Delft University of Technology - Hystream B.V.

ME-EFPT Research Assignment

ME55015

# Manufacturing Cost Analysis of Catalyst Coated Membrane (CCM) of a Zero-Gap Alkaline Water Electrolysis Cell

M.F.H. Ansarul Huq (5545943)

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# Preface and Acknowledgement

This report presents the work conducted during my internship at Hystream B.V. as a part of my Master's in Mechanical Engineering (Energy, Flow, and Process Technology) at TU Delft. For 3.5 months, from August to November, I extensively searched and reviewed various literature on water electrolysis.

Various findings from the literature review, data published by government-funded studies, and market research of the current suppliers of electrolyzers have aided in several calculations and cost analyses presented in this work. During my literature review, I realized there needs to be more transparency in the data available publicly. Research discussing the cost of various electrolyzer systems needs to elaborate on the manufacturing scale. Hence, there needs to be more consensus on the actual system costs. Access to scale-based cost figures is crucial for potential market entrants to assess the requirements of this growing industry. Therefore, techno-economic studies must present cost models with better transparency—something I have ensured is discussing the methodology and results in this work.

I express my sincere gratitude to Mr. Joep Coenen and Mr. Albert Haak from Hystream B.V. for their time and energy in guiding me and trusting my abilities. Their positive reinforcement and constructive criticism have motivated me during this internship and have shaped my work ethic as an engineer. I also want to thank Prof. Ad van Wijk for agreeing to supervise my work. Our interactions have helped me understand the intricacies of setting up a time-sensitive project. The initial feedback and review from Prof. Ad have introduced practicality in my approach, setting targets based on available resources. Lastly, I thank my family and friends for their emotional support and uplifting words.

# Executive Summary

As green hydrogen gains popularity as a fuel, it is essential to reduce the cost of production, storage, transportation, and utilization. In this study, we focus on hydrogen production from water electrolysis. Global electrolyzer manufacturing capacity in 2020 was above 2 GW per annum, and it is forecast to exceed 4.5 GW based on current expansion commitment [12]. Therefore, large-scale electrolyzer stack manufacturing would be crucial to achieving such high numbers. Several works of literature attempt to estimate the CAPEX of electrolyzers, but with a significant variance [27]. Hence, executing and publishing more transparent bottom-up cost analyses is crucial to estimate the CAPEX accurately. We aim to present the methodology and perform the cost analysis and the cost of manufacturing Catalyst Coated Membrane (CCM) for zero-gap alkaline electrolyzers.

Mayyas et al. [21] systematically present the method for the direct manufacturing cost of the CCM. The methodology has been adapted for this work, with the material and cost data relevant to an alkaline CCM. Due to the technology still being in the research phase, with no standard specifications, we use the exact functional specifications for the electrolysis cell presented in [21]. As the fabrication method is similar, and the membrane dimensions are unchanged, we use the cost of the spray coating machine and other vital parameters from [21]. Material costs were estimated from price quotes available online [31, 32, 33, 34, 35]. Other cost components were calculated based on official data and published information, which can be found in the Section 3 of the report.

The results show that the cost of the alkaline CCM is lower when compared to PEM CCM. The stack plots (Figure 7 and 6) show how various cost components respond to the increase in production size. Table 8 shows the cost components and the total cost for 10, 35, and 1000 units of a 1 MW electrolyzer stack. The cost of the CCM is then compared to the cost of PEM CCM and alkaline separator in Table 9. The total stack cost needs to be analyzed to compare the CAPEX of zero-gap alkaline electrolyzer to PEM and the conventional alkaline electrolyzer.

Acquiring industry partners and using price quotations based on the order size would significantly improve the accuracy and confidence level of the calculated final cost of the CCM. Several assumptions were made to reach the final cost figure of the alkaline CCM, due to unavailability of data. Future research is required to perform the bottom-up cost analysis on all the stack components (Bipolar plates/current collectors, electrodes, casing, assembly) to estimate the cost of a 1 MW stack and help improve the business case for the technology.

## Abbreviations and Symbols

AEM - Anion Exchange Membrane

CAPEX - Capital Expenditure

CBR - Catalyst-to-Binder Ratio

CCM - Catalyst Coated Membrane

DC - Direct Current

EPO - European Patent Office

IRENA - International Renewable Energy Agency

MEA - Membrane-Electrode Assembly

NREL - National Renewable Energy Laboratory

$NiCo_2O_4$ - Nickel Colbaltite

$NiFe_2O_4$ - Nickel Ferrite

OPEX - Operational Expenditure

PEM - Proton Exchange Membrane

PGM - Platinum Group Metal

PSU - Polysulfone

PV - Photovoltaic

SMR - Steam Methane Reforming

$ZrO_2$ - Zirconium Dioxide

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# 1 Introduction

As more countries pursue extensive decarbonization strategies, hydrogen will have a critical role to play [2]. Despite great technological advancements, it is impossible to match the predictable peaks and troughs of energy demand with the unpredictable peaks and troughs of energy supply from renewable sources [7]. In addition to that, certain industries (e.g. steel and cement) are difficult to electrify due to their high process temperatures. Therefore, hydrogen offers a clean alternative to oil and natural gas, and is forecasted to be the green solution. Hydrogen shows promise due to its ability as a medium for long-term chemical energy storage, a versatile energy carrier, and a feedstock for various industries [37], e.g., fine chemicals and petrochemical refineries.

Hydrogen production is possible via numerous pathways, including electrolytic, chemical, biological, photolytic, and thermochemical [37]. Most commonly, hydrogen is produced from natural gas via a process known as Steam Methane Reforming (SMR). In addition to hydrogen, this process also produces carbon dioxide and is not a viable solution to the pollution-free production of hydrogen from excess renewable energy. A cleaner way for hydrogen production is via electrolysis of water. In this process, electricity (electro-) is used to break down (-lysis) water, $H_2O$, into its component parts of oxygen and hydrogen with no harmful or polluting side products [7]. Combining renewable electricity with an electrolyzer system producing hydrogen from the excess power would ideally allow us to overcome the challenges presented by the seasonal variation in renewable energy sources. However, various pieces of this hydrogen puzzle must be in place to realize this energy vector. We need to secure infrastructure for the production, transportation, storage, and utilization of hydrogen as a fuel.

Global electrolyzer manufacturing capacity in 2020 was above 2 GW per annum, and it is forecast to exceed 4.5 GW on the basis of current expansion commitments [12]. While exact figures for the volume of hydrogen produced vary, the literature suggests 55 million tonnes up to 70 million tonnes of hydrogen are produced annually. Around 96 percent of global hydrogen production comes from fossil fuel sources, with 48 percent from natural gas via SMR and 48 percent from coal gasification or other chemical processes (such as chlorine production). Only 4 percent comes from electrolysis [12]. Figure 1 [2] shows the required electrolyzer capacity in 2030 and the expected capacity per the current strategy. The graph shows the existing gap and the need for large-scale projects. Therefore, extensive research and development and lucrative policies are required to experience a rapid growth rate similar to solar PV [2].

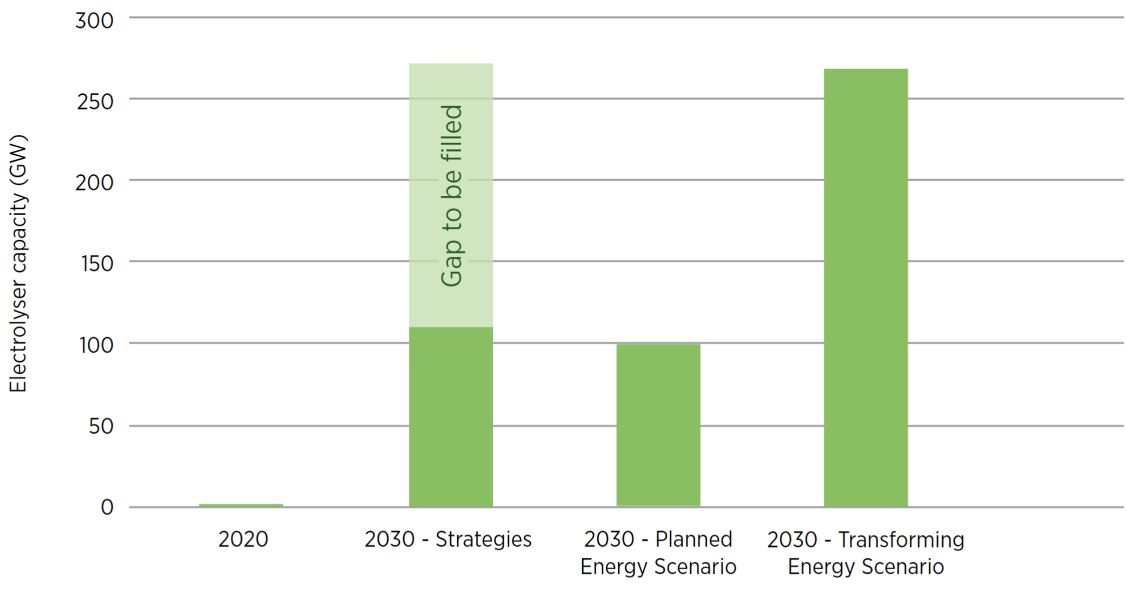


Figure 1: Electrolyser capacity comparison between national strategies and IRENA's scenarios for 2030 [2]

The challenge to increase the contribution of hydrogen production from electrolysis (also called Green Hydrogen) comes down to:

1. A large part of the Operational Expenditure (OPEX) is the cost of electricity. So, the cost of electricity generated from solar and wind sources must reduce, which is the current trend as more large-scale projects

are announced and completed.

2. Electrolyzer systems have a high Capital Expenditure (CAPEX), especially systems linked with renewable energy. Reducing CAPEX while maintaining efficiency is a key challenge.

3. Storage, compression, and transportation in a large-scale application is a multifaceted problem, with production location and utilization playing a key role. Re-purposing existing pipelines and infrastructure is currently being explored, and cost estimates are tricky and require experiments and data to confirm various analyses.

4. Infrastructure for utilization dictates the production and purity requirements. Fuel cells are the most efficient system to utilize hydrogen fuel, but they are expensive and challenging to scale up to a gigawatt scale. Hydrogen-powered turbines and internal combustion engines are being studied for large-scale power production and offshore applications.

This study focuses on the CAPEX of an alkaline electrolysis system. An alkaline system is chosen due to its technology maturity and feasibility to increase the global capacity on a gigawatt scale. Currently, using rare metal electrocatalysts in PEM electrolysis systems is a bottleneck in large-scale implementations. Iridium, used in the oxygen evolution reaction, is a critical raw material [36], and the current global supply is insufficient as per the electrolyzer targets set by IRENA [2]. Therefore, alkaline electrolysis is expected to be popular until research on reducing catalyst loading and developing new electrocatalysts is successful. Figure 2 [18] shows the cost comparison between alkaline and PEM systems for large capacities. OPEX is higher for alkaline electrolyzers due to the cost of compression and maintenance. However, this is offset by the lower CAPEX of the system [18].

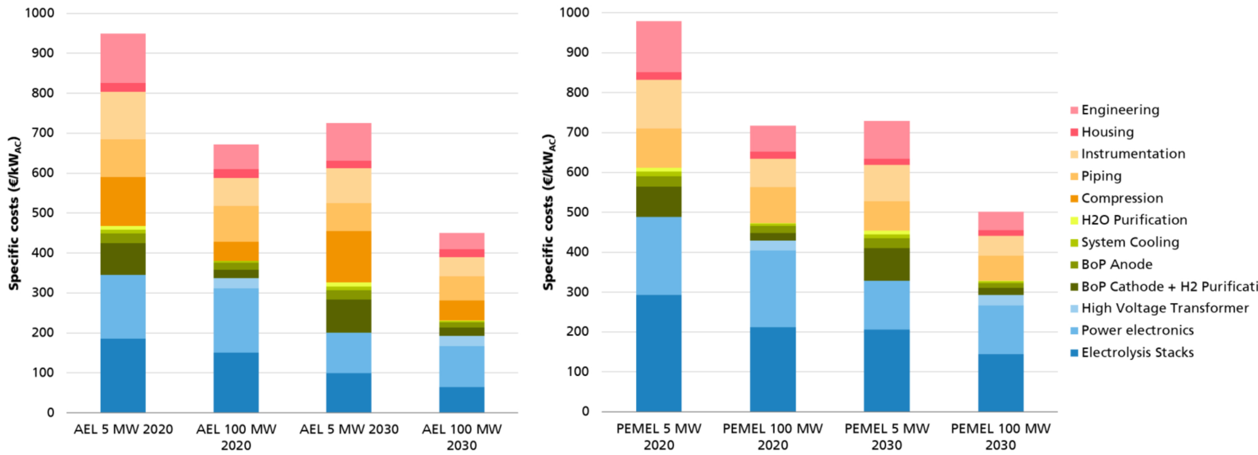


Figure 2: Alkaline electrolysis and PEM electrolysis system cost [18]

During the initial phase of the study, recent electrolyzer stack designs and fabrication methods for various components were studied. Based on the findings, a zero-gap configuration (Figure 3) was understood to be the evolution of commercial alkaline electrolyzers. The separator (also called diaphragm, membrane) in the alkaline electrolyzer cell was chosen as the main focus, based on the availability of data and the limitation on time. The goal was to analyze the at-scale manufacturing cost of the membrane coated with the catalyst material, a method similar to that of Proton Exchange Membrane (PEM) electrolyzers. Plevova et al. [26] present a novel fabrication method, which is the basis for the cost analysis. The hot spray coating technique is similar to the methods used to fabricate the Catalyst Coated Membrane (CCM) for PEM electrolyzers. The methodology for the cost computation has been adopted from work presented in Mayyas et al. [21], where a scaled-based direct manufacturing cost analysis has been discussed and presented for a PEM electrolyzer system.

Due to the choice of material to fabricate the alkaline CCM and the zero-gap concept not being available in a commercial context, various assumptions were crucial to compute the final cost of manufacturing the CCM. It was also necessary to use outdated data in certain instances that have been adjusted for inflation and currency conversion. All the assumptions and estimations will be discussed systematically in the Results (4) section.

This study aims to present the cost of manufacturing the CCM for a zero-gap alkaline electrolyzer based on the scale of production. The cost computations have been discussed more transparently, and the raw data

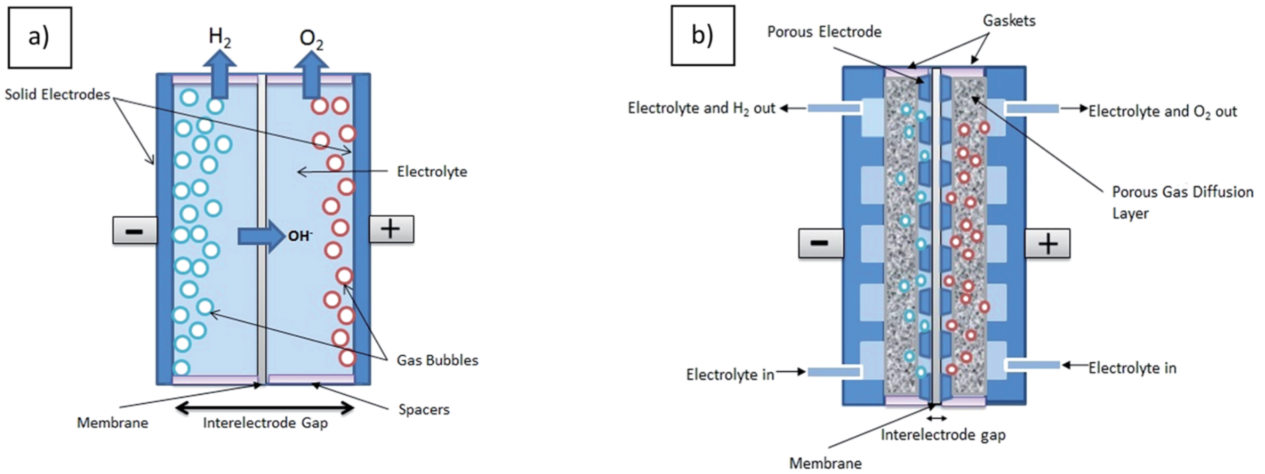


Figure 3: (a) Standard setup, (b) zero gap setup – showing the principal differences in design [25]

is made available to view the cost trends in a production size range of choice. The results show the optimum production size where the manufacturing cost is minimum. As we expect a rapid increase in electrolyzer capacity, adequate manufacturing infrastructure is crucial to achieve the required numbers to decarbonize our society.

# 2 Background

## 2.1 Literature Review

Reviewing recently published work in the field of study is an essential first step to setting the project's scope and understanding the tasks involved in obtaining desired results. Firstly, literature on various electrolysis technology provided a system-level overview, with processes such as water treatment, electrolysis, purification, and compression [7, 30, 37, 11, 10, 23]. The report published by the International Renewable Energy Agency (IRENA) [2] dives deeper into the cost of an Alkaline and PEM electrolyzer system, with the cost breakdown of critical processes and components used to produce green hydrogen. Techno-economic studies were reviewed [20, 11], which also included a literature review showing recent developments in the field of electrolysis. Such studies also compared the various technology from an economic standpoint, confirming that alkaline electrolysis is the cost-effective option in large-scale hydrogen production with the current technology.

Recent progress in alkaline electrolysis [3, 42] shows the research trends and innovations currently being tested in lab-scale setups. Using better materials in the electrolysis cell and managing product gas bubbles are the main focus areas in future designs. More recent literature [5] focuses on factors to consider when using renewable power sources. The zero gap cell design is discussed in detail, with the benefits being lower ohmic losses and improved bubble management. Brauns et al. [5] also consider the material that goes into the cells and the stack. With the information gathered, it is decided that focusing on the material aspect of the electrolysis stack would have the most impact on efficiency, as it fundamentally affects the electrochemical reaction kinetics and transport aspects.

It is crucial to understand the economics of the electrolysis stack and cell design and its impact on the final CAPEX of the system. Several literature [41, 8, 29] provide an overview of investment costs and the overall cost of hydrogen production. The work published by IRENA [2] gave crucial insights into the cost of producing the electrolyzer stack components with a bottom-up cost analysis. A cost analysis report [18] from Fraunhofer ISE, Germany, uses data gathered from various electrolyzer suppliers and creates a cost model to show the cost of the stack components. It is interesting to note that the alkaline stack cost in the IRENA report [2] and Fraunhofer report [18] do not match, as the stack sizes are different, and there is no detail about the effect of manufacturing scale. This shows the inconsistencies in the cost figures presented in various studies. Reksten et al. [27] analyze the published literature in alkaline electrolysis from 2000-2022 and plot the cost figures mentioned in studies, with projected numbers and calculated cost data. A size-based cost function was derived using the data set, with the year of calculation as an additional input. The cost calculated for a 5 MW electrolyzer from the cost function [27] was closely correlated with the cost figures presented by Fraunhofer [18]. However, future techno-economic analyses should use this tool cautiously, as the standard error range is significant.

There is a need for bottom-up cost calculations that portray the effect of the manufacturing scale of the alkaline stack. The work published by Mayyas et al. from the National Renewable Energy Laboratory (NREL), USA [21] is an excellent example of such work. Mayyas et al. [21] focus on a PEM electrolyzer, presenting the methodology of performing a bottom-up cost calculation (also called a direct manufacturing cost analysis), along with illustrations that show how the cost of the components and the entire assembled stack reduces based on the scale of manufacturing. The report also mentions the various cost figures used, which allows researchers to reproduce the calculations. The team has also performed similar computations for alkaline electrolyzers, which was only presented in a conference [28]. As the format is short, several essential input information has been omitted.

One of the ways to understand how academic research translates to an industrial application is the patent filing trends. A report published by the European Patent Office (EPO) in collaboration with IRENA presents trends in the uptake of new technologies to facilitate the further implementation of the large-scale use of hydrogen [24]. Patent application data from EPO's free Espacenet 13 database contains more than 130 million documents from over 100 countries [24]. Cell operation conditions & structure and separators have the highest number of international patent applications. Therefore, it is a critical component in the materials category and forms the rationale behind the focus of this study.

A zero-gap configuration has several alternatives. It can be very similar to a conventional electrolyzer, with electrodes coated with catalysts, with the distance between the electrodes reduced. However, another prospect that has gained more attention recently is coating both sides of the separator with the electrocatalysts and sandwiching the electrodes (Nickel mesh or plates). A novel electrolyzer technology with alternate electrodes and catalyst material, with an Anion Exchange Membrane (AEM), is being explored academically, with commercialization done by Enapter, Italy [1]. Recent review literature [40, 22, 13] provide detailed information regarding AEM electrolyzers. The Catalyst Coated Membrane (CCM) fabrication in the case of an alkaline separator can be similar to the methods currently used for PEM electrolyzers. The assembly would also be similar, where a CCM is fused to electrodes (Ni mesh or plates) to form the Membrane-Electrode Assembly (MEA) (also called Diaphragm-Electrode Assembly in various literature to distinguish it from PEM). The MEA concept for alkaline electrolysis was initially explored by Vermeiren et al. [38] with more recent literature focusing on fabrication methods, and characterization of the CCM [15, 26, 19] for an alkaline electrolysis cell. Since the fabrication methods are still being tested, no large-scale production exists. Therefore, it would be interesting to understand the economics of fabricating an alkaline CCM in a large-scale facility.

## 2.2 Scope of the Study

The literature review has provided the foundation for this study, from which we can build our desired cost analysis. In this section, we will outline the research question along with the citations for the source of data and information. The details about the implementation are elaborated in the Methodology section. The separator (henceforth called *membrane* for uniformity) is the component of interest in the cell and the stack. Therefore, the other parts, such as the electrodes, casing, electrolyte, electronics, and balance of plant (water treatment, power electronics, purification, drying, compression), will be omitted in further discussions. The methods and data presented in the literature have been chosen based on relevance, availability, and ease of implementation.

### 2.2.1 Materials

Plevova et al. [26] discuss the fabrication method starting from synthesizing the polymer material for the membrane to the hot spray coating of the catalyst prepared from base chemicals. $NiFe_2O_4$ and $NiCo_2O_4$ are the catalyst used in this study and are Platinum Group Metal (PGM) free electrocatalysts. Several electrocatalysts are discussed in various literature, but we restrict our scope to using the catalyst presented by Plevova et al. [26] for the cost calculations. Due to time constraints, we use the cost of the base chemical from Sigma-Aldrich [33, 31, 32], a reagent supplier for laboratory applications. However, obtaining a more accurate cost figure from a quotation for different bulk order sizes is recommended.

The fabrication method discussed by Karacan et al. [19] uses a pre-fabricated Zirfon membrane. A Zirfon membrane has a composition of 85% Zirconium Dioxide ($ZrO_2$) and 15% Polysulfone (PSU) [39]. The Fraunhofer report [18] also mentions using a $ZrO_2$ based membrane for the alkaline electrolyzer. Therefore, Zirfon (sold as Zirfon UTP 500 by AFGA [43]) is the membrane of choice. Due to time constraints, we use the cost of $ZrO_2$, and PSU from Sigma-Aldrich [35, 34], which is a reagent supplier for laboratory applications. However, obtaining a more accurate cost figure from a quotation for different bulk order sizes is possible.

Karacan et al. [19] use a Nafion ionomer as a binder for the catalyst with the Zirfon membrane. Plevova et al. [26] use a 93-7 Catalyst-to-Binder Ratio (CBR), which is the ratio used to calculate the cost of the catalyst and binder used to coat the membrane. The price of Nafion ionomer is obtained from Ion Power [17], a supplier of Nafion PFSA material.

### 2.2.2 Fabrication Technique

The hot spray coating method used in [26] is similar to the ultrasonic spray coating (Figure 4) used for PEM CCM fabrication [21]. Ansar et al. [3] also mention that PEM and Alkaline CCM fabrication can use similar coating techniques. The cost of the spray coating machine is obtained from [21] as the coating procedure is comparable to our case, and getting a quotation from equipment suppliers is time-consuming. The energy consumption of the spray coating equipment is back-calculated from the cost information presented in [21] and the other input data available in the report.

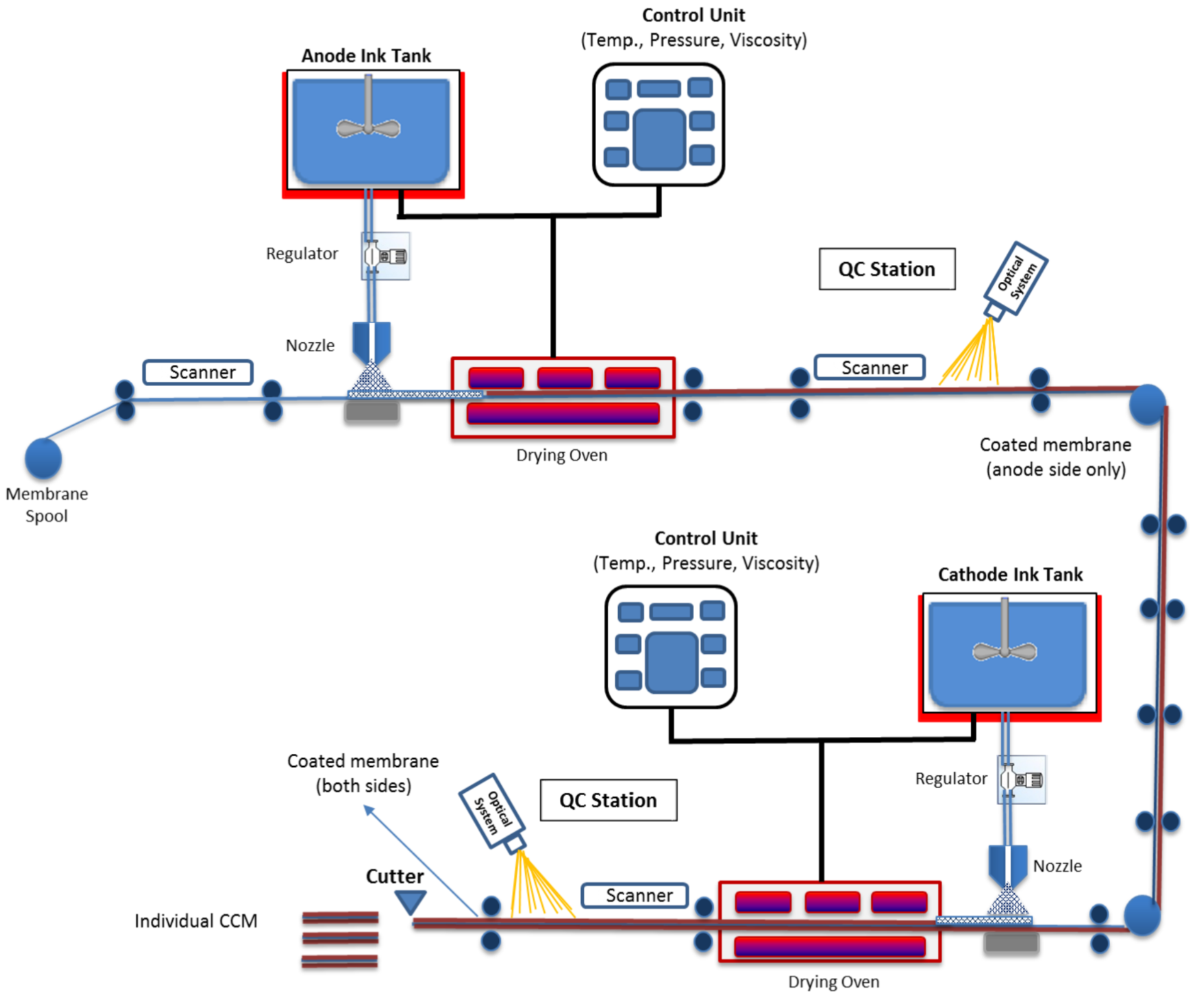


Figure 4: Process flow for catalyst deposition using spray coating [21]

### 2.2.3 Technical Specifications

The technical specifications include parameters such as cell voltage, current density, total cell area, and rated stack power. Since the electrocatalysts from [19] are chosen, we use the current density - voltage curve obtained for the specific catalyst loading and CBR. However, the maximum current density in the data is only up to 0.2 A/cm$^2$. Therefore, we extrapolate the curve for higher current densities (Figure 5) with a logarithmic fit, which is the general trend observed in literature [21, 19]. Since the equipment in consideration is from [21], a similar cell area is used for the stack, thus keeping other parameters of the spray coating process close to the original work. Considering a zero-gap design, this plot is estimating a higher cell voltage for the current densities chosen. So, more number of cells would be required for a single stack, which would have a minor impact on the production cost.

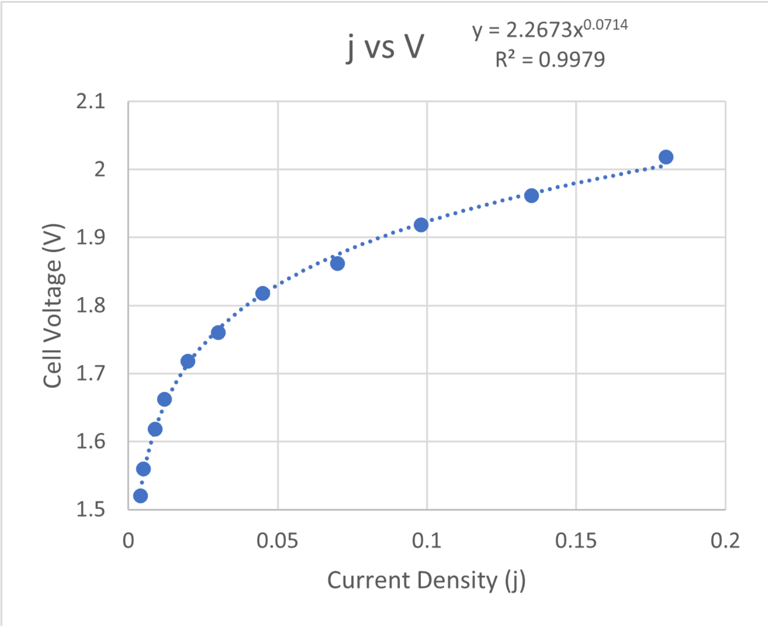


Figure 5: Current density vs cell voltage plot, extrapolated from Plevova et al. [26]

To compare the results with alkaline and PEM electrolyzers, we use a *1 MW Rated Stack Power* in this study. However, from a renewable energy point of view, there are two ways of sizing an electrolyzer. The conventional way is to collect all the power generated by solar/wind energy with power lines and appropriate electrical converters, and feed it to a central electrolyzer. Unfortunately, there are power losses in the electrical conversion, which would be significant if we consider large distances e.g. offshore wind/solar farms. Therefore, another approach is to install smaller electrolyzers, directly connected to a single windmill or a set of Photovoltaic (PV) panels. By this method, we avoid the energy losses due to electrical conversions and directly feed the power generated in Direct Current (DC). However, transportation of the generated $H_2$ should be studied extensively. Multiple electrolyzers would have to be linked to common product feed, and pumped towards storage tanks. Electrolyzers operating at atmospheric pressure would require compressors to increase the pressure. There is a possibility of reverse flow due to suction if the pipelines are operated near atmospheric pressure. In summary, this idea needs further exploration and quantitative analysis to compare the two implementations from a CAPEX and OPEX perspective.

#### 2.2.4 Cost-Related Information

There are various cost components involved in the bottom-up cost analysis. The data published by Eurostat [16] provides the hourly worker's wages in Europe. Since the equipment cost presented in [21] is from the year 2015, an inflation calculator from the U.S. Department of Labor Bureau of Labor Statistics [9] is used along with an average currency exchange rate to obtain the value of the equipment in 2022 in euros. The average cost of electricity and industrial floor space rent in Europe is obtained from Statista, a specialist in market and consumer data [14, 4].

# 3 Methodology

In the case of any manufacturing facility, it is essential first to understand the operational aspect. The functional specifications of the stack are outlined next, which helps define what one unit of the product would be, and the amount of material required. The first two sections provide the groundwork for detailed cost calculations. In the last sub-section, each cost component of the total manufacturing cost is explained, and preliminary estimates are presented systematically for the reader to recreate the calculations.

The calculations have been performed using the NumPy package in Python and Microsoft Excel, with visualization using the Matplotlib package in Python.

## 3.1 Operational Parameters

Table 1 lists several critical operational parameters for the manufacturing facility. These values are collected from various sources, which have been systematically cited.

Table 1: Operational parameters of the manufacturing facility

| **Parameter** | **Value** | **Unit** |
|---|---|---|
| Operating hours [21] | 16 | hours |
| Annual operating days [21] | 250 | days |
| Tool lifetime [21] | 15 | years |
| Energy cost [14] | 9.97 | €/kWh |
| Floor space cost [4] | 81.63 | €/m$^2$ |
| Hourly labor cost [16] | 29.1 | €/hour |
| Number of workers [21] | 2 | /line |

## 3.2 Functional Specifications

The electrolysis cell parameters decide the size of the stack and the amount of membrane required in the cells. The current density-voltage curve from [26] was extrapolated using a power function in Microsoft Excel. Using the extrapolated values, the cell voltage was deduced for a current density of 1 A/cm$^2$. The cell areas are obtained using the total cell area from [18], with the active cell area calculations provided in [21]. The values are reported in Table 2 with key stack specifications.

Table 2: Functional specifications of the alkaline electrolysis stack

| **Parameter** | **Value** | **Unit** |
|---|---|---|
| Reference Voltage | 2.2673 | V |
| Current density | 1 | A/cm$^2$ |
| Power density | 2.2673 | W |
| Catalyst loading | 2.5 | mg/cm$^2$ |
| CCM-coated cell area [21, 18] | 781.61 | cm$^2$ |
| Active cell area [21, 18] | 711.26 | cm$^2$ |
| Rated stack input power (DC) | 1 | MW |
| Number of cells | 621 | per 1 MW |

## 3.3 Manufacturing Cost Components

The bottom-up manufacturing cost analysis involved various cost components and assumptions in obtaining a final cost of production per unit/product. These cost components can be broadly classified into direct and indirect costs. Table 3 shows the various cost components in each category.

Table 3: Cost components of the bottom-up manufacturing cost analysis [21]

| Direct Manufacturing Cost | Indirect Manufacturing Cost |
|---|---|
| Capital costs | Research and development costs |
| Facilities/building costs | General and administration costs |
| Materials costs | Sales and marketing costs |
| Scrap costs (yield losses) | Product warranty costs |
| Labor costs | Debt service costs |
| Energy costs | Transportation costs |
| Maintenance costs | |

In this study, we consider only the direct manufacturing costs, excluding the scrap cost. The assumption is that the salvage cost of the equipment would be equal to the uninstalling cost [8]. The indirect costs are estimated to be 50% of the direct cost, as per literature [21]. However, this analysis will not include the indirect cost in the final results. Economic parameters such as discount rate, income tax, property tax, energy tax credit, building depreciation, and recovery costs are intentionally omitted, which can be included in future work, focusing on the operational costs of a manufacturing facility.

### 3.3.1 Capital Costs

The capital cost of the spray coating machinery and the supporting tools is obtained from the data published by Mayyas et al. [21]. However, the cost data is from 2015 and in US Dollars. Table 4 shows the adjusted capital cost in Euros using the inflation calculation tool [9] and average conversion rates as of November 4, 2022.

Table 4: Adjusted capital cost calculation for one coating line

| | |
|---|---|
| **Base Cost [21]** | $1,000,000 |
| **Inflation (2015 to 2022) [9]** | 25.2% |
| **Exchange Rate (USD to EUR)** | 1 USD = 0.9475 EUR |
| **Adjusted Cost** | €1,186,280 |

It is important to note that the capital costs will increase as the production size increases. The coating machine has a maximum output beyond which additional coating lines are necessary. Table 5 outlines the specifications of the coating line, along with the maximum output value of a single machine, using the specifications found in Appendix C of [21].

Table 5: Specification of the spray coating machine [21]

| Parameter | Value | Unit |
|---|---|---|
| Coating line footprint | 88.2 | $m^2$ |
| Line speed | 50 | cm/min |
| Web width | 109 | cm |
| Spray coating process yield | 90% | |
| Maximum output | 117720 | $m^2$/year |

#### 3.3.2 Building Costs

The floor space cost is calculated based on the footprint of the spray coating machine and the average industrial rent in Europe [4]. The building cost would increase as more coating lines are added based on the production size.

#### 3.3.3 Material Costs

As discussed in Section 2.2.1, the cost of the catalyst and membrane are calculated from the cost of base constituents required to synthesize the final product. A Zirfon membrane of 500 µm is chosen as per literature [19]. One of the assumptions used is a generic manufacturing estimation, where the material cost contributes to half the product's final cost. Additionally, since the membrane cost would ideally reduce at large order sizes, we introduce a price trend captured in [21] to mimic a reduction in price as the production size increases. Table 7 provides the inputs to calculate the final membrane cost for the smallest production size (10 units).

Table 6: Zirfon membrane properties and cost calculations

| | Value | Unit |
|---|---|---|
| Density [43] | 1200 | $kg/m^3$ |
| $ZrO_2$ cost [35] | 205 | €/kg |
| PSU cost [34] | 614 | €/kg |
| Material cost | 159.81 | €/kg |
| Final cost | 319.62 | €/kg |

Similar to the membrane cost calculations, the cost of the two catalysts is calculated from the cost of the base chemicals used to synthesize the catalysts. As per the technique mentioned in [26], the three chemicals in the appropriate ratio are chosen, and the final costs are computed using the price data. The assumption of 50% cost linked to the material is again applied in the final catalyst costs. The cost of the catalyst is assumed to be constant and unaffected by the manufacturing scale, as we lack data showing the price correlation to the order size. Table 7 outlines the inputs used to calculate the final catalyst cost.

Table 7: Catalyst cost calculations

| | **Value** | **Unit** |
|---|---|---|
| $Co(NO_3)_2 \cdot 6\,H_2O$ cost [31] | 710 | €/kg |
| $Ni(NO_3)_2 \cdot 6\,H_2O$ cost [33] | 1912 | €/kg |
| $FeCl_3 \cdot 6\,H_2O$ cost [32] | 150.67 | €/kg |
| $NiCo_2O_4$ cost | 1109.75 | €/kg |
| $NiFe_2O_4$ cost | 731.91 | €/kg |
| Final $NiCo_2O_4$ cost | 2219.5 | €/kg |
| Final $NiFe_2O_4$ cost | 1463.82 | €/kg |

The cost of Nafion ionomer is obtained from the Ion Power [17] and is quoted at **2.9 €/g**.

#### 3.3.4 Labor Costs

Labor cost is obtained from Eurostat [16], and the average value in Europe is **€29.1 per hour**. As per the operational specification, two workers per line are necessary. Therefore, the labor cost would also increase as the production size increases.

#### 3.3.5 Energy Costs

The energy consumption of the spray coating machine is calculated using the final cost results presented in [21] and back-tracking the energy use for the smallest production size (10 units). This value is found to be **227 kWh/m²**, which is scaled overall by the size of the production, as this component has a minor contribution to the final cost.

#### 3.3.6 Maintenance Costs

As the maintenance cost is also a minor component in the total cost, a similar method is employed where the per unit price for the smallest production size (10 units) is calculated from the results in [21]. This value is scaled overall by the production size.

# 4 Results and Discussion

The individual cost components are presented in a stack plot to visualize the contribution at various production scales. Figure 6 and Figure 7 show the cost in €/$m^2$ and €/kW respectively. The data shows how the price of the different cost components decreases as the production capacity increases. Here, one unit of the product is the membrane that goes into producing a 1 MW alkaline electrolysis stack.

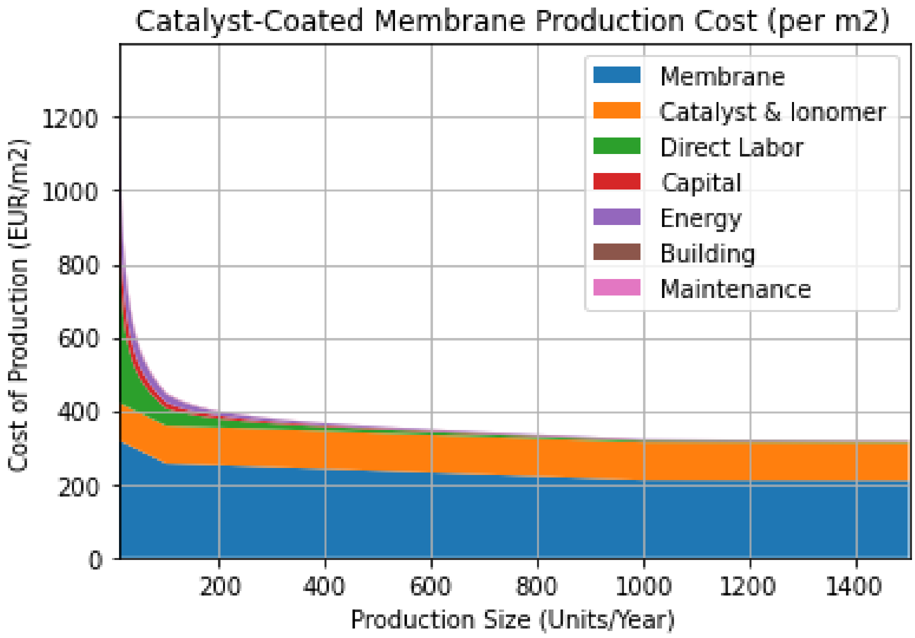


Figure 6: CCM production cost (per $m^2$)

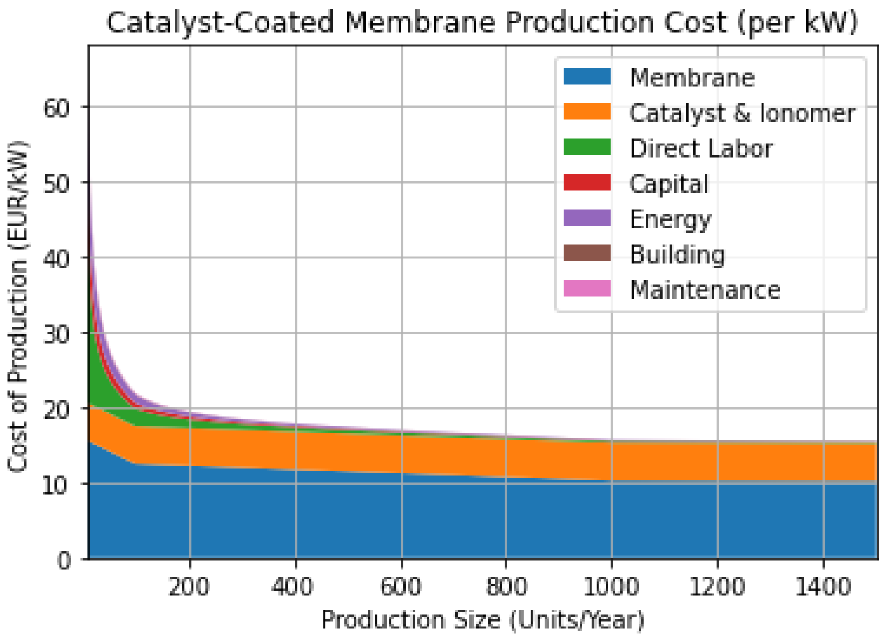


Figure 7: CCM production cost (per kWh)

The stack plots show that the material cost components are significant in determining the cost of the CCM. Naturally, as the production size increases, the material required increases. A price reduction can be expected when the material is purchased in bulk orders. Price quotation documents from prominent suppliers are necessary to confirm this. It is also essential to understand that the per unit prices used for both the membrane and catalyst have been obtained from a laboratory scale reagent supplier (Sigma-Aldrich) [35, 34, 31, 32, 33]. The prices at such scales are higher in the context of large-scale manufacturing. Therefore, there is scope for further reduction in the material cost.

The next most significant value pertains to labor costs, which drop quickly as production increases to 1000 units. The other cost components are influential at smaller production sizes and quickly decrease as production increases. Table 8 shows the cost breakdown for the three significant cost reductions.

Table 8: CCM production cost (in €/m2 and €/kWh) for (i) 10, (ii) 35, and (iii) 1000 production units

| **Production Size** | 10 | 35 | 1000 |
|---|---|---|---|
| **Capital** | 162.94 | 46.55 | 1.63 |
| **Building** | 14.83 | 4.24 | 0.15 |
| **Membrane** | 319.62 | 301.86 | 210.24 |
| **Catalyst** | 102.99 | 102.99 | 103.00 |
| **Labor** | 479.62 | 137.04 | 4.80 |
| **Energy** | 226.32 | 64.66 | 2.26 |
| **Maintenance** | 26.69 | 7.63 | 0.27 |
| **Total (€/m2)** | 1333 | 665 | 322 |
| **Total (€/kWh)** | 65 | 32 | 16 |

The calculated CCM cost is now compared to other reported values from the literature. The cost per unit area of the membrane would be used in this comparison, as the stack sizes are different in all the cases. Table 9 list the CCM cost quoted in their calculations.

Table 9: CCM cost comparison in €/m2

| **Source** | **Year** | **Stack Capacity** | **Technology** | **Production Size** | **CCM Cost** |
|---|---|---|---|---|---|
| This work | 2022 | 1 MW | Alkaline[1] | 10 | €1333 |
| This work | 2022 | 1 MW | Alkaline[1] | 1000 | €322 |
| Fraunhofer [18] | 2021 | 2.5 MW | Alkaline[2] | Unknown | €199 |
| Fraunhofer [18] | 2021 | 1 MW | PEM | Unknown | €6150 |
| Mayyas [21] | 2019 | 1 MW | PEM | 10 | €2250 |
| Mayyas [21] | 2019 | 1 MW | PEM | 20000 | €1080 |

The comparison reveals that the alkaline CCM costs are lower when compared to PEM due to cheaper catalyst material and membrane costs. As anticipated, the CCM would cost more than the separator cost in conventional alkaline technology. The coating process and additional material would increase the separator's cost but reduce the cost of the electrodes, as off-the-shelf Nickel plates/mesh can be used. The cost of the Membrane-Electrode Assembly (MEA) needs to be verified from further studies.

The benefits of an MEA-based design for alkaline electrolysis cells go beyond performance improvements, ease in high-pressure operation, and improved gas purity. From a manufacturing point of view, a single infras-

[1]Zero-gap design
[2]Conventional design

tructure could be set up for both PEM and alkaline cell fabrication, thus reducing the idle time of the production lines and providing flexibility in manufacturing. Additionally, we can expect a further reduction in the manufacturing cost, as the learning rates for PEM stack manufacturing are quoted to be higher [2, 18]. Therefore, more research and development in spray coating and MEA-based stack production would also translate into a cost reduction for the alkaline MEA.

The direct manufacturing cost components have been estimated in various ways, which have been systematically introduced in this section. The best way to obtain a cost estimate with a higher confidence level is to contact suppliers for each item and receive a bulk order price quotation with the varying order size. Therefore, cooperation from organizations is crucial to obtain cost figures closer to reality. The parties involved would also benefit, as the new entrant to the industry would take their business to the companies based on the data citations.

# 5 Conclusion and Future Work

This study analyzes the cost of manufacturing a Catalyst Coated Membrane (CCM) for a zero-gap alkaline electrolysis cell. An extensive literature review was performed to decide the scope of the project. Publicly accessible information is used to perform this task, which reveals the current challenge of estimating the cost of an electrolysis system.

Using a Direct Manufacturing Cost Analysis [21], we consider each cost component individually, providing supporting information for the assumptions and considerations. The cumulative cost trend of the CCM is plotted for a production size ranging from 10 to 1500 units of 1 MW stacks, with data presented in a per unit area and per unit stack power. We draw various inferences from the individual cost components and the shortcomings of certain assumptions. The calculated CCM costs are then compared to published data for PEM and alkaline electrolyzer membranes. Several assumptions have been made from either outdated data [21] or generic industry observed figures [6], which would not necessarily apply to all product manufacturing. Therefore, future work must focus on extensive data gathering from several industry partners to obtain more realistic cost figures with high confidence. Economic aspects of operating a large-scale manufacturing operation must be considered, adjusting cost components with parameters such as discount rate, income tax, property tax, energy tax credit, building depreciation, and recovery costs. The bottom-up cost analysis must be performed on all the stack components to obtain the total stack cost for a zero-gap design. Based on the stack cost, we can make a business case for the commercialization of the zero-gap concept.

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