Cost-effective PROton Exchange MEmbrane WaTer Electrolyser for Efficient and Sustainable Power-to-H2 Technology

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D6.3 Techno-economical report including potential upscaling for PROMET-H2

system

WP6 Cost model, evaluation and LCA

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2	07/09/2022	FHA	Second Draft Version
3	13/09/2022	AL	Second Draft Version with comments
4	09/11/2022	FHA	Third Draft Version
5	11/01/2023	AL	Third Draft Version with comments
6	23/02/2023	FHA	Four Draft Version
7	06/03/2023	AL	Revised and commented version
8	09/03/2023	FHA	Draft final version
9	20/03/2023	FHA	Draft final version with cost elements review by Propuls and Chemours
10	23/03/2023	AL	Revised and Commented Draft Final version
11	24/03/2023	FHA	Final Version
12	24/03/2023	AL	Final Version

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Abbreviations

TEA	Tecno-economic analysis
PEM	Proton exchange membrane
BoP	Balance of plan
NPV	Net Present Value
IRR	Internal Rate of Return
CAPEX	Capital expenditures
OPEX	Operational expenditures

Executive Summary

This document, *D6.3 Techno-economical report including potential upscaling for PROMET-H2*, includes the Techno-Economic Analysis (TEA) carried out for the 25 kW PROMET-H2 electrolyser, its up-scaling up to MW scale and the cost assessment for a methanol plant fed by the scaled-up electrolyzer system. In addition, it also includes a comparison of the cost of the different components used in the PROMET-H2 stack developed in the project with reference baseline stack, built up by using standard materials.
The PROMET-H2 25 kW stack cost data used in this study were provided directly by the project partners involved in the development of each of its components (1.778 €/kW). This cost data was benchmarked against a standard PEM baseline stack of 25kW. The benchmarking result shows major improvement in the electrodes, current distributors and plot plates of the electrolyser system. In the absence of operational data at the date of preparation of this study, the selected operational data are based on the manufacturer's specifications of the 25 kW base-line stack and on the market scenario defined in work package 5 and 7. The costs of the balance of plant equipment were obtained directly from the manufacturer and represent their acquisition cost (13.103 €/kW). The scaling method used for the MW scale the stack has been performed under various literature assumptions applying scaling methods commonly reported by other authors for each component of the stack (537 €/kW). The balance of plant, BoP, scaling data for 1 MW was obtained from bibliographic references which includes accurate values directly provided by manufacturers. The BoP cost was updated to the 2022 cost using CEPCI indicators (548 €/kW). In addition, the cash flows leading to the Levelized Cost Hydrogen; LCOH, has been calculated, achieving a value of 6,10 €/kg H_2. The possible cost reductions are studied in a sensitivity analysis concluding that the highest decreases in the value of LCOH are achieved by decreasing the value of OPEX, according to the assumptions considered in this study.

PROMET-H2 has the ambitious goal of developing a pressurised PEMWE with the lowest capital cost ever achieved (500-750 €/kW) without compromising performance and durability. The authors consider that in the coming years the increased deployment of electrolysers will lead to a further decrease in the cost of electrolyser systems and that therefore the future cost of the PEM system is very probable to be in the range of the target cost set in the Grant Agreement. For current costs at MW scale of the system (1.084 €/kW), it would be possible to achieve these cost values assuming

a 20% discount on the price for a 10-x increase in the quantity purchased. Thus, the stated target costs of the Grant Agreement would be reached for purchases between 100 and 1000 units.

Power-to-methanol technology plays a crucial role in the shift towards a low-carbon economy by enabling the storage and utilization of renewable energy in hard-to-decarbonize sectors. The findings of the techno-economic evaluation emphasize that the cost of hydrogen is the most significant contributor to the overall production cost of CO_2 based methanol. This cost is heavily dependent on the efficiency and capital expenditure of the electrolyser system. The PROMET-H2 project aims to address this challenge by achieving up to three times lower CAPEX and 10% reduced power consumption, paving the way for one of the most competitive LCOH in the market and subsequently also for a viable green methanol production.

The levelized cost of methanol, LCOM, estimated in this study takes into account various costs such as the electrolyser system CAPEX, MeOH synthesis CAPEX, CO_2 costs, and operation and maintenance charges. The CAPEX for the electrolyser system was based on purchasing 100 and 1000 units of the up-scaled MW PROMET-H2 system, while the MeOH synthesis CAPEX and OPEX were estimated based on published literature for various capacities. The analysis over the 25 year plant lifetime has resulted in various insights on the key metrics affecting the methanol production costs using an electrolyser system.

To summarize, the market cost of methanol has been affected by the global economic environment. The cost has risen from an average cost of approximately 300 €/t before 2022 to as high as 500 €/t by the end of 2022. The cost of methanol produced using PROMET-H2 technology is at ~800 €/t which is still higher than the market average. However, the major reason for this is the higher CAPEX of the electrolyser system. But as the technology develops and improves over time, the costs are expected to come down due to more efficient stack and large scale productions. A lower CAPEX and increased efficiency can help reduce the cost of methanol below the current market value of 500 €/t. Another major factor that affect the cost of e-methanol is the cost of electricity. Therefore, if the technical targets are met and the electricity cost works in favour of the electrolyser system, CO_2 based methanol can become as competitive as fossil based methanol.

1 Introduction

The need to decarbonise society is an urgent issue with social and political attention. The European Commission identified hydrogen as a key instrument to meet the Green Deal objectives and boost economic recovery after the Covid-19 crisis.[1] Its EU Hydrogen Strategy[2] sets out the guidelines needed to develop the role of hydrogen in the efficient reduction of emissions in the EU economy.
Sectors that need to address decarbonisation in the coming years include the production of high-value chemicals and fuels, such as methanol, which currently requires hydrogen derived from hydrocarbons and causes high CO_2 emissions. Green hydrogen produced by water electrolysis coupled to renewable sources is presented as the main alternative for the decarbonisation of valuable chemicals that require hydrogen as a reagent in their production process.
Proton exchange membrane water electrolysis (PEMWE) is one of the most suitable technologies for this process due to its compactness and flexibility. However, the dependence on precious metal catalysts and expensive titanium components poses a serious threat to the scale-up and market penetration of this technology.

The PROMET-H2 project aims to develop a pressurised PEMWE based on hydraulic compression technology, containing improved membranes and electrodes with reduced or even precious metal-free contents, and coated stainless steel bipolar plates (BPP) and porous transport layers (PTL) with the lowest capital cost ever achieved (€500-750/kW) without compromising performance and durability. These innovations are being implemented in a 25 kW PEMWE PROMET-H2 system that will be coupled to a pilot plant to produce methanol from CO_2. At the same time material recycling strategies, Life Cycle Analysis, and cost assessment are being carried out to ensure that the new PEMWE can be scaled up to meet the demands of large industrial methanol plants.

This report provides the results that have been achieved in the framework of Task 6.1: "Cost model and life cycle analysis including upscaling to multi-MW for large capacity hydrogen storage" and Task 6.3: "Evaluation of CAPEX and OPEX" in the framework of PROMET-H2 project. The four main sections found in this report are:

[1] European Green Deal. https://www.consilium.europa.eu/en/policies/green-deal/

[2] A hydrogen strategy for a climate-neutral Europe, Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301&from=EN

- The techno-economical study of the 25 kW PROMET-H2 system.
- The techno-economic study for the scale-up to MW PROMET-H2 system.
- The cost assessment of the methanol production based on the MW PROMET-H2 system.

In accordance with the PROMET-H2 Grant Agreement, this work aims to achieve the objectives defined for Tasks 6.1 and 6.3.

The *Deliverable 6.1 Cost model description including first assessment of material costs.*[3] specifically addressed three objectives:

(1) Obtaining a model for a cost analysis of the components and systems developed in PROMET-H2, considering the scalability of the solutions.

(2) Defining the scenario for the production and use of hydrogen based on the inputs of *Task 7.2: Analysis of and contributions to roadmaps and standards* and *Task 7.3. Commercial Assessment, Revision of Exploitation and Business Plans*.
This scenario has been used for the techno-economic assessment in the present study, specifically for the OPEX assumptions for the 25 kW system, for the up-scaled 1 MW system and for the cost evaluation of the methanol plant.

(3) Calculation of the economics considering the scalability of the solutions. The economic results are presented in the techno-economic studies for two capacities: 25 kW and the scaling-up to MW and for the cost evaluation for the methanol plant.

The present *Task 6.3: Evaluation of CAPEX and OPEX in the framework of PROMET-H2 project* aims to:

(1) Gather the quantity and costs of materials and components, as well as information regarding the manufacturing process used for the construction of the stack and the PROMET-H2 system. For this purpose, a questionnaire was developed and provided to the partners which provided all the information on the cost and materials used for the PROMET-H2 systemn. This study contains and evaluates these figures, considering the manufacturing and operational stages of the PROMET-H2 system.

[3] Deliverable 6.1 Cost model description including first assessment of material costs, FHA, 2021.

The complete information regarding the whole life cycle cost will be analysed in the Deliverable 6.4: Final LCC and LCA.

(1) Validate the system in relevant environment

For the validation in a relevant environment, it was planned to gather consumption figures of the Promet H2 system for the OPEX calculation (Task 5.4: "Baseline characterization and validation of PROMET-H2 in relevant environment"). However, due to delays in WP5 caused by external crises such as the Covid-19 pandemic, data for Task 5.4 were not available at the time of the elaboration of this study. Therefore, the technical data considered in this deliverable are the technical specifications of the baseline system that have been published in *Deliverable 5.2: Definition of test plan of electrolyser only and coupled system*.[4] An update including the results of Task 5.4 will be published in D6.4.

(2) Analyse the total cost including OPEX and CAPEX.

In the context of cost assessment, it is imperative to mention the current socio-political context of the last 3 years, namely the Covid-19 crisis and the Ukraine war. These have led to a very extraordinary current scenario, in which there is no continuity in the markets as both crises have a high impact on price developments within the EU. In consequence an increase in procurement cost of the 25 kW PEM electrolyser system was observed, which was not foreseen during the proposal drafting phase or in the grant agreement. A techno-economic analysis under these circumstances is challenging, as there is a high uncertainty about how prices will evolve in the future.

[4] Deliverable 5.2: Definition of test plan of electrolyser only and coupled system, Air Liquide, 2021.

1.1 State of the art: PEM electrolyser CAPEX in literature

In this chapter, a literature review is performed with a focus on the costs of PEM electrolysers. PEM electrolysers are a promising technology for hydrogen production, as they can operate at low temperatures and have high conversion efficiencies. However, one of the main challenges in their widespread application is their cost, a challenge that is addressed by PROMET-H2 project. The goal of this literature survey is to provide an overview about the current cost of PEM electrolysers, as well as to identify areas where further research is needed to improve our understanding of this important topic.

In recent years, significant developments have taken place in Proton Exchange Membrane (PEM) technology, leading to improved performances and reduced costs. This section investigates several publications from reputable organizations such as the International Renewable Energy Agency (IRENA), International Energy Agency (IEA), and others, to provide an understanding of various stack and BoP costs.

One of the most comprehensive and reliable reports is the IRENA publication, which closely monitors market developments and uses inputs from various manufacturers to estimate costs accurately.[5] The report estimates the cost of stack and Balance of Plant (BoP) to be at around 400 and 700 €/kW, respectively, leading to total system costs of around 1100 €/kW. The report also highlights the potential for cost reductions of more than 25% through advancements in power electronics, water circulation units, hydrogen processing units, porous transport layers, and bipolar plates.

The Fraunhofer Institute for Solar Energy Systems conducted a study based on the underlying production process of each component of the electrolyser system. The report estimates the cost of stack and BoP to be 380 and 600 €/kW, respectively[6]. The study also evaluated the scale-up of equipment for larger plants and its potential impact on reducing costs in future scenarios.

The Lazard publication also provides insights into the cost of the electrolyser system, utilizing reports from IRENA and IEA. However, slight cost variations exist due to their internal optimization process.[7]

[5] IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi

[6] Fraunhofer Institute for Solar Energy Systems ISE (2021),Cost Forecast for Low –Temperature Electrolysis – Technology driven bottom-up prognosis for PEM and Alkaline Water Electrolysis Systems

[7] Lazard (2021), Lazard's Levelized Cost of Hydrogen Analysis – Version 2.0

The Oxford Institute of Energy Studies (OIES) estimates the average cost of PEM systems to be around 1000 €/kW. The study uses learning rates to estimate future cost reductions and emphasizes the importance of policy-making for green hydrogen economies.[8]

The IEA publishes an annual global hydrogen review, which provides an overview of developments in hydrogen production and aids member states in policy planning. The latest review estimates the average cost of PEM systems to be approximately 1000 €/kW.

The Institute of Sustainable Process Technology conducted a Gigawatt study, which developed a state-of-the-art design and cost estimate for a 1-GW water electrolysis plant, based on a 1 MW stack and a centralised BoP for a GW installation. The report highlights the potential for cost reduction in the stack components, power electronics, and balance of the plant through scale-up. The study reports the stack cost to be around 486 €/kW and BoP cost at 528 €/kW[9]. Figure 1 provides a breakdown and comparison of the different studies mentioned and also gives the average system CAPEX based on these literature data.

[8] Oxford Institute for Energy Studies (2022), *Cost - competitive green hydrogen: How to lower the cost of electrolysers?*

[9] Institute for Sustainable Process Technology (2020), Baseline Design and Total Installed Costs of a GW Green Hydrogen Plant

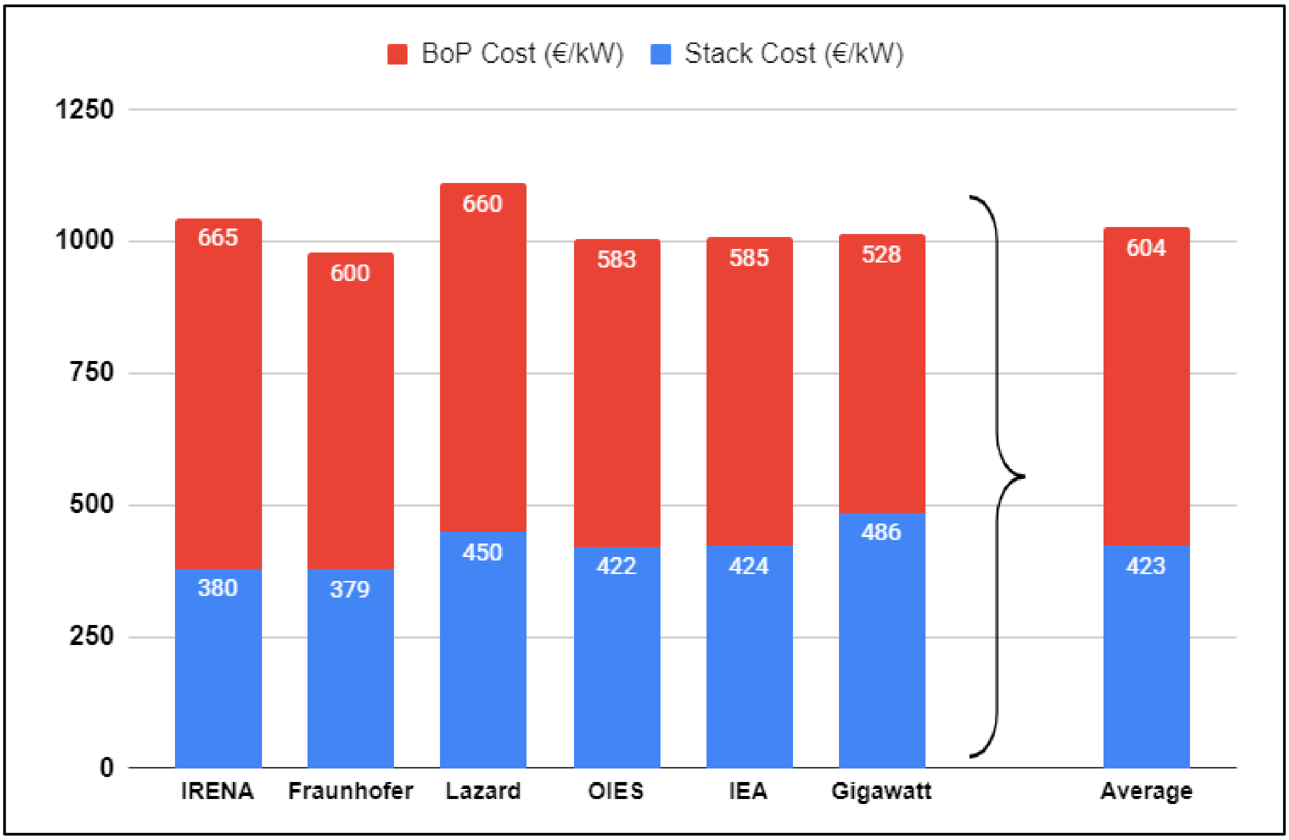

Figure 1. Current Electrolyser System Cost from various public literature and upscaled CAPEX from PROMET-H2 system (1MW).

(For OEIS and IEA BoP costs are assumed to be at 60% of the total system cost. This assumption is based on the BoP costs from other literature sources as a % of total system costs.)

1.2 Assumptions for OPEX calculation

The scenario considered for the calculation of the OPEX of the 25 kW and MW scale-up is defined in D7.6[10]. It is related to an optimal location for low-carbon methanol production. It was considered that this location should have a relatively low RE cost with high availability to increase the number of operating hours of the methanol plant. In addition, it should be located close to chemical industries, thus providing CO_2 feedstock and low carbon methanol consumers.

Therefore, the chosen location is the city of Brunsbüttel in northern Germany, a place with ample wind power availability and a lively industrial activity (there are several industrial parks within a 100 km radius), which makes it a good location for methanol consumers with minimised transport costs. For example, green methanol can be supplied to nearby companies such as Sasol Germany GmbH, which operates one of the largest olefins production plants in Brunsbüttel. The values for electricity sourcing for the scenario considered in this context is shown in Table 1.

Table 1. Breakdown of operational hours and electricity costs. Source: D7.6.[11]

Electricity Source	Number of Hours	Cost (€/MWh)
Electricity from the wind farm	6.000	40-82
Electricity consumed with Go certificates	1.000	37-40

In this study, the OPEX considers the electricity cost, the water cost, and the maintenance cost of components, as explained in the lines below.

- Electricity cost

Based on the electricity prices shown in Table 1, three scenarios are proposed for the calculation of OPEX.

- Optimistic Scenario: this scenario considers for the proposed 7.000 h of operation the lowest prices of the range considered in D7.6.[11] Thus, for the 6.000 h of operation with electricity from wind farm, a price of 40 €/MWh is chosen, and for the 1.000 h of operation from electricity consumed with GO certificates a price of 37 €/MWh is considered.

[10] Deliverable 7.6. Assessment of the market potential, Air Liquide, 2021.

- Baseline Scenario: this scenario considers for the proposed 7.000 h of operation the medium prices of the range considered in D7.6.[11] Thus, for the 6000 h of operation with electricity from wind farm, a price of 61 €/MWh is chosen, and for the 1.000 h of operation from electricity consumed with GO certificates a price of 38,5 €/MWh is considered.

- Pessimistic scenario: this scenario considers for the proposed 7.000 h of operation the high prices of the range considered in D7.6.[11] Thus, for the 6.000 h of operation with electricity from wind farm, a price of 80 €/MWh is chosen, and for the 1.000 h of operation from electricity consumed with GO certificates a price of 40 €/MWh is considered.

The both annual electricity cost, for 25 kW and 1 MW techno-economic analysis, were calculated considering that the BoP consumes 20% of the power of the stack.[11]

- Maintenance cost

To calculate the electrolyser maintenance cost associated with the OPEX involves the formula published for the Fraunhofer Institute for Solar Energy Systems ISE[12]:

$$Annual\ maintenance\ cost\ \left(\frac{€}{kW}\right) = (15 \pm\ 5) * kW$$

Thus, three scenarios were defined for the maintenance cost:

- Optimistic Scenario:

$$Annual\ maintenance\ cost\ \left(\frac{€}{kW}\right) = (15 - 5) * kW$$

- Baseline Scenario:

$$Annual\ maintenance\ cost\ \left(\frac{€}{kW}\right) = 15 * kW$$

- Pessimistic Scenario:

$$Annual\ maintenance\ cost\ \left(\frac{€}{kW}\right) = (15 + 5) * kW$$

[11] HyJack Project. Available on-line at: https://hyjack.tech/

[12] M. Holts et. al, Cost forecast for low-temperature electrolysis – technology driven bottom-up prognosis for PEM and alkaline water electrolysis systems, Fraunhofer Institute for Solar Energy Systems ISE, 2021. Available on-line at: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/cost-forecast-for-low-temperature-electrolysis.pdf

The both maintenance cost, for 25 kW and 1 MW techno-economic analysis were calculated considering that the BoP consumes 20% of the power of the stack.[11]

- Water cost

The cost associated with the water consumption was calculated based on a ratio of 18 kg of water per kg of hydrogen produced and a cost of 1,15 €/m^3 H2O. [13,14]

[13] Böhm, H., Zauner, A., Rosenfeld, D. C., & Tichler, R. (2020). Projecting cost development for future large-scale power-to-gas implementations by scaling effects. Applied Energy, 264, 114780.

[14] Lampert, D. J.; Cai, Hao; Elgowainy, Amgad (2016). Wells to wheels: water consumption for transportation fuels in the United States. Energy Environ. Sci.

1.3 Economical assumptions

For the calculation of cash flows and the main profitability indicators Net Present Value (NPV) and the Internal Rate of Return (IRR) the following assumptions were considered:

- Plant life time: 25 years (defined in the D5.2 for the system)
- Taxes: 25 % according to the Spanish Law. For the German Law, the corporate tax usually ranges from 15-20%.
- Installation cost: 20% of the total equipment cost[11]
- Straight line amortisation of the investment: 2 stacks assuming 87.500 operating hours each.
- According to the scenarios considered in D7.6[11] the electrolyser operates about 7.000 equivalent hours. For the operation during the 25 years of the system lifetime, it is considered that a replacement of the stack will be necessary in year 13, since according to different bibliographic references[15,16] the lifetime of the PEM stacks is between 50.000-90.000 hours. In the cash flows, the CAPEX considers two stacks in year zero, making a linear amortisation of the same during the 25 years.
- Hydrogen production was calculated considering 7.000 h of full load of the electrolyser, as defined in the scenario of D7.6[11]. It was assumed a system efficiency of 64 kWh/kgH_2, defined in the D5.2 for the 25 kW PROMET-H2 stack, with an annual amount of hydrogen produced of 2.734 kg H_2. For the up-scaling to the MW techno-economic analysis, it was assumed a system efficiency of 54 kWh/kgH_2 according to the scenarios given in the D7.6, with annual amount of hydrogen produced of 129.630 kg H_2.

[15] O.Schmidt et al., Future cost and performance of water electrolysis: An expert elicitation study, International Journal of Hydrogen Energy. Volume 42, Issue 52, 28 December 2017, Pages 30470-30492. https://doi.org/10.1016/j.ijhydene.2017.10.045

[16] IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi. Available on-line at: https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

- In the cash flow calculation model, a hydrogen price was fixed, which was determined for a certain rate of return considered. The hydrogen price determines the annual profits of the model, which are considered constant during the 25 years of study. The rate of return (or discount rate) expresses the expected percentage benefit applicable in the cash flows. The Net Present Value, NPV, is calculated with the cash flows and the rate of return values. In addition, the model calculates the Internal rate of return, IRR, which provides the value of the discount rate that would be obtained for the model in the case that the NPV = 0 .
  For the techno-economic analysis of 25 kW the results were obtained after an iterative process in which, by varying the hydrogen price, that determine a specific rate of return (from 15 €/kg H_2 and 1% of rate od return to 21 €/kg H_2 and 5% of rate of return), it was determined the NPV and IRR for each individual case, five cases in total.

  For the techno-economic analysis of 1 MW, the selling price of hydrogen was set at a rate of return of 7%. For this case, the NPV and IRR were determined.

2 Techno-economic analysis of the 25 kW pilot plant

This section of the report presents the techno-economic analysis of the PROMET-H2 25 kW PEM electrolyser pilot plant, that includes both CAPEX and OPEX analysis of the system. While the CAPEX data were provided by the project partners and the manufacturers directly involved, the OPEX data have been calculated according to the system specifications provided in D5.2 *Definition of test plan of electrolyser only and coupled system*[5] according to the scenarios defined in D7.6. *Assessment of the market potential*[11]. This was necessary since at the time of this study the system was not ready yet for gathering experimental data. Finally, certain assumptions were defined to calculate the cash flows from which the *Levelized Cost of Hydrogen*, LCOH is derived.

2.1. CAPEX

In the assessment of the CAPEX, it must be considered that the 25 kW PROMET-H2 system is a demonstration plant, where many hand-made processes are involved and that the purchase quantities were very small, which leads to a much higher cost. In addition, some elements of the BoP were purchased additionally due to the test bench character of this project, e.g. supplemental heat exchangers were installed allowing to heat up the system to a specific temperature which would not be considered for an industrial installation. Furthermore, as it was mentioned in the introduction, the purchase orders for materials, elements and equipment for the 25 kW PROMET-H2 system were issued in the context of a socio-economic crisis, such as Covid-19 and the war in Ukraine, which led to an increase in the cost of materials, resulting in an increase in the overall CAPEX of the first demonstration plant of the 25 kW PROMET-H2 system.

In the following sections, the CAPEX is broken down into two main sections: the stack and the BoP.

2.1.1 CAPEX for PROMET-H2 stack and base-line stack

The project partners CSIC, CENMAT, CNR-ITAE, JÜLICH, DLR and Propuls provided valuable data on the components of the newly developed PROMET-H2 stack (Table 2). In this study, the cost of the membrane includes the cost of Nafion provided by Chemours (~2.000 $/m^2$, 1.884 €/m^2). Similarly, the costs of all components of the stack are based on the cost of the materials.

Table 2. Materials, quantity of material per stack (g/stack) and price per stack (€/stack) of each element for the PROMET-H2 stack.

As can be seen for each component involved the materials used are specified and the quantity needed (g/stack) as well as the material cost (€/stack) are given. In total the cost of the PROMET-H2 stack including the hydraulic system amounts to a total of 44.454 €, thus 1.778 €/kW.

The breakdown of the total stack cost is shown in Figure 2. It is obvious that the main cost driver in the stack is the pressure vessel with 44%. This equipment is needed for the hydraulic compression technology invented and patented by Propuls together with the feed throughs for process media and sensors as well as with the current connectors. In contrast to conventional PEM stacks this innovative hydraulic compression system takes advantage of a homogeneous and reproducible cell compression, the possibility to operate the cell at very high pressure up to 100 bar (design for 40 bar in PROMET-H2) and a uniform and controlled temperature distribution inside the single cells.[17]

In case of a high H2 output pressure needed by the customer that cannot be reached by conventional systems (up to 30 bar output pressure) the hydraulic compression system can lead to savings by making the installation of a downstream compressor superfluous. Also, the better and more uniform temperature control inside the cell is beneficial for reaching a higher stack lifetime.

[17] Wasserstofftechnik - Innovative Energiesysteme. Propuls. Available on-line at: https://www.propuls.de/leistungen/wasserstofftechnik/

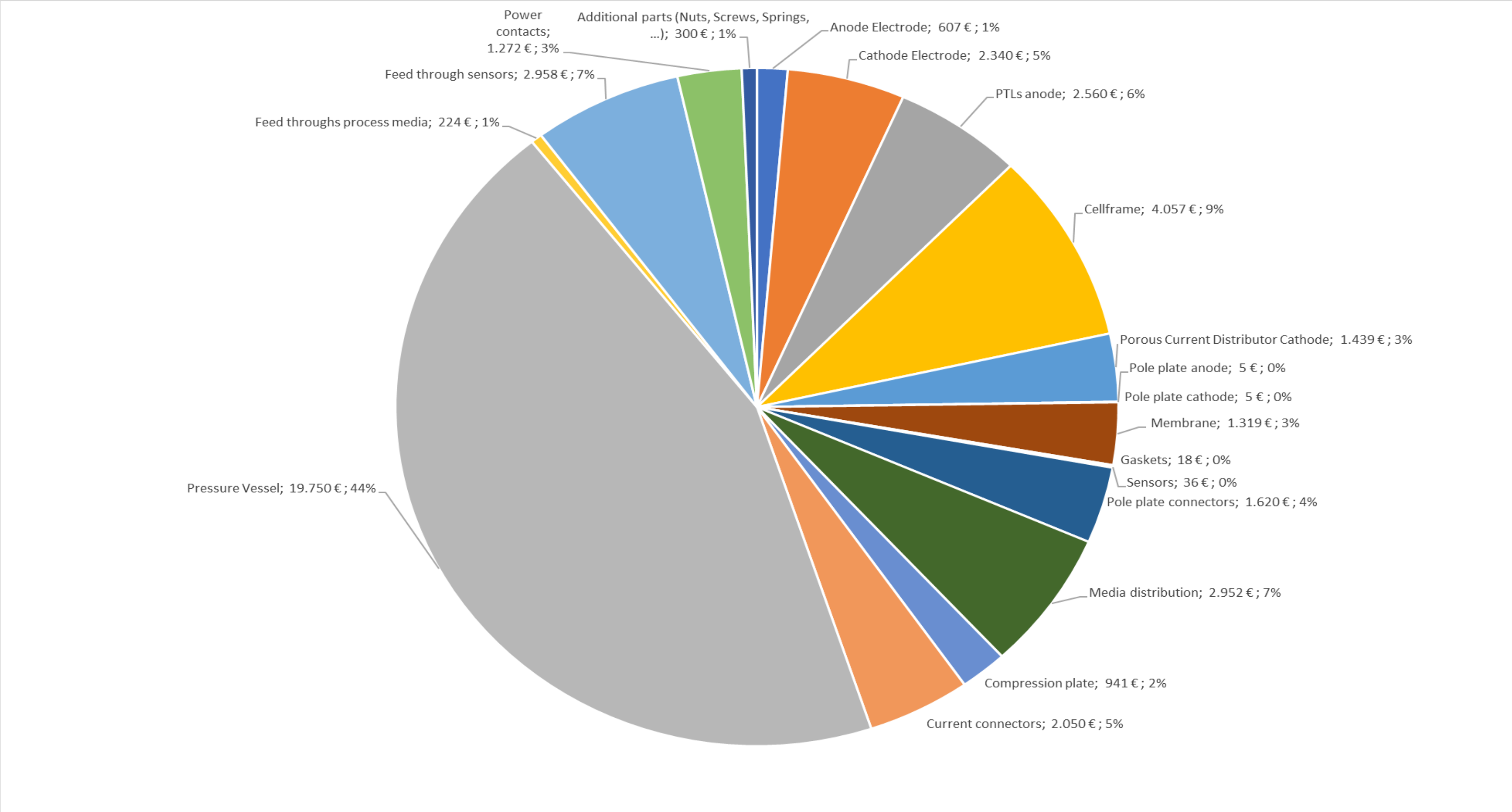

Figure 2. Element contribution % to CAPEX PROMET-H2 stack.

In order to define a baseline for comparison of the materials developed in PROMET-H2, ProPuls fabricated a 25 kW PEM electrolyser stack also based on hydraulic compression technology but using commercially available or state-of-the-art components (see also *Task 4.3: Stack assembly and component integration*, ProPuls, iGas and DLR).

Table 3 shows the costs of the components and the comparison of the total cost of the two stacks built in the project: the base-line stack and PROMET-H2 stack.

Table 3. Material purchase cost for the base-line stack, PROMET-H2 stack and percentage difference between the cost of elements.

	Components involved	Base-line stack Material cost (€/stack)	PROMET-H2 STACK Material cost (€/stack)	% difference
1	Electrodes	5.314 €	2.947 €	-45%
2	PTLs	5.710 €	2.560 €	-55%
3	Cellframe	4.057 €	4.057 €	
4	Porous Current Distributor Cathode	1.439 €	1.439 €	
5	Pole plate anode	568 €	5 €	-99%
6	Pole plate cathode	67 €	5 €	-93%
7	Membrane	1319 €	1319 €	
8	Gaskets	420 €	18 €	-96%
9	Sensors	36 €	36 €	
10	Pole plate connectors	1.620 €	1.620 €	
11	Media distribution	2.952 €	2.952 €	
12	Compression plate	941 €	941 €	
13	Current connectors	2.050 €	2.050 €	
14	Pressure Vessel	24.881 €	19.750 €	-21%
15	Feed throughs process media	224 €	224 €	
16	Feed through sensors	2.958 €	2.958 €	
17	Power contacts	1.272 €	1.272 €	
18	Additional parts (Nuts, Screws, Springs, …)	300 €	300 €	
	Stack Cost (€)	**56.126 €**	**44.454 €**	
	Stack Cost (€/kW)	**2.245 €/kW**	**1.778 €/kW**	

As can be seen in Table 3 the baseline stack with a total cost of 56.121 euros was 21% higher than the cost of the PROMET-H2 stack (44.454 €).

PROMET H2 project aims to reach a cost reduction by the development and implementation of new materials. Therefore, in PROMETH2 stack electrodes with lower content of precious metals have been implemented, leading to a decrease in price of 45 % compared to standard material electrodes.

In the pole plates, a very marked difference in cost is observed, since the PROMET-H2 post plates do not have a coating, so they are manufactured exclusively in stainless steel.

As explained earlier a huge part of the stack cost (~53 ± 3%) can be attributed to the hydraulic pressure concept. Especially for the pressure vessel the cost has been extremely high, due to its special design and the fact that it was ordered only once. It is expected that a substantial decrease in cost can be reached with increased purchase orders.

However, when comparing the PROMET-H2 stack containing the new developed materials with literature data, it seems appropriate to also compare the stack without the hydraulic pressure system, to be able to compare the cost at the same pressure level. By doing this, a specific stack cost of 1.130 €/kW for the baseline stack and 779 €/kW for the PPROMET-H2 have been calculated. In this case, a reduction of 31% in the CAPEX of the PROMET-H2 stack compared to the base-line stack is observed.

From Table 3 it becomes also obvious that the purchase cost of small systems and components are subject to fluctuations, - this was especially true during the last 3 years. One example is the pressure vessel, the same equipment with the same specifications was ordered at 2 different points in time at different suppliers and in case of the baseline stack the price was 21% higher. Also, for the gaskets the price for the baseline stack and PROMET H2 stack differed significantly, in this case 96% cost increase for PROMET-H2 stack was observed.

2.1.2 CAPEX Balance of Plant

The electrolyser system comprises the electrolyser stack as the device where the chemical reaction for hydrogen production takes place, as well as the balance of plant (BoP) necessary to operate the entire electrolyser system.

The system consists of a containerised solution, adding the container itself. It is built by iGas Energy GmbH, which has provided the specification, material and quantity involved, as well as the purchase cost of each component defined as input for this study.

The total cost of the BoP was 372.574 €, the detailed cost information can be found in Table 4. It can be anticipated that the 33,4% of the total cost is associated with three elements: switch cabinet (9,4%), rectifier (11,8%) and container (20,87%).

Table 4. Component, details, and cost of the BoP components.

nº	Component	Cost (€)	%	nº	Component	Cost (€)	%	nº	Component	Cost (€)	%
1	Container	40.000 €	12,20%	17	Chiller	4.520 €	1,40%	33	Valve terminal	3.288 €	1,00%
2	Rectifier	38.600 €	11,80%	18	Rack for dryer	1.380 €	0,40%	34	Instrument block	233 €	0,10%
3	Refill pump	3.577 €	1,10%	19	Dryer container	4.650 €	1,40%	35	Proportional valve	3.564 €	1,10%
4	Cooling water pump stack	9.347 €	2,90%	20	DeOxo	1.450 €	0,40%	36	mass flow controller	3.260 €	1,00%
5	Cathode pump	5.400 €	1,60%	21	Catalyst for DeOxo	2.864 €	0,90%	37	control valves	12.620 €	3,80%
6	Anode pump	5.400 €	1,60%	22	Separators	6.900 €	2,10%	38	Pressure reducer/ pressure control valves	6.200 €	1,90%
7	Cooling circuit inlet pump	673 €	0,20%	23	Ultrapure water tank	1.775 €	0,50%	39	Safety Valves	3.150 €	1,00%
8	Cooling circuit pump	4.666 €	1,40%	24	Pipes	15.000 €	4,60%	40	3-way valves, other valves	10.000 €	3,10%
9	Pump rectifier	303 €	0,10%	25	Tank with heating element	1.360 €	0,40%	41	Analysis H2 in O2	2.250 €	0,70%
10	Heat exchanger	1.248 €	0,40%	26	Fittings, Sealing, Hy-Lok	12.000 €	3,70%	42	Analysis O2 in H2	1.584 €	0,50%
11	Heat exchanger2	754 €	0,20%	27	Condensate separator	5.200 €	1,60%	43	Pressure transmitter	4.250 €	1,30%
12	Heat exchanger3	754 €	0,20%	28	Gas preheater	1.190 €	0,40%	44	Dew point measurement	3.612 €	1,10%
13	Heat exchanger4	115 €	0,00%	29	Siphon	2.500 €	0,80%	45	Smoke&Flame detector, H2 mass flow meter	11.343 €	3,50%
14	Water treatment	17.440 €	5,30%	30	Switch cabinet	30.800 €	9,40%	46	Temperature measure	3.600 €	1,10%
15	Recooler	5.249 €	1,60%	31	Ball valve	5.717 €	1,70%	47	Conductivity sensor	8.000 €	2,40%
16	Chiller	2.087 €	0,60%	32	Membrane valve	5.434 €	1,70%	48	Level sensor	4.500 €	1,40%
								49	Other	8.000 €	2,40%

2.2 OPEX

The total cost considered for the OPEX is 16.533 € per year. The considerations for the calculation are explained in section *1.3 "Assumptions for OPEX calculation*" of this document. The values corresponding to the different contributions to OPEX are shown in Annex I of this document.

2.3 Cost effectiveness indicators

To evaluate the profitability parameters, Net Present Value (NPV) and the Internal Rate of Return (IRR) different hydrogen sales prices have been evaluated with a rate of return that gives a positive figure for the NPV. It will be noted that the figure of IRR is the maximum interest that the investment returns when the NPV, the sum of the flows considering the rate of return, minus the initial investment is zero which means that the investment is recovered.

The rate of return (or discount rate) is the value that is expected to be the profit, so it is the value that is applied in the cash flow calculation. The IRR value is the discount rate that would have the case study analysed, where the rate of return has been applied, to obtain the NPV = 0.

The Table 5 evaluates the IRR value from 0,5 to 7%, for its optimal selling price of hydrogen. 7% is a typical IRR value for renewable energy projects, but it must be considered that a pilot plant (25 kW) is being evaluated, which is not expected to be highly profitable, but rather a technological validation. Therefore, in the case evaluated, a 25 kW system is not suitable for evaluation under profitability criteria applicable to large renewable energy projects, as will be the case in the evaluation of MW scaling. Thus, the project profitability associated with the 25 kW electrolyser can be more flexible and not expect such a high interest rate, and be operated and evaluated as a pilot project. The study on the cost-effectiveness of scaling up to MW of the PROMET-H2 system is assessed in section 3.3 of this report.

Table 5. 25 kW system: NPV and IRR.

Hydrogen price (€/kg H2)	Rate of return (%)	NPV	IRR
15	1	12.859 €	1%
16,5	2	14.305 €	2%
18	3	11.959 €	3%
19,5	4	7.186 €	4%
21	5	946 €	5%

The Annex II shows the cash flows for the first case in Tables 5, with a selling price of hydrogen of 21 €/kg H_2 and a rate of return of 5%.

2.3.1 Calculation of the Levelized Cost of Hydrogen (LCOH)

The Levelized Cost of Hydrogen (LCOH) has been analysed with the formula used by the Fuel Cells and Hydrogen Observatory (FCHO) [18]:

$$LCOH\ (€/kgH_2\ ) = \frac{CAPEX + \sum_{t=0}^{t=25} \frac{(OPEX, t)}{(1+\tau)^t}}{\frac{kgH_2}{(1+\tau)^t}} \quad (1)$$

Discount rate τ and year of operation t is a method of valuing a project, which gives a present value to all future cash flows, incoming and outgoing. The used figures were:

[18] Levelised Cost of Hydrogen, FCHO. Available on-line at: https://www.fchobservatory.eu/observatory/technology-and-market/levelised-cost-of-hydrogen-grid-connected-electrolysis

τ: Discount rate, 8%, according to the usual values used by the IEA.[19]

t: System lifetime, 25 years.

The result of the analysed case shows a value of 23,24 €/kg H_2 for the LCOH.

[19] Internacional Energy Agency, Global average levelised cost of hydrogen production by energy source and technology, 2019 and 2050. Last updated 23 Sep 2020. Available on-line at: https://www.iea.org/data-and-statistics/charts/global-average-levelised-cost-of-hydrogen-production-by-energy-source-and-technology-2019-and-2050

3 Scale-up to MW size: Techno-economic analysis

The aim of scaling-up to a higher capacity is to achieve a unit cost reduction, in the case of electrolysis in €/kW_{elec}, €/(kg/h) or €/(Nm^3/h). Note that these units are related to each other by means of the efficiency of the electrolyser installed and the density of hydrogen.

The potential sources of cost reduction by scale-up are listed below:

- **By scaling-up (sizing-up) of components**: Sizing-up stands for an increase in component dimensions, for example in cell area or in energy and mass flows, such as the hydrogen volume flow of a compressor. When the capital cost increases less than the size this is called economy of scale. Sizing-up the stack only shows a moderate potential for cost reduction, which can partially be explained by keeping a similar stack design.
- **By increasing production volumes of electrolyser components (numbering-up)**: Numbering-up considers the effect of increasing the size of a production plant by increasing the number of the single components installed, for example by increasing the number of stacks in an electrolyser. Due to the higher purchase number better purchase offers can be reached. It also allows sharing common costs of the manufacturing plant (such as capital costs, facilities/building costs, scrap costs, labor costs, energy costs, maintenance costs) between a larger number of units, leading to a unit cost reduction.
- **By technological advancements on stack level**: improvements in the electrochemical performance of the stack. For instance, reducing the use of iridium and platinum with thinner coatings may reduce cost, as well as a replacement of titanium in bipolar plates and porous transport layers with a high conductivity/stable coating on low-cost materials such as steel[20]. Technological advancements on stack level are not considered since this would lead to a different stack.

[20] Chatenet, M., Pollet, B. G., Dekel, D. R., Dionigi, F., Deseure, J., Millet, P., ... & Schäfer, H. (2022). Water electrolysis: from textbook knowledge to the latest scientific strategies and industrial developments. *Chemical Society Reviews*.

- **By improvements in production technologies:** A numbering-up or sizing up of the production capacity of the single electrolyser components like the stack also leads to a decrease in cost. It can be reached by an increasing level of automatization of the production technologies and by improvements of the process due to the experience gained, examples in case of the stack are the reduction of scrap material or more effective ways of catalyst deposition. However, this effect is not easy to assess because the current manufacturing costs of the stack are not available, only the material costs are provided. NREL[21] and Fraunhofer Institute[22] have studied the effect of this measure.

In this document the effect of sizing-up and improvements in production technologies are assessed considering:

- Scaling-up is assessed by means of scaling factors, which include the nonlinear behaviour of equipment cost when the capacity increases.
- Improvements in production technologies is estimated by means of learning rates thanks to the experience gained due to historical cumulative production.

This section focuses on the cost reduction approach by means of sizing-up. The cost variation due to a size change are estimated through Equation (2).

$$C_b = C_a \left(\frac{S_b}{S_a}\right)^{-f} \qquad (2)$$

- C_b cost at the desired size
- C_a cost at the reference size
- S_b desired size
- S_a reference size
- f scaling factor

[21] Mayyas, Ahmad, Mark Ruth, Bryan Pivovar, Guido Bender, and Keith Wipke. 2018. Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolysers. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72740. https://www.nrel.gov/docs/fy10osti/72740.pdf.

[22] Holst, M., Aschbrenner, S., Smolinka, T., Voglstätter, C., & Grimm, G. (2021). Cost Forecast for Low-Temperature Electrolysis-Technology Driven Bottom-Up Prognosis for PEM and Alkaline Water Electrolysis Systems. A Cost Analysis Study on Behalf of Clean Air Task Force.

3.1 General considerations for the scale-up of stacks

In the stack design, the cells may be arranged electrically in series, parallel, or series/parallel arrangements to allow us to select DC current and voltage inputs of a manageable level. High currents mean big conductors, expensive power controls, and high ohmic losses- high voltages mean lower currents, but also the potential for currents flowing through undesired paths or places, so this is a trade-off solution.[23]

The key parameter for stack design is current density, i.e., the current, in amperes, which flows through each unit of electrode/cell area (A/cm^2). Lower current density means lower voltage per cell and hence higher efficiency, but also means more capital cost per unit of H_2 production (or power input) because each unit of electrode area produces less hydrogen per unit time. The scaling method applied to the PROMET-H2 stack assumes that the current density remains constant from the 25 kW stack to the 1MW stack.

It is desirable to produce the hydrogen product under pressure because less mechanical compression is needed before the transport or storage, so the electric consumption of later stages is reduced. Figure 3 shows that if the pressurization occurs inside the stack (green and blue lines), the global power consumption is lower than the scenario where mechanical compression is needed. Regarding high pressure electrolysis (green and blue lines), lower power consumption is expected when differential (unbalanced) pressure is applied instead of balanced pressure.

[23] Martin, Paul. Scaling Object Lesson #2: Water Electrolyzers For Hydrogen Production: https://www.linkedin.com/pulse/scaling-lesson-2-water-electrolysis-paul-martin/?trackingId=PZHTZ9o8QFO0fN9%2Fu7jZCA%3D%3D

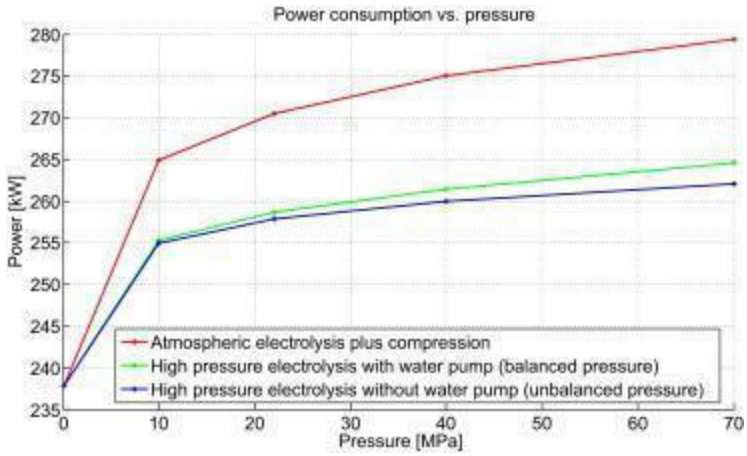

Figure 3. Comparison of the power requested to produce 1 mol/s (80.64 Nm3/h) of hydrogen by electrolysis as a function of pressure. Source: Marangio et al. [24]

However, pressure acting on a unit of area generates a force that tends to separate the stack plates, which could make the electrolyser leak- so the larger the plate or cell, the stiffer it must be and the more carefully the fastening must be designed. Moreover, the differential pressure acts as a driving-force for the hydrogen and oxygen cross-over permeation through the membrane, which reduces the purity of hydrogen flow and the safety, since the hydrogen concentration on the anode side may exceed the 2 mol% H_2 in O_2 usually recommended (lower explosion limit of 4 mol % H_2 in O_2).

Thus, there are some physical issues that hinder the upscaling of the stack working at differential pressure putting practical limits on how large each plate can be made and how much cost reduction can be achieved by means of scaling-up the size of the stack. The hydraulic cell compression (balanced pressure) concept developed in this project aims to overcome this issue. Pressure within a hydraulic medium is equally distributed. Considering this phenomenon, there is the same force applied everywhere to a planar surface facing hydraulic pressure. With two or more planar, parallel, and flexible components, like e.g., thin metal plates, inserted into a flexible pocket, which is surrounded by a hydraulic medium, a completely homogeneous compression of these components is ensured. Therefore, using the described setup to compress a PEMEL cell assembly, homogeneous cell compression and current density distribution are

[24] Marangio, F., Pagani, M., Santarelli, M., & Cali, M. (2011). Concept of a high-pressure PEM electrolyser prototype. International Journal of Hydrogen Energy, 36(13), 7807-7815.

guaranteed to be independent of the size of the actual active area. Furthermore, the pressurization of the hydraulic medium may be adjusted to the gas output pressure keeping the cell compression at a given value independent of the actual hydrogen production pressure. With an additional circulation of the hydraulic medium, also extra cellular temperature management is possible[25]. For further information regarding this topic, Salehmim et al.[26] provide a comprehensive review that faces the benefits and drawbacks of high-pressure electrolysis.

3.1.1 Scale-up of the PROMET-H2 stack

The stack developed in this project includes 14 cells with 500 cm^2 of active area. According to the inputs given by the manufacturer for the up-scaling to one MW 175 cells with an active area of 1600 cm^2 were considered. 1500 cm^2 as active area are currently SOR for a stack size of 1 MW, but also active areas in the range of 3000 cm^2 have been reported with the aim of overcoming 10,000 cm^2 in 2050 [6] [11]. Hence, there is room for improvement in this field.

Since some of the values considered (scaling factors) are taken from Bohm et al. [27] [28], the initial breakdown is arranged to fit the breakdown provided in that source (Table 6).

[25] Wirkert, F. J., Roth, J., Jagalski, S., Neuhaus, P., Rost, U., & Brodmann, M. (2020). A modular design approach for PEM electrolyser systems with homogeneous operation conditions and highly efficient heat management. *International Journal of Hydrogen Energy*, *45*(2), 1226-1235.

[26] Salehmin, M. N. I., Husaini, T., Goh, J., & Sulong, A. B. (2022). High-pressure PEM water electrolyser: A review on challenges and mitigation strategies towards green and low-cost hydrogen production. *Energy Conversion and Management*, *268*, 115985.

[27] Böhm, H., Zauner, A., Rosenfeld, D. C., & Tichler, R. (2020). Projecting cost development for future large-scale power-to-gas implementations by scaling effects. Applied Energy, 264, 114780.

[28] Böhm, H., Goers, S., & Zauner, A. (2019). Estimating future costs of power-to-gas–A component-based approach for technological learning. International Journal of Hydrogen Energy, 44(59), 30789-30805.

Table 6. Scaling factors for each stack's component. Source: Bohm et al.

Component	Scaling factor
Small parts	50%
Catalyst cathode	100%
Catalyst anode	100%
Membranes	100%
Current collectors cathode	95%
Current collectors anode	95%
Bipolar plates	95%
Pressure plates	95%

Table 7 summarizes the stack component cost breakdown at 25 kW (reference scenario) and 1 MW (upscaled scenario). The "Up-scaling relation" column in Table 7 details the relationship by which the scaling ratios (power, cell area, cell size, number of cells) detailed in Equation 2 were applied. For the power contacts, the manufacturer specified that the same cost is expected in both stacks.

The cost of up-scaling 1 MW stack based on PROMET-H2 25 kW stack was 536.520 €, which translates to 536 €/kW.

Table 7. Stack component cost breakdown for 25 kW and 1 MW.

	Component	Material cost 25 kW (€/stack)	Scaling factor	Material cost 1 MW (€/stack)	Up-scaling relation
1	Anode Electrode	607 €	1,00	24.272 €	Power
2	Cathode Electrode	2.340 €	1,00	93.600 €	Power
3	PTLs	2.560 €	0,95	85.152 €	Power
4	Cellframe	4.057 €	1	97.373 €	Power
6	Porous Current Distributor Cathode	1.439 €	0,95	47.848 €	Power
7	Pole plate anode	5 €	0,95	182 €	Power
8	Pole plate cathode	5 €	0,95	182 €	Power
9	Membrane	1.319 €	1,00	52.752 €	Power
10	Gaskets	18 €	0,50	114 €	Power
11	Sensors	36 €	0,50	228 €	Power
12	Pole plate connectors	1.620 €	0,50	10.246 €	Power
13	Media distribution	2.952 €	0,50	5.281 €	Cell area
14	Compression plate	941 €	0,50	1.684 €	Cell area
15	Current connectors	2.050 €	0,95	6.189 €	Cell area
16	Pressure Vessel	19.750 €	0,44	98.750 €	Size
17	Feed throughs process media	224 €	0,50	401 €	Cell area
18	Feed through sensors	2.958 €	0,50	10.458 €	nº cells
19	Power contacts	1.272 €	not applied	1.272 €	Propuls (same cost)
20	Additional parts (Nuts, Screws, Springs, …)	300 €	0,50	537 €	Cell area

3.2 Scale up of BOP

Originally it was planned to use the cost of the 25 kW system for the CAPEX calculation of the 1MW BOP by scale-up. However, as already stated in chapter 1 during project execution the procurement prices were influenced a lot by the current crisis including increased and fluctuating prices for the offers with a high uncertainty. Therefore, the available data and its quality of the 25 kW BoP was a limiting factor in calculating the MW BoP cost, as it directly influences the derived results for the 1 MW plant. Inaccuracies in the cost data propagate to the total cost model, resulting in an inaccurate and difficult to assess LCOH.

Additionally, scale-up numbers >10 also lead to a high uncertainty and a lot of process knowledge including the availability of cost databases is needed to come up with reasonable cost figures for the up-scaled BoP. Technical and cost data for electrolysis systems are, in general, neither transparent nor easy to obtain. This is due to confidentiality reasons and possible competitive advantages in a small market with only a few manufacturers and systems deployed in the several MW capacity ranges investigated so far.

Due to the inaccuracy of the 25 kW BoP cost, the lack of data and insider knowledge and the high scaling factor of 40, it was decided to consider the disaggregated data for a BoP of 1 MW published by A.Mayyas et al. in 2019[29]. The cost values for all elements were updated to the current cost value (October 2022) using CEPCI indicators,[30,31] and the dollar to euro conversion used was the one published by the Central European Bank in October 2022[32].

[29] Mayyas, Ahmad, Mark Ruth, Bryan Pivovar, Guido Bender, and Keith Wipke. 2018. Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72740. https://www.nrel.gov/docs/fy10osti/72740.pdf.

[30] Economics Indicators, Chemical Engineering. https://www.nxtbook.com/accessintelligence/ChemicalEngineering/chemical-engineering-august-2020/index.php?startid=50#/p/50

[31] C. Maxwell, cost indices, Towering Skills. https://www.toweringskills.com/financial-analysis/cost-indices/

[32] Resolution of October 31, 2022, of the Bank of Spain, which publishes the euro exchange rates corresponding to October 31, 2022, published by the European Central Bank, which will be considered official exchange rates, in accordance with the provided in article 36 of Law 46/1998, of December 17, on the Introduction of the Euro. https://www.boe.es/diario_boe/txt.php?id=BOE-A-2022-17959

Table 8. 1 MW BoP cost breakdown.

System	Subsystem	1 MW
Power Supplies	Power Supply	268.361 €
	DC Voltage Transducer	305 €
	DC Current Transducer	461 €
	Total	**269.127 €**
Hydrogen Processing	Dryer Bed	49.591 €
	Water/Hydrogen Separator	35.768 €
	Tubing	10.272 €
	Valves & Instrumentation	10.272 €
	Controls	7.784 €
	Total	**113.688 €**
Deionized Water Circulation	Oxygen Separator Tank†	54.214 €
	Circulation Pump	14.857 €
	Polishing Pump	6.777 €
	Piping	20.543 €
	Valves and Instrumentation	15.408 €
	Controls	6.228 €
	Total	**118.027 €**
Cooling	Plate heat exchanger	14.265 €
	Cooling pump	5.146 €
	Valves, instrumentation	6.228 €
	Piping	3.113 €
	Dry cooler	10.116 €
	Total	**38.869 €**
Miscellaneous	Valve air supply – nitrogen or compressed air	2.711 €
	Ventilation and safety requirements	5.421 €
	Total	**8.132 €**
	Total Price BoP	**547.843 €**

As shown in Table 8 the CAPEX associated with the scaling-up of the balance of plant to 1 MW sum up to 547.843 €, thus 548 €/kW.

3.3 Total 1 MW system CAPEX

The cost of the MW stack achieved is 536.520 € (537 €/kW) and the cost of the balance of plant considered is 547.843 € (548 €/kW). Therefore, the total CAPEX associated with the MW upscaled system is 1.084.363 € (1.084 €/kW), including the hydraulic pressure technology.

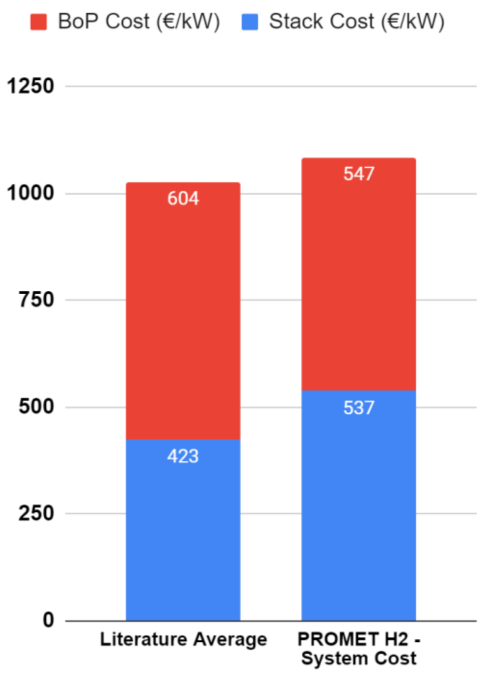

Figure 4. Comparison of the SOR CAPEX given in literature (cf. chapter 1.2) with the cost of PROMET-H2 1 MW system as of today.

Figure 4 shows the prices for the 1 MW system developed in the framework of the project, are 25% higher than that of the State of the art: PEM electrolyser CAPEX in literature. This is majorly due to the economic implications of the crisis as mentioned in section 1. In addition, the hydraulic system increases the PROMET-H2 costs, which also brings advantages. Further research will show whether a longer lifetime can be achieved, and in which cases the additional CAPEX of the stack is paid for by the savings of an external compressor.

It is foreseen that in the future years the increased deployment of electrolysers will further lead to a decline in the cost of the electrolyser systems. Among them PEM has the highest potential of cost reductions due to the technology gaining more maturity. Especially when using lower cost metals, cost can be decreased further. Therefore, it is very likely that the future cost of the PEM system will be in the range of the cost target set in the grant agreement at 500-750 €/kW.

However, A. Mayyas et al. assumed a 20% price scaling for a 10x-factor increase in the purchased quantity for the generic and power electronics parts. As an hypothesis, it was considered that a similar price discount applies to the total system costs. The following table shows the prices that would be obtained for the total system cost of PROMET-H2 under this assumption, meeting the CAPEX targets of the project for the purchase of between 100 and 1.000 units.

Table 9. Assumption of a 20% discount on the price for a 10-fold increase in the purchase quantity

Purchase Units	1	10	100	1.000	10.000	100.000
€/kW	1.084 €	867 €	694 €	555 €	444 €	355 €

3.4 OPEX

The value considered to the annual OPEX is 604.657 € per year for the MW scaling-up calculations.

3.5 Cost Effectiveness indicators

In this study a **selling price of 6,3 €/kg of hydrogen** was considered as the minimum price that gives a rate of return of 7%. This price provides positive values for the NPV, and an IRR shown in the next Table 10.

Table 10. MW system NPV and IRR

Rate of return	7%		
NPV	97.280 €	**IRR**	7,6 %

3.5.1 Levelized Cost of Hydrogen

According to formula 1 defined in this deliverable, the **LCOH calculated for this model is 6,10 €/kg H_2.**

3.6 Sensitivity Analysis

The sensitivity analysis presented in this section is based on the results obtained for the MW scaling of the PROMET-H2 system. The behaviour of the economic indicators (hydrogen price, VNA, IRR and LCOH) is studied when certain variables reduce their economic contribution. In the following points the major economic contribution of the elements of the CAPEX. Also, the results for the OPEX optimistic scenario and the OPEX medium scenario defined in the section 3.2 are presented.

3.6.1 CAPEX stack

The contributions of the two elements with the highest contribution to the CAPEX of the PROMET-H2 stack have been studied: the pressure vessel and the cellframe, with contributions of 19% and 18%, respectively of the total cost. Thus, the economic value of both elements was reduced by 10%, 20%, 30%, 40% and 50% to study their implication on the economic indicators mentioned above. The results of these evaluations are shown in the next figures and the detailed data can be consulted in the Annex 5.

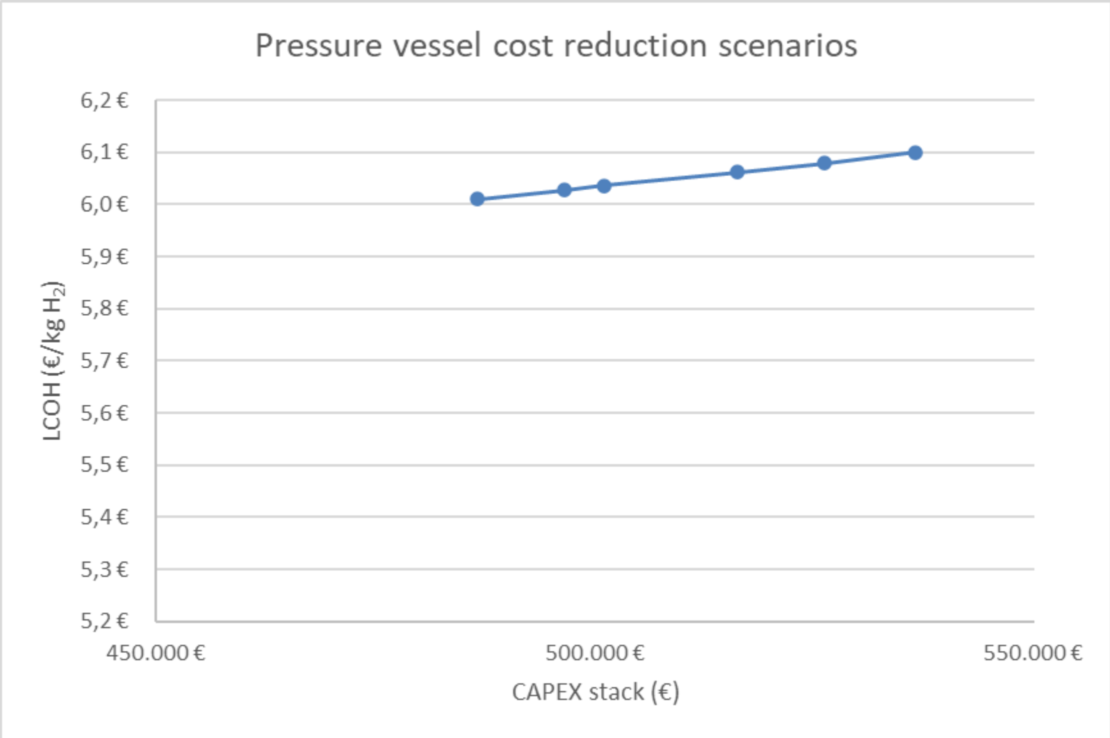

Figure 5. Sensitivity analysis for pressure vessel: total CAPEX system(€) vs LCOH (€/kg H_2)-

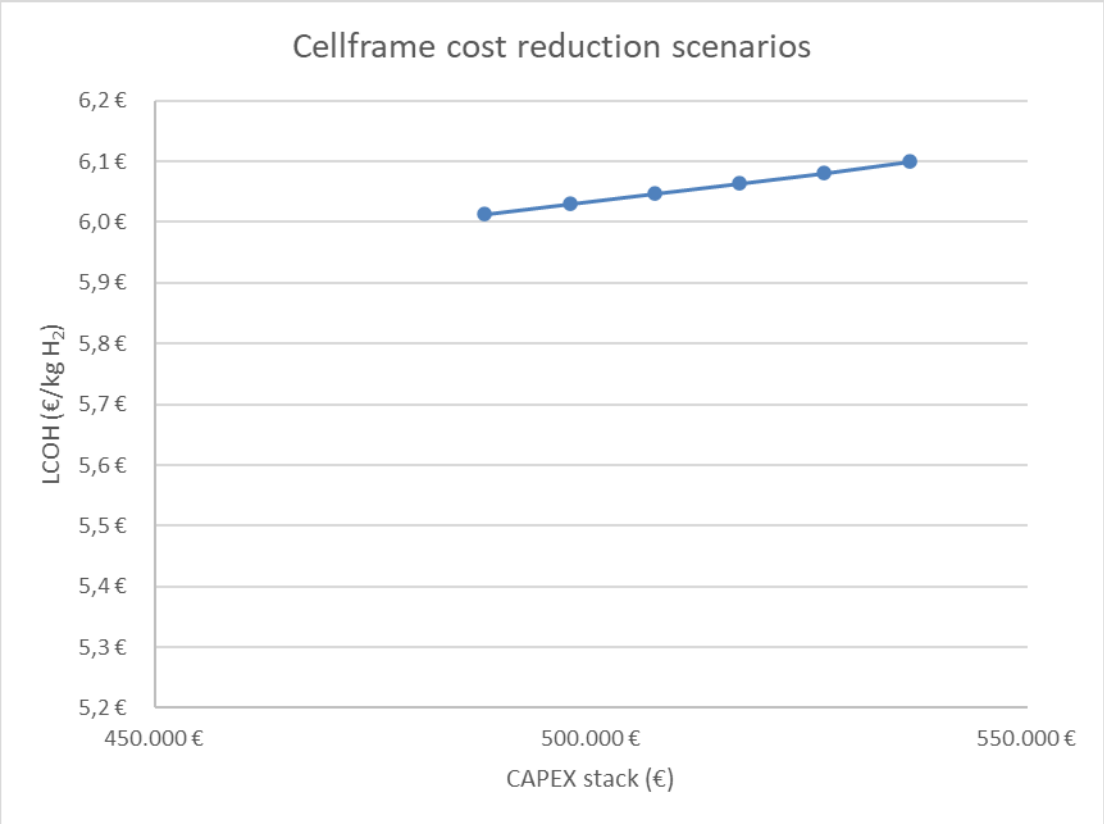

Figure 6. Sensitivity analysis for pressure vessel: total CAPEX system(€) vs LCOH (€/kg H_2)-

Note that the hydrogen prices for each specific case have been kept constant for all iterations. Thus, the price considered as a result is the one that provides an IRR equal to or greater than 7,0% for the base case. More details on the assumptions considered in the cash flow calculations can be found in sections 1.3 and section 2.2.

3.6.2 CAPEX BoP

The results for the economic indicators were studied for specific prices for a 1 MW BoP provided by reference G. Bristowe et al.[33] published a specific price range in the year 2021. As in the

[33] Bristowe, G.; Smallbone, A. The Key Techno-Economic and Manufacturing Drivers for Reducing the Cost of Power-to-Gas and a Hydrogen-Enabled Energy System. *Hydrogen* **2021**, *2*, 273-300. https://doi.org/10.3390/hydrogen2030015

methodology applied for the scaling of the BoP, the cost values were updated to the current value through CEPCI indicators, and the currency exchange used was the same.

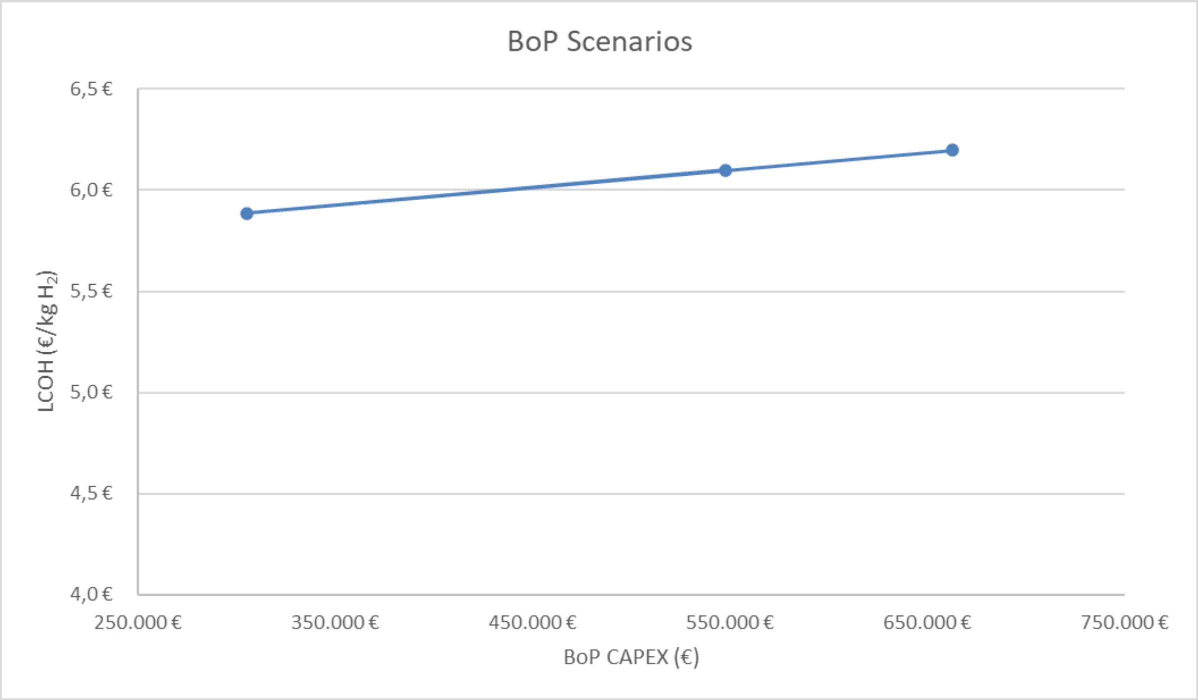

Figure 7. Sensitivity analysis for the BoP cost: BoP CAPEX (€) vs LCOH (€/kg H_2)-

The economic indicators have been calculated following the same procedure as described in the previous section.

3.6.3 OPEX

The breakdown of OPEX for the study of economic indicators was explained in section 2.2. In this section, three potential operating scenarios based on Deliverable 7.3 are presented. The results presented in section 2.3 are based on the application of the pessimistic scenario.

In this section, the results of the economic indicators obtained from the three scenarios (optimistic, baseline and pessimistic) are compared. The results obtained are shown in the next figure.

The economic indicators have been calculated following the same procedure as described in the section 3.4.1. The figure below shows the relationship between the three OPEX scenarios the LCOH obtained for each one.

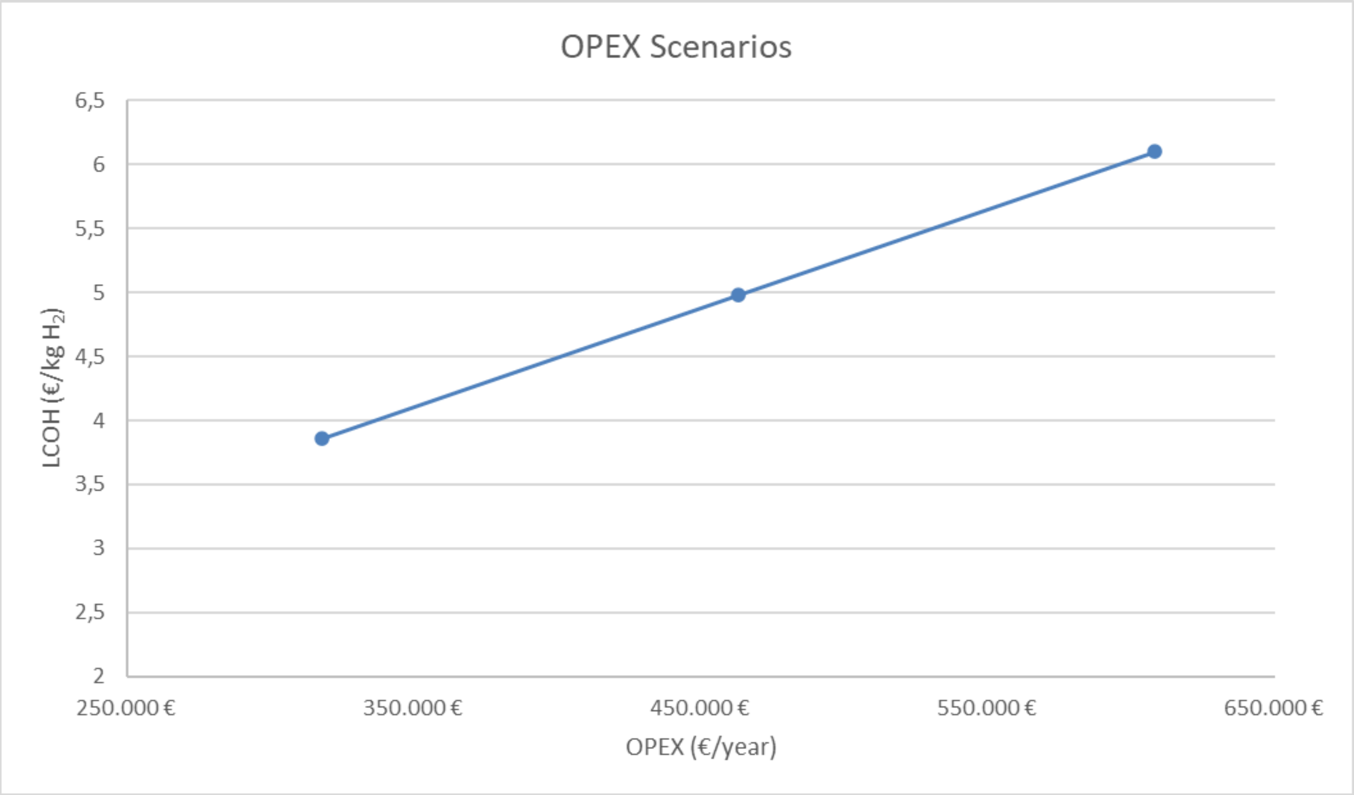

Figure 8. LCOH results for the three OPEX scenarios considered.

4 Methanol synthesis

Methanol is conventionally manufactured by reacting a pressurised synthesis gas (a mixture of H_2, CO, and CO_2) over a catalyst to yield CH_3OH and water. The downstream processing step involves purifying this mixture to obtain 99.99% CH_3OH. As the reaction is highly exothermic, continuous heat removal is necessary to prevent any side reactions and harm to the catalyst. The synthesis gas employed in the reaction is produced through the steam reforming of natural gas. However, in lieu of this fossil-based method, this study explores an alternative route for MeOH synthesis, utilizing electrolytic hydrogen and captured CO_2.

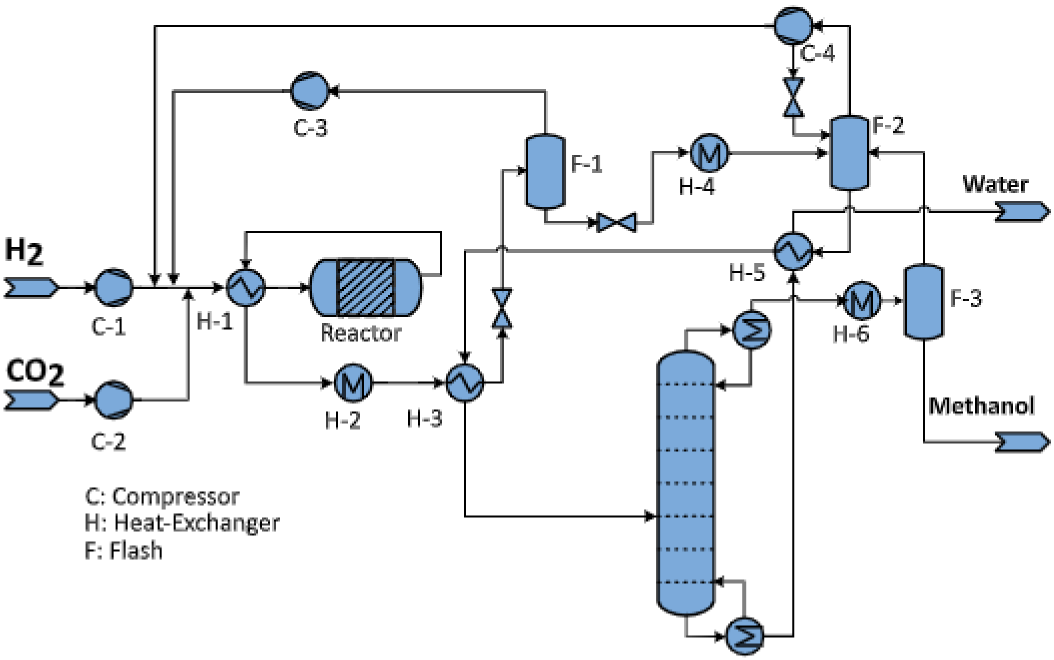

Figure 9 : Schematic representation of MeOH synthesis using green H2 and CO2[34].

Figure 9 illustrates the schematic of a CO_2 hydrogenation process that utilizes electrolytic hydrogen. In their work, Schorn et al. describe the methanol synthesis reaction occurring at a pressure of 80 bar and a temperature of 250 °C[35]. To meet the necessary reaction conditions, the feed hydrogen and CO_2 are compressed and heated prior to entering the reaction stage. The reactor outlet stream is subsequently separated to recycle the unreacted feedstock and further purify the MeOH. A

[34] Felix Schorn, Janos L. Breuer, Remzi Can Samsun, Thorsten Schnorbus, Benedikt Heuser, Ralf Peters, Detlef Stolten, Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations, Advances in Applied Energy, Volume 3, 2021.

distillation column is utilized to separate water and attain MeOH with a purity of 99.99%. The exothermic reaction provides the heating duty necessary for the distillation column. As the reactants enter the system at a pressure of 30 bar, there is a need for additional power to compress the reactants to 80 bar. Table 11 presents various technological metrics that constitute the OPEX of this process.

Table 11. Consumption figures for MeOH Synthesis

Description	Unit / t MeOH	Value
CO_2	tonnes	1.37
H_2	tonnes	0.189
Electricity	MWh	0.154

4.1 CAPEX for MeOH Synthesis:

As a preliminary step in estimating the plant cost, one could rely on historical plant costs and scale them to the desired capacities. However, to date, the only operating CO_2-to-MeOH plant is operated by CRI in Norway, with a capacity of 12 t/d[35]. Although several ongoing research projects are exploring the potential of power-to-liquid technology, the commercial data on this front remains limited.

Another approach to estimate plant costs involves determining the size of the equipment required and using the methodology presented in Peters et al[36]. Various academic publications were reviewed to obtain plant costs at different capacities. The literature largely follows a similar cost estimation approach: equipment is first sized, and then the total plant cost is calculated. Platforms such as Aspen, Matlab, and Comsol are employed to simulate the CO_2-to-MeOH process, predicting the material and energy balances of the process and helping to design the process equipment and eventually estimate plant costs.

Table 12 lists the MeOH plant costs for various capacities. As the studies were conducted in different years, it is important to adjust the costs for inflation. To that end, all costs have been adjusted for the year 2021 using the Chemical Engineering Plant Cost Index (CEPCI) through the following equation:

[35] IRENA AND METHANOL INSTITUTE (2021), Innovation Outlook : Renewable Methanol, International Renewable Energy Agency, Abu Dhabi.
[36] Peters, M. S., Timmerhaus, K. D., West, R. E., & West, R. E. (Ronald E. (2003). Plant design and economics for chemical engineers (5th ed.). McGraw-Hill.

$$Cost\ of\ plant_{\ 2021} = Cost\ of\ plant\ in\ the\ reference\ year * \left(\frac{CEPCI_{2022}}{CEPCI_{ref.}}\right) \qquad ....(3)$$

The index values for the respective years were retrieved from the CEPCI official website[37]

Table 12. CO2-to-MeOH plant cost for various capacities from the literature after adjusting them for 2021.

Source	Cost,M€	Capacity,t/d	Year of publication
Hank et al.[38]	10	30	2018
Campos et al.[39]	357	3480	2022
	462	3480	2022
Bos et al.[40]	12	195	2020
Zhang et al.[41]	29	309	2019
Mignard et al.[42]	51	372	2003
	24	178	2003
	28	201	2003
	24	175	2003
Clausen et al.[43]	192	864	2010
Matzen et al. [44]	32	97	2015

[37] Chemical Engineering Plant Cost Index (CEPCI), 2021. https://www.chemengonline.com/pci-home
[38] C. Hank, S. Gelpke, A. Schnabl, R. J. White, J. Full,N. Wiebe, T. Smolinka, A. Schaadt, H.-M. Henning and C. Hebling,Sustain, Energy Fuels, 2018.
[39] Lacerda de Oliveira Campos B, John K, Beeskow P, Herrera Delgado K, Pitter S, Dahmen N, Sauer J. A Detailed Process and Techno-Economic Analysis of Methanol Synthesis from H2 and CO2 with Intermediate Condensation Steps, Processes. 2022
[40] M.J. Bos, S.R.A. Kersten, D.W.F. Brilman, Wind power to methanol: Renewable methanol production using electricity, electrolysis of water and CO2 air capture, Applied Energy,2020.
[41] Zhang, H., Wang, L., Van Herle, J., Maréchal, F., Desideri, U., 2019. Techno-Economic Optimization of CO2-to-Methanol with Solid-Oxide Electrolyzer , Energies 12, 2019.
[42] Mignard, D., Sahibzada, M., Duthie, J. M., & Whittington, H. W. (2003). Methanol synthesis from flue-gas CO2 and renewable electricity: A feasibility study. International Journal of Hydrogen Energy, 2003.
[43] Clausen, L. R., Houbak, N., & Elmegaard, B. Techno-economic analysis of a methanol plant based on gasification of biomass and electrolysis of water, Energy, 2010
[44] Matzen, Michael J.; Alhajji, Mahdi H.; and Demirel, Yaşar,Chemical storage of wind energy by renewable methanol production:Feasibility analysis using a multi-criteria decision matrix",Chemical and Biomolecular Engineering -- All Faculty Papers, 2015.

Boulamanti et al.[45]	288	1320	2015
Tremel et al. [46]	53	107	2015
Rivera-Tinoca et al.[47]	13	50	2016
J Nyari et al.[48]	454	5000	2020
Bellotti et al.[49]	20	146	2019
Szima and Cormos [50]	65	300	2018
Räuchle et al.[51]	680	5003	2016

[45] Boulamanti, Aikaterini & Perez-Fortes, Mar & Tzimas, Evangelos. Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment, Applied Energy, 2015.

[46] Alexander Tremel, Peter Wasserscheid, Manfred Baldauf, Thomas Hammer,Techno-economic analysis for the synthesis of liquid and gaseous fuels based on hydrogen production via electrolysis, International Journal of Hydrogen Energy, 2015.

[47] R. Rivera-Tinoco, M. Farran, C. Bouallou, F. Auprêtre, S. Valentin, P. Millet, J.R. Ngameni,Investigation of power-to-methanol processes coupling electrolytic hydrogen production and catalytic CO2 reduction, International Journal of Hydrogen Energy, 2016.

[48] Nyári, J., Magdeldin, M., Larmi, M., Järvinen, M., & Santasalo-Aarnio, A. Techno-economic barriers of an industrial-scale methanol CCU-plant. Journal of CO2 Utilization, 2020

[49] D. Bellotti, M. Rivarolo, L. Magistri, Economic feasibility of methanol synthesis as a method for CO2 reduction and energy storage, Energy Procedia, 2019.

[50] Szabolcs Szima, Calin-Cristian Cormos, Improving methanol synthesis from carbon-free H2 and captured CO2: A techno-economic and environmental evaluation, Journal of CO2 Utilization, 2018.

[51] Räuchle, K., Plass, L., Wernicke, H.-J. and Bertau, M., Methanol for Renewable Energy Storage and Utilization. Energy Technology, 2016.

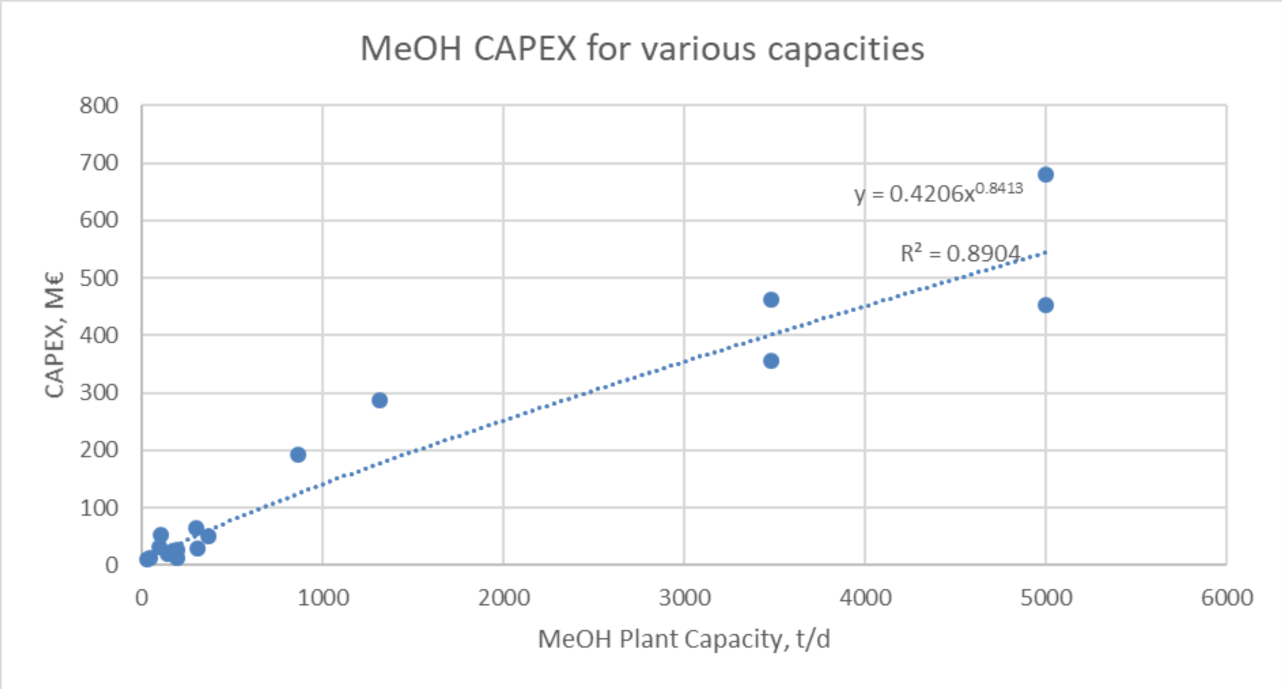

Figure 10. MeOH CAPEX against various production capacities

While these preliminary cost estimates do provide valuable insights, it is important to acknowledge that they come with a degree of uncertainty and should be interpreted accordingly. Given above in Figure 10, is the plot of various plant capacities vs CAPEX of the plant. This yields a correlation which is used to estimate the plant CAPEX at various production capacities. The equation is as given below,

$$CAPEX = 0.4206 * \left(Plant\ Capcity\ in \frac{t}{d}\right)^{0.8413}$$

Table 13. CAPEX of Methanol Plant for various capacities

Capacity, t/d	CAPEX, in M€
250	43.78
500	78.44
1000	140.53

The future of methanol production is looking bright with the potential for even larger-scale electrolyser installations on the horizon. Thanks to the economy of scale of the process equipment, larger plant capacities can lead to significant cost reductions. As a result, it is reasonable to expect that methanol production plants will continue to increase in capacity in the coming years. This trend is not only financially sound, but it also holds great promise for meeting our growing demand for sustainable fuels and reducing our dependence on fossil fuels.

4.2 LCOM estimation

The following section outlines the calculation methodology used to predict the levelized cost of methanol (LCOM). The cost model for the CAPEX and OPEX along with various economic assumptions is given in the figure 11 below.

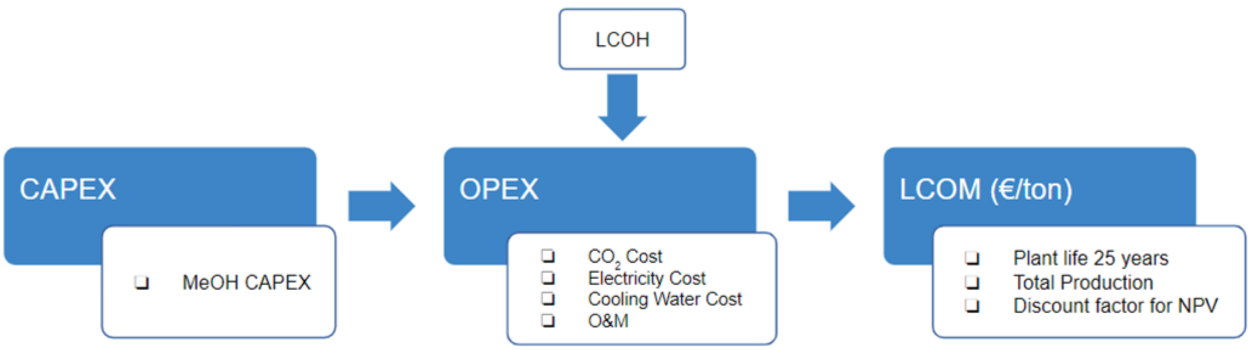

Figure 11. Flowchart for LCOM estimation

As given above, the MeOH associated CAPEX cost included the purchasing, installation and associated indirect cost before the start of the plant. Further on top of which comes the OPEX, these costs include the cost of raw materials and utilities. The LCOH estimated in the previous section is also considered as a part of the OPEX.

The equation presented in section 2.3.1 for LCOH estimation is further modified as given below,

$$LCOM\ (€/tonnes\ MeOH\ ) = \frac{CAPEX + \sum_{t=0}^{t=25} \dfrac{(OPEX, t)}{(1+\tau)^t}}{\dfrac{tonnes\ MeOH}{(1+\tau)^t}} \tag{2}$$

Wherein,

τ , is the discount rate of 8%

t , is the lifetime of the system assumed to be 25 years

CAPEX, is the MeOH plant capital expenditure

OPEX, is the associated operation costs like CO2, electricity, H2, etc

Although significant improvements in MeOH synthesis are not expected during the period, the PROMET-H2 project anticipates several advancements in the electrolyser system. These developments are expected to reduce the power consumption per kilogram of H_2 produced and lower the required installed power of the electrolyser for corresponding MeOH production capacity. The grant agreement sets a target for electrolyser efficiency of 55.7 kWh/kg H2, with a further reduction to 50 kWh/kg H2 expected in the near future[52]. Given below in Table 14. are various technological and economical metrics as used for to the economic assessment,

Table 14. Various parameters for Current and Future Scenarios

Technological Parameter	Unit	Current Scenario	Future Scenario
MeOH Production	t/d	250	1000
Electrolyser Power Consumption	kWh/kg H2	55.7	50
Installed Electrolyser Power	MW	110	394
Annual Availability	Hours	7000	
Economical Parameter			
Electrolyser Stack CAPEX	€/kW	344	275
Electrolyser BoP CAPEX	€/kW	350	280
MeOH CAPEX	M€	44	141
Cost of Electricity	€/MWh	40	20
Cost of CO_2	€/t	60	

52 Directorate - General for Research and Innovation, Grant Agreement Number 862253 - PROMET-H2, European Commission,2020

The metrics have been categorized into two distinct scenarios - current and future. In the future scenario, a larger scale MeOH synthesis using CO_2 and H_2 is expected, facilitated by a multi-hundred MW scale electrolyser system with improved power consumption. It is assumed that the system's availability will remain consistent with that used in the previous sections of LCOH estimation.

The economic parameters regarding the CAPEX of the electrolyser system are assumed at 100 and 1000 units of production, as outlined in Table 9. Additionally, the CAPEX for MeOH synthesis has been adjusted to account for a four-fold increase in production capacity (250 → 1000 t/d). The cost of electricity is estimated to be approximately 40 €/MWh. This cost is the average electricity cost observed in Germany in 2019[53], owing to various factors these costs have substantially risen in recent years. It is further assumed that the future electricity costs can decrease due to the increase in renewable energy installations in the coming years. Moreover, presently operational renewable energy sources would have already been depreciated and would be capable of providing electricity at a significantly lower cost. The grant agreement predicts that electricity costs will drop to 20 €/MWh in a highly optimistic scenario. In order to evaluate the potential cost of MeOH utilizing electrolytic hydrogen, we assume the same cost of electricity for the future scenario. The cost of CO_2 is contingent upon the emission source, which is discussed in D7.6.[11] For evaluation purposes, we assume an average cost of 60 €/t CO_2.

The LCOM presented here is the estimated total production cost per tonne of methanol over the entire lifespan of the plant. This cost excludes any internal rate of return and encompasses the depreciation of the infrastructure, feedstock, and energy costs. The calculation of yearly cash flows for MeOH synthesis is provided in Annex 6. The OPEX is adjusted with the discount rate to adjust the future cash flow to present values. The final results from both scenarios are depicted below in figure 11,

[53] https://www.smard.de/page/en/topic-article/5892/206870

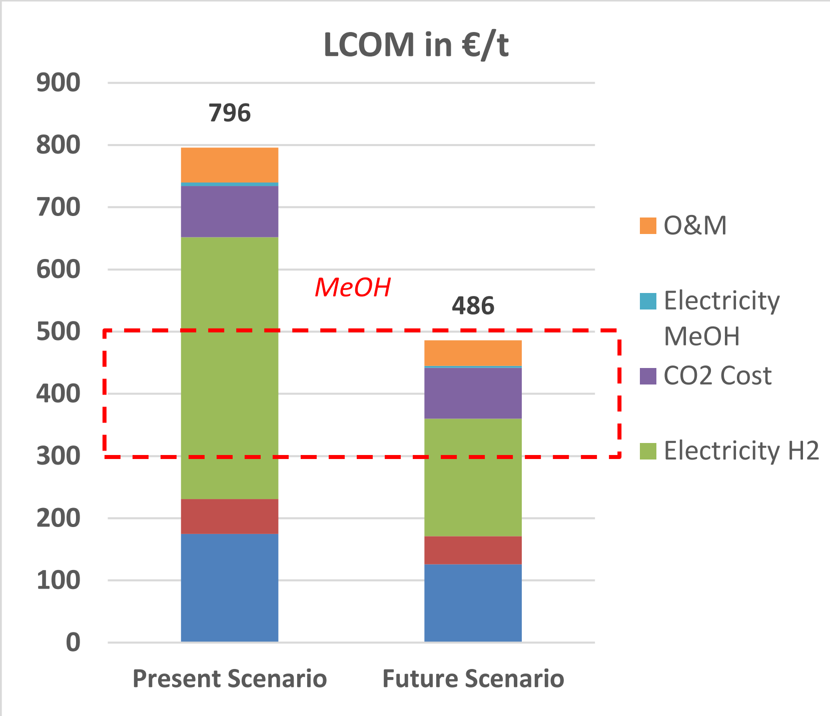

Figure 11. Breakdown of LCOM for present and future scenarios.

The global economic environment has significantly impacted the market cost of methanol, which has fluctuated between 300-500 €/t in the past year[54]. However, the uncertain market conditions make it challenging to predict the future cost of methanol.

As illustrated in figure 11, the current cost of MeOH utilizing green hydrogen is almost double that of fossil-based MeOH. The primary cost contributor for these expenses is the electricity required for hydrogen production, followed by the CAPEX of the electrolyser. Together, these two costs represent more than 75% of the total methanol production cost. The MeOH synthesis CAPEX, CO_2 costs, and O&M charges for both plants contribute to the remaining costs. However, the cost for future scenarios could decrease by up to 40% if all improvements are achieved. The impact of these improvements on the methanol cost is depicted in figure 12.

[54] ChemAnalyst, Methanol Price Trend and Forecast,2023

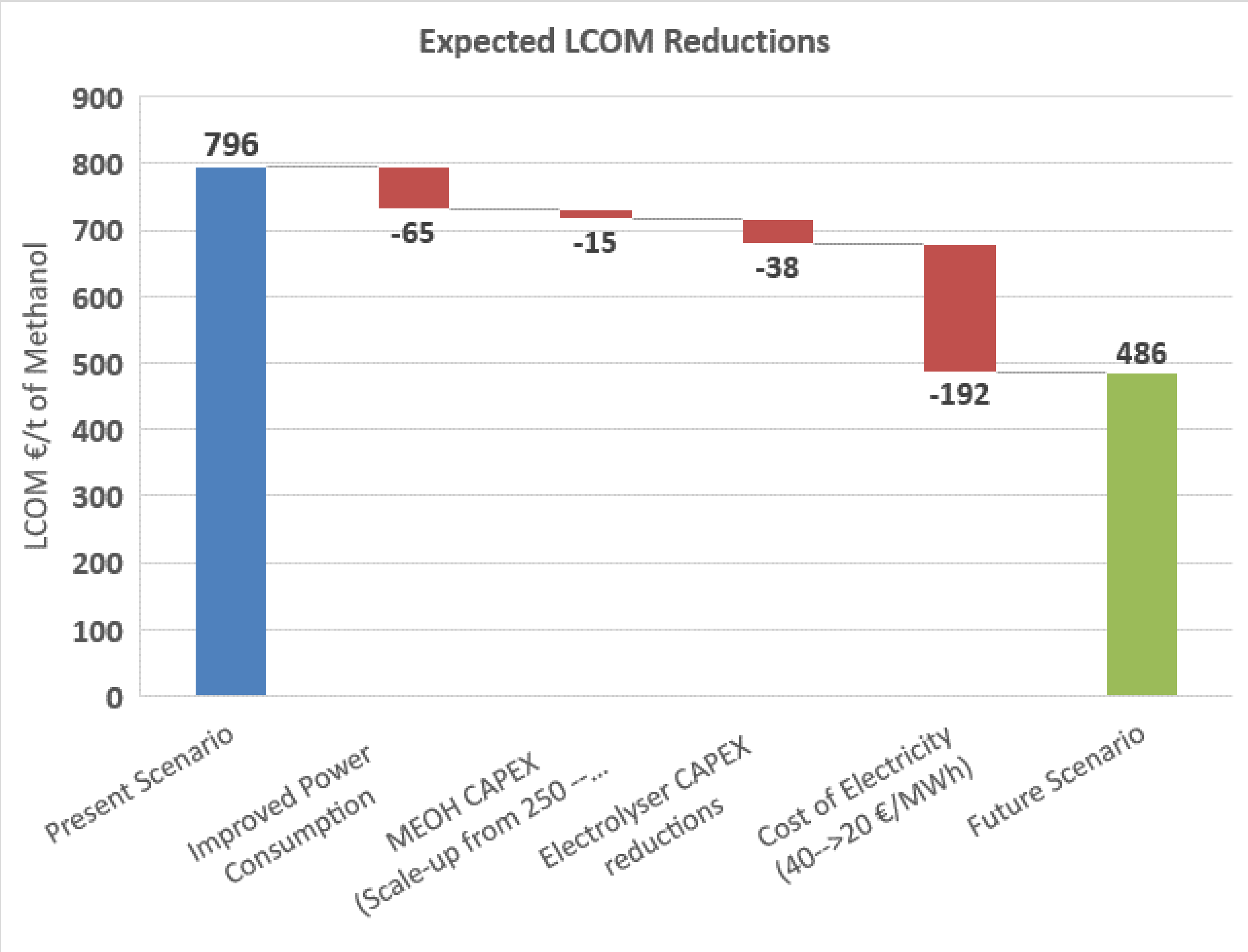

Figure 12. Effect on technological improvement on the LCOM

The improvement in electricity efficiency reduces power consumption and the total installed electrolyser power, making it the second most impactful factor on the cost with a reduction of 65 €/t. While large scale production benefits the MeOH CAPEX significantly, it has a minimal impact on the final production costs. Lower electricity costs have the highest impact on the production cost, with a decrease in electricity cost alone able to reduce the cost of methanol by approximately 25%. Therefore, it is reasonable to expect that future scenarios, with the right development conditions, can help bring down the cost of green methanol to the same level as traditional methanol.

5 Results and Conclusions

The economic evaluation of the PROMET-H2 25 kW system provided a clear view on the price of each component of the system. The construction and design of the PROMET-H2 25 kW stack was carried out during the European crisis period due to the impact of the pandemic and the war in Ukraine, which impacted on a rise in commodity prices in all sectors across Europe. As a result, the PROMET-H2 pilot stack was impacted by this crisis which resulted in higher than estimated prices for different components such as the pressure vessel of the stack. Nevertheless, the CAPEX of the PROMET-H2 stack (1.778 €/kW) was reduced by 21% compared to the CAPEX of the base-line stack (2.245 €/kW). Excluding hydraulic compression technology of the CAPEX, values decrease to 1.130 €/kW for the base-line stack and 779 €/stack for the PROMET-H2 stack with a reduction of 31% of the CAPEX for the PROMET-H2 stack. Although the hydraulic system increases the PROMET-H2 costs, it also brings advantages, such as the hydrogen output at 40 bar. Further research will show whether a longer lifetime can be achieved, and in which cases the additional CAPEX of the stack is paid for by the savings of an external compressor.

In the techno-economic analysis of the scaling to MW of the PROMET-H2 system, a scaling of all components based on scaling factors was carried out for the stack, while the cost of 1MW for the BoP was obtained from the literature and updated to the current cost using CEPCI. Thus, this system was evaluated to obtain a 7% return over a 25-year lifetime considering a pessimistic scenario for OPEX. This evaluation provided a price per kilogram of hydrogen of 6,3 €/kg to obtain this internal rate of return, with an NPV of 97.280 €. The LCOH obtained is 6.1 €/kg H2. This value demonstrates the cost reduction potential of the PROMET-H2 system through scaling up to MW.

In addition, the sensitivity analysis showed the behaviour of the profitability indicators with reductions in the economic costs of the pressure vessel, the cellframe or with an OPEX based on the baseline and optimistic scenario. To assess the influence of the CAPEX of the BoP on the profitability indicators, the cost range limits provided by G.Bristowe et al. updated with CEPCI indicators to 2022 cost were evaluated. The optimistic OPEX scenario is the variable that returns the most competitive results, with a LCOH of 3,9 €/kg H_2. This value demonstrates that, under the assumptions considered in this study, the novel PROMET-H2 technology can deliver cost-competitive results that have scope for profitability improvement if competitive electricity pricing arrangements are achieved through PPAs.

Moreover, the PROMET-H2 project includes in its Grant Agreement the ambitious goal of developing a pressurised PEMWE with the lowest capital cost ever achieved (500-750 €/kW) without compromising performance and durability. In section 4 of this report, it was demonstrated that the cost of the PROMET-H2 system (1.084€/kW) is aligned with the state of art analysed, with an average value of 1.030 €/kW found in the literature. According to the cost reduction assumptions presented in the bibliography, which assume a 20% cost reduction in the total cost of the system by increasing the purchase units by a factor of 10, the target cost of the project could be achieved for the purchase quantity between 100 and 1.000 units.

The economic assessment of the levelized cost of methanol in the framework of PROMET-H2 project estimates production for both current and future scenarios. In the current scenario, the cost of green methanol is almost double that of fossil-based methanol due to the high cost of electricity required for hydrogen production and the CAPEX of the electrolyser system. The total cost of production for e-methanol is estimated at around ~ 800 €/t, while the market cost of methanol fluctuates between 300-500 €/t. However, the results also suggest that future improvements in electricity efficiency, large-scale production benefits, and lower electricity costs could reduce the cost of green methanol by up to 40% (490 €/t), making it more competitive with traditional methanol.

However, the economic assessment also highlights challenges and uncertainties in the green methanol market. The cost of electricity will be the most crucial factor contributing to the final cost of the methanol. Developments in the renewable energy sector can help to reduce these costs. Additionally, the cost of CO2, which is an essential feedstock in methanol production, can vary widely based on the emission source. Despite these challenges, the PROMET-H2 project's focus on reducing production costs of hydrogen can help produce cheaper CO2 based methanol.

Annex 1. 25 kW system OPEX detailed

Table A1.1. Total and breakdown OPEX for the 25 kW system

	Annual electricity cost to 25 kW system		
	OPTIMISTIC SCENARIO	BASELINE SCENARIO	PESSIMISTIC SCENARIO
Electricity from the wind farm	7.200 €	10.980 €	14.760 €
Electricity consumed with GO certificates	1.110 €	1.155 €	1.200 €
Total	8.310 €	12.135 €	15.960 €
	Annual water cost to 25 kW system		
Total	68 €		
	Annual maintenance cost to 25kW electrolyser		
	OPTIMISTIC SCENARIO	BASELINE SCENARIO	PESSIMISTIC SCENARIO
Total	250 €	375 €	500 €
	Total annual OPEX to 25 kW system		
	OPTIMISTIC SCENARIO	**BASELINE SCENARIO**	**PESSIMISTIC SCENARIO**
Total	**8.628 €**	**12.578 €**	**16.528 €**

Annex 2. 25 kW system cash flows

Table A2-1 Cash flow for the 25 kW system.

YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12
CAPEX	501.933,85 €												
Income		57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €
OPEX		16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €
Maintenance		500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €
Water		67,92	67,92	67,92	67,92	67,92	67,92	67,92	67,92	67,92	67,92	67,92	67,92
Electricity		15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €
Amortization		20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €
Profit before tax		20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €
Taxes		5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €
Profit after tax		15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €
Amortisation		20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €
Cash flow	-501933,852	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €
Accumulated	-501933,852	- 466.249,95 €	- 430.566,06 €	- 394.882,16 €	- 359.198,26 €	- 323.514,37 €	- 287.830,47 €	-252.146,57 €	-216.462,68 €	-180.778,78 €	-145.094,88 €	-109.410,98 €	- 73.727,09 €

YEAR	13	14	15	16	17	18	19	20	21	22	23	24	25
CAPEX													
Income	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €	57.414,00 €
OPEX	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €	16.527,92 €
Maintenance	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €
Water	67,92	67,92	67,92	67,92	67,92	67,92	67,92	67,92	67,92	67,92	67,92	67,92	67,92
Electricity	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €	15.960,00 €
Amortization	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €
Profit before	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €	20.808,72 €
Taxes	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €	5.202,18 €
Profit after ta	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €	15.606,54 €
Amortisation	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €	20.077,35 €
Cash flow	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €	35.683,90 €
Accumulated	- 38.043,19 €	- 2.359,29 €	33.324,60 €	69.008,50 €	104.692,40 €	140.376,30 €	176.060,19 €	211.744,09 €	247.427,99 €	283.111,88 €	318.795,78 €	354.479,68 €	390.163,58 €

Annex 3. 1 MW system detailed OPEX

Table A3.1. Total and breakdown OPEX for the 25 kW system

	Annual electricity cost to 25 kW system		
	OPTIMISTIC SCENARIO	BASELINE SCENARIO	PESSIMISTIC SCENARIO
Electricity from the wind farm	264.000 €	402.600 €	541.200 €
Electricity consumed with GO certificates	40.700 €	42.350€	44.000 €
Total	304.700 €	444.950€	585.200 €
	Annual water cost to 25 kW system		
Total	2.952 €		
	Annual maintenance cost to 25kW electrolyser		
	OPTIMISTIC SCENARIO	BASELINE SCENARIO	PESSIMISTIC SCENARIO
Total	10.000 €	15.000 €	20.000 €
	Total annual OPEX to 25 kW system		
	OPTIMISTIC SCENARIO	**BASELINE SCENARIO**	**PESSIMISTIC SCENARIO**
Total	**317.652 €**	**462.902 €**	**608.152 €**

Annex 4. 1 MW system cash flows

Table A4.1. Cash flows for 1 MW system

YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12
CAPEX	1.945.059,60 €												
Income		816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €
OPEX		608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €
Maintenance		20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €
Water		2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €
Electricity		585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €
Amortization		77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €
Profit before tax		130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €
Taxes		32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €
Profit after tax		98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €
Amortisation		77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €
Cash flow	-1945059,6	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €
Accumulated	-1945059,6	- 1.769.221,01 €	- 1.593.382,41 €	- 1.417.543,82 €	- 1.241.705,23 €	- 1.065.866,63 €	- 890.028,04 €	- 714.189,45 €	- 538.350,85 €	- 362.512,26 €	- 186.673,67 €	- 10.835,07 €	165.003,52 €

YEAR	13	14	15	16	17	18	19	20	21	22	23	24	25
CAPEX													
Income	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €	816.669,00 €
OPEX	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €	608.151,67 €
Maintenance	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €	20.000,00 €
Water	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €	2.951,67 €
Electricity	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €	585.200,00 €
Amortization	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €
Profit before	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €	130.714,95 €
Taxes	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €	32.678,74 €
Profit after ta	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €	98.036,21 €
Amortisation	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €	77.802,38 €
Cash flow	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €	175.838,59 €
Accumulated	340.842,12 €	516.680,71 €	692.519,30 €	868.357,90 €	1.044.196,49 €	1.220.035,08 €	1.395.873,68 €	1.571.712,27 €	1.747.550,86 €	1.923.389,46 €	2.099.228,05 €	2.275.066,64 €	2.450.905,24 €

Annex 5. Sensitivity Analysis Tables

Table A5.1. Sensitivity analysis results for the evaluation of main economics components of CAPEX stack up-scaling WM.

	Up-scaling MW results	10% reduction of price component	20% reduction of price component	30% reduction of price component	40% reduction of price component	50% reduction of price component
Pressure Vessel	98.750 €	88.875 €	79.000 €	69.125 €	59.250 €	49.375 €
CAPEX STACK, €	536.520 €	526.108 €	516.233 €	500.945 €	496.483 €	486.608 €
CAPEX STACK Reduction, %		98%	96%	93%	93%	91%
CAPEX STACK Contribution, %	18%	17%	15%	14%	12%	10%
HYDROGEN PRICE, €/kg H2	6,3 €	6,2 €	6,2 €	6,2 €	6,2 €	5,6 €
NPV, €	97.280 €	12.025,92 €	31.594 €	61.889 €	70.730 €	90.299 €
IRR, €	7,6%	7,1%	7,2%	7,4%	7,5%	7,6%
LCOH, €	6,1 €	6,1 €	6,1 €	6,0 €	6,0 €	6,0 €
Cellframe	97.372,80 €	87.635,52 €	77.898,24 €	68.160,96 €	58.423,68 €	48.686,40 €
CAPEX STACK, €	536.520 €	526.783 €	517.045 €	507.308 €	497.571 €	487.834 €
CAPEX STACK Reduction, %		98%	96%	95%	93%	91%
CAPEX STACK Contribution, %	18%	17%	15%	13%	12%	10%
HYDROGEN PRICE, €/kg H2	6,3 €	6,2 €	6,2 €	6,2 €	5,6 €	5,6 €
NPV, €	97.280 €	10.689 €	29.984 €	49.280 €	68.575 €	87.871 €
IRR, €	7,6%	7,1%	7,2%	7,3%	7,4%	7,6%
LCOH, €	6,1 €	6,1 €	6,1 €	6,0 €	6,0 €	6,0 €
The rate of return remains constant in all cases at 7%.						

Table A5.2. Sensitivity analysis results for the evaluation of main economics components of CAPEX BoP up-scaling MW.

	NREL	G. Bristowe	G. Bristowe2
CAPEX BoP, €	547.843 €	305.252 €	663.095 €
HYDROGEN PRICE, €/kg H2	6,30 €	6,00 €	6,40 €
NPV, €	97.280 €	19.979 €	88.976 €
IRR, €	8%	7%	8%
LCOH, €	6,1 €	5,9 €	6,2 €
The rate of return remains constant in all cases at 7%.			

Table A5.3. Sensitivity analysis results for the evaluation of the three OPEX scenarios for the up-scaling MW system.

	Pessimistic Scenario	Baseline Scenario	Optimistic Scenario
OPEX, €/year	608.152 €	462.902 €	317.652 €
Hydrogen price, €/kgH_2	6,3 €	5,1 €	4,0 €
VNA, €	97.280 €	13.097 €	34.800 €
IRR, €	7,6%	7,1%	7,2%
LCOH, €/kgH_2	6,1	5,0 €	3,9 €
The rate of return remains constant in all cases at 7%.			

Annex 6. Cash flows for levelized cost of methanol - Present Scenario

Table A6.1.Cash Flows for levelized cost of Hydrogen (without including profits)

YEAR		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
CAPEX			6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15
OPEX	M€		31.56	29.22	27.06	25.05	23.20	21.48	19.89	18.41	17.05	15.79	14.62	13.53	12.53	11.60	10.74	9.95	9.21	8.53	7.90	7.31	6.77	6.27	5.80	5.37	4.98
Discount Rate			1.08	1.17	1.26	1.36	1.47	1.59	1.71	1.85	2.00	2.16	2.33	2.52	2.72	2.94	3.17	3.43	3.70	4.00	4.32	4.66	5.03	5.44	5.87	6.34	6.85
Hydrogen Production	t /yr		12522	11595	10736	9941	9204	8523	7891	7307	6765	6264	5800	5371	4973	4604	4263	3948	3655	3384	3134	2902	2687	2488	2303	2133	1975

Table A6.2. Cash Flows for levelized cost of Methanol (without including profits)

YEAR		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
CAPEX	M€/yr		1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
OPEX Total			236.14	218.65	202.45	187.46	173.57	160.71	148.81	137.79	127.58	118.13	109.38	101.28	93.77	86.83	80.40	74.44	68.93	63.82	59.09	54.72	50.66	46.91	43.44	40.22	37.24
Discount Rate			1.08	1.17	1.26	1.36	1.47	1.59	1.71	1.85	2.00	2.16	2.33	2.52	2.72	2.94	3.17	3.43	3.70	4.00	4.32	4.66	5.03	5.44	5.87	6.34	6.85
Electricity	M€/yr		0.42	0.39	0.36	0.33	0.31	0.28	0.26	0.24	0.22	0.21	0.19	0.18	0.17	0.15	0.14	0.13	0.12	0.11	0.10	0.10	0.09	0.08	0.08	0.07	0.07
H2			45.79	42.40	39.26	36.35	33.66	31.16	28.86	26.72	24.74	22.91	21.21	19.64	18.18	16.84	15.59	14.44	13.37	12.38	11.46	10.61	9.82	9.10	8.42	7.80	7.22
Co2			5.56	5.14	4.76	4.41	4.08	3.78	3.50	3.24	3.00	2.78	2.57	2.38	2.21	2.04	1.89	1.75	1.62	1.50	1.39	1.29	1.19	1.10	1.02	0.95	0.88
Maintenance			1.22	1.13	1.04	0.97	0.89	0.83	0.77	0.71	0.66	0.61	0.56	0.52	0.48	0.45	0.41	0.38	0.35	0.33	0.30	0.28	0.26	0.24	0.22	0.21	0.19
Methanol Production	t/yr		67593	62586	57950	53657	49683	46002	42595	39440	36518	33813	31308	28989	26842	24854	23013	21308	19730	18268	16915	15662	14502	13428	12433	11512	10659

Annex 7. Cash flows for levelized cost of methanol - Future Scenario

Table A7.1.Cash Flows for levelized cost of Hydrogen (without including profits)

YEAR		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
CAPEX			17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59	17.59
OPEX	M€		59.73	55.31	51.21	47.42	43.91	40.65	37.64	34.85	32.27	29.88	27.67	25.62	23.72	21.96	20.34	18.83	17.44	16.14	14.95	13.84	12.82	11.87	10.99	10.17	9.42
Discount Rate			1.08	1.17	1.26	1.36	1.47	1.59	1.71	1.85	2.00	2.16	2.33	2.52	2.72	2.94	3.17	3.43	3.70	4.00	4.32	4.66	5.03	5.44	5.87	6.34	6.85
Hydrogen Production	t /yr		51132	47345	43838	40591	37584	34800	32222	29835	27625	25579	23684	21930	20305	18801	17409	16119	14925	13820	12796	11848	10970	10158	9405	8709	8064

Table A7.2. Cash Flows for levelized cost of Methanol (without including profits)

YEAR		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
CAPEX	M€/yr		5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62	5.62
OPEX Total			516.02	477.80	442.41	409.64	379.29	351.20	325.18	301.09	278.79	258.14	239.02	221.31	204.92	189.74	175.69	162.67	150.62	139.46	129.13	119.57	110.71	102.51	94.92	87.89	81.38
Discount Rate			1.08	1.17	1.26	1.36	1.47	1.59	1.71	1.85	2.00	2.16	2.33	2.52	2.72	2.94	3.17	3.43	3.70	4.00	4.32	4.66	5.03	5.44	5.87	6.34	6.85
Electricity	M€/yr		0.83	0.77	0.71	0.66	0.61	0.57	0.52	0.49	0.45	0.42	0.39	0.36	0.33	0.31	0.28	0.26	0.24	0.23	0.21	0.19	0.18	0.17	0.15	0.14	0.13
H2			97.81	90.57	83.86	77.65	71.90	66.57	61.64	57.07	52.85	48.93	45.31	41.95	38.84	35.97	33.30	30.83	28.55	26.44	24.48	22.66	20.99	19.43	17.99	16.66	15.42
Co2			22.22	20.58	19.05	17.64	16.34	15.13	14.01	12.97	12.01	11.12	10.29	9.53	8.83	8.17	7.57	7.01	6.49	6.01	5.56	5.15	4.77	4.42	4.09	3.79	3.50
Maintenance			3.90	3.61	3.35	3.10	2.87	2.66	2.46	2.28	2.11	1.95	1.81	1.67	1.55	1.44	1.33	1.23	1.14	1.06	0.98	0.90	0.84	0.78	0.72	0.66	0.62
Methanol Production	t/yr		270370	250343	231799	214629	198730	184010	170379	157759	146073	135252	125234	115957	107368	99415	92051	85232	78919	73073	67660	62648	58007	53711	49732	46048	42637