

Catalysts at the cathode facilitate this reaction by lowering its energy barrier. In the mild alkaline setting of the AEM electrolyzer, any remaining hydroxyl ions (OH^-) from the HER cycle back to the anode half-cell via the membrane. These exchanged OH^- ions are anions, giving the AEM its name. In contrast, in a PEM electrolyzer, protons (H^+) are transported through the PEM in a highly acidic environment demanding expensive materials to withstand the corrosive acidic conditions. The diluted KOH solution used in an AEM electrolyzer is significantly safer to handle compared to the highly alkaline electrolyte with a pH of 14 in a traditional AEL.

Once OH^- ions are transported back to the anode side of the AEM electrolyzer, they participate in the oxygen evolution reaction (OER):

$$\textbf{Anode:} \quad 2OH^- \longrightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

The overall cell reaction is then:

$$\textbf{Overall cell:} \qquad H_2O \longrightarrow H_2 + \frac{1}{2}O_2$$

For every two units of hydrogen produced, one unit of oxygen is generated by transferring four units of electrons. Consequently, the OH^- concentration in the electrolyte can remain constant by continually supplying water without additional KOH. The OER is initiated by the potential difference at the catalytic sites on the anode, and the resulting oxygen is expelled from the anode half-cell via the GDL along with the electrolyte circulation. The overall process is shown in the following figure (Figure 6).

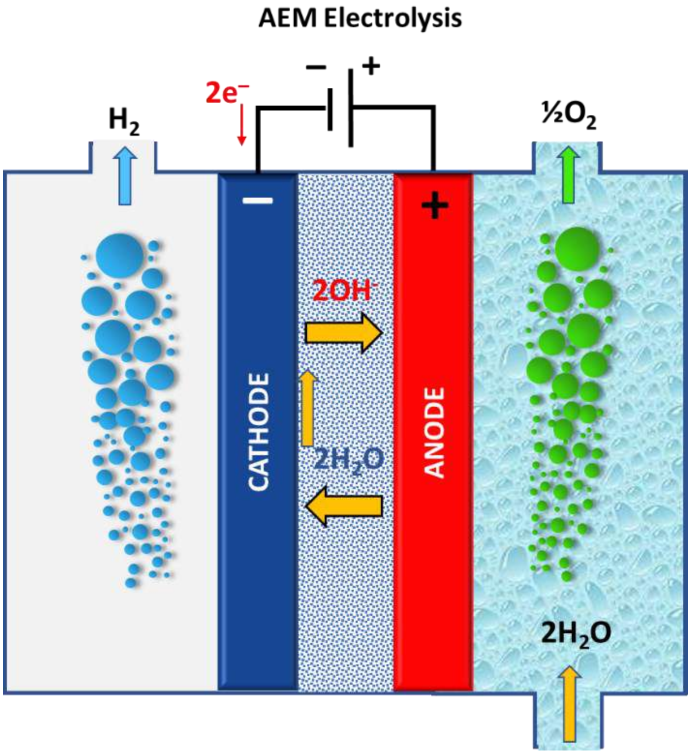


Figure 6 Schematic illustration of AEM water electrolysis

Operating in an alkaline environment similarly to traditional AEL, AEM offers flexibility to utilize low-cost, non-precious metal catalysts and materials, as well as the option to employ low concentrations of alkaline electrolytes (~1% KOH) or even distilled water. This departure from the high alkalinity required by conventional alkaline processes not only reduces operational costs but also offers improved process efficiency, operation in higher current density and lower gas penetration aligning more closely with sustainability goals. Moreover, the membranes and ionomers employed in AEM embody a shift towards greener alternatives, featuring hydrocarbon backbones and cationic groups for hydroxide ion conduction. This departure from perfluorinated membranes like Nafion™, which are not only costly but also release hydrogen fluoride (HF) upon chemical decomposition, underscores AEM's commitment to environmental stewardship.

Despite its promising advantages though, AEM is still in the research and development phase, lagging behind the more established PEM and AEL technologies. However, its potential to revolutionize hydrogen production cannot be overlooked. As advancements continue and scalability is achieved, AEM holds the promise of becoming a cornerstone of the green hydrogen economy, offering a pathway to sustainable and affordable hydrogen production on a large scale.

The following figure (Figure 7), illustrates the integration of both alkaline and PEM electrolyzers to form an AEM electrolyzer. This combination harnesses the advantages of both technologies to create a more efficient and versatile system for hydrogen production.

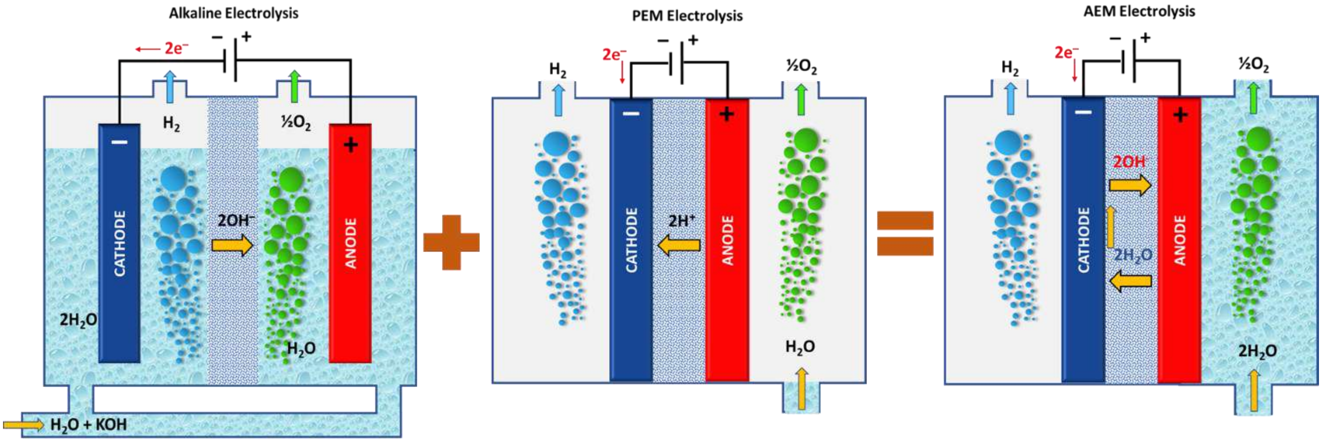


Figure 7 Combination of AEL and PEM technologies to create AEM electrolysis

2.3 Comparison of water electrolysis technologies

Alkaline and PEM electrolysis technologies have firmly established themselves in the market, benefitting from years of refinement and deployment. AEL, in particular, has a rich history of application within industries such as chlor-alkali production. While both technologies have reached TRL9 for dedicated hydrogen production, their continued competitiveness against fossil fuel-based methods relies on ongoing policy support and technological advancements to enhance efficiency and reduce costs.

PEM electrolysis has found significant application in small-scale hydrogen production. Its ability to operate at low temperatures and utilize a proton-conducting polymer membrane, sets it apart. The high efficiency of PEM electrolysis comes from its capability to function effectively even at high current densities and its rapid response to fluctuations in demand. However, this technology requires expensive catalysts and adherence to stringent maintenance protocols to ensure optimal performance. With advancements in technology and operational practices, PEM electrolysis systems have achieved high electrical efficiencies (stack and system), to around 50 kWh/kg H_2. These efficiency gains contribute to the overall viability and attractiveness of PEM electrolysis for various applications, especially where real-time responsiveness and compactness are essential considerations.

Alkaline electrolyzers on the other hand, utilize an alkaline solution, typically potassium hydroxide (KOH), as the electrolyte. While they may not achieve the same performance at high current densities as PEM electrolyzers, alkaline electrolysis offers the advantage of using less expensive catalysts, no critical raw materials and does not require a specific membrane. This characteristic makes it an appealing choice for large-scale applications, particularly in industrial hydrogen production settings. The system electrical efficiency of industrial-sized AELs typically ranges below 78 kWh/kg H_2, down to 50 kWh/kg H_2. They typically operate within a temperature range of 70 to 90°C and exhibit a current density of 0.2 to 0.8 A/cm^2. These operating parameters contribute to a stack lifetime of approximately 100,000 hours, highlighting the robustness and longevity of AEL systems. Despite its lower current density compared to the other alternatives, alkaline electrolysis remains a viable and cost-effective solution for large-scale hydrogen production applications.

Meanwhile, Solid Oxide Electrolysis (SOE) is rapidly progressing towards commercialization, offering promising prospects for large-scale hydrogen production with its high efficiency and adaptability to various operating conditions. SOE cells (SOEC) operate at high temperatures and employ a ceramic electrolyte that conducts ionic oxides. Although they rely on external heat sources for operation, SOECs have the advantage of being able to utilize residual heat from other industrial processes, thereby enhancing their overall efficiency. This capability contributes to the global efficiency of SOECs, making them a compelling option for hydrogen production, particularly in settings where waste heat is readily available, such as industrial hubs. Given that SOEC operation necessitates temperatures exceeding 700°C, industrial environments with existing heat sources can benefit greatly from the deployment of SOEC technology.

In contrast, AEM electrolysis is still in its early stages of development (TRL 4-5), despite being produced and commercialized on a smaller scale. The maturation of AEM technology holds potential for further innovation in the electrolysis landscape, offering the possibility of improved efficiency, cost-effectiveness, and environmental sustainability in hydrogen production. Continued research and investment in AEM electrolysis could lead to its broader adoption and contribution to the transition towards a hydrogen-based economy.

A summary of some characteristics of water electrolysis technologies described in the previous sections and from literature, are given in the following table (Table 3).

Table 3 Summary of characteristics of water electrolysis technologies [2] [3] [10] [11] [12] [13] [14]

Specification	PEM	AEL	AEM	SOE
Maturity (TRL)	Commercial (6-9)	Commercial (9)	Early Commercial (4-5)	Early Commercial (4-5)
Charger carrier	H^+	OH^-	OH^-	O^{2-}
Electrolyte	Solid polymer Perflurosulfonated acid (PFSA)	Aqueous solution KOH/NaOH 10-40%	Solid polymer KOH/NaOH ~1%	Solid ceramic Yttria stabilized Zirconia (YSZ)
Working fluid	Distilled water	High concentration solution	Distilled water or Low concentration solution	Steam
Separator	Nafion ®	Asbestos/Zirfon/Ni	Fumatech quaternary ammonia polysulfone (QAPS)	Solid electrolyte YSZ
Anode material (O_2)	Ir, Ru	Nickel coated perforated stainless steel	Nickel or NiFeCo alloys	LSMYSZ, $CaTiO_3$ Perovskites (LSCF, LSM) (La, Sr, Co, FE) (La, Sr, Mn)
Cathode material (H_2)	Pt, Pt carbon	Nickel coated perforated stainless steel	Ni, Ni-Fe, $NiFe_2O_4$	Ni/YSZ
Temperature, ˚C	50-80	70-90	40-60	700-900
Operation pressure	15-40 bar	2-30 bar	up to 35 bar	<10 bar
Hydrogen purity	99.9–99.9999%	99.5–99.9998%	99.9–99.9999%	99.9%
Voltage Efficiency (LHV)	50% - 68%	50% - 68%	52% - 67%	75% - 85%

Electrical efficiency (stack) (kWh/Kg H_2)	47 - 66		47 - 66		51.5 - 66		35 - 50	
Electrical efficiency (system)(kWh/Kg H_2)	50 - 83		50 - 78		57 - 69		40 - 50	
Cell voltage	1.4 - 2.5 V		1.4 - 3.0 V		1.4 – 2.0 V		0.95 - 1.50 V	
Cell area	<0.15m^2		1 - 3 m^2		<0.03 m^2		<0.02 m^2	
Current density	0.6 - 2 A/cm^2		0.2 - 0.8 A/cm^2		0.2 - 2 A/cm^2		0.3 - 1 A/cm^2	
Cold start (to nominal load)	<20 minutes		<50 minutes		<20 minutes		>60 minutes	
Stack lifetime	50,000 - 80,000 h		100,000 h		> 10,000 h		< 40,000 h	
Capital costs (stack) minimum		Target by 2050		Target by 2050		Target by 2050		Target by 2050
1 MW ($/kW)	400	<100	270	100	-	<100	>1200	<200
Capital costs (system) minimum 10 MW ($/kW)	700-1400	<200	500-1000	<200	-	<200	-	<300
Cathode reaction	$2H^+ + 2e^- \longrightarrow H_2$		$2H_2O + 2e^- \longrightarrow H_2 + 2OH^-$		$2H_2O + 2e^- \longrightarrow H_2 + 2OH^-$		$H_2O + 2e^- \longrightarrow H_2 + O^{2-}$	
Anode reaction	$H_2O \longrightarrow 2H^+ + \frac{1}{2}O_2 + 2e$		$2OH^- \longrightarrow \frac{1}{2}O_2 + H_2O + 2e$		$2OH^- \longrightarrow \frac{1}{2}O_2 + H_2O + 2e^-$		$O^{2-} \longrightarrow \frac{1}{2}O_2 + 2e^-$	
Total reaction	$H_2O \longrightarrow H_2 + \frac{1}{2}O_2$		$H_2O \longrightarrow H_2 + \frac{1}{2}O_2$		$H_2O \longrightarrow H_2 + \frac{1}{2}O_2$		$H_2O \longrightarrow H_2 + \frac{1}{2}O_2$	

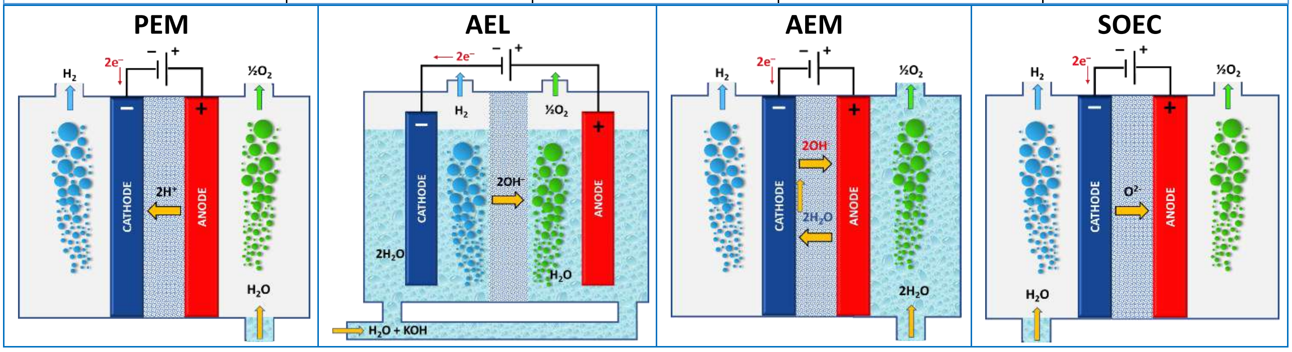


Table 4 below, summarizes the advantages and disadvantages of water electrolysis technologies.

Table 4 Advantages and disadvantages of water electrolysis technologies [3] [10] [12] [14]

Electrolysis Technology	Advantages	Disadvantages
PEM water electrolysis	- Commercialized technology - Compact and simple design - Fast response and startup - Operates higher current densities - High hydrogen purity - Suitable for load fluctuation	- Use noble materials - High membrane cost - Low durability - Acidic corrosion environment - Shorter lifetime
Alkaline water electrolysis (AEL)	- Well established Technology - Commercialized for large scale industrial applications (MW stacks) - Relatively low capital cost - Long term stability and durability - No use of noble material	- Corrosive electrolyte - Limited current densities - Relatively low H_2 purity - Slow startup - Crossover of the gasses - Relatively low operational pressure
AEM water electrolysis	- A mixture of the advantages of PEM and AEL - Suitable for load fluctuation	- Early stages of development - Commercial only at small scale - Low ionic conductivity

	- Cheap components - Low concentrated (1M KOH) liquid electrolyte	- Low membrane stability - Low lifetime
Solid Oxide water electrolysis (SOE)	- It can be used as a fuel cell - Can utilize residual heat from other industrial processes to achieve high efficiency - Due to the absence of noble material, the capital cost is low - High working temperature - Enhanced kinetics and thermodynamics	- Under development - Not commercial at large scale yet - Unstable electrodes - Safety and sealing problems - Bulky design - Using brittle material - High-temperature maintenance - Unsuitable for fluctuating and dynamic situations

Based on the analysis provided, both AEL and PEM technologies emerge as favorable options for the EPHYRA project. These established technologies have undergone extensive development and are already commercialized for large-scale hydrogen production, making them reliable choices for industrial applications. Despite their drawbacks, such as the use of costly materials and corrosive electrolytes, their proven track record and readiness for large-scale deployment outweigh these concerns. Therefore, the tender process for a large-scale industrial electrolyzer procurement in the EPHYRA project, initiated by the MOH, focuses exclusively on AEL and PEM technologies, recognizing their suitability and maturity for the project's objectives.

3 Vendor Evaluation Process

In this section, a detailed overview of the tender process and the evaluation of vendors' quotes is provided. The tender process involves several key steps, including the issuance of requests for quotes, the submission of vendor proposals, and the evaluation of these proposals against predefined criteria (commercial and technical). The evaluation process begins with the assessment of vendors' quotes based on various factors such as cost, quality, reliability, and compliance with project requirements.

3.1 Tender process

Figure 8, presents the timeline of the vendors’ evaluation process, which lasted approximately 11 months. The process started in May 2023 with the invitation to tender that was sent in thirteen technology vendors with AEL and PEM systems. Nine vendors responded with ten offers in total (one vendor provided two different technical proposals one with a 6x5 MW system and one with a 3x10 MW system). The technical proposals included two PEM and eight AEL systems. Most of the offers were pressurized technology with output pressures ranged from 14-30 barg. An atmospheric solution was also included among the offers.

The ten offers were tabulated and assessed (see Section 3.2) and a shortlist with six offers (five vendors) was generated based on the accept/reject criteria (see Section 3.4.1) in October 2023 (M5). Two rounds of clarifications were conducted with the shortlisted vendors, which concluded on a second shortlist of four offers (three vendors) in November 2023 (M6). A cost alignment of the four offers was performed to re-evaluate their proposals on an equal basis resulting in the final shortlist consisted of 3 offers (2 vendors) in February 2024 (M9). Detailed technical clarifications and commercial negotiations were carried out with the final two shortlisted vendors that concluded on the preferred vendor. A site visit to the manufacturing facility and to selected reference production plants was conducted in end-April 2024 (M11). Through the site visit in the selected reference production units, the proper and robust operation of the proposed technology by the vendor was verified as well as the manufacturing capability of the supplier. In end-May 2024 (M12) the award notice was sent to the winning bidder.

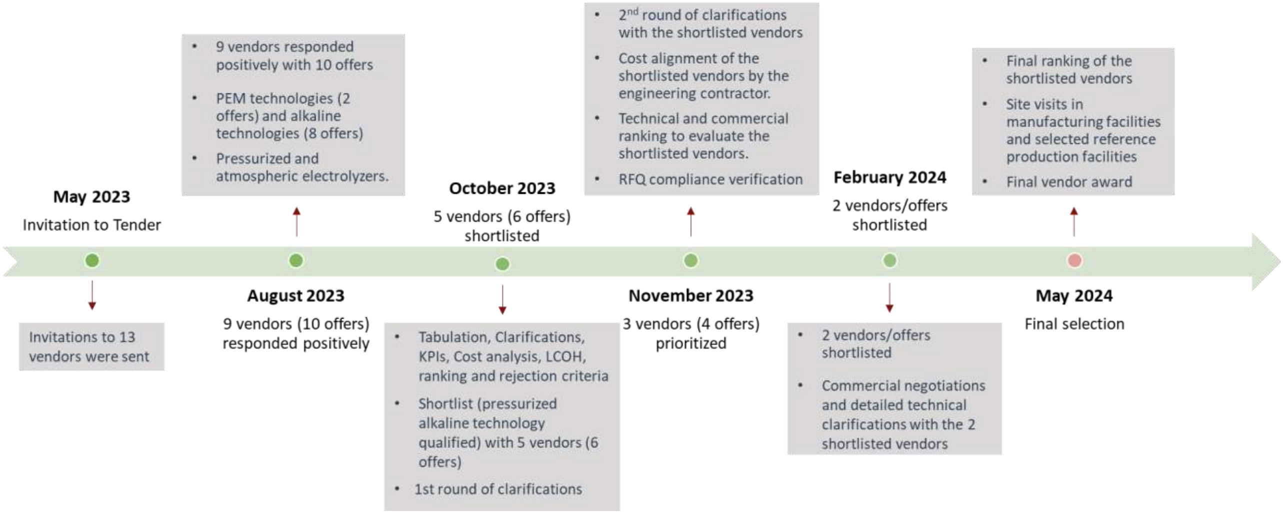


Figure 8. The timeline of the vendors' evaluation process.

Throughout the process two different methodologies were employed complementary to assess the technical and commercial offers:

- one methodology was developed by the engineering contractor with whom MOH collaborates for the Electrolyzer project at the Refinery premises (the engineering contractor that performs the FEED of the electrolyzer).
- the other methodology was developed by CERTH (partner of the EPHYRA project) to support the Task 1.1 *Technology validation of the EPHYRA project*.

The two evaluation methodologies are described in detail in Section 3.4.2 and Section 3.4.3. Section 3.2 describes the tabulation of the vendors and Section 3.3 provides an overview of the in-house LCOH tool developed by MOH. Both the vendor tabulation and the LCOH calculations supported significantly the comparison of the vendors in terms of both technical and commercial proposals and provided valuable input to the CERTH evaluation methodology.

3.2 Vendor tabulation

Vendor tabulation can provide a detailed view of vendor quotes in a structured format enabling a transparent comparison of the received offers. Therefore, MOH created a comprehensive tabulation of the electrolyzer vendors collecting all the technical and commercial data of the bidders and recording the key performance indicators (KPIs) of the quoted systems. More than 100 KPIs were considered in the tabulation covering the following categories and including the 2024 SRIA targets (Annex 1):

1. Performance data, e.g. power consumption, water consumption, degradation rate, productivity, availability
2. Financial data, e.g. LCOH, CAPEX, OPEX, O&M costs (incl. LTSA contract for maintenance)
3. Operating conditions, e.g. outlet pressure
4. Operation, e.g. turndown ratio
5. Design, e.g. stack capacity
6. BoP scope

7. After sales support
8. Support during project implementation
9. Certificates
10. Guarantees and warrantees
11. List of references and experience
12. EU presence

The vendor tabulation was used as input to the LCOH tool developed by MOH and to the CERTH evaluation methodology. Annex 1 and Annex 2 present the range of several important KPIs for the 30 MW electrolyzer and cost data based on the tender. The SRIA 2024 targets (when available) are also shown for comparison.

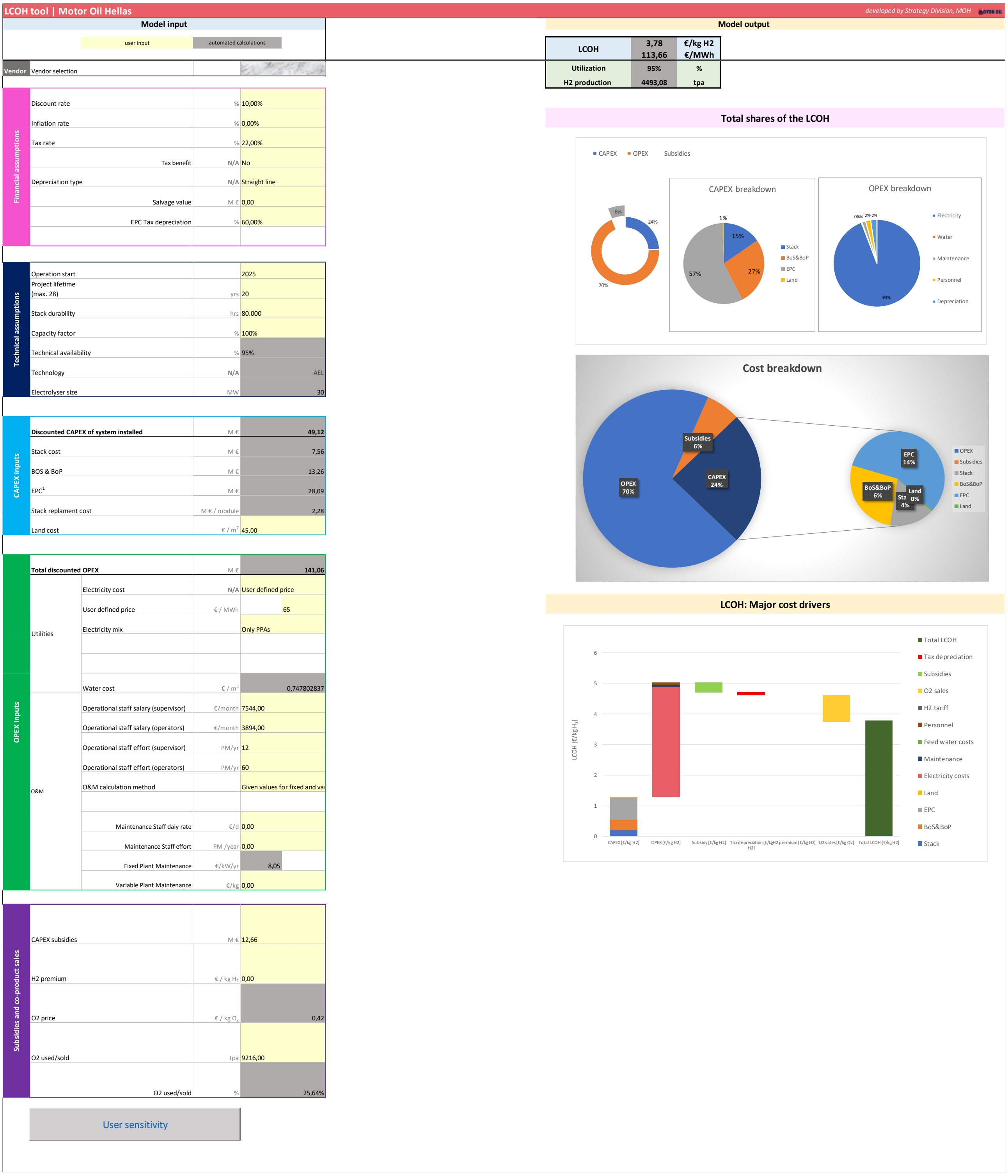
3.3 LCOH tool

The Levelized Cost of Hydrogen (LCOH) is considered a key performance indicator that entails both technical and financial data. MOH developed an in-house tool that calculates the LCOH of all vendors based on their tabulation (see Section 3.2). The resulted LCOH supported the vendors' evaluation and was also used as input/KPI to CERTH evaluation methodology. The tool was developed mainly for the purposes of vendors' evaluation within EPHYRA project; nonetheless, it was expanded to a more generic tool for future use and further technology assessments. To this end, the tool has the capability to calculate the LCOH based on user-defined data (both technical and financial) with certain degrees of freedom. It has a user-friendly interface and produces also informative graphs with the total LCOH shares and major cost drivers (Figure 9). It has been successfully validated against other similar tools commercially available.

The LCOH formula is given by the following equation:

$$LCOH = \frac{I_o + \sum_{t=0}^{n} \frac{M_t - D_t \cdot Tax\ rate}{(1+r)^t}}{\sum_{t=0}^{n} \frac{H_t}{(1+r)^t}}$$

where I_o is the total initial investment, M_t are the O&M costs (stack refurbishment costs every 10 years are also included in the operational expenses) in year t, D_t is the depreciation in year t, r the discount rate (in our case the company's WACC for the project) and H_t is the hydrogen production in year t. Index *n* is the project's lifetime. The tool is expanded to account also CAPEX subsidies and/or other allowances based on produced H_2 volumes as well as benefit from O_2 sales (savings from O_2 utilization in other units within the Refinery or external sales). With these additional functionalities the tool can estimate the LCOH under the industrial symbiosis that the EPHYRA project supports and promotes. The energy which is the major cost driver for hydrogen production is computed based on the PPA price (estimate) plus the grid charges. The tool has also the capability to account for an energy mix from PPA and own renewables for the electrolyzer (10 MW solar and 1 MW ORC, see also Section 4.1) and adjust the energy price according to their share.



LCOH tool | Motor Oil Hellas

developed by Strategy Division, MOH

Model input

user input | automated calculations

Vendor	Vendor selection		
Financial assumptions	Discount rate	%	10,00%
	Inflation rate	%	0,00%
	Tax rate	%	22,00%
	Tax benefit	N/A	No
	Depreciation type	N/A	Straight line
	Salvage value	M €	0,00
	EPC Tax depreciation	%	60,00%
Technical assumptions	Operation start		2025
	Project lifetime (max. 28)	yrs	20
	Stack durability	hrs	80.000
	Capacity factor	%	100%
	Technical availability	%	95%
	Technology	N/A	AEL
	Electrolyser size	MW	30
CAPEX inputs	**Discounted CAPEX of system installed**	M €	**49,12**
	Stack cost	M €	7,56
	BOS & BoP	M €	13,26
	EPC[1]	M €	28,09
	Stack replament cost	M € / module	2,28
	Land cost	€ / m²	45,00

OPEX inputs	**Total discounted OPEX**		M €	**141,06**
	Utilities	Electricity cost	N/A	User defined price
		User defined price	€ / MWh	65
		Electricity mix		Only PPAs
		Water cost	€ / m³	0,747802837
	O&M	Operational staff salary (supervisor)	€/month	7544,00
		Operational staff salary (operators)	€/month	3894,00
		Operational staff effort (supervisor)	PM/yr	12
		Operational staff effort (operators)	PM/yr	60
		O&M calculation method		Given values for fixed and va
		Maintenance Staff daiy rate	€/d	0,00
		Maintenance Staff effort	PM /year	0,00
		Fixed Plant Maintenance	€/kW/yr	8,05
		Variable Plant Maintenance	€/kg	0,00

Subsidies and co-product sales	CAPEX subsidies	M €	12,66
	H2 premium	€ / kg H_2	0,00
	O2 price	€ / kg O_2	0,42
	O2 used/sold	tpa	9216,00
	O2 used/sold	%	25,64%

Model output

LCOH	3,78 113,66	€/kg H2 €/MWh
Utilization	95%	%
H2 production	4493,08	tpa

Figure 9. LCOH tool dashboard.

For comparison of the vendors on an equal basis a cost alignment of the offers has been carried out. For the missing items from the scope of supply in the proposals, estimates have been used and added to the quoted price. The initial investment, I_o , in the LCOH tool corresponds to the total CAPEX on installed basis, i.e. it also includes the EPC costs, to account for the total investment cost (TIC). The installation and construction costs were estimated by the engineering contractor and include the electrolyzer construction (with miscellaneous), civil works, buildings, pipe material and their construction, electrical connections, engineering, management and permits, other and unforeseen. It should be noted that these are estimates and the final installation and construction costs will be defined during the phase of detailed engineering (WP4). Therefore, the LCOH presented in this Deliverable might change when the actual costs of the electrolyzer installation and the PPA agreement for the energy provision is finalized are considered.

The main assumptions for the LCOH calculations during the vendors' evaluation process are:

- 20 years project lifetime (refurbishment costs included)
- 100% capacity factor (max. H_2 production based on vendors' technical availability)
- Power price 65 €/MWh (PPA+grid charges)
- Discount rate (WACC=10%)

Figure 10 shows the LCOH of the six shortlisted vendors sorted from highest to lowest value. It is shown that the LCOH is ranged between 4.8-5.1 €/kg H_2, which is a quite competitive price for green hydrogen, considering that based on the Hydrogen Europe [15] the cost of producing renewable hydrogen was increased from 4.4 €/kg in 2021 to approximately 7 €/kg in 2022 (EU average). Please, note that vendor 4 and 5 are the same supplier with different solutions (a 6x5 MW system and a 3x10 MW system, respectively)

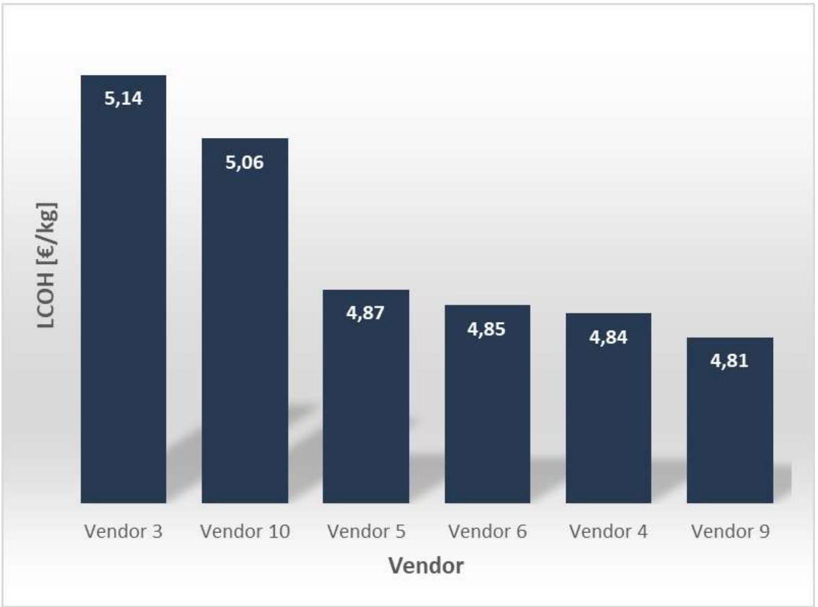


Figure 10. The LCOH for the six shortlisted vendors[1].

3.4 Evaluation methodologies

In this section, an analysis of the methodologies used for evaluating the vendor's offers is presented. Initially, the criteria used to determine whether to accept or reject vendor proposals are outlined, followed by the criteria used for ranking the offers. Then, the evaluation methodologies from MOH and CERTH are described in Sections 3.4.2 and 3.4.3 respectively. The results of both evaluation methodologies are shown in Section 3.5.

3.4.1 Accept/reject criteria

In both evaluation methodologies there were some accept/reject criteria that could automatically disqualify the vendors from the tender process. Some of these accept/reject criteria were set, because they were

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[1] Benefit from O_2 utilization in the Refinery Claus unit is excluded from these calculations. Thus, the related CAPEX costs, e.g. O_2 recovery system costs, are also excluded in this LCOH calculation. EPHYRA subsidy is also not taken into account in these calculations.

prerequisites for the EPHYRA project (e.g. pressurized technology, stack size) and others because they could jeopardize the timeline of project execution (e.g. long delivery time). The accept/reject criteria along with their pass and fail value are shown in Table 5.

Table 5. Accept/reject criteria.

Rejection criteria	Units	Pass value	Fail value
CE marking/certifications	-	Yes	No
Output Pressure	barg	>=14	<14
Delivery time	months	<=18	>18
FAT	-	Yes	No
SAT supervision and sign-off	-	Yes	No
Nominal Capacity per stack	MW	>5	<5
Total capacity	MW	[27-33]	<27 & >33

3.4.2 Technical evaluation compliance

In line with MOH policy, an external consultant (engineering contractor) supported the tender and evaluation process, which was dedicated to adhering to the highest standards of procurement. This methodology scores the vendors according to their technical compliance based on the Request for Quotation (RfQ) for the 30 MW Electrolysis system. Commercial terms are not considered in this methodology. Contrast to the more holistic approach described in Section 3.3, the idea of this methodology is to select the lowest bidder that better complies with the RfQ technical requirements (higher score).

The scoring has a range from 1-5 (integer values only). The key parameters that were included in the scoring process are:

- Scope of Supply (main equipment, electrical equipment, Instrumentation and Control (I&C) equipment)
- Scope of Services (FAT, SAT, transport to MOH site incl packages and taxes)
- Delivery time
- Guarantee figures (overall power demand, power consumption, H2 pressure at battery limit, water consumption, flexibility, min. turndown ratio, hot and cold ramp idle time, H2 production rate, operation hours to reach 10% degradation, heat rejection, total required plot area)
- General items (list of references)

As an example of the scoring methodology for **quantitative** items we present below (Table 6) the score for the overall power demand of the system (AC) and the hot idle ramp time:

Table 6 Example of quantitative items scoring

Score	Overall Power demand of the system
5	Lowest consumption
4	up to +5%
3	>+5% to +10%
2	>10%
1	no information

Score	Hot idle ramp time
5	≤ 2 min
4	≤ 3 min
3	≤ 5 min
2	≤ 10 min
1	>10 min, no data

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Clean Hydrogen Partnership

As an example of the scoring methodology for **not quantitative** items we present below (Table 7) the score for the scope of supply of main equipment and the scope of services:

Table 7 Example of not quantitative items scoring

Score	Scope of supply
5	Full scope of supply according RfQ
4	Minor items excluded (e.g. interconnecting piping, equipment of cooling system)
3	**One** Major item excluded (e.g. water treatment, H_2 purification)
2	>1 Major items excluded
1	Electrolyzer core delivered only

Score	Scope of services
5	all requirements fulfilled
4	minor restrictions
3	One major restriction
2	> 1 major restriction
1	no information

Based on this methodology the vendors received a score and the ones with the highest scores were further assessed based on their commercial offer/bids to conclude on the preferred vendor.

3.4.3 Ranking methodology based on commercial and technical data

For the vendor evaluation process, CERTH developed an evaluation methodology based on the weighted point method and using the vendor tabulation prepared by MOH. The tabulation is based on the commercial and technical data gathered from the tender process.

The weighted-point method is a methodology utilized for allocating benefits or rewards based on a predetermined set of criteria. It is widely utilized across various industries, including project management, procurement, and performance management, providing a transparent and objective means of assessing, comparing and evaluating different options, such as products, services and vendors. In this method, various attributes (criteria) that hold significance to stakeholders, are assigned weights based on their importance levels. Evaluators then assess each supplier's performance across these attributes and assign scores accordingly. These scores are subsequently multiplied by the respective weights of each attribute. Finally, the weighted scores are aggregated to determine the overall performance rating of each supplier. The supplier achieving the highest score is identified as the top performer. Therefore, the Weighted Point method consists of three main components:

1 Criteria: These are the standards or benchmarks used to evaluate options. Criteria can include both qualitative and quantitative factors such as cost, quality, performance, and sustainability. These criteria help establish the parameters against which options will be assessed.
2 Weightage: This refers to the importance or significance assigned to each criterion. Weightage determines the relative priority of each criterion in the decision-making process. Criteria deemed more critical or impactful may be assigned higher weights to reflect their importance.
3 Score: Scores represent the rating or assessment given to each option based on the criteria and their respective weightage. Each option is evaluated against each criterion, and scores are assigned accordingly. These scores are then used to calculate the overall performance or suitability of each option relative to others.

Together, these components form the basis of the Weighted Point System, providing a structured and systematic approach to decision-making by considering multiple factors and their relative importance.

3.4.3.1 Ranking criteria and Weightage

Table 8 shows the ranking criteria and the respective weights that were used in the evaluation methodology. These criteria prioritize aspects of the offers according to their importance to the project's objectives.

Nineteen KPIs were selected with different weighted factors based on the vendors' tabulation (Section 3.2). The ranking criteria were selected to cover technical and financial data, as well as commercial terms.

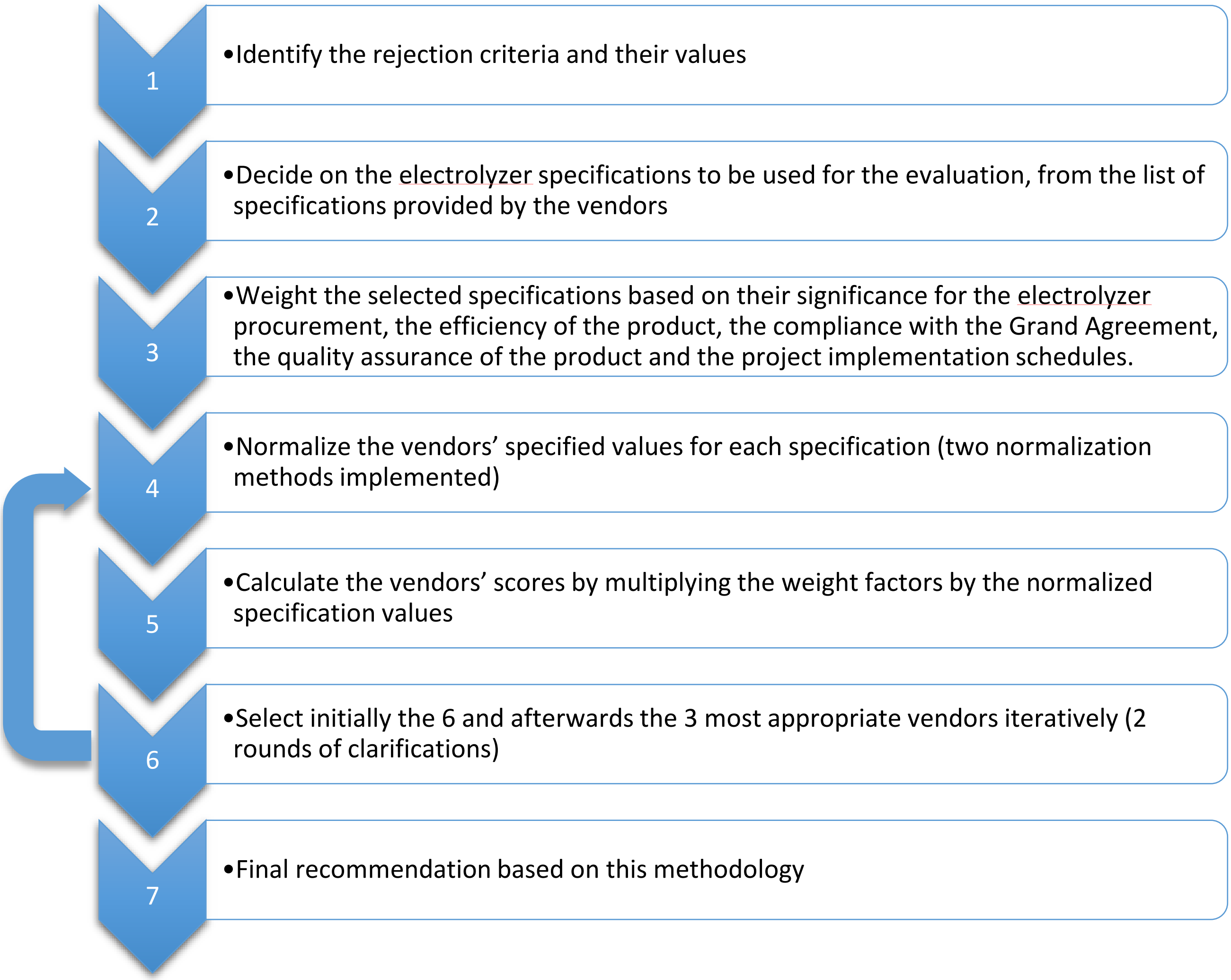
Table 8 Ranking criteria with their weighted factors

Category	Ranking criteria	Weighted factors
Costs (35%)	LCOH	15,00%
	Capital cost (electrolysis system)	5,00%
	EPC CAPEX of Complete System +BoP on installed basis (Calculated)	5,00%
	Total specific OPEX	5,00%
	O&M costs	5,00%
System Operation (30%)	System electricity consumption	5,00%
	Overall System Power	5,00%
	H2 production, nominal @ rated capacity @ max availability	5,00%
	H2 stack delivery pressure	5,00%
	Minimum achievable turndown ratio (Overall)	5,00%
	Hot idle ramp time	2,50%
	Cold idle ramp time	2,50%
System specifics (15%)	Degradation	5,00%
	Footprint	5,00%
	Stack lifetime	5,00%
Delivery & Experience (20%)	Delivery time	5,00%
	Warrantees	5,00%
	Presence in Europe/ EU content	5,00%
	References In Operation (Built & Operating)	5,00%

3.4.3.2 Scoring of the Vendors

As far as it concerns the scoring of the vendors, in the methodology applied in EPHYRA project, the scoring for each vendor was not assigned by an evaluator, but resulted from the values of the attributes provided on the technical specifications after applying normalization.

Based on the SRIA 2024 and the prerequisites of the EPHYRA project, there are some defined target KPIs concerning electrolyzers operation and hydrogen production. The bid invitation requested compliance with these targets, but none of the responded vendors, met all these targets. Therefore, in the methodology followed, two methods were applied for normalizing the values of the criteria, described on the subsequent sections. The steps followed on CERTH's methodology are shown in Figure 11 where steps 4 through 6 were iteratively implemented three times: first for the 10 vendors, then for the 6 selected from the initial 10, and finally for the three selected from the second round of evaluation, to conclude to the awarded vendor.



1. Identify the rejection criteria and their values
2. Decide on the electrolyzer specifications to be used for the evaluation, from the list of specifications provided by the vendors
3. Weight the selected specifications based on their significance for the electrolyzer procurement, the efficiency of the product, the compliance with the Grand Agreement, the quality assurance of the product and the project implementation schedules.
4. Normalize the vendors' specified values for each specification (two normalization methods implemented)
5. Calculate the vendors' scores by multiplying the weight factors by the normalized specification values
6. Select initially the 6 and afterwards the 3 most appropriate vendors iteratively (2 rounds of clarifications)
7. Final recommendation based on this methodology

Figure 11 Steps followed in CERTH's methodology to evaluate the vendors' offers

3.4.3.2.1 First normalization method

The first normalization method, normalizes the values of each ranking criterion in the range [0,1]. The final value depends on the minimum and maximum value responded by the vendors for each criterion and the preferred value of the criterion. More specifically, if a higher value is preferred for a particular criterion, then the normalization formula used is:

$$Normalized\ Value = \frac{Vendor_{val} - MIN_{val}}{MAX_{val} - MIN_{val}} \in [0,1]$$

where $Vendor_{val}$ is the value responded by the vendor, MIN_{val} and MAX_{val} are the minimum and maximum values of all responded values for the criterion, respectively. An example of this procedure is shown in the following table (Table 9).

Table 9 Example of ranking criterion values normalization with higher preferred value

Vendor	1	2	3	4	5	6	7	8	9	10
H2 production, nominal @ rated capacity @ max availability (tpa)	4352	4491	4588	4493	4493	5099	4838	5991	4447	4830
Normalized value (%)	0,0	8,5	14,4	8,6	8,6	45,5	29,6	100,0	5,8	29,2

Similarly, if a lower value is preferred for the criterion, the formula used is:

$$Normalized\,Value = 1 - \frac{Vendor_{val} - MIN_{val}}{MAX_{val} - MIN_{val}} = \frac{MAX_{val} - Vendor_{val}}{MAX_{val} - MIN_{val}} \in [0,1]$$

An example of this procedure in shown in Table 10.

Table 10 Example of ranking criterion values normalization with lower preferred value

Vendor	1	2	3	4	5	6	7	8	9	10
Electricity consumption (kWh/kg)	50	52	49,34	51,12	51,12	51,12	51,79	48,9	47,79	50,56
Normalized value (%)	36,7	0,0	63,1	20,9	20,9	20,9	5,1	73,6	100,0	34,1

3.4.3.2.2 Second normalization method

The second normalization method, separates the ranking criteria into two groups, based on whether a target value is applied on that criterion or not, as shown in Table 11 (criterion 18 is treated as binary).

Table 11 Grouping of ranking criteria

	Ranking criteria	**Units**	**Target value**		**Flexibility %**
			AEL	**PEM**	
1	LCOH	€/kg H2	4,5[2]	4,5[2]	20
2	Capital cost (electrolysis system)	€/kW	480	700	5
3	EPC CAPEX of Complete System +BoP on installed basis	€			
4	Total specific OPEX	€/kg/yr			
5	O&M costs	€/(kg/d)/y	43	30	5
6	Electricity consumption	kWh/kg	49	52	10
7	Overall System Power	MW			
8	H2 production, nominal @ rated capacity @ max availability	tpa	4898	4898	5
9	H2 stack delivery pressure	barg			
10	Minimum achievable turndown ratio (Overall)	%			
11	Hot idle ramp time	sec	30	1	5
12	Cold idle ramp time	sec	900	10	5
13	Degradation	%/1000 hrs	0,11%	0,15%	5
14	Footprint	m3			
15	Stack lifetime	hrs			
16	Delivery time	months			
17	Warrantees	yrs			
18	Presence in Europe	-	Yes	Yes	
19	References In Operation (Built & Operating)				

The first group includes criteria without target values. The normalization of values on this group, follows the previous method. The second group includes criteria, where target values from SRIA 2024 or prerequisites of the EPHYRA project, apply. As previously mentioned, the bid invitation requested compliance with these targets, but none of the responded vendors, met all these targets. Therefore, a flexibility percentage on the target values was applied, in order to identify and benefit the vendors that are closest to the target values.

This methodology, also categorizes criteria based on a higher or lower preferred value.

For **higher** preferred values on the criterion:

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[2] This is an initial estimated value without considering industrial symbiosis e.g. O_2 utilization, waste-heat recovery etc.

- If the vendor's value is below the flexible target value, then the vendor is assigned with a value of 0.
- If the vendor's value is between the flexible target value, and the target value, then the vendor is assigned with a value in the range [0,1].
- If the vendor's value is above the target value (where the target is reached), then the vendor is assigned with a value in the range [1,2] based on the normalization of all vendors' values, in the range *[$Target_{Val}$, MAX_{Val}]*.

The formula used is given below:

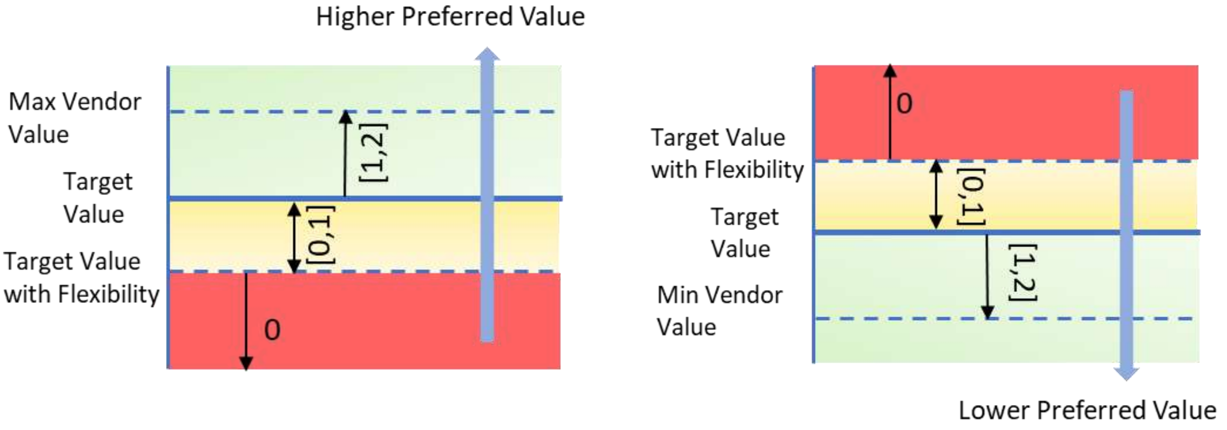
$$Normalized\,Value = \begin{cases} 0, & Vendor_{val} < Flex\_Target_{val} \\ 1 - \dfrac{Target_{val} - Vendor_{val}}{Flex\% * Target_{val}}, & Flex\_Target_{val} \leq Vendor_{val} < Target_{val} \\ 1 + \dfrac{Vendor_{val} - Target_{val}}{MAX_{val} - Target_{val}}, & Vendor_{val} \geq Target_{val} \end{cases}$$

where $Target_{val}$ is the target value, $Flex\%$ is the flexibility percentage given to the target value and $Flex\_Target_{val}$ is the new flexible target value.

For **lower** preferred values, similar reasoning is applied, where the formula used is:

$$Normalized\,Value = \begin{cases} 1 + \dfrac{Target_{val} - Vendor_{val}}{Target_{val} - MIN_{val}}, & Vendor_{val} < Target_{val} \\ 1 - \dfrac{Vendor_{val} - Target_{val}}{Flex\% * Target_{val}}, & Target_{val} \leq Vendor_{val} < Flex\_Target_{val} \\ 0, & Vendor_{val} \geq Flex\_Target_{val} \end{cases}$$

A schematic describing the above process is given in Figure 12a and 13b, respectively.



(a) (b)

Figure 12 Schematic describing the normalization of vendors values using flexibility percentage on target value. a) higher preferred values and b) lower preferred values on the criterion

3.5 Results of evaluation

In this Section the results of the two evaluation methodologies are shown, which concluded to the **same preferred vendor**. The preferred vendor is presented in Section 3.7.

3.5.1 Technical evaluation compliance

Figure 13 shows the score of the ten vendors that responded to the RfQ sorted by value. In addition to the score, the accept/reject criteria presented in Section 3.4.1 and the commercial criteria (price) were considered by MOH to shortlist the vendors. Thus, vendors 2, 1, 8 and 7 were rejected and not qualified for the next tender phase even though they might have higher score than others. Specifically, vendor 2 was rejected due to the high price and LCOH, vendor 1 was rejected due to the high price and long delivery time (24 months), vendor 7 was rejected due to the high price and LCOH, small stack capacity and long delivery time (22 months), and vendor 8 was rejected because it was an atmospheric and oversized system with small stack capacity. All shortlisted vendors were pressurized Alkaline Technology (AEL) (as per EPHYRA GA requirements).

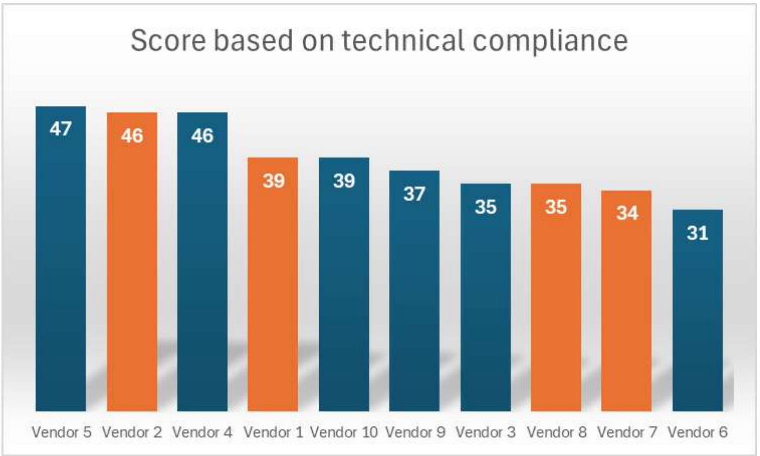


Figure 13. Vendors' score based on technical compliance with RfQ (sorted from highest to lowest score).

The above scoring methodology was repeated for the 6 shortlisted vendors after the 1st round of technical clarifications. The new score for the shortlisted vendors is shown in Figure 14 (sorted by value). Vendors 5, 4 and 9 have the highest scores, while vendor 6 is the vendor with the lowest score. In addition, vendors 5, 4, 9 had among the lowest quoted prices. The lowest quoted price was offered by vendor 6, however, it was rejected and did not proceed to the next phase because it could not offer the entire scope of supply (this is also reflected in its low score). Vendor 3 was also rejected as SAT was not included in the offer, transport to site was not offered and the scope of supply and services was restricted (limitations that are reflected to its low score).

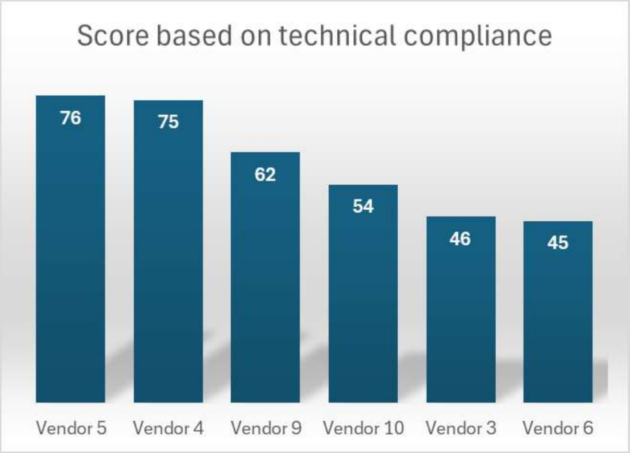


Figure 14. Score of the shortlisted vendors based on technical compliance with RfQ (sorted from highest to lowest score).

MOH proceeded in a 2nd round of clarifications with the four top score vendors (vendor 5, 4, 9, 10), which provide technology suitable for MOH requirements, mainly generating high amount of hydrogen with less fluctuations, and at the comparatively low quoted price.

Based on the scoring and the lowest bids the final shortlist after the 2nd round of clarifications consisted of vendor 5, 4[3] and 9 (*it is worth noted that both evaluation methodologies concluded on the same final shortlist*). A final detailed clarification round was followed. In the next phase, vendor 5 was rejected due to limited reference, smaller flexibility and higher power consumption. Between vendor 4 and 9 the evaluation process concluded on vendor 4 as the preferred vendor, because of its full scope of supply, low quoted price, low energy consumption, EU content, local support during project implementation and after sales services. Vendor 4 is **METACON AB** and is the **selected solution**.

3.5.2 Ranking methodology based on commercial and technical data

In this section the results of CERTH's methodology for evaluating the vendors are presented. Specifically, mostly the ranking results of the vendors at each stage are presented, while the argue behind the decisions for the vendors evaluation in the relative stages, are presented in short, since it is analyzed in detail in MOH's methodology in the previous section.

CERTH, as mentioned Section 3.4.3, applied two normalization methodologies on the technical data values for scoring the vendors. According to the tabulated vendors' offers data provided by MOH, including the calculated LCOH from MOH's tool, the first phase ranking results of the ten vendors is depicted in Figure 15. As discussed in Section 3.5.1, vendors 1,7 and 8 were rejected from the tender process due to the specified rejection criteria. Vendor 1 was rejected due to long delivery time (24 months), vendor 7 due to long delivery time (22 months) and low nominal capacity per stack (1 MW) and vendor 8 due to atmospheric output pressure of the electrolyzer, low nominal capacity per stack (2,425 MW), high overall capacity (38,8 MW), and low complete scope of supply (59,7%). Vendor 2 was rejected due to the high price and LCOH. Vendors 3 and 6, despite categorized as rejected in the first phase, (vendor 3 did not include SAT, and vendor 6 had relatively low value on complete scope of supply), they were proceeded in the next phase of evaluation, as after the 1nd round of technical clarifications and negotiations, the issues might be resolved.

(a) (b)

Figure 15 Ranking of ten vendors. a) first normalization method, b) second normalization method with flexibilities on target values

In the second phase after the 1nd round of clarifications, the ranking of the remaining 6 vendors is shown in Figure 16. Vendors 3 and 6 were rejected, since they did not eventually include SAT and higher scope of supply in their offers, respectively, after the negotiations. Therefore, 4 vendors remain for ranking, from which vendors 4,5 and 9 with the highest scores and after the 2nd round of clarifications, qualify for the next phase.

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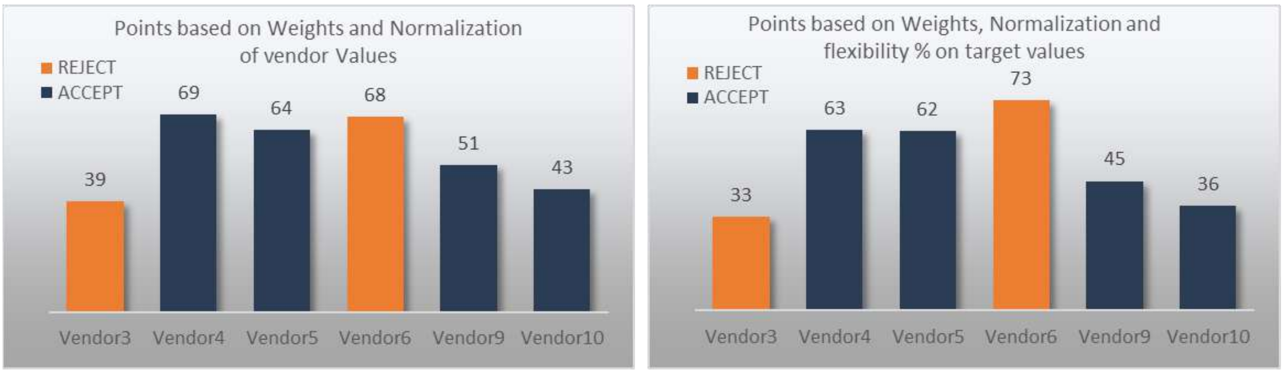
[3] Vendor 4 and 5 is the same manufacturing company offering two different solutions.



(a) (b)

Figure 16 Ranking of six vendors. a) first normalization method, b) second normalization method with flexibilities on target values

In the final phase, from the 3 remaining vendors (Figure 17) vendor 5 was excluded from the ranking due to limited references (as already explained in Section 3.5.1) and finally after having the results of commercial negotiations and detailed technical clarifications from MOH on the 2 highest score vendors, vendor 4 was suggested for the procurement of the electrolyzer which offers superior performance with respect to the ranking methodology.

(a) (b)

Figure 17 Ranking of three vendors. a) first normalization method, b) second normalization method with flexibilities on target values

As can be seen at all phases, both normalization methodologies provided similar ranking of the vendors, and most importantly in the final two phases after the clarifications (6 and 3 vendors), where the ranking was identical.

3.6 Evaluation conclusions

For the selection of the Electrolyzer technology and technology provider a tender process was carried out evaluating 10 offers/bids that responded to the RfQ prepared by MOH. The offers were evaluated using rigorous methodologies in line with MOH policy with the aim of selecting a solution with the best value for money offering.

The following criteria were considered and assessed in the evaluation process:

- **Total cost of ownership by estimating the LCOH**
- **Verification of technical compliance with RfQ (using a ranking/scoring methodology developed by the engineering contractor that performs the FEED of the electrolyzer)**

- **Technical and commercial evaluation that assess both the technical and financial data (using a ranking/scoring methodology developed by CERTH). The 2024 SRIA targets were also considered as ranking criteria**
- **Quoted price (bid)**
- **Acceptance/rejection criteria requirements**
- **EU content requirements**

For consistent comparison on an equal basis (because not all vendors offered the complete scope of supply) a cost alignment of the offers was carried out with the support by the engineering contractor. In parallel, accept/reject criteria (see Section 3.4.1) were set based on the EPHYRA project's requirements (e.g. nominal capacity, stack size) and KPIs that could jeopardize the project (FAT/SAT not offered) and its timeline (long delivery time). Vendors that did not meet this accept criteria were rejected and disqualified from the tender process without considering their score in the ranking methodologies. In addition, vendors with high quoted price and higher LCOH compared to the rest of the offers were also rejected and not proceed to the next tender phase.

At the first phase, vendors 1, 2, 7 and 8 were rejected because they did not meet all the abovementioned accept criteria (as described in Section 3.5 in detail). The qualified vendors proceeded to the next phase which involved a series of clarification rounds. The final shortlist with three offers (vendor 4, 5 and 9) was concluded based on their level of technical compliance with the RfQ (based on their score), the total cost of ownership (LCOH), their rank/score based on commercial and technical data (CERTH ranking methodology) and the quoted price. However, vendor 5 was disqualified next due to the limited reference, smaller flexibility and higher power consumption compared to the other two candidates.

Between the two final candidates, vendor 4 had the highest score based on both ranking methodologies, but vendor 9 had a lower quoted price and marginally lower LCOH. However, vendor 9 does not comply with the EU content, as the complete plant including BoP is manufactured in China. On the contrary, vendor 4 complies with the EU content requirements (EU components exceed 60% of contract value incl. the technical service agreement for the after sales organization). Based on all the above, vendor 4 (**METACON AB**) was selected as preferred solution, because it combines **low total cost of ownership** with higher flexibility and efficiency - KPIs that are reflected also in its score- but it also constitutes a solution with **EU presence** compared to vendor 9. The EU content of vendor 4 will not only provide support during project implementation and reliable after-sales services but it will also contribute to achieving the overarching objectives of the CHJU topic and the EPHYRA project. Its selection will enhance EU industrial competitiveness and it will support EU manufacturers in fostering a sustainable and robust European ecosystem for green hydrogen production.

To sum up, the selected vendor offers superior Total Cost of Ownership (LCOH) with highest technical and commercial ranking which at the same time complies with acceptance criteria, MOH technical requirements and EU content requirements.

3.7 The selected vendor

As described in the previous Sections, Motor Oil (Hellas) has conducted a comprehensive and detailed tender process aimed at selecting the most suitable electrolysis equipment system to produce green hydrogen, considering also the with Clean Hydrogen Partnership "Strategic Research & Innovation Agenda (SRIA)" KPI's for 2024. This process was meticulously designed to align with the principles of best value for money, ensuring that the chosen solution not only meets but exceeds the project's expectations in terms of efficiency, cost-effectiveness, and support.

The selection criteria were exhaustive and inclusive, taking into consideration not only the cost and technical capabilities of the equipment but also the degree of alignment with all the objectives of the Clean Hydrogen

Partnership. This includes a robust evaluation of the Total Cost of Ownership (TCO) including the after-sales support organization and services in line with the objectives of EPHYRA project, which we regard as crucial for the long-term success and sustainability of the project.

The rigorous evaluation process that is described in this Deliverable concluded on a preferred vendor, which is METACON AB (vendor 4). Our assessment concluded that the preferred vendor not only meets the project's stringent requirements to a greater extent compared to the rest candidates but also significantly contributes to achieving the overarching objectives of the CHJU topic and the EPHYRA project. Their proposition stands out in terms of innovation, efficiency, and the ability to provide a sustainable solution for hydrogen production in the EU.

In addition, the preferred vendor has confirmed with a formal letter the EU content of their proposal, which attests to their compliance with the local content requirements set forth by the CHJU contributing to EU competitiveness and industrial leadership. In their letter, the preferred vendor confirms its role as a key supplier for the electrolyzer package for Motor Oil refinery emphasizing their comprehensive and active involvement in the design, manufacture, and provision of energy systems for hydrogen production. Highlighting their commitment to enhancing EU industrial competitiveness and fostering a strong European hydrogen supply chain, the preferred vendor outlines their extensive experience and innovative approach in developing green hydrogen technologies. Significantly, their participation in the project is set to enhance the European knowledge base in green hydrogen, supporting their strategic plans to develop a manufacturing facility within the EU. They also detail the structure of their supply chain for the project, underscoring the substantial European content exceeding 60% of the contract value (incl. the technical service agreement for the after sales organization). Their supply chain is predominantly comprised of EU-based suppliers, with the assembly of critical components primarily conducted within the EU, ensuring a comprehensive European manufacturing footprint. Additionally, their after-sales support services and operational frameworks are exclusively positioned within the EU, reinforcing their integral role in fostering a sustainable and robust European ecosystem for green hydrogen production.

The METACON technology comprises a 30 MW pressurized alkaline electrolyzer as a turn-key solution (entire scope of supply, stack and BoP). Table 12 shows the LCOH and the SRIA 2024 KPIs of the 30 MW electrolysis system indicating that the selected vendor supports the EPHYRA's targets to a satisfactory extent. It should be noted that none of the candidate vendors met all the targets.

Table 12. Selected vendor compliance with EPHYRA targets.

	Assessment criteria	Units	EPHYRA Targets[4]	METACON AB
Total cost of ownership	**LCOH[5]**	**€/kg**	**-**	**4,84**
	Normalized LCOH[6]		**3,3**	**3,02**
SRIA KPIs	Electricity consumption @ nominal capacity	kWh/kg	**49**	**49,45**
	Capital cost (stack+BoS)	€/(kW)	**480**	**396**
	O&M cost	€/(kg/d)/y	**43**	44
	Hot idle ramp time	sec	**30**	180
	Cold start ramp time	sec	**900**	1080
	Degradation	%/1,000h	**0,11%**	**0,10%**

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[4] As per SRIA 2024.

[5] Without O_2 benefit, EPHYRA subsidy and system integration benefits (behind the meter energy supply incl. ORC power recovery and discounted grid charges-to be confirmed).

[6] With O_2 benefit, EPHYRA subsidy and system integration benefits (behind the meter energy supply incl. ORC power recovery and discounted grid charges-TBC).

	Current density	A/cm2	**0,7**	0,35
	Use of critical raw materials as catalysts	mg/W	**0,3**	**None**

Finally, Figure 18 shows the LCOH of the selected vendor at project level and how it is affected by considering the following factors of the integrated system under an industrial symbiosis environment:

- CAPEX (estimate) with O_2 recovery & purification system and auxiliary BoP systems by EPC (N_2, chiller etc.) – base case
- Subsidy (as per EPHYRA grant)
- O_2 sales (9216 tpa O_2 utilized in the Refinery Claus unit @ 0.42 €/kg)
- Behind the meter energy supply and grid discounts for Electrolyzers (to be verified during execution)

Figure 18. The LCOH of the selected vendor (METACON AB).

4 Technical requirements of the integrated industrial green hydrogen production system

In addition to the technology assessment and vendor evaluation methodology, the deliverable also includes an assessment of the technical requirements essential for the successful integration of an industrial green hydrogen production system. This assessment aims to identify the necessary components, specifications, and operational considerations needed to achieve project objectives effectively. The technical requirements for the integrated system include:

- Provision of green electricity: Ensuring that the electricity used in the hydrogen production process is sourced from renewable sources to minimize environmental impact.
- Utilization of waste heat to support electrolyzer operation: Leveraging waste heat generated by industrial processes to enhance the efficiency and performance of the electrolyzer.
- Non-freshwater usage: Implementing water conservation measures and exploring alternative water sources to minimize freshwater consumption in the production process.
- Utilization of produced oxygen within the MOH Refinery: Maximizing the use of by-products from the hydrogen production process, such as oxygen, within the refinery's operations to improve overall efficiency and sustainability.

- Technology validation for the required pipeline work: Ensuring that the pipeline infrastructure necessary for the integrated system meets the required standards and specifications for safe and efficient operation.

By addressing these technical requirements comprehensively, the project aims to optimize the efficiency, sustainability, and reliability of the industrial green hydrogen production system within the MOH Refinery.

4.1 Provision of green electricity

The European Commission approved the Additional Delegated Act [16] which identifies two scenarios for hydrogen to be considered fully renewable: a) The Hydrogen production facility can be directly connected to the renewable energy resources and there is no connection to the grid, b) the hydrogen facility is connected to the grid, but the electricity used can be demonstrated that comes from renewable resources.

In Ephyra project, green electricity to the electrolyzer will be provided combining different renewable energy sources (RES) distributed in Greece. These resources comprise solar power plants and wind farms. They will operate as a virtual power plant (VPP) combining their energy and subscribing a green power purchase agreement (PPA) with MOH to define the cost of the energy for long-term periods. For the first stage of the project, where the electrolyzer has to operate at reduced power (~50% of 30MW), MOH has secured solar Power Purchase Agreement (PPA) for the electrolyzer project from MORE. MORE is a subsidiary company of the Motor Oil Group and a leading force in the field of RES as one of the largest RES producers in Greece and one of the most important in South-eastern Europe.

In addition to the RES operating as VPP, the power plant for the electrolyzer will include an Organic Rankine Cycle (ORC) that can generate up to 1MW of electric power based on the wasted heat energy of the electrolyzer. Additionally, MOH has already installed 2MW of solar panels and envision to install up to 10MW in the future (4.9MW in 2024 and 3.1MW in the future) at the premises of the Refinery to complement the supply of green power. It defines a redundant power supply system for the electrolyzer where the energy contribution of each source can be optimized to minimize the total cost of energy for the H2 production.

To configure the operation of the power plant, it is necessary to consider the behaviour of each of the resources that comprise the plant. Solar and wind RES externals to MOH, normally will operate as VPPs, associated with a PPA contract. The solar power generated at the premises of the Refinery will incur only in cost of maintenance and operation (minimum). The ORC will provide energy with minimum costs for the system. More details about the ORC system and the net energy that that can be utilized by the Electrolyzer can be found in Section 4.2.

During operation, the total RES power will be variable due to weather conditions and, at some time instant, it can be larger than the maximum power capacity of the electrolyzer. In that case, the plant can sell the excess energy to the electric market or use it in the Refinery plant. This will provide a net benefit for the system due to the price different of the electricity between the one in the PPA and the market clearing price (MCP). All these operating conditions have to be taken into account by the system´s energy management control to optimize the benefits in the H_2 production. When the total renewable power produced is lower than the maximum capacity of the electrolyzer, this device will operate at reduced power, consuming the maximum power generated by both the RES and the ORC. It is important in this case, to combine different types of RESs to conform the VPP in order to balance or distribute the power generated along the day. For example, combing wind and solar power, the wind energy can provide power during the night when the solar power plant is shut-down.

4.2 Valorization of waste heat

An Organic Rankine Cycle (ORC) is a thermodynamic cycle that converts thermal power into mechanical power. The operating principle is equivalent to that of a traditional Rankine Cycle, with the difference being the working fluid used. In fact, an ORC uses an organic fluid, which allows the exploitation of thermal sources at low to medium temperatures, whereas a traditional Rankine steam cycle requires thermal sources at high temperatures. A typical schematic of an ORC is shown in Figure 19.

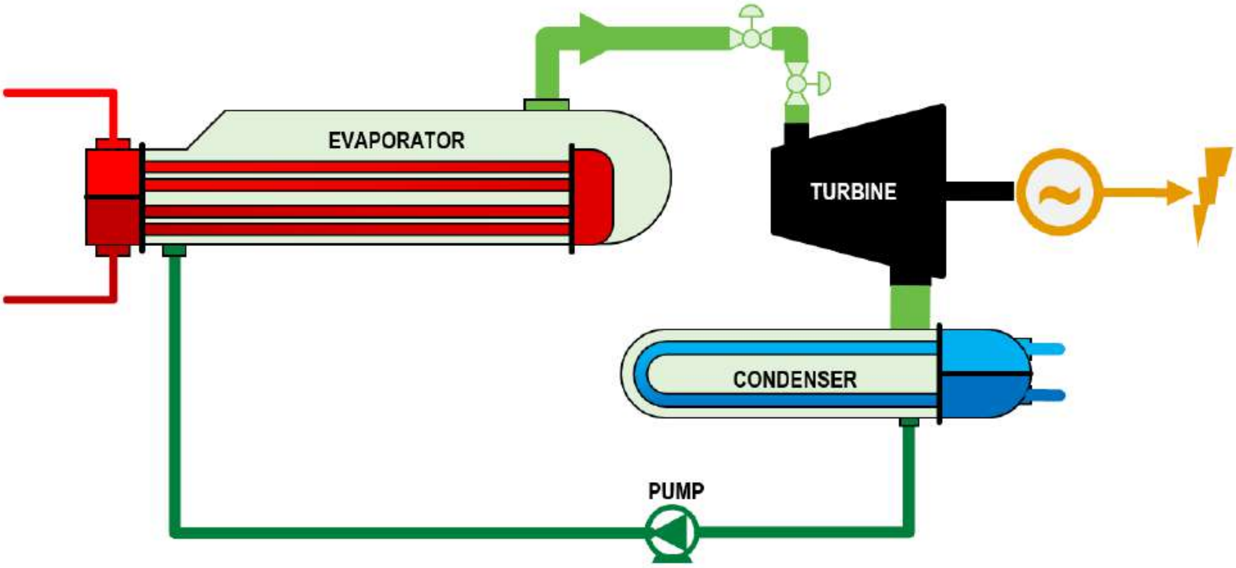

Figure 19 Schematic of an ORC

This is a closed cycle in which the pump compresses the cold organic fluid that is taken from the condenser and sent to a heat exchanger (evaporator) where it is evaporated. At the outlet of the evaporator, organic fluid vapor (which may be saturated or superheated, depending on the case) expands through a turbine. This, being connected to an electric generator, generates electricity. If the organic fluid vapor discharged from the turbine is still at a high temperature, a recuperator can be used to heat the fluid at the pump outlet. The cycle ends with the low-pressure, low-temperature vapor being condensed in the condenser, which can be air- or water-cooled.

As part of the EPHYRA project, a study was carried out during the first year to investigate the possibility of integrating an ORC to a 30 MW electrolyzer in order to valorize its waste heat. The electrolyzer stacks must be kept at a constant temperature in the range of 85-90°C. For this purpose, a cooling water loop is foreseen. The purpose of the study conducted in T2.1 is to provide a preliminary assessment of the solution in which the cooling water loop is replaced by an ORC.

Five test cases are considered in the study.

- Scenario #1) Electrolyzer cooled by an ORC with air-cooled condenser (Figure 20)
- Scenario #2) Electrolyzer cooled by an ORC with cooling water condenser (Figure 21)
- Scenario #3) Electrolyzer cooled by cooling water circuit and ORC using another source of waste heat available in the refinery (Figure 22)
- Scenario #4) The ORC fluid pre-heated in the electrolyzer and vaporized in an external source from the refinery streams (waste heat at about 150°C), with ORC using air-cooled condenser (Figure 23)

- Scenario #5) The ORC fluid pre-heated in the electrolyzer and vaporized in an external source from the refinery streams (waste heat at about 150°C), with ORC using water-cooled condenser (Figure 24)

Scenario #1 would avoid the use of water for cooling the electrolyzer. On the other hand, this configuration presents a major risk with regard to the effective ability to cool the electrolyzer during summer operation. The study is done with the assumption that the air-cooled condenser is designed to keep 20°C as a difference between the condensation temperature of the organic fluid and the air temperature: in the nominal case (air temperature at 20°C), the condensation temperature of the organic fluid in the condenser is 40°C. If the heat exchanger for cooling the electrolyzer stacks is designed for this nominal case, in the summer case (air temperature above 40°C) this will not allow the electrolyzer to be cooled effectively to maintain the stack temperature at 85-90°C. Mitigating this risk requires a major overdesign of the exchanger dedicated to cooling the electrolyzer, with a major impact on the investment cost for this component.

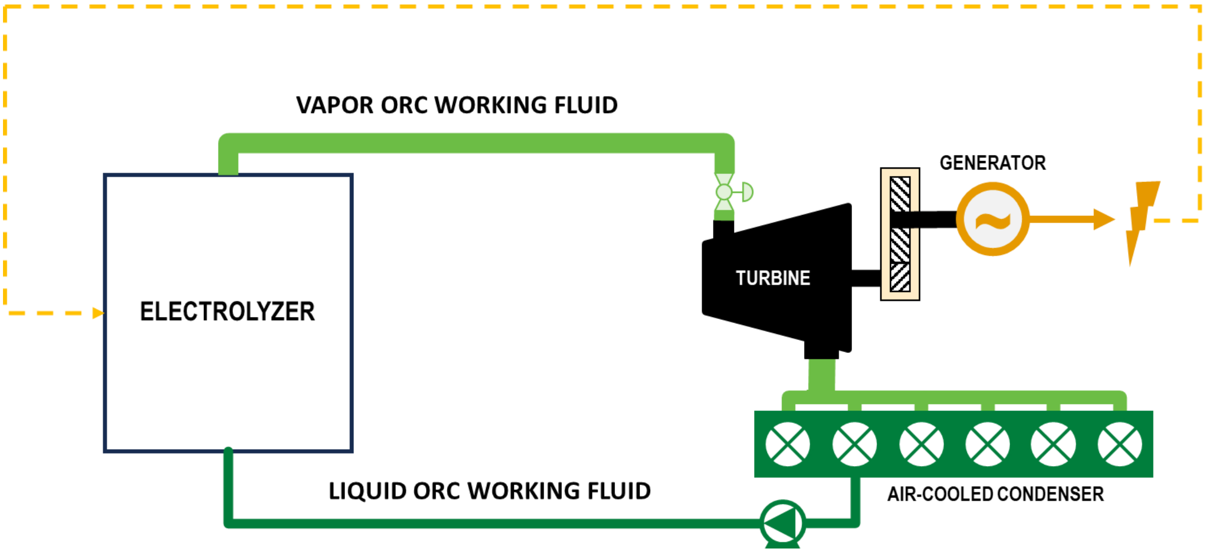

Figure 20 Scenario 1

Scenario #2 introduces a water-cooled condenser loop for the ORC condenser. The water-cooled condenser allows for an important reduction in fluctuations of condensation temperature during the annual operation of the system and actually mitigates the risk just presented for Scenario #1. In any case, considering the low temperature difference between which the ORC operates (about 35-40°C), the efficiency is between 4.5%

and 5%, with an electrical output of about 310-335 kW. As a result, the cooling water loop must be sized to dissipate almost all the thermal power that the ORC recovers from the electrolyzer.

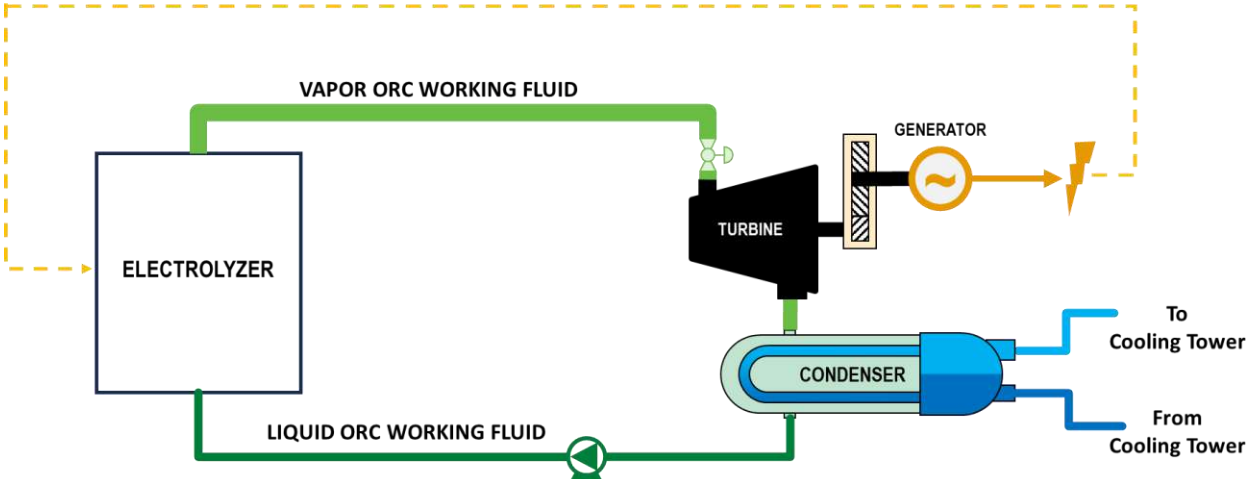

Figure 21 Scenario 2

Scenario #3 considers decoupling the electrolyzer from the ORC: the electrolyzer will be cooled with a cooling water loop while the ORC will be installed elsewhere in the refinery to take advantage of waste heat available in the 100-150 °C range. Moreover, this solution minimizes the risks associated with Scenario#1 and Scenario #2 for integrating the electrolyzer with the ORC. It also allows the ORC to work with heat sources that can produce at least 1 MW and are normally stable throughout the year, unlike the waste heat from the electrolyzer which is more variable throughout the year as it depends directly on the load of the electrolyzer.

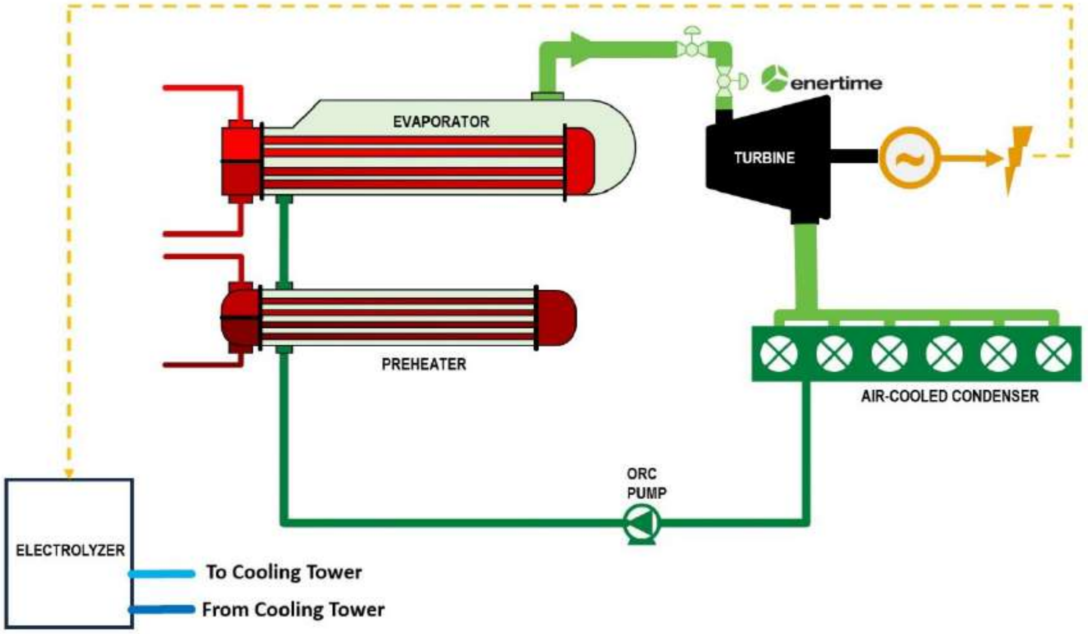

Figure 22 Scenario 3

Scenario #4 and Scenario #5 use first the waste heat from the electrolyzer in a first preheater. Then, a refinery stream in the range 100-150 °C is used in a second pre-heater and in the evaporator, where the ORC working fluid evaporates before entering the turbine. Scenario #4 considers and ORC with an air-cooled condenser, while scenario #5 presents an ORC with water cooling.

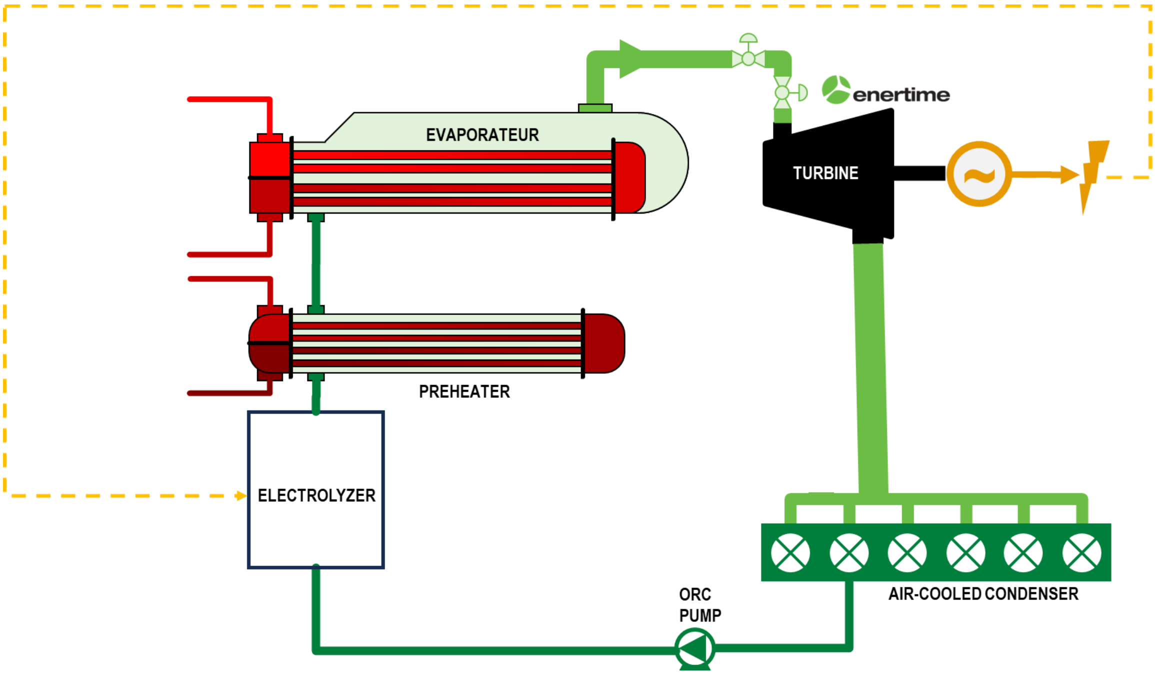

Figure 23 Scenario 4

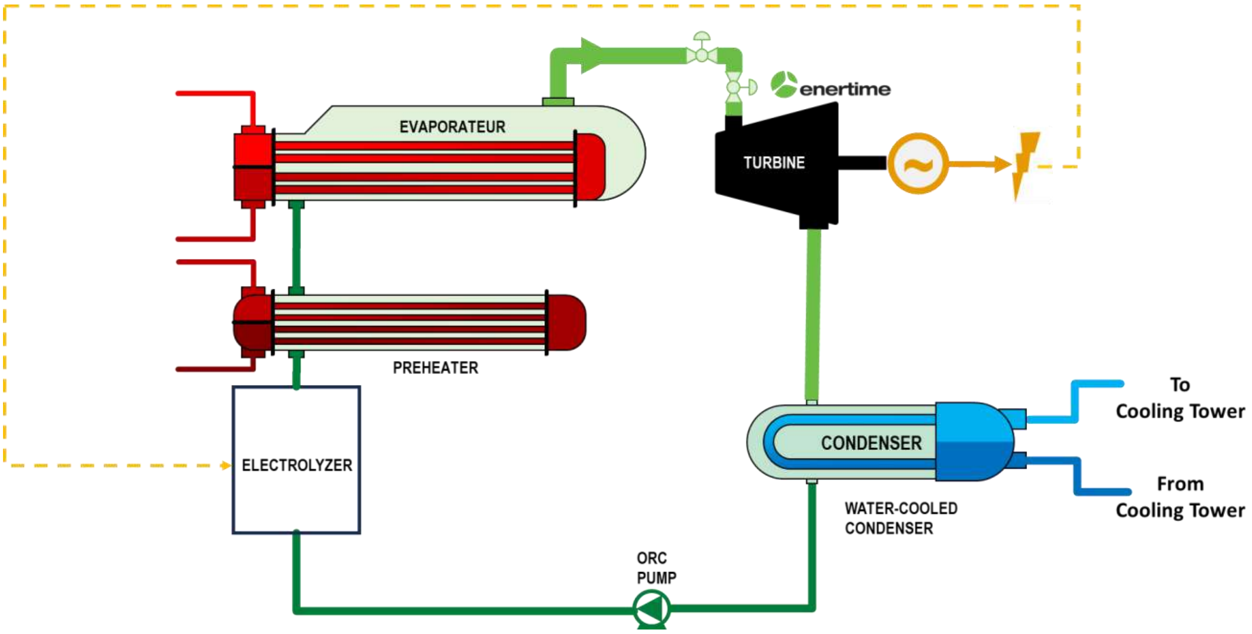

Figure 24 Scenario 5

About Scenario#4 and Scenario #5, since the refinery stream used in the evaporator is in the range of 100-150 °C (as for Scenario #3), the ORC net output is maximized when cooling the hot source to approximatively 85°C.

As most of the ORC heat input is used to evaporate the working fluid at approximatively 105°C, only ~15% of the exchanged heat is used in preheating the working fluid at 70°C, which could be possible with the electrolyzer stack at about 85/90 °C. Hence, adding the waste heat from the electrolyzer stack to the existing refinery stream (working in the preheater between 100 and 85°C) will not affect the performance, but will increase the costs for the system. As no performance increase is expected in comparison to Scenario #3, but cost will increase, Scenario #4 and Scenario #5 are dropped from the comparison proposed in Table 13.

A comparison of the first three scenarios is provided in Table 13. More details on the assumptions, modelling and calculation of this study are provided in D2.1.

Table 13 Comparison of the 3 scenarios

	Scenario #1	Scenario #2	Scenario #3
Case	Electrolyzer + ORC with air-cooled condenser	Electrolyzer + ORC with water-cooled condenser	Electrolyzer & ORC decoupled
Cooling water loop duty	0 MW_{th}	6,9 MW_{th}	7,2 MW_{th}
Electricity net generation	255 kWe (BOL) 280 kWe (EOL)	310 kWe (BOL) 335 kWe (EOL)	> 1000 kWe
Risk	Electrolyzer cooling + Integration uncertainties	Integration uncertainties	-
Cost [€/kW]	~ 9000 - 10000 €/kW	~ 7500 - 8500 €/kW	~2500 €/kW

In conclusion, considering the comparison provided in Table 13, Scenario 3 is suggested for implementation within EPHYRA project.

4.3 Non-freshwater use

A typical challenge for the chemical industry is the appropriate treatment of process wastewater (PWW). Organic compounds (or trace organic chemicals – TrOC) represent a major group of PPW; these compounds can be highly toxic and should be removed or transformed to avoid their discharge into the aquatic environment and reduce their environmental footprint. Furthermore, PWW should be further purified from persistent organic contaminants to recycle/reuse the water in industrial processes, while ensuring its physicochemical specifications for demanding applications (e.g., water electrolysis). Among the conventional water treatment methods (biological and physicochemical), wet oxidation is the most suitable approach to be implemented right after any separation techniques (wherever applicable). This technique is widely applied for the degradation of pollutants from the pharmaceutical industry that exhibits a very high environmental factor. Advanced oxidation processes (AOPs) have shown high oxidation efficiency compared to other wet chemical treatment while having no secondary pollution [17]. AOPs are based on the generation of strong oxidative species, e.g., hydroxyl radicals (·OH), which 'attack' and degrade a wide range of common organic pollutants (pesticides, pharmaceuticals, dyes, phenols, etc). AOPs involve a wide range of methods for activation as well as generation of oxidative species, employing several combinations among them; an overview of both established and emerging technologies are shown in Figure 25. These methods can be classified into O3-based, UV-based, electrochemical, catalytic (Fenton, photocatalytic) and physical (plasmas, microwaves, etc) AOPs.

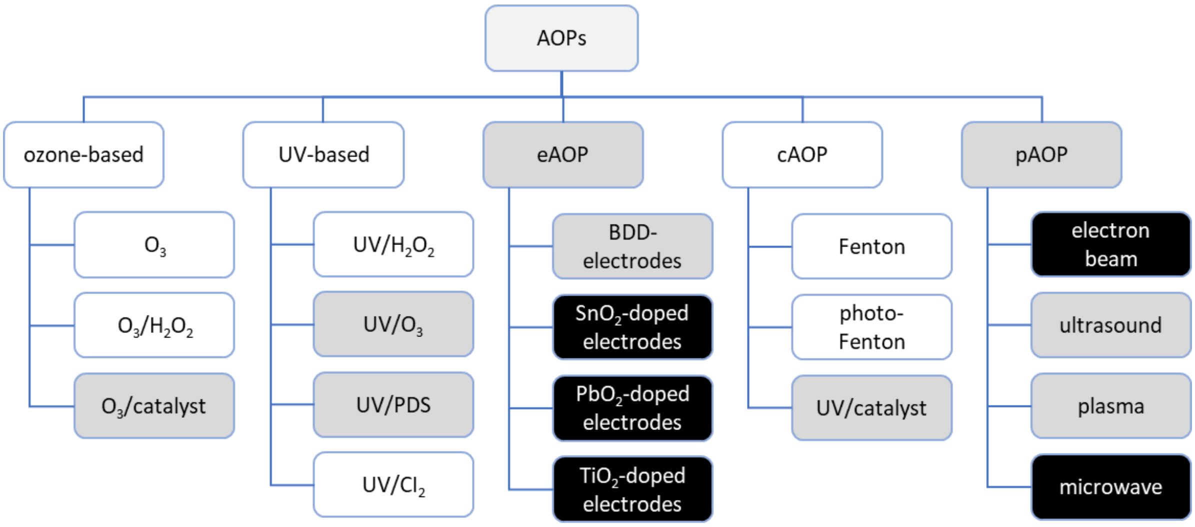

Figure 25 Overview of different AOPs. Some of these are well-established at full-scale (white), some are investigated at lab- and pilot-scale (grey), and some tested only at lab-scale (black) [18].

Regarding the Reverse Osmosis (RO) unit existing on the refinery, at the first stage the seawater passes at high pressure through membrane filters which allow clean water entrance only. This is the main method of producing clean water which is used for economic reasons. These units consume only power and are supplied with a mixture of fresh cold sea water and warm sea water returns from the cooling water processes of the refinery. These units have three treatment stages, two reverse osmoses in series and an "electrodialysis" (EDI) stage. Finally, a resins unit of the desalination plant is used to improve the water quality. The Electrolyzer unit will also have a water polishing step to ensure the electrolyzer specs and minimum impact on the electrolyzer degradation. The need of the polishing unit will be verified during the electrolyzer FEED based on the specs of the RO plant and the specs required by the selected electrolyzer vendor. The desalination units are operated and maintained on a 24-hour basis to avoid or contain any possible leakage and avoid causing any damage to the membranes. The unit connection is described in the below flow diagram (Figure 26), while further description of the units will be provided in detail in D2.3 of the EPHYRA-WP2.

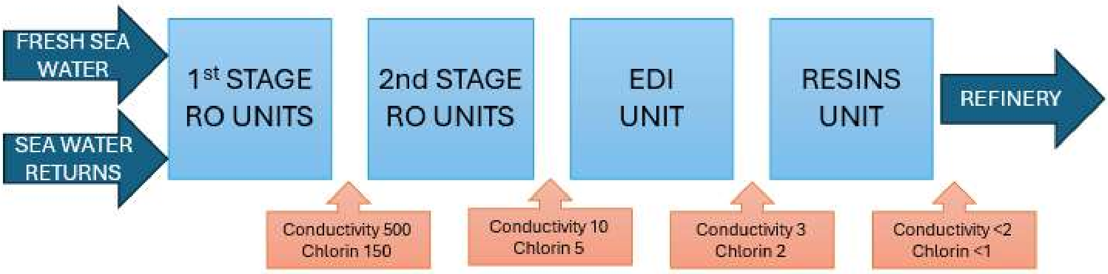

Figure 26. The flow diagram of the water treatment unit of the Refinery.

One of the most promising AOPs is based on the use of non-thermal plasma (NTP). Due to the high reactivity inside a plasma discharge caused by energetic electrons and collisions of the latter with gas/liquid phase molecules, rich chemistry is obtained which includes hydroxyl radical, hydroperoxyl radical, atomic hydrogen and oxygen, as well as other radicals and active chemical species like ozone (powerful agents for the degradation of organic chemical compounds) [19]. Ultraviolet (UV) light is also produced by plasma discharges that could replace the need for UV light sources. The high population of active species produced inside a plasma discharge can be directly generated inside the liquid phase (typically inside bubbles) or in the gas phase surrounding the liquid, diffuse through the gas-liquid interface and induce targeted oxidation reactions. The reactor system is driven by electricity, is typically simple and inexpensive, present high modularity for upscaling which renders the whole process a totally electrified, green technology (coupled with e.g., RES) of high efficiency and great potential for industrial use with no secondary pollutants. The ease of tunability of plasma parameters through the reactor design, working conditions (working gas/liquid, pressure, temperature), power source (DC, AC, pulsed, MW, excitation voltage, frequency, and repetition rate) can promote reactions and species depending on the end-user needs. Characteristic reactor configurations for plasma-liquid interactions are presented in Figure 27.

Authors in [20], defined E_{EO} (electrical energy per order) as a measure to compare different AOPs as for their efficiency and energy consumption, with the latter being the main fraction of operating costs. Electrical energy per order was defined as "the electrical energy in kWh required to degrade a contaminant C by one order of magnitude in 1 m^3 of contaminated water". A rough overview of the E_{EO} values coming from published works are given in [18] (Figure 28). The major limitation associated with this technology is the high electrical energy requirement. Moreover, the skilled labor desired to operate the plasma reactors also adds to the limitations of this technology. However, the advantages are even more profound: 1) Only electricity is required, which can be produces locally using renewable resources, 2) No hazardous chemicals are needed, which reduces the environmental footprint; e.g., highly-concentrated hydrogen peroxide needs to be transported, thus appropriate storage and handling is required to reduce the risk of explosive decomposition. In plasma-water interactions, the oxidative species are generated in-situ. 3) No catalysts are needed, which also reduces the cost and complexity of the system significantly.

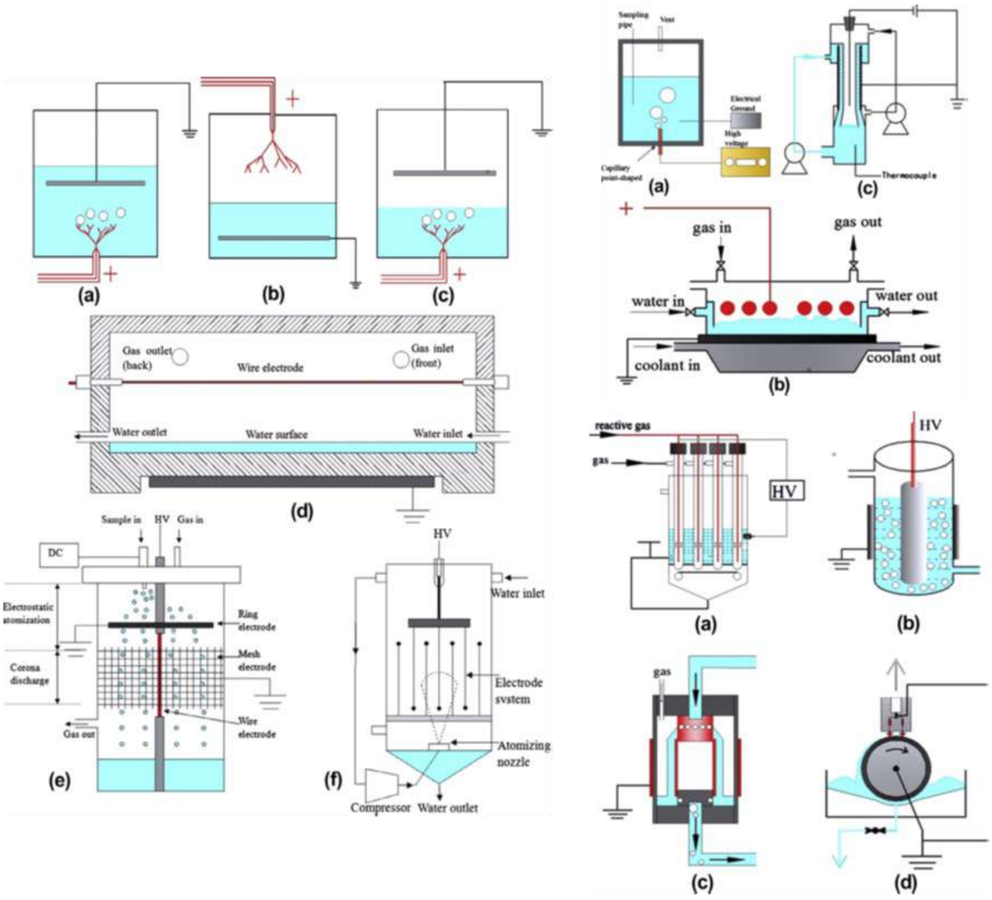

Figure 27 Reactor configurations for treatment of water using non-thermal plasma discharges [19].

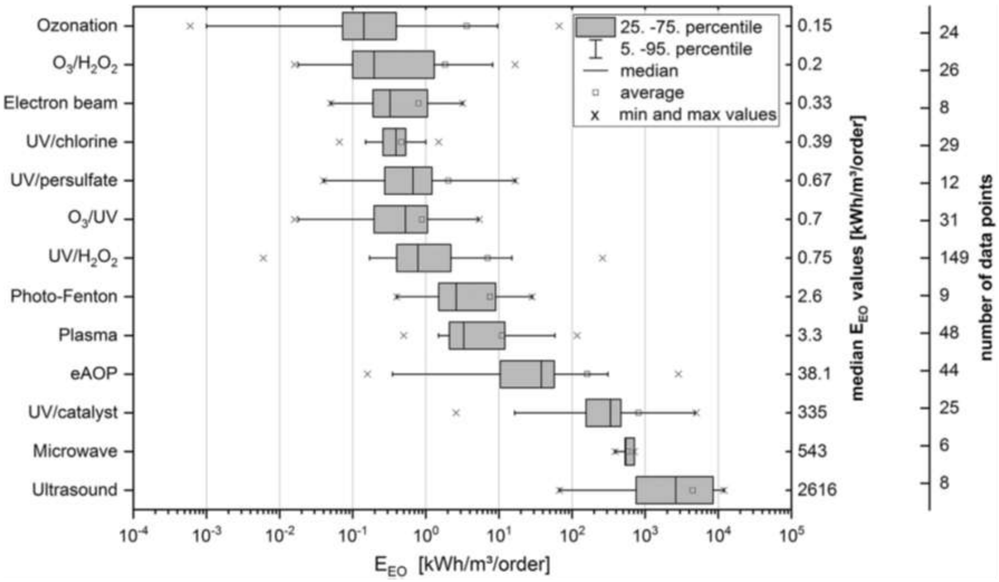

Figure 28 Overview of published E_{EO}-values of different AOPs sorted according to median values [18]

Pilot-scale plasma processes have been investigated for the treatment of organic contaminants, however, no full-scale application currently exists [21]. A 150-L pilot plant was operated for the degradation of pharmaceuticals and endocrine-disrupting chemicals in wastewater from Israel. The plasma treatment showed low energy requirements and achieved almost complete degradation of carbamazepine and meprobamate, suggesting that plasma-based technology is a viable alternative to peroxide-based AOPs. Another 200-L pilot plant was implemented to treat solvents and disinfection by-products in tertiary wastewater effluent, with the plasma process achieving a 90% transformation of the three contaminants. Plasma-based technologies exhibit major advantages over currently employed AOP systems, however, they require high electrical energy.

As organic compounds represent a major group of PPW which can be highly toxic and detrimental to the electrolyzer unit operation, EPHYRA will investigate and apply lab-scale plasma-based PWW treatment to the wastewater stream of MOH’s refinery (typical COD > 100 mg/l) to degrade the organic contaminants towards meeting the physicochemical specifications for water electrolysis (COD < 10 mg/l). The following plasma-based concepts will be investigated in lab-scale for the purification of the water and PWW streams:

1. Direct treatment of PPW using only air plasma discharges in contact with the liquid stream
2. Direct treatment of PPW using inert gas (e.g., Ar) discharges in contact with the liquid stream aiming to maximize the H_2O_2 (strong oxidant) formation
3. PPW treatment with O_2 plasma which could potentially come directly from the electrolyzer

The overall effects will be parametrized over relevant variables (discharge power, electrode gap, treatment time etc.). CERTH will assess the efficiency in PWW purification according to the standards required for water use in the electrolyzer and provide preliminary guidelines for future upscaling. MOH will provide input to CERTH concerning the quality and specifications of the PWW streams to conduct these lab-scale experiments and investigate the improvement of the environmental and socio-economic performance of electrolyzer. For this activity, CERTH has already installed in-situ optical measurements (optical emission spectroscopy – OES) to characterize the plasma discharges and proceed with tests in a pin-to-plate DBD reactor in DI water and upon addition of an organic contaminant. CERTH will record time evolution of concentration the main reactive oxygen and nitrogen species (RONS) formed in the water during the air plasma processing. CERTH is currently studying the synergy of plasma and plasma-Fenton processes in the pollutant degradation kinetics and the RONS evolution in the treated water by constructing a plasma device with controlled atmosphere to proceed with testing and benchmarking with other plasma chemistries (O_2, Ar). Model compounds are used for process development and benchmarking of different plasma studies (e.g., organic dyes) while real samples from the refinery will also be tested in terms of TOC content. This innovative activity is being performed in CERTH's laboratories at TRL4 and will not have any effects on the integrated industrial hydrogen production system during EPHYRA. The main requirements for this action which is performed under the framework of Task 2.3, is the timely delivery of well characterized PWW samples from MOH so that CERTH can perform the plasma treatment and assess the applicability of this technology in an industrial framework, based on the water specifications provided by MOH. CERTH and MOH are in continuous communication to align and coordinate on this matter.

4.4 Produced oxygen use

In the framework of the EPHYRA project, MOH will investigate the utilization of oxygen in the Refinery Claus unit (oxygen enrichment to increase the capacity of sulfur recovery of the unit) by means of a cost-benefit analysis along with technical and economic feasibility and will perform the design and engineering within the EPHYRA-WP2, and the installation within the EPHYRA-WP4. In addition, within the EPHYRA-WP2 MOH and CERTH will perform a desktop study on certain improvements in FCC unit for debottlenecking and decarbonization of the unit. At this stage there will be no project implementation for this application, but it will set the basis for future use of the significant oxygen excess production after its utilization in the Refinery Claus unit.

The use of oxygen in another unit within the Refinery contributes to the industrial symbiosis and the development of an integrated system with the 30 MW electrolyzer as its core. An important synergy of the project with the selected electrolyzer system is the prevention of an oxygen compressor to utilize the oxygen at the refinery as the electrolyzer already generates oxygen at elevated pressure sufficient to provide to the Claus unit and overcome any pressure drop of the supply system.

The 30 MW electrolyzer when operating at full capacity (based on technical availability) produces 35,945 tpa of oxygen. The Refinery Claus unit can utilize by design approximately 9216 tpa O_2 (~26% of the produced O_2 mass). Based on the 2023 Refinery data the actual use of O_2 in the Claus unit was approximately 20% of the design capacity corresponding to 1843.2 tpa O_2. The cost-benefit analysis based on the actual and design values will be performed within WP2, and it will be presented in D2.2 Report on the internal use of electrolysis generated oxygen within MOH Refinery.

For the oxygen utilization in the Refinery Claus Unit a FEED study has been conducted based on the FEED study of the 30 MW electrolyzer. The study indicated that an oxygen recovery system facility is required. The main equipment of the oxygen recovery system is:

- Electrical Pre-Heater
- De-Hydrogenator
- Dehydration Facility, adsorber and desorber
- Heaters
- Coolers
- Filters
- Separators
- Pressure Reduction to Claus Unit's pressure level (it is required to maintain proper pressure level in the downstream user)
- Piping and Valving
- O2 slip stream control

As far as the electrical connections a low voltage (LV) power supply to oxygen recovery facility shall be provided by connecting to local power supply of electrolyzer package.

For the mechanical installation and integration, the following scope items have been identified:

- Processing equipment
    - Oxygen Recovery Facility (ORF)
    - Oxygen Purification unit
- Energy feed units:
    - LV Switchgear
    - Unit Control Panel
- Piping
    - Oxygen piping from Electrolyzer plant to Claus Units inside the refinery
    - Condensate from oxygen recovery unit to centralized refinery collection and treatment
    - Interconnecting piping for integration of oxygen compression unit as option, if required.
    - Oxygen injection to the Claus inlet tie-in point

The main civil installations for the oxygen recovery and purification system on the Electrolyzer plant are:

- Foundation and shelter for oxygen recovery facility
- Foundation and shelter for oxygen purification unit
- Sleepers and pipe racks
- Cable trenches

The unit control panel (UCP) of the oxygen recovery facility shall be integrated into the electrolyzer control system. Interfaces with existing refinery control system for necessary exchange of status, alarm and control parameters will be done via the electrolyzer control system. The UCP of the oxygen compression unit (if optionally required) will be integrated into the electrolyzer control system similarly.

4.5 Technology validation and GAP analyses for the required pipeline work

This Section outlines the introduction to the SoluForce product, the process for project approval and the present experiences from Dutch projects, which can contribute to structure and support the approval for the SoluForce system for hydrogen transport in European projects and the decarbonization of the MOH refinery process. It includes ensuring compliance with local regulations, which involves identifying and assessing these regulations to determine if the SoluForce system can meet them or if there are deviations. Any deviations found will need to be examined in detail, with supporting information gathered to facilitate discussions with local regulators.

4.5.1 SoluForce production introduction

SoluForce® high pressure Flexible Composite Pipe (FCP) developed by SoluForce has been fully certified for hydrogen transport. In contrast to steel pipes, it can be deployed from 400m spools greatly reducing cost for groundworks and welding, while being completely permeation-free for hydrogen. Furthermore, the CO_2 footprint is reduced to 30% when using the Soluforce pipe compared to traditional solutions.

The Soluforce hydrogen certified pipe is available in 4 and 6” and can be used for hydrogen up to 52 bar and maximal 65°C. The pipes are packed in a 400 m package which is easy to transport and is also used for uncoiling the pipe at the right of way.

Furthermore the SoluForce pipe does not corrode and can also be used for other (harsh) product streams up to 65°C. This means that the SoluForce pipe can also be used in the other process streams outside the H_2 stream.

The SoluForce pipe consists of four layers: a PE100 liner pipe for leak free transport, an anti-permeation layer making sure the hydrogen permeation is nihil, an Aramid reinforcing layer to bear the strength for the high pressures and a cover layer to protect the pipe from environmental influences. The pipe system, pipe and fitting system, is fully non-metallic. The SoluForce pipes are inter-connected by an electro fusion coupler system. First the liner pipe is butt-fused for a leak free connection and next the electro fusion sleeve is centrally placed over the butt-weld for the necessary strength. This connection is stronger than the pipe itself. For connecting the pipe to the hydrogen production or offtakers, an electro fusion end-fitting is used. The end-fitting is mechanically connected to steel parts with an ANSI flange or a weld stub. In order to connect different offtakers, producers, process sections or a connection to a large back-bone along the SoluForce pipeline an electro fusion T-piece is also being developed.

4.5.2 Experience from Netherlands installation

Soluforce is in the process of installing their reinforced polymer pipeline in several Dutch Hydrogen pilots: Wieringerwerf Duwaal, Groningen-seaport and Deventer in the Northern Netherlands connecting H_2 production to H_2 offtakers. Already hydrogen pipeline pilots have been installed in Denmark and Japan. While the whole process of ordering till commissioning is already fully matured during the 24 years of use, the point of focus is the approval to be allowed to use the SoluForce pipe locally, where specific standard and regulations shall apply. For some of the projects the approval process has been finalized. The full qualification works and the approval process experience will be used to accelerate the approval process for the Ephyra project.

4.5.3 Considerations for EPHYRA project

The long term experience of SoluForce with this product in the oil and gas industry and the results of the Northern Netherlands pipeline approval process, pipeline routing engineering and installation will be used in the Ephyra project. Analyses will be made to identify the transport fluids which can be transported with the SoluForce pipe among others at least the hydrogen transport. Together with MOH and other partners SoluForce will work to find the optimal deployment plan, including regulatory affairs, for the installation of SoluForce pipelines for the Hydrogen transport and possible other process streams.

4.5.4 General qualification and regulations

For the SoluForce pipe’s use to be allowed for hydrogen and other fluid transport, Authority approval will be necessary. The general items for approval are:

1. Synchronized pipe and project specifications;
2. Pipeline routing (ROW);
3. Approval present pipe certification / qualification (API 15S and Kiwa) by local authority;
4. Comply to local regulations for pipeline engineering and installation.

Part of these items will be defined during the detailed engineering phase, where also the required sizing of the pipes will be defined. Multiple pipelines may be required with different sizes.

4.5.4.1 Synchronize pipe and project data

The SoluForce pipe portfolio consists of several fixed products. In order to be able to use the SoluForce pipe system in the project, the project specifications need to fall into the SoluForce pipe system specifications.

The SoluForce datasheet lists the specifications of the SoluForce portfolio products. The first step is the process is to see if one of the SoluForce products meets the project specifications. This includes the dimension of the pipe. The final specifications will be defined in the detailed engineering phase.

4.5.4.2 Pipeline Routing

A first quick check of the pipeline routing (right of way (ROW)) is not a direct must, but it can make already clear if the long length pipes can be applied in the project. It will be also necessary for potential risk assessments.

4.5.4.3 General certification of the product

The specific generally used qualification standard for the SoluForce pipe (FCP pipes) is the API 15S. By using this standard the pipes can be qualified for certain operational parameters for specific fluids or fluid groups. The API15S certificate will need to be accompanied by the quality management system standard API Q1. API 15S does not specifically mention hydrogen and therefore an extra API15S assessment has been performed by Kiwa in the Netherlands to check the details for hydrogen application. Kiwa is a Dutch worldwide acknowledged certification institutes certifying products, processes and services in among others the energy sector.

In order to be allowed to use the SoluForce pipe the local authorities need to acknowledge these standards.

4.5.4.4 Comply to the local standards

For the design, installation, and application of pipelines, international and local regulations and standards are in place. SoluForce pipes are already successfully used for 25 years in the oil and gas industry. The advantages of the SoluForce products are recognized by hydrogen and new energy customers, especially because SoluForce has already hydrogen certified products. In the oil and gas industry the oil companies have often their own standards and material approvals in combination with international standards. In order to use the SoluForce pipe in the Ephyra project it is necessary to check the local Greek national regulations and Motor Oil regulations and international standards that the Refinery follows. By performing a gap analyses the possible differences or extra aspects between these standards and the present international standards will be found. These differences can be analyzed and solved in order to harmonize these standards.

4.5.5 First Dutch hydrogen SoluForce pipe learnings

4.5.5.1 Qualification

The first step in the hydrogen journey was to qualify the SoluForce pipe for hydrogen. Kiwa assessed the SoluForce pipe system for hydrogen applications against API 15S. This resulted in several extra tests. The extra main items for the hydrogen application to check are:

1. Chemical compatibility of the used materials against hydrogen;
2. Permeation of hydrogen;
3. Rapid decompression of pipe system.

The Kiwa assessment was finalized with a certificate for the application of hydrogen laid down in a Kiwa covenant (K101779). The SoluForce datasheet for hydrogen application lists all the specifications.

4.5.5.2 Project versus Pipe system specifications

Due to the innovative drive of multiple Dutch companies a project for a local industrial hydrogen backbone was made. In the Groningen-seaport different companies are clustered where already hydrogen is a side product. Together with a hydrogen production, the industries on the area will use the hydrogen for their activities.

The project specifications, including the performance of the electrolyser, were compared with the pipe system specifications and showed to be in line.

4.5.5.3 Risk assessment

To ensure project approval, a comprehensive quantitative risk assessment (QRA) is required. Typically, QRAs are straightforward when dealing with standard fluids and materials. However, this project involves the use of hydrogen and a not commonly used pipe material, making the risk assessment significantly more complex and extensive. The SoluForce certification for the German gas standard DVGW VP642 had already included a risk assessment, providing a substantial advantage.

In a project team supported by the Dutch authorities RIVM (RijksInstitute voor Volksgezondheid en Milieu, Governmental institute for health and environment) a full risk assessment was performed. The base for the risk assessment are the BEVB (besluit externe veiligheid buisleidingen, decision external safety pipelines) and REVB (regeling externe veiligheid, regulation external safety pipelines). A list of risks is analysed and given a probability number according to specific rules and next are put in the risk assessment calculation program SAFETI (P010319/2020.00724). The conclusion was that the SoluForce pipe could be installed for this Hydrogen project.

These risk assessment documents are available. The information and the base of these documents can be used as reference point to make a risk assessment for the Ephyra project. Local engineering regulations

To be allowed to construct a pipeline in the Netherlands it is mandatory to comply to the Dutch local regulations / standards NEN3650 and NEN3651 and associated documents. NEN3650 is the general standard and the NEN3651 is a special regulation for waterways. The NEN3650 consists of several parts, starting with a general part and parts for specific pipeline materials:

- NEN3650-1 General
- NEN3650-2 Steel pipes
- NEN3650-3 Non-metallics and GRE pipes (solid wall)
- NEN3650-6 FCP pipes (to be finalized Q1 2025)

This standard describes how to design a pipeline and which issues have to be taken care of. The standard takes into account the transportable fluid and divides the application in classes. All kind off issues have to be taken into account and the designed pipeline needs to be modelled in a software program. Typically the PLE program is used for this modelling. In the Dutch case for the Groningen-seaport project the NEN3650-3 was used. The SoluForce pipe has the same properties as a standard HDPE pipe when there is no pressure, but behaves like a composite when under pressure. In NEN3650-3 both are described. The standard HDPE pipe part is used for the situation where there is no pressure and for the situation with pressure the GRE part is used. This is possible because GRE pipes also have different specifications for axial and radial direction. An engineering company has designed the Groningen-seaport pipeline and made the procedure for calculating the SoluForce pipeline according to NEN3650-3. This calculation was checked and approved by Lloyds. This means that for this project the pipe design with the SoluForce pipe complied to the local engineering regulations.

When looking into the standards it shows that many NEN regulations are also EN NEN regulations and applicable for other European countries. It seems that the NEN3650 and NEN3651 are Dutch regulations and not European. The Dutch regulations are tight because of the large risk of soil deformation resulting from the high water tables and different weak soils. For the Ephyra project it is necessary to identify the local pipeline design regulations.

4.5.6 GAP analyses

This section describes the process and the list of found regulations from the Ephyra project regulation search as well as from other EU projects.

4.5.6.1 EPHYRA project

In order to define if the SoluForce pipeline can be used in the Ephyra project at least the following steps are necessary:

1. Define process operational parameters for H_2 and other possible process streams;
2. Check the SoluForce pipe specifications with the process operational conditions;
3. Define right of way and select installation procedure;
4. Lists the local standards and regulations to which needs to be complied;
5. Gap analyses of available qualification and performed regulations versus the list of local standards and regulations;
6. Set up a deployment plan for the different SoluForce pipelines.

Upon the detailed engineering phase the full details of the necessary pipelines will become clear and can be further analyzed if and where the SoluForce pipe can be used.

This GAP analyses focuses only on the local regulations. This means that international and local Greek regulations need to be tracked down and assessed.

4.5.6.2 Greek/Motor Oil (international) regulations

Tracking down the applying regulations is not always an easy task. Therefore, the starting point was the Motor Oil basic design data document 076971C. In this document the necessary basic design parameters are listed (par 1.2) and project process and environmental specifications (par 1.4). Furthermore, specific regulations are listed (par 1.3). The last two paragraphs mention about pre- and pro-design and engineering documentation.

4.5.6.2.1 076971C Design parameter

The project design parameters required in the basic design data document can be given for the SoluForce system. Once the operational specifications are available the right SoluForce product can be selected. The specified project process and environmental specifications can be met by SoluForce. Only the fire resistant specification has to be checked.

4.5.6.2.2 076971C Codes / regulations

In the basic design data provides a list is given of regulations to comply to for the whole system. In Table 14the regulations are listed. Several of these regulations are not applicable for the SoluForce system. These regulations are applicable for the systems around the Soluforce pipe in the right of way. Table 14 shows also which regulations are applicable to the SoluForce pipe system.

Table 14 List of regulations from 076971C

#	Product group	Standard group	GAP
a	Pressure vessels	ASME, NACE: ASME available (I, IIA-D, IX, V, VIII), NACE MR0175	no
b	Boilers	ASME available (I, IIA-D, IX, V, VIII)	no
c	Fired heaters	API560 (tubes calculation acc. API530 / ISO 13704)	n.a.
d	Electricity	IEEE /IEC I CEI/ CENELEC/ATEX I API	n.a.
e	Noise Control	OSHA	n.a.
f	Wind and Earthquake	EN 1991-1-41NA I Greek seismie code EAK 2000 (and its' 2003 amendments)	Earthquake yes
g	Instruments	ISA I ASME /IEEE / API / IEC / DIN /ISO / CENELEC / ASTM / ANSI / NACE	n.a.
h	Machinery	API/ ASME / ISO	n.a.

i	Concrete Structure	Greek Code for reinforced Concrete ΕΚΩΣ 2000 (and its' 2004 amendments)	n.a.
j	Steel Structures	EN 1993-1-1 (2005) / EN 1993-1-2 (2005)	n.a.
k	Piping	ASME / EN / NACE / ANSI / ASTM / MSS / TPIT engineering practices	no n.a. unknown

4.5.6.3 Regulations from other EU projects

SoluForce is also acting in other EU projects where SoluForce is considered to be used for the transportation of hydrogen. These projects involve short connections from the production to a fuel station, a horizontal drilling project to under-cross a river and a backbone to different industrial off-takers. For these international projects local regulations have been also checked. Table 15 shows the list of regulations that were checked for these projects.

Table 15 List of regulations from other EU projects

#	Product group	Standard group	Gap
1	ASME B31.12	Hydrogenpipelines and pipelines	no
2	ASME B31.8-2020	Gas transmission- and distribution piplinesystems	no
3	CGA G-5	Hydrogen	no
4	CGA G-5.3	Commdity specification for hydrogen	no
5	CGA G-5.4	standard for hydrogenpipelinesystems at user locations	remark
6	CGA G-5.5	standard for hydrogen ventilation systems	no
7	CGA G-5.6	Hydrogen pipeline systems	remarks
8	NEN-EN 1127	Explosive environment	remarks
9	NEN-EN 12186	Gas infra structure - gas pressure regulation stations for transport and distribution, functional specifications	remarks
10	NEN-EN 1594 2014	Gas infra structure - pipelines for a maximum working pressure larger than 16 bar. Functinal specifications	no
11	NEN 60302	pipelines for gaseous fuels. Locations	no
12	NEN 60305	pipelines for gaseous fuels. Safety zones and design coefficients for specific locations	no
13	ISO 9001	Quality Management System – Requirements	no
14	ISO/TR 15916:2015	Principle considerations for the safety of hydrogen systems	no
15	ISO TS 18226	Plastic pipe and fittings - reinforced thermoplastics pipe sysrtem for the supply of gaseous fuels for pressure up to 4 MPa (40 bar)	no
16	ISO 13628-10	Petroleum and natural gas industries - Design and operation of subsea production systems - Part 10: Specification for bonded flexible pipe (ISO 13628-10:2005,IDT)	n.a.
17	NCSE-02. NFPA 2	Earthquake resistant constructions standard code for hydrogen technology	
18	API 15S	Spoolable Reinforced Plastic Line Pipe”	no
19	API SPEC Q1	Specification for Quality Management System Requirements for Manufacturing Organizations for the Petroleum and Natural Gas Industry	no
20	API 17B	Recommended Practice for Flexible Pipe	n.a.
21	API 17J	Specification for Unbonded Flexible Pipe	n.a.

#	Product group	Standard group	Gap
22	French Ministerial decree	French Ministerial decree Chapter V of Title V of Book V of the Environmental Code and regulating the safety of pipelines for the transmission of natural gas or similar gas, hydrocarbons and chemical products	remarks

4.5.6.4 Main GAP analyses outcome

The GAP analyses resulted in two items which need to be addressed in case SoluForce is going to be used in the Motor Oil refinery, being Fire and earthquake resistance. These two items will be discussed in section 4.5.7.1. The GAP analyses resulted also in a list of remarks, which are items that need to be taken into account when designing a (hydrogen) pipeline, thereby, also when using the SoluForce pipe system. These items are discussed in Section 4.5.7.2.

4.5.7 GAP analyses results

This Section will describe in more details the outcome of the GAP analyses, where two main items are discussed as well as the remarks extracted from the assessed regulations.

4.5.7.1 Main items from GAP analyses

4.5.7.1.1 Fire resistance

SoluForce pipe has been tested by the University of Manchester for jet fire resistance. The pipe was filled with water under 50 bar and heated with a jet fire flame of 1000°C. The pipe released the pressure after 6 minutes because at the jet fire area the polyethylene material of the pipe wall was pressed through the mase of the aramid reinforcement. The pipe did not explode because the aramid reinforcement was still in takt. The polyethylene material protected the aramid fibers which can withstand very high temperatures itself. In addition, the pipe did no start to burn.

Additionally, SoluForce pipe has been in grass fires where the pipe was installed in an area where people burned the grass to excess places. Also, in this case the pipe did not burn and was actually only black colored by the burning of the grass.

In large heavy fires the SoluForce pipe will not survive and will start burning. Therefore, in the case of theMotor Oil Refinery, the SoluForce pipe will need to be protected from being exposed to direct fires or overload of heat.

There are several means to protect the SoluForce and other pipe systems for fire. The main options are:

- Bury the pipe, fully or at least at area’s with increase fire risk;
- Cover the pipe with fire retarding tape, which makes sure the pipe will not catch fire;
- Fire resistant insulation, which makes sure the pipe will not catch fire and will not be heated.

Note: links to different commercial products are in the GAP analyses excel sheet [[22]]

It should be noted that buried pipelines raise cost issues and challenges during construction and Motor Oil Refinery currently does not typically follow the practice of burying pipelines. Thus, the use of buried pipelines is not a standard practice at Motor Oil Refinery and may not be foreseen in the EPHYRA project.

4.5.7.1.2 Earthquake resistance

In the 076971C design data document at paragraph 1.3f and 1.4.6 earthquake resistance is mentioned. Reference is made to the Greek seismic code EAK 2000 and amendments. In the main document there are no specifications found related to a pipeline and no soil movement specifications.

SoluForce does have experience with land / soil slides. The SoluForce pipe was installed as a liquid gas condensate pipe in Brunei in 2004. The pipe was buried and run along a water drainage channel. During the installation of the pipe this channel was being build but not ready. The SoluForce pipe was installed including several pre-installed HDPE casing pipes to overcome small creaks. The pipe was commissioned and worked on 55 bar. During a large rain shower the construction area for the drainage channels, where the SoluForce pipe was running, was fully flooded and the soil moved. Eventually the SoluForce pipe was pushed in a 90° bend with a bending radius of less than 0.5 meters [[23]]. The SoluForce pipe withstand this deformation easily and the pipe kept on running until it was shut down and SoluForce relocated the pipe while the drainage channel was completed. This shows how flexible and resilient the SoluForce pipe is for soil movements and earthquakes.

When more details about the earthquake resistance specification become available during the detailed engineering, the GAP analyses can be finalized for this item.

4.5.7.2 *Important remarks from the assessed regulations*

From the GAP analyses several remarks were consolidated in relation to the engineering of a (hydrogen) pipeline. Some remarks are related to any pipe (general remarks) and some are specific for non-metallic pipes.

4.5.7.2.1 General remarks

Table 16 General remarks from GAP analysis

standard	Remark
ASME B31.12	Welding according to ASME IX boiler and pressure vessels code BPVC
ASME B31.8-2020	Non-metallics allowed, HDPE, PA11
CGA G-5.4	Fitting system pf 316L Fitting system CS if meeting ASME B13.12 temp limits Static electricity O-rings H2 designed Gasket not of plastics Use weld stubs if possible
CGA G-5.6	Temp range -40 C to 175 Pressure range 1 MPa to 21 Control of third party interference Safety mitigations
ISO TR 15916 2015	Static electricity Overpressure Gas detection Training for emergency handling (fire fighting, flow stop) Emergency procedures Hydrogen properties annex A **Steel:** hydrogen embrittlement
NEN-EN 1594 2014	Gas pipes >16 bar Natural gas only Safety measures
NEN-EN 1127-1	Risk assessment Risk reduction Ignition by friction => note: H2 does not heat up during release Static electricity

NEN-EN 12186	Hydrotesting >16 bar EN1594 <16 bar EN12007-1 Pt = MOP x 1.25 NEN-EN 12327
French decree	Flexible pipes are introduced Inspection Warning tape / detectable tape? 10 meter from buildings Risk probabilities less than 10-6 (people involved <= 300) FMEA QRA Hydrotest (strength and leak test) witnessed by authorized body Monitoring parameters Pipeline examination at least every 10 years Leak detection system? Safety management system SGS If no NDT available then every three years pipe condition test.

4.5.7.2.2 SoluForce and non-metallics related remarks

Table 17 Specific remarks concerning non-metallic pipes

Standard	Remark
CGA G-5.4	Permeation control for Plastics
CGA G-5.6	Elastomer permeation rates
ISO TR 15916 2015	Permeation
French decree	Flexible pipes are introduced

4.5.8 GAP analyses conclusions

From the GAP analyses reveals that many standards pertain to the engineering and the safety measures of the pipeline, regardless of the material used, and are more focused on the fluid risk level. When the regulations are followed and the recommendations taken into account the SoluForce pipe can be utilized effectively.

Different standards emphasize the importance of minimizing permeation. Although no maximum levels are specified, permeation is a critical consideration during the qualification of the pipeline system, especially for gas applications. The SoluForce hydrogen pipe, SoluForce H2T, features a special gas-tight layer that reduces permeation to nearly zero.

Earthquake resistance is highlighted as a key issue in both the Motor Oil Basic Design document and the NCSE regulation. Since the standards do not provide direct specifications for pipelines, it is essential to check local earthquake parameters for every project. The SoluForce pipe is very flexible and can handle large soil movements without failure.

Fire resistance is the another concern raised in the Motor Oil Basic Design document. While SoluForce can withstand a jet fire for six minutes and small fires like burning grass, they will melt and burn in large fires. In high fire risk ares, as the oil refinery environment, additional measures should be taken, like applying fire retardant tape, fire protecting insulation or burying the pipeline. Buried pipelines typically are not a common practice in a refinery and may not be utilized in the project. This may be a limiting factor for using SoluForce pipelines within the surrounding refinery environment with the existence of flammable materials.

Finally, every pipeline system must implement a risk management strategy. Using non-metallic pipes eliminates concerns about corrosion and embrittlement.

The primary issues, as highlighted in several standards, include third party interference and monitoring of the operational conditions to ensure they remain within pipeline specifications. During pipeline engineering, a risk assessment (QRA) must be conducted, and depending on local regulations, additional precautions may be necessary. These may include warning tape if the pipeline is buried, maintaining a safe distance from buildings occupied by personnel, and ensuring leak detection and monitoring operational parameters.

5 Conclusions

In conclusion, this deliverable marks a significant milestone in the EPHYRA project, focusing on the initial stages of technology validation and procurement planning for industrial green hydrogen production. Through a comprehensive technology assessment, the project has identified key methodologies and technologies for green hydrogen production, aligning with the Clean Hydrogen Partnership's strategic objectives.

One of the key takeaways from this deliverable is the emphasis on thorough technology assessment and vendor evaluation processes. By meticulously evaluating different hydrogen production technologies and selecting a vendor through rigorous evaluation process employing two different but complementary methodologies, the project ensures that it leverages the most efficient, cost-effective, and sustainable solutions available in the market. This approach adds robustness to the selection process, ensuring that the selected vendor is truly the best fit for the project's requirements. Furthermore, not only maximizes the project's chances of success but also lays the foundation for scalability and replicability in future deployments.

The outcome of the evaluation process identified METACON AB (vendor 4) as the preferred choice and thus METACON AB is the selected vendor. The assessment concluded that this vendor meets the project’s stringent requirements more effectively than other candidates and significantly contributes to the overarching goals of the CH JU topic and the EPHYRA project. METACON proposal distinguished itself through its efficiency and potential to deliver a sustainable hydrogen production solution in the EU.

Based on the evaluation conducted in this document and the tender process, it is concluded that pressurized AEL (Alkaline Electrolyzer) is the most appropriate technology for the EPHYRA project. Several factors contributed to this determination:

1. Commercial Availability: AEL technology is commercially available and has a long history of deployment in various industries, including the production of hydrogen. This ensures reliability and proven performance, essential for an industrial-scale project like EPHYRA.
2. Cost-Effectiveness: AEL technology offers cost advantages, particularly in terms of lower-cost catalysts and materials compared to other electrolyzer technologies. This aligns with the project's objectives of achieving competitive pricing for green hydrogen production.
3. Compatibility with Industrial Operations: AEL technology is well-suited for integration with industrial operations, such as those at the MOH Refinery. Its robustness and scalability make it suitable for large-scale hydrogen production within existing industrial infrastructures. Also, the selected electrolyzer system already produces hydrogen and oxygen at elevated pressures that match the

refinery H2 network pressure (20barg) and prevents the need for installation of an oxygen compressor to utilize oxygen in the refinery process units.

4. Technical Requirements: AEL technology meets the technical requirements outlined for the integrated industrial green hydrogen production system, including the provision of green electricity, utilization of waste heat, and non-freshwater usage.
5. Environmental Considerations: AEL technology aligns with environmental sustainability goals, as it enables the production of green hydrogen without carbon emissions, contributing to the reduction of greenhouse gas emissions and promoting clean energy practices.

Furthermore, the assessment of technical requirements provides valuable insights into the necessary components and operational considerations for the successful integration of the hydrogen production system within the MOH Refinery. By addressing factors such as green electricity provision, waste heat utilization, non-freshwater usage, and oxygen utilization, the project aims to optimize efficiency and sustainability while minimizing environmental impact and promoting industrial symbiosis. Finally, a GAP analysis of the Soluforce non-metallic pipelines is conducted for their potential use in Motor Oil's refinery. The analysis showed that the major concerns are related to earthquake and fire resistance. More specifically, for the fire resistance of the pipelines additional measures should be taken, like underground pipelines, However, buried pipelines are not a common practice in a refinery and thereby this may be a limiting factor for using SoluForce pipelines in the EPHYRA project.

Overall, the findings and methodologies outlined in this deliverable set the stage for the successful implementation of the EPHYRA project, paving the way for the deployment of an innovative industrial green hydrogen production facility in South-eastern Europe. Through collaboration with a strong consortium and adherence to rigorous standards and objectives, the project aims to contribute significantly to the advancement of the European hydrogen economy and the transition towards decarbonized industrial processes.

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Annex 1 KPIs for electrolyzer based on tender

Table 18 KPIs for AEL technology based on tender in comparison with the selected vendor KPIs.

	Assessment criteria	Units	2024 SRIA targets	Range based on tender	Selected vendor (METACON AB)
SRIA KPIs [24]	Electricity consumption @electrolyzer level	kWh/kg	49	48-52	**49.45**
	Hot idle ramp time	sec	30	1-360	**180**
	Cold start ramp time	sec	900	1080-25200	**1080-1800**
	Degradation	%/1000h	0.11%	0.06-0.19%	**0,1%**
	Current density	A/cm^2	0.7	0.3-0.96	**0.35**
Other KPIs	Electricity consumption @system level+BoP	kWh/kg	-	53-56	**53.90**
	CAPEX (stack + BoS)	€/kW	-	328-908	**396**
	Total O&M specific costs[7]	€/kg	-	3.77-4.09	**3.77**
	Equipment delivery time	months	-	10-22	**12**

Table 19 KPIs for PEM technology based on tender[1]

	Assessment criteria	Units	2024 SRIA targets	Range based on tender
SRIA KPIs [24]	Electricity consumption @electrolyzer level	kWh/kg	52	50-52
	Hot idle ramp time	sec	1	60
	Cold start ramp time	sec	10	1200-3600
	Degradation	%/1000h	0.15	0.13-0.25%
	Current density	A/cm^2	2.4	3
Other KPIs	Electricity consumption @system level+BoP	kWh/kg	-	51.12-57
	CAPEX (stack + BoS)	€/kW	-	892-1113
	Total O&M costs	€/kg	-	3.81-4.13
	Equipment delivery time	months	-	14.5-24

[1] Based on the two vendors that responded to the bid invitation.

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[7] Total OPEX annualized for 10 years (electricity costs are included) per H2 mass produced based on technical availability of each vendor.

Annex 2 Technical specifications and cost data of AEL and PEM Electrolyzers based on the Tender

Table 20 Technical Specifications and cost data for AEL Electrolyzers based on the Tender process for the 30 MW Electrolyzer within EPHYRA project.

Parameter	Units	2024 SRIA targets	Selected vendor (METACON AB)	Vendor 3	Vendor 5	Vendor 6	Vendor 7	Vendor 8	Vendor 9	Vendor 10
Electricity consumption @electrolyzer level	kWh/kg	49	**49.45**	**49.34**	**51.12**	**51.12**	**51.79**	**48.9**	**47.79**	**50.56**
Hot idle ramp time	sec	30	**180**	**2160**	**180**	**1**	**60-240**	**600**	**300**	**180**
Cold start ramp time	sec	900	**1080-1800**	**5400**	**1080**	**1800-3600**	**2400**	**3600-7200**	**2700**	**25200**
Degradation	%/1000h	0.11%	**0,1%**	**0.12%**	**0.1%**	**0.06%**	**0.3%**	**0.15%**	**0.19%**	**0.15%**
Current density	A/cm^2	0.7	**0.35**	**N/A**	**0.35**	**N/A**	**0.38-0.96**	**N/A**	**0.3**	**N/A**
Electricity consumption @system level+BoP	kWh/kg	-	**53.90**	**52.79**	**55.57**	**55.79**	**54.45**	**N/A**	**52.45**	**54.01**
CAPEX (stack + BoS)	€/kW	-	**396**	**760**	**430**	**449**	**908**	**542**	**328**	**683**
Total O&M specific costs[8]	€/kg	-	**3.77**	**3.79**	**3.88**	**3.86**	**4.09**	**3.84**	**3.88**	**3.89**
Equipment delivery time	months	-	**12**	**10-12**	**12**	**10**	**22**	**16**	**8-12**	**18**

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[8] Total OPEX annualized for 10 years (electricity costs are included) per H_2 mass produced based on technical availability of each vendor.

Table 21 Technical Specifications and cost data for PEM Electrolyzers based on the Tender process for the 30 MW Electrolyzer within EPHYRA project.

Parameter	Units	2024 SRIA targets	Vendor 1	Vendor 2
Electricity consumption @electrolyzer level	kWh/kg	52	50	52
Hot idle ramp time	sec	1	60	N/A
Cold start ramp time	sec	10	3600	1200
Degradation	%/1000h	0.15	0.25%	0.13%
Current density	A/cm^2	2.4	N/A	3
Electricity consumption @system level+BoP	kWh/kg	-	51.12	57
CAPEX (stack + BoS)	€/kW	-	1113	892
Total O&M costs	€/kg	-	3.81	4.13
Equipment delivery time	months	-	24	14.5-17

Annex 3 Fundamentals of water electrolysis – water electrolysis thermodynamics

Typically, low-temperature water electrolysis occurs at temperatures below 100°C, primarily due to the constraints posed by the thermal stability of membranes. The overall electrochemical water splitting reaction is represented as follows:

$$H_2O(l) \longrightarrow H_2(g) + \frac{1}{2}O_2(g)$$

where the two half reactions occur: the Hydrogen Evolution Reaction (HER) at the cathode and the Oxygen Evolution Reaction (OER) at the anode. Both of these reactions are pH-dependent, as illustrated in Figure 29a. The equilibrium half-cell potentials (E^0) at 1 atm and 25˚C (298.15 K) *versus* Standard Hydrogen Electrode (SHE) are as follows [10]:

in acidic electrolytes (pH = 0):

$$Cathode\ (HER):\quad 4H^+ + 4e^- \longrightarrow\ 2H_2,\qquad E_c^0 = 0.000\,V$$

$$Anode\ (OER):\quad 2H_2O\ \longrightarrow O_2 + 4H^+ + 4e^-\qquad E_a^0 = 1.229\,V$$

in neutral electrolytes (pH = 7):

$$Cathode\ (HER):\quad 4H_2O + 4e^- \longrightarrow\ 2H_2 + 4OH^-,\qquad E_c^0 = -0.414\,V$$

$$Anode\ (OER):\quad 2H_2O\ \longrightarrow O_2 + 4H^+ + 4e^-\qquad E_a^0 = 0.815\,V$$

in alkaline electrolytes (pH = 14):

$$Cathode\ (HER):\quad 4H_2O + 4e^- \longrightarrow\ 2H_2 + 4OH^-,\qquad E_c^0 = -0.828\,V$$

$$Anode\ (OER):\quad 4OH^- \longrightarrow O_2 + 2H_2O\ + 4e^-\qquad E_a^0 = 0.401V$$

where E_c^0 and E_a^0 are the equilibrium half-cell potentials at the cathode and anode, respectively [23].

The water splitting reaction is categorized as an endothermic reaction, defined by the equation:

$$\Delta H^0 = \Delta G^0 + T\Delta S^0$$

where $\Delta G^0 = 237.1\ kJ\ mol^{-1}$, is the change of the Gibbs free energy, $\Delta H^0 = 285.8\ kJ/mol$ is the enthalpy change, and $T\Delta S^0 = 48.7\ kJ/mol$ is the thermal energy under standard temperature and pressure conditions ($298.15\ K, 1\ atm$) [26].

The total energy, known as enthalpy, is a contribution from both electrical and thermal energy. Considering these thermodynamic perspectives, the water splitting reaction under standard conditions can be further expressed as follows:

$$H_2O(l) + 237.1\ kJ\ mol^{-1} electricity + 48.7\ kJ\ mol^{-1} heat \longrightarrow H_2(g) + \frac{1}{2}O_2(g)$$

This implies that the process of splitting one mole of liquid water to produce 1 mole of H_2 under standard conditions necessitates a theoretical total energy (ΔH^0) of 285.8 kJ, comprising 237.1 kJ from electricity (ΔG^0) and 48.7 kJ from heat ($T\Delta S^0$). In low-temperature water electrolysis, heat can be supplied by additional heat sources or through Joule heating resulting from electric and ionic currents flowing through the cell resistances. The thermodynamic reversible voltage (E_{rev}^0) corresponding to the change of the Gibbs free energy ΔG^0 is 1.23 V under standard conditions, calculated using the following equation:

$$E_{rev}^{0} = -\frac{\Delta G^{0}}{nF}$$

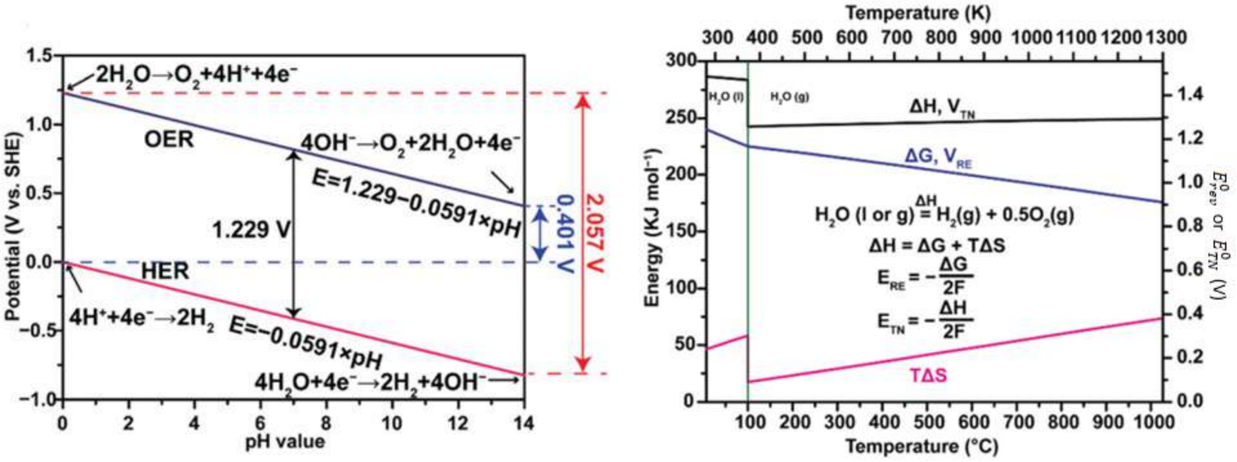
where *n=2* is the number of transferred electrons for producing 1 mol H_2 and *F* is Faraday's constant (*F= 96485 J/V-gram-equivalent)*. E_{rev}^{0} is the theoretical voltage to initiate the water electrolysis.

The thermoneutral voltage E_{TN}^{0} is based on the enthalpy change and calculated as follows

$$E_{TN}^{0} = -\frac{\Delta H^{0}}{nF}$$

Under standard conditions, this voltage is 1.48 V [27]. This difference comes from the entropy change ($T\Delta S^{0}$) in the overall process and necessitates either the supply or removal of heat from the system. When heat is entirely supplied by Joule heating from electric and ionic currents flowing through the internal resistances, this heat requirement is directly linked to the electricity supplied. Essentially, 285.8 kJ of electricity, rather than 237.1 kJ, is the minimum required to split water, resulting in a thermoneutral voltage of 1.48 V. If an electrolyzer operates at 100% efficiency (i.e., at 1.48 V under standard conditions), the heat generated equals the heat needed for electrolysis, achieving a thermoneutral state where neither heat is released nor absorbed from the environment. If the voltage is below 1.48 V (but above 1.23 V), the electrolysis cell functions as a refrigerator, continuously absorbing heat from the surroundings. Conversely, if the voltage exceeds 1.48 V, excess heat is produced and must be removed for isothermal operation [27]. It's noteworthy that all practical low-temperature water electrolyzers operate above a cell voltage of 1.48 V due to energy losses in the cells, necessitating heat removal as a crucial engineering aspect. Additionally, energy losses encompass activation, ohmic resistance, and mass transport voltage losses, leading to an "overpotential" descriptor for both HER and OER, which requires efficient electrocatalysts and optimization of electrolyte and mass transfer of reactants [26].

All the above, apply to water electrolysis conducted at 25°C (298.15 K), where liquid H_2O serves as the reactant. However, as shown in Figure 29b, both ΔG and ΔH for the water splitting reaction change with temperature. Consequently, both the reversible voltage (E_{rev}^{0}) and the thermoneutral voltage (E_{TN}^{0}) also vary with temperature. When the reaction temperature exceeds 100°C, gaseous water vapor ($H_2O(g)$) becomes the reactant, resulting in a significant decrease in ΔH at 100°C, primarily due to the latent heat of vaporization of water ($40.8\ kJ/mol$). Beyond the boiling point of water, steam electrolysis is conducted using modified high-temperature PEM water electrolyzers (100–200°C), or intermediate-temperature (400–600°C) or high-temperature (700–900°C) solid oxide electrolysis cells (SOEC). Generally, these high-temperature water electrolyzers exhibit higher efficiency due to reduced internal resistance losses and improved kinetics for both the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER).



(a) (b)

Figure 29 (a) Thermodynamic potentials of the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER) in aqueous electrolytes with different pH values under standard conditions (298.15 K, 1 atm). (b) Thermodynamics of water splitting as a function of temperature at 0.1 MPa [10]

In Figure 29b, ΔG is correlated with the thermodynamic reversible voltage (E_{rev}^{0}), while ΔH is correlated with the thermal neutral voltage (E_{TN}^{0}) in water electrolysis. ΔG and E_{rev}^{0} share the same plot but refer to the left and right y axes, respectively. $E_{rev}^{0}$and E_{TN}^{0} share the same plot but refer to the left and right y axes, respectively. Note that liquid water ($H_2O(l)$) is the reactant at temperatures lower than 100 ˚C, while gaseous water vapor ($H_2O(g)$) is the reactant at temperatures higher than 100 ˚C [10].