



Prospective LCA of alkaline and PEM electrolyser systems

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ABSTRACT

This prospective life cycle assessment (LCA) compares the environmental impacts of alkaline electrolyser (AE) and proton exchange membrane (PEM) electrolyser systems for green hydrogen production with a special focus on the stack components. The study evaluates both baseline and near-future advanced designs, considering cradle-to-gate life cycle from material production to operation. The electricity source followed by the stacks are identified as major contributors to environmental impacts. No clear winner emerges between AE and PEM in relation to environmental impacts. The advanced designs show a reduced impact in most categories compared to baseline designs which can mainly be attributed to the increased current density. Advanced green hydrogen production technologies outperform grey and blue hydrogen production technologies in all impact categories, except for minerals and metals resource use due to rare earth metals in the stacks. Next to increasing current density, decreasing minimal load requirements, improving sustainable mining practices (including waste treatment) and low carbon intensity steel production routes can enhance the environmental performance of electrolyser systems, aiding the transition to sustainable hydrogen production.

1. Introduction

The use of hydrogen as a clean energy carrier has been gaining attention in recent years as a potential solution to decarbonize various sectors of the economy such as transportation, power generation, and industry. One of the key technologies for producing hydrogen is through the electrolysis of water, which separates the hydrogen and oxygen atoms in water molecules using an electrical current. Two main types of electrolysers are currently available for hydrogen production: alkaline electrolysers (AE) and proton exchange membrane (PEM) electrolysers. These two types are also likely going to be deployed on a large scale in the coming decade. Based on all global projects in the pipeline, the IEA [1] projects 134–240 GW of installed capacity by 2030 and states that electrolysis capacity needs to be expanded above 700 GW globally to be on track with the Net Zero Emissions (NZE) by 2050 scenario. To achieve these targets, electrolyser capacity needs to be scaled from an MW to a GW scale. The research focus has been placed on bringing down the cost, scaling up and improving the performances of both types of electrolysers. With the expected high deployment, it is also necessary to assess their environmental impacts and identify hotspots and improvement opportunities at an early stage of development.

A life cycle assessment (LCA) is a tool used to evaluate the environmental impacts of a product or process from its cradle-to-grave stages. The literature reviews conducted by Bhandari et al. [2], Valente et al. [3,4], Mehmeti et al. [5] and Kanz et al. [6] revealed 34 LCA studies on electrolysers (AE and PEM). The system boundary in these studies is mostly cradle-to-gate: resource extraction, production and supply of hydrogen to the end user. The electricity source during the operation phase used in these studies was mostly wind, followed by PV, nuclear, grid-based and hydro. The above-mentioned literature reviews, state that the electricity generating source (irrespective of electricity generating technology) required for the process of electrolysis accounts for the highest share in environmental impact. The LCA studies account for the manufacturing and installation of the electricity-producing technology, however, no detailed analysis or inventory of the stacks is provided because the stacks are assumed to contribute to a small share of Global warming potential (GWP). To the best of our knowledge, only five studies conducted a detailed assessment of the environmental impacts of electrolyser stacks. Bareiß et al. [7] investigated a 1 MW PEM stack performance and addressed near future developments by incorporating future electricity mix scenarios in Germany. Gerloff [8] expanded on the work conducted by Bareiß et al. [7] by including Solid Oxide Electrolysis Cell (SOEC) and AE systems and distinguishing

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List of abbreviations*Acronyms*

AE	Alkaline electrolysis
Al	Aluminum
BoP	Balance of Plant
BPP	Bipolar Plate
BF-BOF	Blast Furnace - Basic Oxygen Furnace
CCS	Carbon Capture and Sequestration
DRI	Direct Iron Reduction
EAF	Electric Arc Furnace
GWP	Global Warming Potential
Au	Gold
Ir	Iridium
LCA	Life Cycle Assessment

MEA	Membrane Electrode Assembly
Ni	Nickel
Nb	Niobium
Pt	Platinum
PSU	Polysulfon
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
PTL	Porous Transport Layer
PE	Power Electronics
PEM	Proton Exchange Membrane
SOEC	Solid Oxide Electrolysis Cell
SS	Stainless steel
SMR	Steam Methane Reforming
Ti	Titanium
TRL	Technology Readiness Level

between onshore and offshore wind in future German electricity mix scenarios. Both authors do not account for alternate materials and designs used in AE and PEM stacks to improve performance and reduce costs. Zhao et al. [9] investigate the environmental impact of current AE, PEM and SOEC stacks but do not perform a comparative assessment with future designs. Furthermore, they do not account for the impact of electricity and Balance of Plant (BoP) and Power Electronics (PE). They assume with the increasing share of renewables, the environmental impact from electricity generation will be minimal. They cite lack of available data for excluding BoP and PE from their system boundary. Lotrič et al. [10] perform a LCA on high and low temperature fuel cells, AE and PEM electrolysis with a focus on end of life (EoL) strategies. Mori et al. [11] investigated the criticality and life cycle assessment of materials used in fuel-cells and AE, PEM and SOEC electrolyzers. Both Lotrič et al. [10] and Mori et al. [11] do not account for electricity use but focus on the stacks and BoP and PE. Though they have detailed inventory list for the stacks, they do not perform a comparative LCA with future stack designs thereby not accounting for the changes in environmental impact as a result of increasing current density and use of alternate materials to improve stack performance and reduce costs. Electrolyser systems are expected to scale up to a GW scale. This entails larger stacks with higher current density to increase the production rate of hydrogen, reducing the amount of critical raw materials and use of alternate materials to substitute expensive critical raw materials. Furthermore, improved stack designs are expected to reduce the electricity consumption of the stacks, resulting in lower environmental impact. These improvements of stacks in terms of overall costs and technological performance are a major R&D activity for both PEM and alkaline electrolyzers. The potential impacts of these changes on the environmental performance of the hydrogen have so far not been assessed.

To address the knowledge gaps on the environmental effect of scaling up electrolyzers to a GW scale, we conduct a prospective LCA on current and future electrolyzers systems (AE and PEM) producing green hydrogen at a GW scale. This approach enables us to assess the change in environmental impact that improved electrolyser systems can have. We conduct a detailed assessment of state-of-the-art and future stacks by incorporating current and alternate materials and improvements in stack performance. Since we are assessing an electrolyser system, we include the BoP & PE and the electricity source. To produce green hydrogen, the electricity source must be renewable. For renewable sources of electricity, the issue of intermittency needs to be accounted for. Therefore, in addition to the renewable electricity generating source, we also include a steady supply of grid electricity during low supply of renewable electricity. Furthermore, to encapsulate a more realistic picture of the future, we incorporate projected future electricity mixes at several points of the life cycle: 1) grid electricity supplied to

operate the electrolyser and 2) electricity used during the production process of materials within the electrolyser system that could have a major impact on the environment.

The changes in environmental impact as a result of scaling up and improved stack designs will be of interest to a wide range of stakeholders, including policymakers, hydrogen producers, and manufacturers of electrolyzers. The results of the study will provide valuable information for decision-makers and aid in the development of more sustainable hydrogen production methods.

2. Materials and methods

LCA is a methodology used to assess the potential environmental impacts associated with a product in a consistent and comprehensive way. The objective of this LCA study is to compare the environmental impacts of AE and PEM electrolyser systems, considering their entire life cycle, including the production of materials, manufacturing, transportation and operation. The results of this study will provide insight into the environmental benefits and trade-offs of these two electrolyser systems and can aid decision-makers in the selection of the most environmentally friendly option. According to ISO 14040 and 14044 [12], LCA is usually composed of 4 stages:

- Goal and scope definition
- Inventory analysis (LCI)
- Impact assessment (LCIA)
- Interpretation

The goal and scope definition addresses the system boundary of the product for which the environmental impact is assessed and the functional unit to represent the environmental impact. The inventory analysis includes data collection and quantifying inputs and outputs of each unit operation. The impact assessment helps evaluate the significance of potential environmental impacts while the interpretation is associated with analyzing the findings from the inventory analysis and the impact assessment phases to present consistent results based on the goal and scope definition phase of the study.

2.1. Goal and scope

The goal of this study is to assess the environmental impact of AE and PEM systems with a focus on the current state-of-the-art stacks, termed baseline design, and the expected future stacks design commercially available within the decade, termed advanced design. This enables us to determine the potential reduction in environmental impact based on improvements in stack design.

In our study, we conduct a cradle-to-gate environmental assessment.

The use of the produced hydrogen is out of the scope of our research. The scope of this study starts with the acquisition of raw materials, including the mining, processing and transport, to the manufacturing of electrolyser system components using the processed raw materials. The operational phase has been taken into consideration to account for the electricity consumed during the electrolysis process. We do not account for end-of-life or recycling of materials due to the low TRL associated with recycling technologies and the uncertainty regarding the amount of material that can be recycled [13]. We also do not model the water use because it shows minimal environmental impact [9]. For the baseline design, current manufacturing technologies and fuel sources are assumed for the extraction, processing and transport of raw materials and the manufacturing of electrolyser system components. Within the coming decade, the share of renewables and more environmentally friendly production methods are expected to increase. Therefore, for the advanced design, we assume scenario-based projections for future electricity grid mix and manufacturing production routes.

Irrespective of the electrolyser technology, an electrolyser system is comprised of:

- A stack (the H_2 producing unit)
- The Balance of Plant (BoP) and Power electronics (PE) required for pumping water into the stack, purification of the gasses and facilitating the electricity required for water electrolysis.
- Electricity production source.

Fig. 1 shows the system boundary of hydrogen production via electrolysis.

The FC-HyGuide [14,15] has interpreted and adapted the ISO standards specifically for hydrogen producing systems. They state that the recommended functional unit for electrolyser systems is one MWh of primary energy ($/MWh_p$) used, one m^2 of active surface area ($/m^2_{active SA}$) or one kg of hydrogen produced ($/kg H_2$) over the lifetime of the electrolyser system. We chose the functional unit of per/kg H_2 produced as this also accounts for the efficiency of the electrolysers. This is an important consideration for our study since we compare state-of-the-art designs with advanced designs for both AE and PEM. Along with hydrogen, oxygen is also produced as a byproduct but currently, electrolyser operators vent the oxygen into the atmosphere. Therefore, we

model oxygen as an emission and not as a co-product.

The goal of this study is to assess the environmental impact of producing green hydrogen via electrolysis operating with renewable electricity. The geographical scope of our study is the Netherlands, and the assumed source of renewable electricity is offshore wind since it is the best local source for dedicated renewable electricity production. We assume a 1 GW offshore wind farm as the main source of electricity to facilitate green hydrogen production on a GW scale. The electrolyser is expected to run at 4000 full load hours/year based on the offshore wind profile of a GW wind farm with a load factor of 0.42 in the North Sea, as indicated by Ørsted [16]. In events of low to no-availability of electricity from offshore wind, the electrolyser needs to be supplied with backup power to ensure continuous operation. Completely shutting off and turning on the electrolyser can lead to safety issues related to gas crossover and heat management. Therefore, during instances when no electricity is supplied by the offshore wind farm, electricity is sourced from the Dutch grid electricity. The minimal load requirements for the AE and PEM stacks are 15 % and 10 % respectively [16]. The minimal load is limited by the gas purity. Below the minimal load, the amount of hydrogen at the oxygen evolution reaction (OER) side becomes too high. The hydrogen transport through the membrane is independent of load when compared with the oxygen produced which decreases with decreasing load. Therefore, the relative hydrogen content in oxygen increases with decreasing oxygen production [17]. At a hydrogen-in-oxygen content of 2 %, the electrolyser is to be shut down [18]. The difference in minimal load requirements between alkaline and PEM electrolysers is attributed to the material and permeability of the membrane (Personal communication with Nobian, 2022).

The stack specifications for the baseline and advanced designs are derived from Krishnan et al [19]. The baseline AE design is state-of-the-art stacks based on the Norwegian company NEL's design. The goal of the AE advanced stack design is to increase stack capacity and improve efficiency while producing pressurized hydrogen. The advanced design is modelled after a zero-gap design where the electrodes are pressed against the membrane to achieve a "zero gap" between the two electrodes and the membrane. This leads to significantly lower ohmic resistance and helps facilitate operation at a higher current density of $1.3 A/cm^2$ when compared to state-of-the-art densities of $0.245 A/cm^2$ [19].

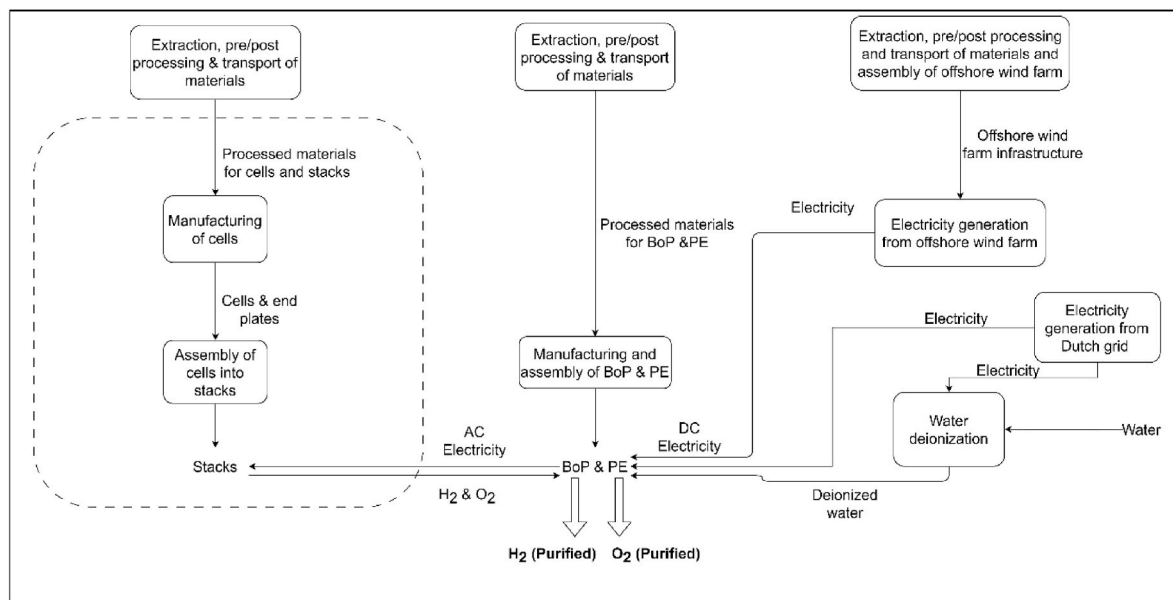


Fig. 1. Electrolyser system. Elements within the dashed box are modelled through primary data. Elements outside the dashed box are modelled through secondary data. Dedicated 1 GW offshore wind farm provides electricity to the electrolyser system for 4000 full load hours. Grid provides electricity to the system at 15 % and 10 % minimal load for AE and PEM respectively. End products are H_2 at 30 bar and O_2 which is vented out.

The baseline PEM design is based on state-of-the-art design manufactured by ITM. The advanced PEM stack design is based on extrapolations from electrochemical models using the targets of current density (3.5 A/cm^2) set by the 2018 FCH-JU multi-annual work program [20] as the starting point and incorporating expected developments in cell design improvements. Table 1 provides the stack specifications for baseline and advanced AE and PEM designs.

2.2. Inventory data

The material selection and their weights used in the electrolyser stacks are part of the foreground process while all other elements within the system boundary are background processes unless otherwise specified. The background system was modelled using ecoinvent database. The foreground data was collected from Krishnan et al. [19] which is based on the work conducted for the ISPT Hydrohub GW Electrolyser project. This includes the electrolyser stack specifications and the materials that make up the stacks.

2.2.1. Electricity source

As mentioned in section 2.1, the electrolysers are supplied with electricity from offshore wind for 4000 full load hours based on the wind profile of a 1 GW offshore wind farm in the North Sea. At minimal load of 15 % and 10 % for AE and PEM systems respectively, the required load hours from the Dutch grid are 161 and 85 h per year, respectively. The inventory data in ecoinvent database for offshore wind in the Netherlands corresponds to 1–3 MW offshore wind turbines. For the advanced design case, which is expected to become commercial within the next decade, offshore wind turbines larger than 3 MW are expected to be deployed. Due to a lack of data availability on larger turbines, currently available data for 1–3 MW turbines were used as proxy to model the advanced design. Data on the Dutch grid electricity mix was collected from ecoinvent database as a medium voltage electricity mix. For the advanced design, the projected 2030 Dutch grid electricity mix by Tennet [21] was used. Fig. 2 shows the projected Dutch grid electricity mix in 2030 based on IEA's Stated Policy Scenario.

2.2.2. Balance of Plant (BoP) and power electronic (PE)

The BoP and PE input data is not based on primary data and stems

Table 1
Stack specifications for baseline and advanced AE and PEM stacks [19].

	AE		PEM	
	Baseline (2020)	Advanced (2030)	Baseline (2020)	Advanced (2030)
Stack Size (MW)	2.2	20	0.67	9.75
No of cells	230	335	150	310
Active surface area (m^2)	2.1	2.6	0.10	0.50
Power density (W/cm^2)	0.5	2.3	4.5	6.3
Current density (A/cm^2)	0.245	1.3	2	3.5
Pressure (bar)	Ambient	5	20	30
Temperature at Nominal load ($^{\circ}\text{C}$)	80	100	55	70
Voltage (V)	1.85	1.79	2.25	1.8
Lifetime (years)	8	8	8	8
Specific energy (kWh/kgH_2)	49	48	58	47
Operating hours at full load (offshore wind) (h/y)	4000	4000	4000	4000
Operating hours at full load (grid electricity) (h/y)	161	161	85	85
Yearly H_2 production (tons/year)	82448	83456	67952	85030

from Bareiß et al. [7] due to a lack of data available from the industry. Because literature studies [7,8,14,22] have shown that the impact of BoP and PE is negligible when compared to other components in an electrolyser system, our study uses secondary data to model the impact of the materials required for the BoP and PE components as seen in Table 2. Bareiß et al. [6] report the weight of materials required for BoP and PE for a 1 MW PEM system. In our analysis, we scale the data from Bareiß et al. [7] for a 1 GW system using a scaling factor of 0.9, a common value used in scaling these type of equipment [8]. BoP and PE components are similar for the AE system [8,16]. Therefore, we assume the same components and hence same materials will be used in BoP and PE for the AE system. Since the baseline and advanced designs are both of a GW scale, we assume the same amount of materials required for the BoP and PE. The BoP and PE components have a lifetime of 20 years.

2.2.3. Stacks

AE and PEM stacks are made up of a recurring number of cells each with a rated power. These cells are connected to each other in series to form a stack. Each cell is made of a number of components. Table 3 describes and Fig. 3 illustrates the components for an AE and PEM cell.

The materials used to facilitate the operating conditions of the stacks are shown in Table 4. The materials used in the baseline design are based on state-of-the-art stacks and the materials for the advanced design were chosen in collaboration with experts from TNO and Nobian to reduce cost while facilitating the improved operating conditions specified in Table 1.

Inventory data for most of the materials contained in the stacks are available in the ecoinvent database except for iridium and niobium. Proxies with similar production chains were used to represent iridium and niobium. Rhodium is used as a substitute for iridium since they are both platinum group metals and have similar physical and chemical properties and also tend to occur together in the same mineral deposits [10]. The characterization factor on resource use for iridium is not available in the EF 3.0 method. Therefore, we could not assess the impact that iridium depletion has on the impact category Resource use, minerals and metals. The inventory data for tantalum extraction was used as a proxy for niobium extraction since it is the main ore from which niobium is obtained and therefore has similar physical and chemical properties. In order to account for the depletion of niobium in the impact assessment, the depletion of the corresponding amount of niobium mineral was incorporated as input in the inventory. The Zirfon membrane, platinum ink and Raney nickel are made up of a mix of materials which have all been accounted for in our inventory data. Table 5 shows the composition of these three materials.

For the Nafion membrane and Nafion DE-521 solution, we use tetrafluoroethylene as the material input for our LCA study due to a lack of information on the exact chemical composition and of the high share of tetrafluoroethylene in the material.

2.3. Impact assessment

The FC-HyGuide recommends the CML method to conduct an impact assessment for electrolyser systems. However, we use the E.F. 3.0 midpoint method (adapted by Pré to be used in Simapro) which is a combination of characterization models recommended by the PEF guidelines. We acknowledge that different sets of impact categories can be chosen to represent the environmental impact of electrolysers and there is no clear cut choice. Nevertheless, we follow FC-HyGuide's recommendations on the impact assessment categories to consider when conducting a LCA, as indicated in Table 6.

The impact category "Human toxicity: cancer and non-cancer" and "Resource use, Minerals & Metals" is not specified in the FC-HyGuide recommendations but we choose to include it in our assessment. Bandhari et al. [2] conducted a literature study on LCA of electrolyser systems and indicated Human toxicity as one of the impact categories assessed. Furthermore, subsequent LCA studies conducted by Mehmeti et al. [5],

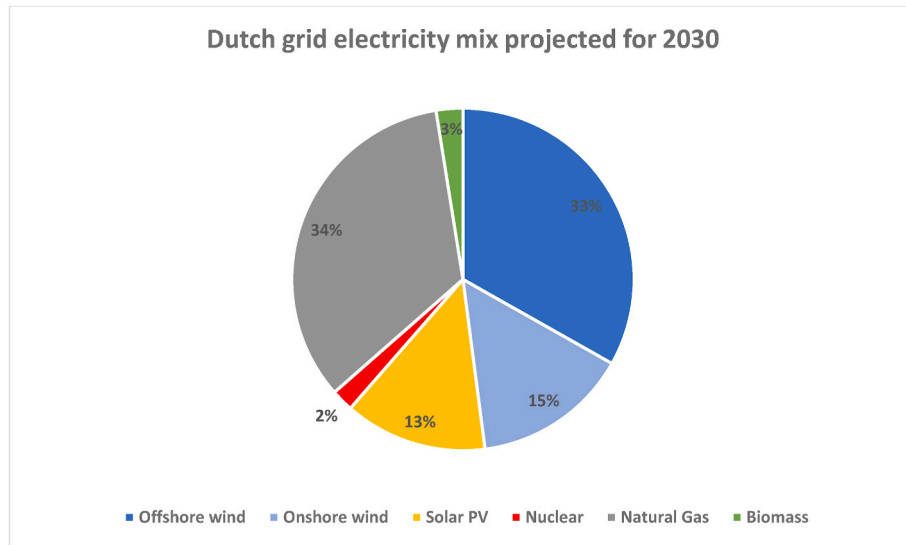


Fig. 2. 2030 projected Dutch grid electricity mix according to IEA's Stated Policy Scenario [21].

Table 2

Materials for BoP and PE. Scaled from a MW system proposed by Bareiß et al. [7] to a GW system using a scaling factor of 0.9.

BoP and PE materials	Material Weight (kg/kgH ₂)			
	AE		PEM	
	Baseline	Advanced	Baseline	Advanced
Low alloy steel	1.46E-03	1.44E-03	1.77E-03	1.41E-03
High alloyed steel	5.77E-04	5.71E-04	7.01E-04	5.60E-04
Aluminum	3.04E-05	3.00E-05	3.69E-05	2.95E-05
Copper	3.04E-05	3.00E-05	3.69E-05	2.95E-05
Plastic	9.12E-05	9.01E-05	1.11E-04	8.84E-05
Electronic material	3.34E-04	3.30E-04	4.06E-04	3.24E-04
Process material	6.08E-05	6.01E-05	7.38E-05	5.89E-05
Concrete	1.70E-03	1.68E-03	2.07E-03	1.65E-03

Bareiß et al. [7], Lotrič et al. [10] and Gerloff [8] have all assessed the impact of electrolyser systems on human toxicity. Additionally, according to Valentine et al. [3,4], human toxicity and photochemical ozone formation were chosen in the CML method which was originally recommended by the FC-HyGuide. AE and PEM stacks use non-noble and noble metals. This is especially relevant in the case of PEM stacks where rare earth metals like platinum (Pt), gold (Au) and niobium (Nb) are used. Therefore, we choose to include “Resource use, Minerals & Metals.”

2.4. Future energy scenario

The advanced design is expected to become commercial within the next decade. According to IEA, country-specific electricity mixes will experience significant changes. The share of fossil-based sources is expected to decrease and replaced with renewable electricity sources. Electricity is a required input in the production chain of materials. Therefore, for the future scenario, it is assumed that the materials with a significant share of the stack weight are produced with the electricity mixes projected by 2030 by the IEA's Stated Policy Scenario.

The manufacturing of silicon and processing of metals like nickel, platinum, iridium and niobium are also energy-intensive processes. For the 2030 scenario, these materials were modelled considering the projected country-specific energy mixes for the processing activity. The activities specific to the processing of the abovementioned raw materials occurs in China [25]. Therefore, we incorporate the 2030 projected electricity mix of China [26,27]. Fig. 4 shows the 2030 projected

Table 3

AE and PEM cell components and their associated function [19].

Component	AE	PEM
Membrane	Helps facilitate the transport of OH ⁻ ions and separation of product gases and provides electrical insulation of electrodes	Helps facilitate the transport of H ⁺ ions and separation of product gases and provides electrical insulation of electrodes
Electrodes (cathode and anode)	Electroplated with non-noble metals to facilitate electrochemical reactions. The membrane and the electrodes together are termed as the Membrane Electrode Assembly (MEA)	Spray coated with noble metals on either side to form the cathode and anode of the electrodes. The electrodes along with the membrane is called the MEA.
Porous Transport Layer (PTL) (cathode and anode)	NA	Facilitates the diffusion of gasses between the bipolar plate and the MEA.
Seals and Gasket	Seals the stacks and prevents the escape of gasses	NA
Compression mattress	Layers of wired metal sheets to form a mattress that is wedged between the bipolar plate and the electrodes to reduce the stress on the electrodes and membrane	NA
Bipolar Plate (BPP)	Provides electrical conduction between the cells and separates single cells in a stack.	Main purpose is to distribute reacting agents within the electrolyser and provide electrical conduction between the cells. Also separates single cells in a stack
End plates	The outermost component of a stack. Their purpose is to apply pressure on the cells to maintain the structure as well as prevent gases from escaping the cells and ensure a uniform compression over the whole cell area.	

electricity mix for China.

Section 2.2 shows that steel constitutes a considerable share in the total weight of materials used in the electrolyser system. Currently steel produced via the commercial blast furnace - basic oxygen furnace (BF-BOF) constitutes 70 % [28] of global steel production with an emission factor of 1.77 tCO₂/t_{cs} [30] while Electric Arc Furnace (EAF) with an emission factor of 0.44 tCO₂/t_{cs} accounts for the remaining 30 %. By 2030, the share of BF-BOF is expected to reduce by 11 % with an increase in less carbon-intensive production routes like EAF, BF-BOF with

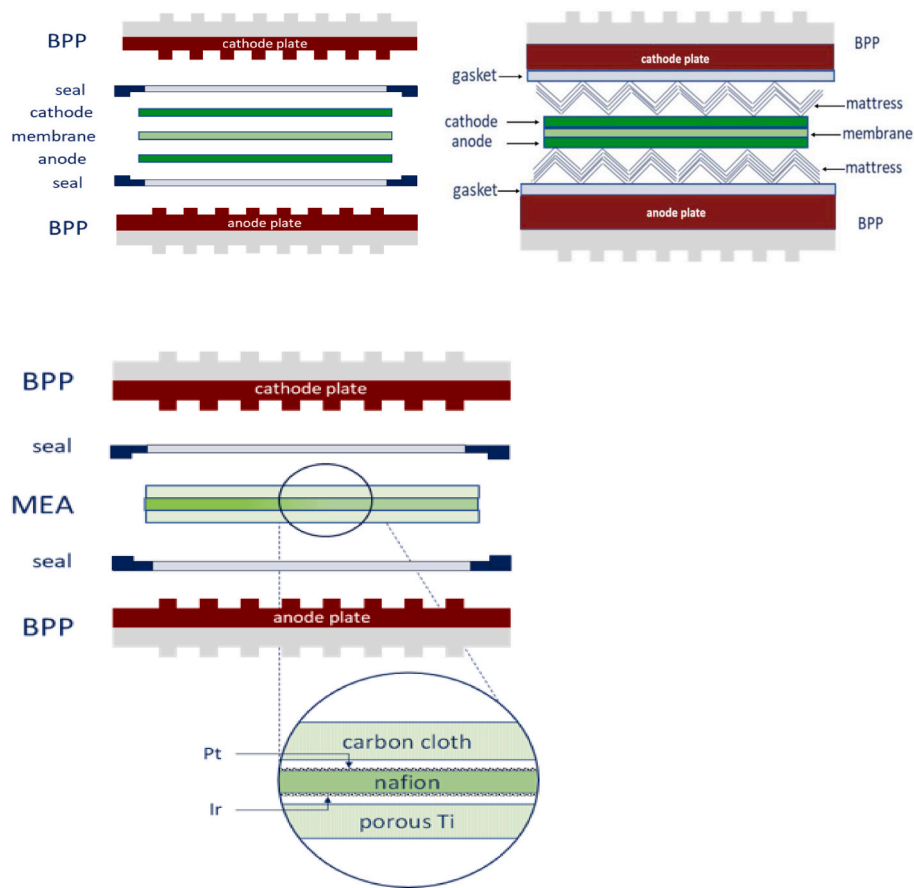


Fig. 3. Top panel: Baseline AE (left side) and advanced Zero-gap (right half) stack design. Bottom panel: Baseline and advanced PEM stack design. Note: the overarching baseline and advanced PEM stack design is the same. Reprinted from Ref. [19].

Table 4

Baseline and advanced AE and PEM stack materials [19]. Note: Manufacturing processes for the advanced AE design were not accounted due to lack of information related to weaving and welding of wire mesh electrodes and nickel mattress [19]. Additionally, energy consumption per functional unit during manufacturing process for PEM is negligible (0.007 kWh/kgH₂). Using the Dutch electricity mix in SimaPro, this generates a GWP of 0.004 kgCO_{2eq}/kgH₂.

AE				
Components	Baseline (2020)		Advanced (2030)	
	Material	Weight (kg/kgH ₂)	Material	Weight (kg/kgH ₂)
Separator	Zirfon UTP 500	1.66E-04	Zirfon UTP 220	1.50E-05
Cathode	Perforated Carbon Steel	0.02	Ni Mesh	9.85E-05
	Ni plated (156 μm)	3.33E-04	Raney Ni Coating (75 μm)	2.05E-05
Anode	Perforated Carbon Steel	0.02	Ni Mesh	9.85E-05
	Ni plated (156 μm)	9.25E-04		
Mattress	Not applicable		Ni mattress	5.82E-04
Frames	Carbon steel	1.60E-03	PSU + 30 % Glass Fiber	1.11E-04
Gasket	Rubber	2.1E-05	PTFE	5.77E-05
Bipolar plate	Carbon Steel	0.04	Carbon Steel	4.13E-03
	Ni coating(200 μm)	1.47E-03	Ni coating (200 μm)	1.68E-04
End plates	Carbon Steel	5.21E-03	Carbon Steel	6.60E-04
PEM				
Components	Baseline (2020)		Advanced (2030)	
	Material	Weight (kg/kgH ₂)	Material	Weight (kg/kgH ₂)
CCM	Membrane	Nafion 117	Nafion 80 μm	3.7E-06
	Coatings	Pt: 0.75 mg/cm ²	Pt: 0.05 mg/cm ²	1.17E-08
		Ir: 2 mg/cm ²	Ir: 0.1 mg/cm ²	2.34E-08
PTL	Anode	Sintered porous Ti	Sintered porous 316 L Stainless steel	5.61E-04
		Au (100 nm)	Nb (20 μm)	8.0E-05
	Cathode	Carbon cloth	Carbon cloth	2.88E-06
Seals/Frames		PPS 40 % Glass Fiber	PPS 40 % Glass Fiber	6.55E-05
Bipolar Plate		316 L Stainless steel	316 L Stainless steel	2.69E-04
		Au (100 nm)	Nb (200 μm)	2.31E-04
End plate		A356 Al	A356 Al	9.9E-06

Table 5

Material composition of platinum ink and Zirfon membrane [23,24].

Platinum ink				Zirfon membrane				Raney Nickel		
Material	Share	Weight (kg/kgH ₂)		Material	Share	Weight (kg/kgH ₂)		Material	Share	Weight (kg/kgH ₂)
		Baseline	Advanced			Baseline	Advanced			
Platinum	6 %	3.09E-07	1.17E-08	Polyphenylene sulfide (PPS)	21 %	4.76E-05	4.28E-06	Nickel	9 %	4.92E-05
Vulcan XC-72 (Carbon Black)	9 %	4.63E-07	1.75E-08	Polysulfone (PSF)	14 %	3.17E-05	2.86E-06	Aluminum	9 %	4.92E-05
Nafion DE-521 solution	72 %	1.85E-07	1.40E-07	Zirconium dioxide (ZrO₂)	64 %	1.43E-04	1.29E-05	NaOH	82 %	1.97E-04
Deionized water	6.5 %	3.35E-07	1.27E-08							
Methanol	6.5 %	3.35E-07	1.27E-08							

Table 6

Assessed impact categories and associated units.

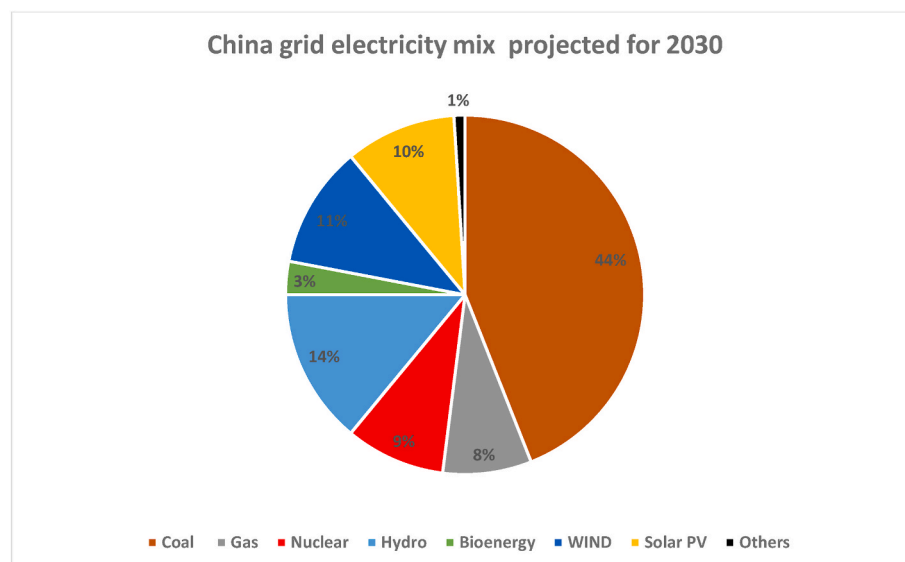
Assessed impact categories	Units
Climate change	kg CO _{2eq}
Photochemical ozone formation	kg NMVOC _{eq}
Acidification	mol H _{eq} ⁺
Human toxicity: cancer	CTUh
Human toxicity: non-cancer	CTUh
Eutrophication: freshwater	kg P _{eq}
Eutrophication: marine	kg N _{eq}
Eutrophication: terrestrial	mol N _{eq}
Resource use, Fossil	MJ
Resource use, Mineral & Metals	kg Sb _{eq}

carbon capture and storage (CCS) and H₂ DRI (Direct Reduction Iron) [29]. Therefore, GHG emissions from the iron and steel industry are expected to decrease by 2030. However, the ecoinvent database does not have data on less carbon-intensive steel production routes other than EAF. Steel products used in the advanced design like low alloy or carbon steel require pig iron and therefore cannot be manufactured via EAF. Therefore, to account for low carbon-intensive steel production in the advanced designs, we increased the share of scrap to 20 % in the blast furnace which is the maximum limit of scrap that can be added. The resulting GHG intensity is 1.42 tCO₂/tcs.

3. Results

Fig. 5 shows the contribution of the electrolyser systems' main components (stacks, BoP & PE, offshore wind and Dutch grid electricity) to the assessed impact categories for both AE and PEM. The absolute value for the results can be found in the supplementary excel file. For the baseline design, we can see that there is no clear winner. PEM and AE score comparable in the majority of the ten assessed impact categories. The impact categories in which AE scores substantially better are marine and terrestrial Eutrophication and Resource use, minerals & metals. In the impact categories Acidification and Human Toxicity (cancer) PEM scores substantially better. For the advanced designs we see a clear reduction (in comparison to the baseline designs) in impact in all categories for both AE and PEM due to improvements in stack design. When comparing the advanced AE with the PEM design, they both show similar contributions in all impact categories thus showing that improvements in both technologies does not lead to one technology outperforming the other in respect to environmental impact. For both technologies, baseline and advanced design, the electricity-generating source accounts for most of the impact followed by the stacks. The BoP and PE show the lowest contribution to the total impact.

Fig. 5 also compares the environmental impact of electrolysers systems with fossil based (natural gas) hydrogen production technologies namely Steam Methane Reforming (SMR) termed as grey hydrogen and SMR with Carbon Capture and Sequestration (CCS) termed as blue hydrogen. We compare our results with two capture rates: 56 % and 90

**Fig. 4.** 2030 projected grid electricity mix of China according to IEA's Stated Policy Scenario: [27,28].

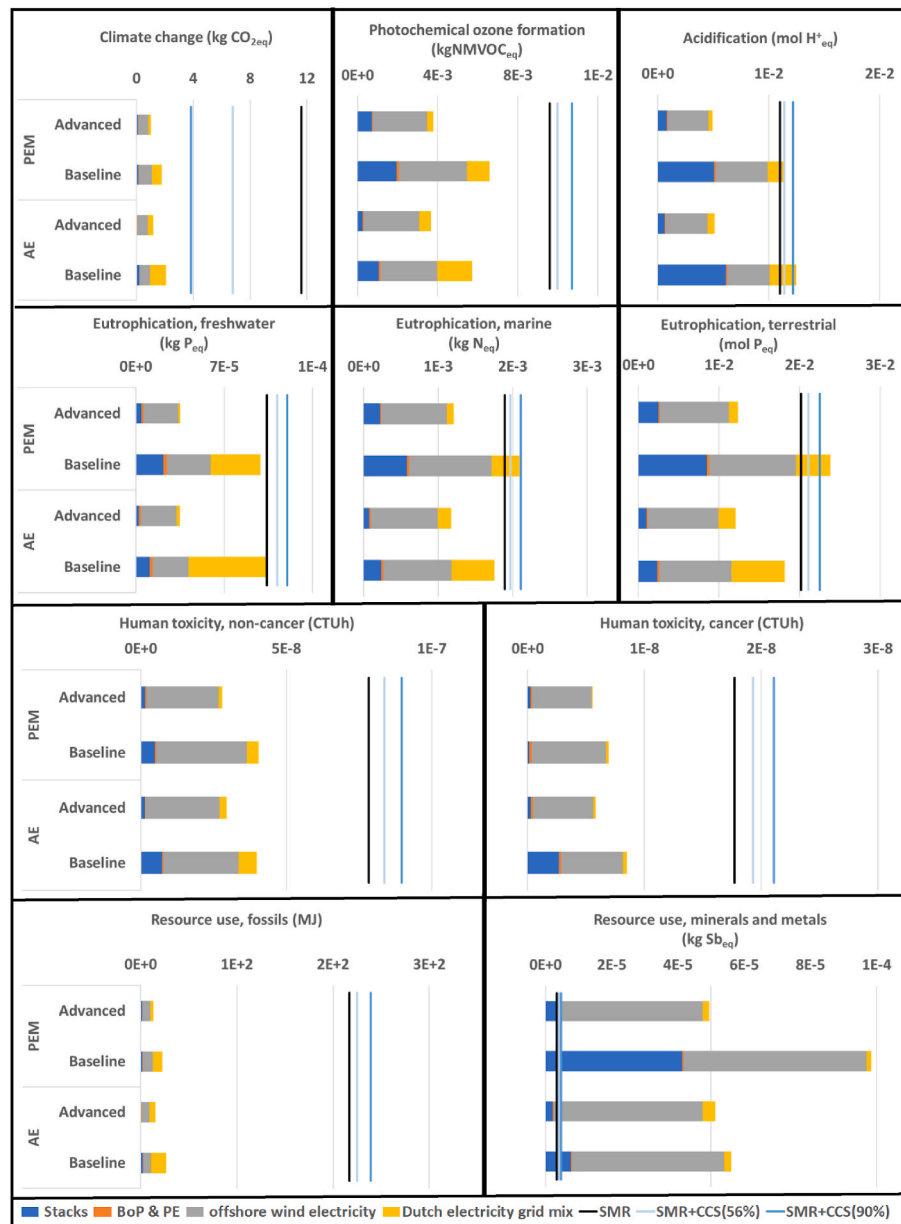


Fig. 5. Cradle to gate contribution of alkaline and PEM systems to the ten assessed impact categories (per kg H₂). Note: see supplementary excel file for absolute values.

%. The analysis on grey and blue hydrogen is based on the work from Hermesmann & Müller [30]. The scope of their study includes cradle-to-gate and the hydrogen production facilities are assumed to be in Germany. The electricity source is assumed to come from offshore wind which they define as the best-case scenario. Therefore, the results from Hermesmann & Müller [30] can best be compared with the advanced electrolyser designs. The advanced design electrolyser systems exhibit lower impacts in nine out of the ten categories when compared to grey and blue hydrogen. In terms of Climate Change, SMR with and without CCS contributes 2 to 6 times more impact than electrolyzers due to emissions from natural gas extraction and the associated SMR processes. The use of natural gas as a fuel input is the primary reason for the high impact of blue and grey hydrogen on Resource use (fossil).

SMR with CCS shows higher impact than grey hydrogen in all categories except Climate Change. This is attributed to the additional environmental impacts associated with materials required for building CCS technology, the transportation of CO₂ to sequestration sites, the use of chemicals like methyl diethanolamine and monoethanolamine for

adsorption and the increased requirement of natural gas resulting from lower efficiency [30]. On the other hand, electrolyzers demonstrate a significantly higher impact than SMR with/without CCS in the category of Resource use (minerals and metals) due to the reliance on rare earth metals in the stack and the use of electricity from dedicated offshore wind farms. The environmental impacts associated with offshore wind is lower in grey and blue hydrogen than green hydrogen due to the lower demand (factor 2) of electricity required to produce 1 kg H₂.

3.1. Electricity

Fig. 5 illustrates that for the baseline design, the electricity generation in the AE system has a higher impact than the PEM system in the categories Climate change, Eutrophication: freshwater and terrestrial, and Resource use: fossil. The main cause of this impact is the use of the Dutch grid electricity, which has a higher impact on the baseline AE design than the PEM design due to the higher minimum load required for the former (15 % vs. 10 %).

The Dutch electricity grid mix has a significant impact on various environmental categories. Hard coal is the largest contributor, causing significant impacts on Climate change and Eutrophication in freshwater, terrestrial, and marine ecosystems. Natural gas-based electricity production is the second-highest contributor to Climate change, while coal and lignite mining spoil mainly impacts Eutrophication in freshwater. Coal production also has significant impacts on Human toxicity (non-cancer) and Resource use (fossil).

The infrastructure of power plants and offshore wind, particularly the coking process and slag treatment, contributes to Human toxicity (cancer). The mining of copper required for power plant generators is the primary contributor to Resource use (minerals and metals). Therefore, when comparing baseline designs, the PEM system has higher impacts on Human toxicity (cancer and non-cancer) and Resource use (minerals and metals) than the AE system due to higher electrical input requirements.

The electricity mix used in wind turbine component manufacturing (especially hard coal) are the main causes for Acidification and Photochemical ozone formation. Both AE and PEM systems show similar contributions because AE systems rely more on grid electricity, while PEM systems utilize more offshore wind electricity. In terms of advanced design, the AE system has a higher impact than the PEM system across all impact categories. This is partly due to the AE system's higher minimum load requirement. However, the advanced PEM design, with improved stack efficiency, requires less electrical input from offshore wind.

Compared to the baseline case, the advanced AE system generally shows a reduction in impact in most categories, except Resource use (minerals and metals). This reduction is attributed to the expected increase in renewable energy sources in the Dutch electricity grid mix by 2030. The advanced PEM design demonstrates a reduction in impact across all categories due to the improved stack efficiency. This improvement outweighs the increase in impact related to Resource use caused by the increased share of renewable energy in the Dutch electricity grid mix.

In summary, the advanced AE system has a higher impact compared to the PEM system, but the advanced designs show reductions in impact compared to the baseline. The increase in renewable energy sources in the grid mix contributes to these improvements, although copper extraction for wind turbines and PV panels remains a significant factor in the overall impact. The advanced PEM design's improved stack efficiency leads to reductions in impact across all categories.

3.2. Balance of Plant (BoP) & power electronics (PE)

The impact of BoP and PE components on an electrolyser system is minimal across all assessed impact categories, as shown in Fig. 5. Both a GW AE and PEM system (baseline and advanced) require the same amount of materials for BoP and PE components. However, the lower efficiency of the baseline PEM design results in higher impact than the baseline AE system across all categories.

Figure A2 (see appendix) illustrates that silicon, used in transformers in power electronics, is the main contributor to most impact categories, accounting for approximately 80 % on average in every category except Human toxicity: cancer and Resource use, Minerals & Metals. The production process for metallurgical grade silicon and high voltage electricity from coal and lignite required to process it into electronic grade silicon are the primary sources of impact for impact categories Climate Change, Photochemical Ozone Formation, Acidification, Eutrophication: freshwater, marine and terrestrial, and Resource use: fossil. For Human toxicity: non cancer, the production process for hydrochloric acid (a feedstock in metallurgical grade silicon manufacturing) coupled with electricity production from hard coal and lignite are major sources of impact. For Human toxicity: cancer, the production of PVC via injection molding, chromium and low alloy steel, specifically ferrochromium production (chromium steel 18/8), and treatment of electric arc

furnace slag (chromium and low alloy steel) contribute significantly to the impact. Most impacts related to Resource use: minerals and metals can be attributed to the mining of copper and chromite ore for chromium steel 18/8 production.

Compared to the baseline design, the advanced designs show a reduction in most impact categories, except for the advanced AE system in the impact category Resource use: minerals and metals. The larger reduction is observed in the advanced PEM system due to a ~17 % improvement in efficiency, and to a lesser extent in the advanced AE system with a minimal (~1 %) improvement in efficiency. Moreover, the assumed increase in scrap content in future steel production, coupled with the projected Chinese 2030 electricity grid mix (44 % coal, 38 % renewables) required for manufacturing electronic grade silicon, reduces the impact of the advanced electrolyser systems. The advanced PEM design has slightly less impact than the advanced AE design due to its marginally higher efficiency (69 % vs. 68 %).

However, the advanced AE design has a higher impact than the baseline design in the impact category Resource use: minerals and metals due to the increase in the share of solar and wind energy in the Chinese 2030 electricity grid mix used for electronic grade silicon manufacturing. As mentioned in section 3.1, an increase in wind farms leads to an increase in copper mining activity, outweighing the marginal improvement in efficiency.

3.3. Stacks

The impact of both baseline and advanced AE and PEM stacks on various assessed impact categories is shown in Fig. 6. The absolute value for the results can be found in the supplementary excel file. The baseline design indicates that the AE stacks have a higher impact than the PEM stacks for certain impact categories such as Climate change, Acidification, Human toxicity: cancer and non-cancer, and Resource use: fossil. This can largely be attributed to the bipolar plate and electrodes of the baseline AE stack.

The production process associated with low alloy steel, particularly hard coal mining and pig iron production, are the major contributors to Climate change and Resource use: fossil for the bipolar plate and electrodes. Furthermore, the treatment of slag from the electric arc furnace has a significant impact on Human toxicity: cancer.

In addition, the nickel content in the bipolar plate and electrodes is the primary contributor to the impact categories Acidification and Human toxicity: non-cancer. This can be attributed to the mining, smelting, and refining operations for nickel and its waste treatment, especially for Human toxicity non-cancer. The steel and nickel content in the bipolar plate is higher than in the electrodes, resulting in a higher impact.

Overall, these findings suggest that improvements in the production process for low alloy steel and nickel, as well as better waste treatment methods, could significantly reduce the environmental impact of the AE stacks.

The baseline PEM stack has a greater impact than the AE stacks for the impact categories, Photochemical Ozone Formation, Eutrophication: freshwater, marine, and terrestrial and Resource use: minerals and metals. The electrodes are a significant source of impact for Photochemical Ozone Formation and Eutrophication: marine and terrestrial. The bipolar plate and PTL anode show similar contributions to Eutrophication: freshwater, but their impact dominates the impact category: Resource use: minerals and metals.

Impacts from electrode production can be mainly attributed to the rock blasting process used to mine platinum and iridium, which releases nitrogen oxide into the atmosphere. Additionally, the electricity required for processing these metals also contributes to the environmental impacts, with Chinese hard coal being the primary source of energy for electricity production, accounting for 59 % of the current grid mix. The spoils from hard coal mining were identified as the major contributor to Eutrophication in freshwater in relation to the electrodes.

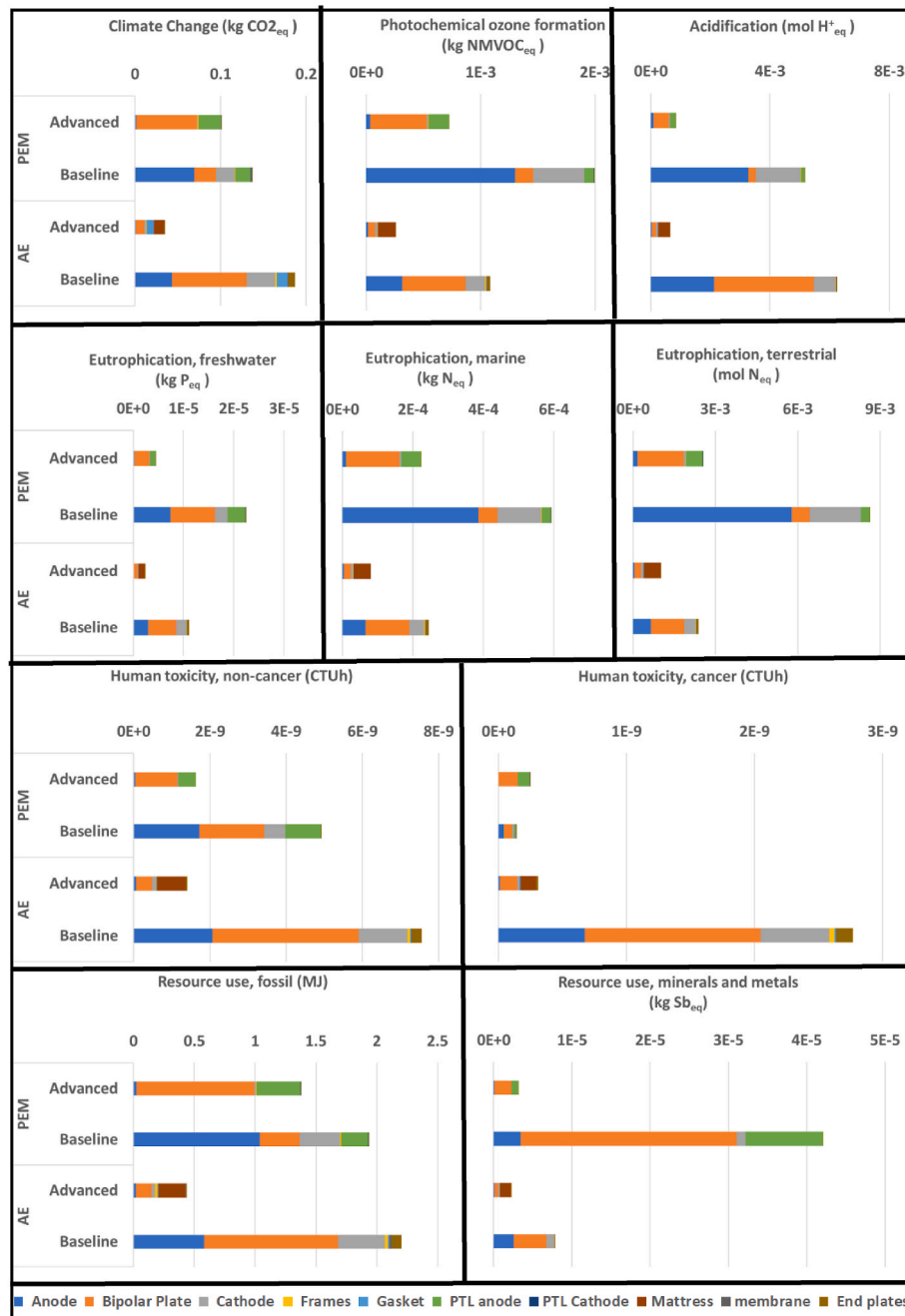


Fig. 6. Breakdown of stack components contribution to the ten assessed impact categories for baseline and advanced AE and PEM stacks (per kg H_2). Note: see supplementary excel file for absolute values.

In the case of the bipolar plates and PTL anode, most of the impact is related to the gold content in these components, mainly due to the treatment of sulfidic tailings from gold mine operations. The base plate materials, chromium 18/8 steel, and titanium powder, have a minimal impact on the environment. For Resource use: minerals and metals, the gold content in the bipolar plates and PTL anode were identified as the main source of impact, associated with the higher extraction rate per reserves in the earth's crust. As mentioned in the methodology section, the impact of iridium on Resource use, minerals and metals is not accounted for because the PEF method implemented in Simapro does not have a characterization factor for iridium.

In relation to the advanced design both AE and PEM stack show a significant reduction in impact in most categories except in the case of Human toxicity: cancer for the advanced PEM stack. A major reason for

the reduction in impact is due to the increase in current density for AE (factor 5.3 increase) and PEM (factor 1.75 increase). An increase in current density leads to an increase in power density per cell and stack. Therefore, fewer stacks are required to achieve the rated power of the system, thereby reducing material usage.

Furthermore, the carbon steel (low alloy steel) in the electrodes of the baseline AE stacks are replaced with pure nickel wire meshes. This is another reason for the reduction seen in the advanced AE stacks since the low alloy steel has a major contribution in most impact categories. Due to the replacement of the nickel-plated carbon steel electrodes with pure nickel wire meshes and the addition of a nine-layers nickel mattress, the nickel content in the advanced design increases. Nickel shows a major contribution to Acidification and Human toxicity: non-cancer as seen in the baseline stack but the increase in current density

outweighs the additional nickel in the advanced AE stack. Therefore, the advanced AE stack shows minimal impact on Acidification and Human toxicity: non-cancer.

The bipolar plate and the nickel mattress of the advanced AE stack are the main contributors to Human toxicity: cancer. The low alloy steel base plate accounts for ~70 % of the contribution from the bipolar plate while the nickel coating accounts for ~23 % of the contribution. Similar to the baseline AE stack, the treatment of slag from the electric arc furnace is the major source of impact. In relation to the nickel, emissions from cobalt production (co-product of nickel and copper production) are the main source of impact.

For the other impact categories too, the bipolar plate and the nickel mattress account for most of the impact. Similar to the baseline design, low alloy steel making and nickel production process are the main contributor to Climate change, Resource use: fossil and Acidification, Human toxicity: non-cancer respectively. But the impact of low alloy steel making is reduced when compared to the baseline design due to the assumed increase in scrap content (from 15 % to 25 %) in the blast furnace. The impact associated with electricity required for nickel production is reduced due to the reduction in coal use in the projected 2030 Chinese grid electricity mix.

In addition to the increase in current density, the advanced PEM stacks also experience a reduction in platinum and iridium loading by a factor of 15 and 20, respectively. This further reduces the impact the electrodes have on all impact categories. When comparing the advanced AE and PEM stack, the PEM stack has a higher impact in most impact categories. For the category Human toxicity: cancer, the advanced AE stack scores slightly higher than the advanced PEM stack. For the advanced PEM stack, the electrodes show minimal impact due to the factor 15 and 20 reduction in platinum and iridium loading, respectively. Most of the impact is associated with the bipolar plate and the PTL anode as seen in Fig. 6. In the advanced design the gold coating in the bipolar plate and the PTL anode is replaced by niobium which contributes to most of the impact. For impact categories Climate change and Resource use: fossil, the electricity and diesel (fuel input for machines) required during the production process of niobium are the main source of impact. For Resource use: fossil the main impact can be attributed to the mining of hard coal and petroleum to produce diesel. Similarly, for impact categories Photochemical ozone formation, Acidification and Eutrophication: marine and terrestrial, the diesel burned in machines are the main source of impact. For Eutrophication: freshwater, most of the impact can be attributed to the treatment of spoils from hard coal mining. Copper is a required material input for mine infrastructure. Activities associated with the mining of copper are the main contributors to the impact categories Resource use: minerals and metals and Human toxicity: non-cancer.

Human toxicity: cancer is the only impact category where the PEM advanced stack has a higher impact than the baseline stack. Similar to other impact categories, the bipolar plate and PTL anode contribute to most of the impact, though a considerable share of the impact from the two components can be attributed to the stainless steel base plate. A major source of the impact in stainless steel manufacturing is the ferrochromium production required for chromium steel 18/8 (stainless steel) manufacturing. In relation to niobium's impact, the pig ironizing process to produce magnesium (required in the production of tantalum) is the major source of impact for Human toxicity: cancer. The impact from stainless steel accounts for 18 % and 56 % for the bipolar plate and PTL anode, respectively. This is due to the fact that the stainless steel content in the PTL anode is higher by a factor 2 than the bipolar plate. Stainless steel production has a significant impact on Human toxicity: cancer and can therefore explain the advanced PEM stack showing a higher impact on Human toxicity: cancer since the advanced stack has additional stainless steel because the titanium base plate in the baseline PEM PTL anode is replaced with 3 mm of stainless steel base plate [19].

4. Discussion

4.1. Comparison of results with literature

To validate our results, we compare the GWP results of the baseline AE and PEM design with results from literature. Literature prior to 2012 was not considered for comparison because the AE stack designs were outdated and the PEM stacks were only available at a small scale (<1 MW). Furthermore, studies that included the use phase and used alternate functional units were not considered for comparison. Fig. 7 shows that previous literature studies indicate that the electricity source has a major impact on GWP similar to our results. The differences in the GWP can be associated with the electricity mix assumed in the studies and the use of back up grid power in this study.

Electricity from wind has the least impact on Climate change [2,5,7,31] with offshore wind having a lower impact than onshore wind due to the higher capacity factor [7]. This is followed by PV [2,5,6,8] and co-generation gas [32] with grid electricity having the highest impact on climate change. It is important to note that Bareiß et al. [7], and Gerloff [8] assumes an electricity mix in which PV accounts for more than 60 % of the mix. Furthermore, emission factors related to renewable technologies are location specific as can be seen in the difference in emission factor for onshore wind between Gerloff [8] and Bareiß et al. [7], Mehmeti et al. [8] and Zhao & Pederson [32]. The study conducted by Gerloff [8] and Bareiß et al. [9] were based on German wind farms while Mehmeti et al. [5] and Zhao & Pederson [32] are based on global average and the Orkney Island in Scotland respectively. The emission factors vary from 0.011 to 0.035 kgCO₂/kWh with Orkney Island showing the lowest emission factor while the global average value from Mehmeti et al. [5] having the highest emission factor. Aside from the electricity sources, an important factor to consider when indicating the difference in GWP between the different studies, are the system efficiencies of the electrolyzers. For AE they vary between 52 and 60 kWh/kgH₂ and PEM around 55 kWh/kgH₂. Therefore, if we compare the baseline AE and PEM systems in this study with the other studies, assuming the same source of electricity within the same geographical scope, the baseline AE system in this study would have less impact on climate change due to the AE system having a higher efficiency (49 kWh/kgH₂). The baseline PEM system in this study would have a higher impact on climate change than the other studies due to its lower efficiency (58 kWh/kgH₂).

The baseline AE and PEM system (stacks + BoP & PE) have a GWP of 0.21 and 0.17 kgCO_{2eq}/kgH₂ respectively. This falls within the range of 0.14–0.25 kgCO_{2eq}/kgH₂ for AE and 0.07–0.4 kgCO_{2eq}/kgH₂ for PEM reported by the studies mentioned in Fig. 7. The variation in GWP for the AE and PEM stacks can be attributed to the hourly H₂ production rate of the stacks. Over time, with investment in R&D and technological progress, stacks can operate at higher current and power densities rendering a higher hydrogen production rate. In some cases, like in Mann & Spath [22], Zhao & Pederson [32] and Mehmeti et al. [5] the stacks are treated as black boxes. Therefore, due to lack of a detailed inventory, it is difficult to pinpoint the causes that lead to differences in GPW. Gerloff [8] extrapolates stack specifications from other sources using scaling factors to scale the stack to 1 MW. Bareiß et al. [7] have a detailed inventory for stacks. In their analysis they do not account for bipolar plates and endplates in the AE stack design while for PEM stacks, they assume titanium bipolar plates while the baseline PEM stack in this study assumes 316L stainless steel bipolar plates coated with gold. Furthermore, they do not account for the PTL anode and cathode.

4.2. Environmental performance of green with grey and blue hydrogen

When comparing the advanced design green hydrogen technologies with grey hydrogen (SMR) and blue hydrogen (SMR with CCS), the latter two show a substantially higher contribution to all impact categories except Resource use, minerals and metals due to the use of rare earth

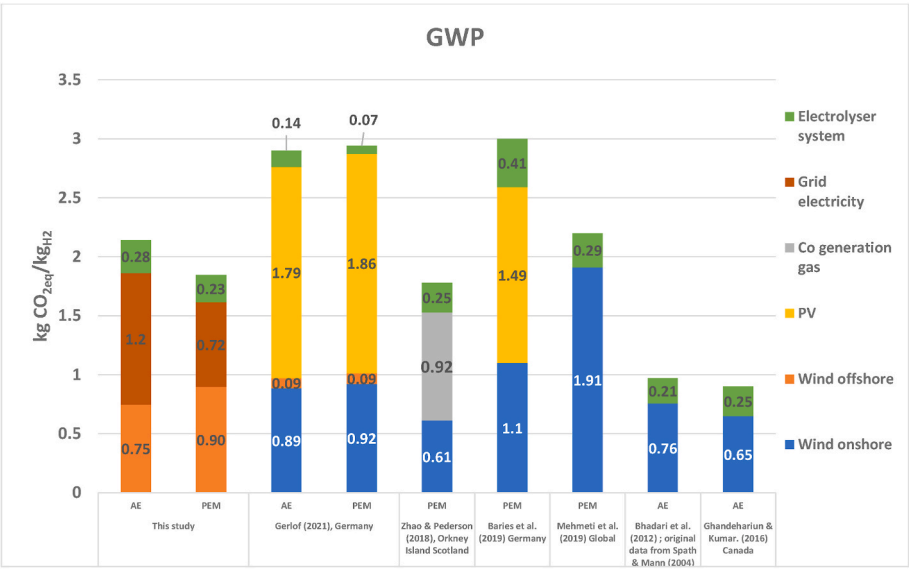


Fig. 7. GWP comparison of AE and PEM systems with other studies.

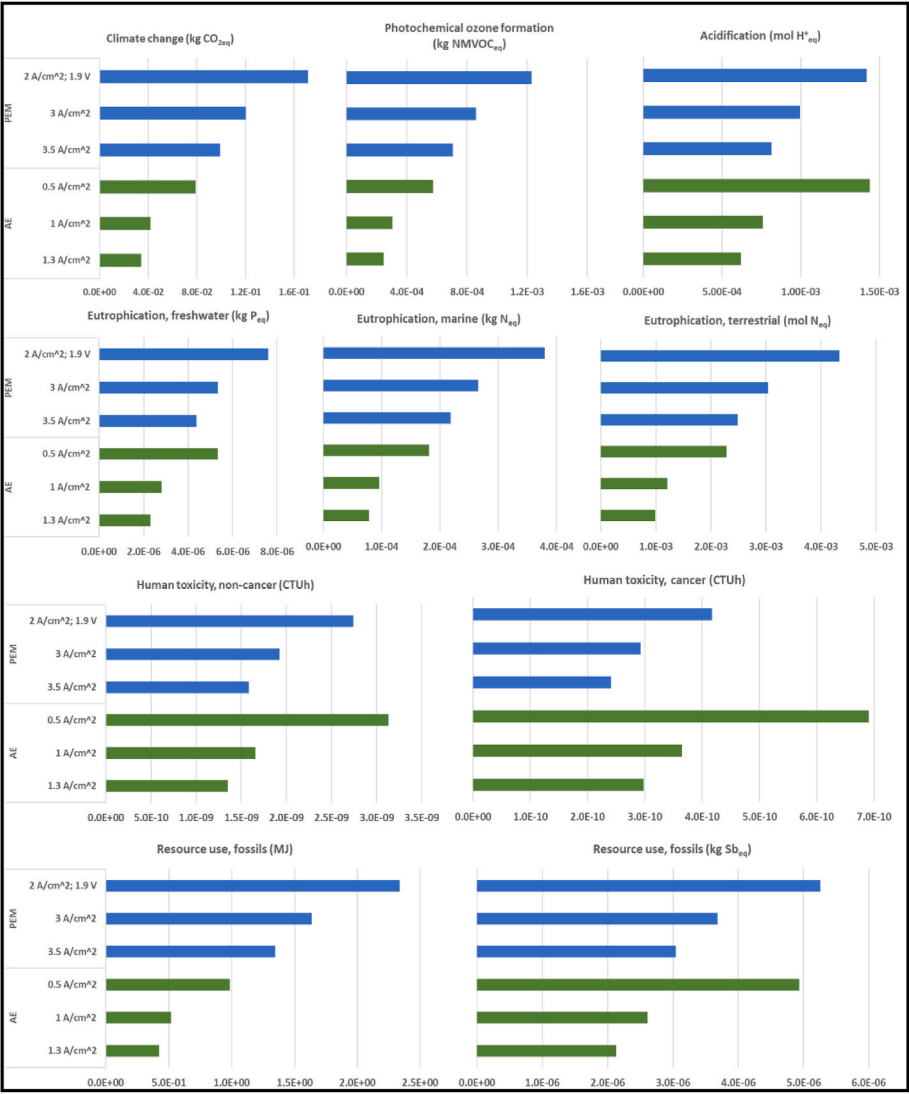


Fig. 8. Effect of varying current density in the advanced AE and PEM designs on assessed impact categories. Target current densities are 1.3 A/cm² (AE) and 3.5 A/cm² (PEM).

metals in the electrolyser stacks. In the study conducted by Hermesmann & Müller [30], the electricity demand for the SMR (grey and blue hydrogen) plants is assumed to be supplied by dedicated offshore wind farms. But currently the electricity is supplied by the German grid electricity mix which will increase the impact of grey and blue hydrogen on the assessed impact categories. Furthermore, Hermesmann & Müller [30] use the E.F 2.0 method, therefore characterization factors might differ from the E.F 3.0. The comparison of the environmental impact between green, blue and grey hydrogen were done at a midpoint level. Therefore, it would be interesting to compare the three technologies at the end point level to assess if one technology outperforms the other in terms of the three broad impact categories: Human Health, Natural Environment and Nature.

In the hydrogen sector, blue hydrogen is seen as a transition from grey to green hydrogen. Except for the impact category Climate Change, blue hydrogen scores worse than grey hydrogen in all other categories. Therefore, from an environmental perspective, transitioning from grey to green hydrogen through blue hydrogen only makes sense if GHG emission reduction are the sole focus.

4.3. Impact of current density on environmental performance

The expected improvements in current density for the advanced designs were evaluated at a mid-Technology Readiness Level (TRL). A sensitivity analysis was conducted to assess the impact of varying current densities on different impact categories, as shown in Fig. 8. The current densities lower than 1.3 A/cm² (AE) and 3.5 A/cm² (PEM) align with the roadmap towards the 2030 targets set by the U.S. Department of Energy (DOE). Changes in current density have significant implications for the contributions of electrolyser systems to the assessed impact categories. Reducing the current density by a factor of 1.2 can lead to an approximate 0.8-fold increase in impact across all categories. The current density plays a crucial role in determining the efficiency of the stack and system. Lowering the current density adversely affects stack and system efficiencies, requiring more stacks to achieve the desired power output. Consequently, this necessitates more materials and results in higher electrical input from the electricity source, which is the primary contributor to the impact in all categories.

4.4. Impact of electricity source and flexibility on environmental performance

In our LCA study, we assume the electrolysers operate using electricity from 1 to 3 MW offshore wind turbines due to lack of data availability on larger offshore wind turbines in the ecoinvent database. But the average offshore wind turbine size within the coming decade is expected by around 3–4 MW [33] which larger than the assumed capacity in this study. This transition to larger offshore wind turbines enables higher capacity factor and therefore aids in reducing the impact offshore wind electricity generation has on the assessed impact categories.

The baseline and advanced AE systems require a 15 % minimal load that is supplied by the Dutch grid electricity. Achieving a lower minimal load of 10 % as demonstrated by de Groot et al [17] reduces the environmental impact of AE system. Therefore, reducing the electricity use from the grid or developing clean and efficient storage technologies could render the advanced AE systems to perform better than the PEM systems in the assessed impact categories.

4.5. Impact of material selection and production methods on environmental performance

A major source of impact for the advanced AE stacks stems from carbon steel (low alloy steel) in the bipolar plates and the nine-layers nickel mattress. For the advanced designs we assume the maximum share of scrap (20 %) that can be fed into a blast furnace to produce low

alloy steel. But according to IEA [28] by 2030, alternate steel production routes like BF-BOF with CCUS (Carbon Capture Usage and Storage) and H₂ DRI to manufacture steel products that require pig iron like low alloy steel will be deployed globally. The BF-BOF with CCUS route has the potential to reduce CO₂ emissions by 40%–76 % (depending on the capture technology) while the H₂ DRI can reduce CO₂ emissions by 96–98 % (assuming green hydrogen) [34]. Furthermore, steel constitutes around 70 % of an offshore wind turbine [34]. Incorporating these alternate steel production routes into our environmental assessment of the advanced designs electrolyser systems can further reduce the negative environmental impacts.

The advanced AE stack employs a 9-layer nickel mattress wedged between the electrodes and the bipolar plates to reduce stress on the electrodes and membrane due to pressure applied by the end plates and to push the electrodes against the membrane to facilitate a “zero-gap” design. Based on the patent [35], the mattress layers can vary between 6 and 12 layers depending on the combined thickness of the electrodes and membrane. The thickness of the mattress needs to be proportional to the combined thickness of the electrodes and membrane. Therefore, reduction in mattress layers can be achieved by reducing the thickness of the membrane and the electrodes which could lead to lower ohmic resistance but could come at the cost of gas crossover issues and higher degradation rate. The use of recombination catalyst can help reduce the degradation rate but could lead to associated environmental impacts. Therefore, it is recommended to optimize the system efficiency while minimizing environmental impact.

For the baseline and advanced PEM stacks, we use rhodium as a proxy for iridium in our LCA study due to the lack of data availability in the ecoinvent database. This could lead to discrepancies in the true representation of the environmental impact associated with the iridium production chain. Added to that, the E.F 3.0 method does not have a characterization factor associated with iridium for Resource use, minerals & metals, rendering us unable to assess the impact iridium has on mineral scarcity. Similarly, we use tantalum as a proxy for niobium for the advanced PEM design stack. Tantalum is the main ore from which niobium is extracted. Therefore, extra processing steps would be expected and could potentially lead to a higher environmental impact. Furthermore, characterization factors reflect scarcity considerations of some years ago, while the demand from these materials is expected to increase in the future, along with their scarcity. So probably, the scarcity issue is underestimated in this study and will become even more of a problem than what is reflected in this study. So, this is an important hotspot that should be considered in the advancement of this technology.

The PEM membrane, binding agents in the electrodes, seals and gaskets in AE stacks contain fluoropolymers which are considered as a PFAS subtype. The EU Chemicals Strategy for sustainability plans for banning and phasing out PFAS (except where essential for society) [36]. Henry et al. [37] and Korzeniowski et al. [38] demonstrated that vast majority of fluoropolymers meet the OECD criteria of ‘polymers of low concern’ since they do not dissolve or contaminate water. But the proposal to ban PFAS in the EU does not make this distinction nor do they define which sectors are considered essential [36]. Therefore, there is a possibility that PFAS in the hydrogen sector could be banned. This could lead to significant implications on upscaling hydrogen production volume as a reliable alternative or substitute with similar characteristics and performance of fluoropolymers do not exist and are not expected to be developed for commercial scale within the next decade.

Materials used for the advanced PEM design stack are associated with a low TRL (3–7) especially the factor 15 and 20 reduction in platinum and iridium loading. Therefore, to account for the plausibility of achieving this reduction in catalyst loading within the next decade, we perform a sensitivity analysis on the catalyst loading. We assume the same loading as the baseline design for the advanced PEM design stack and we term it as a conservative scenario. The conservative scenario shows a substantial increase in all assessed impact categories compared

to the advanced PEM stack due to the increased loading of platinum and iridium (Fig. 9).

4.6. End of life uncertainty and by-product allocation impact

In our LCA, we do not account for end-of-life stages due to the uncertainty in the recycling technologies for platinum, iridium, nickel and niobium. Valente et al. [13] assess mature (hydrometallurgical, pyro-hydrometallurgical, hydrothermal) and novel (acid process, selective electrochemical dissolution, transient dissolution) technologies to recover noble and non-noble metals. Recycling of the PGM using the

above-mentioned methods is essentially nonexistent due to design constraints and the thermodynamics of separation [39]. Most of these technologies are associated with high cost and energy requirements, use of hazardous reactants and release highly toxic and corrosive hydrofluoric acid. Furthermore, the novel technologies have a low TRL and are not expected to become commercial within the coming decade. On the other hand, other stack components that are not part of the MEA like the PTL and bipolar plates can be separated during the disassembly process and recycled via the conventional melting process. These components are coated with thin fine layers of gold or niobium. Removal of metal coatings from plastic surfaces or non-metal coatings from metal surfaces

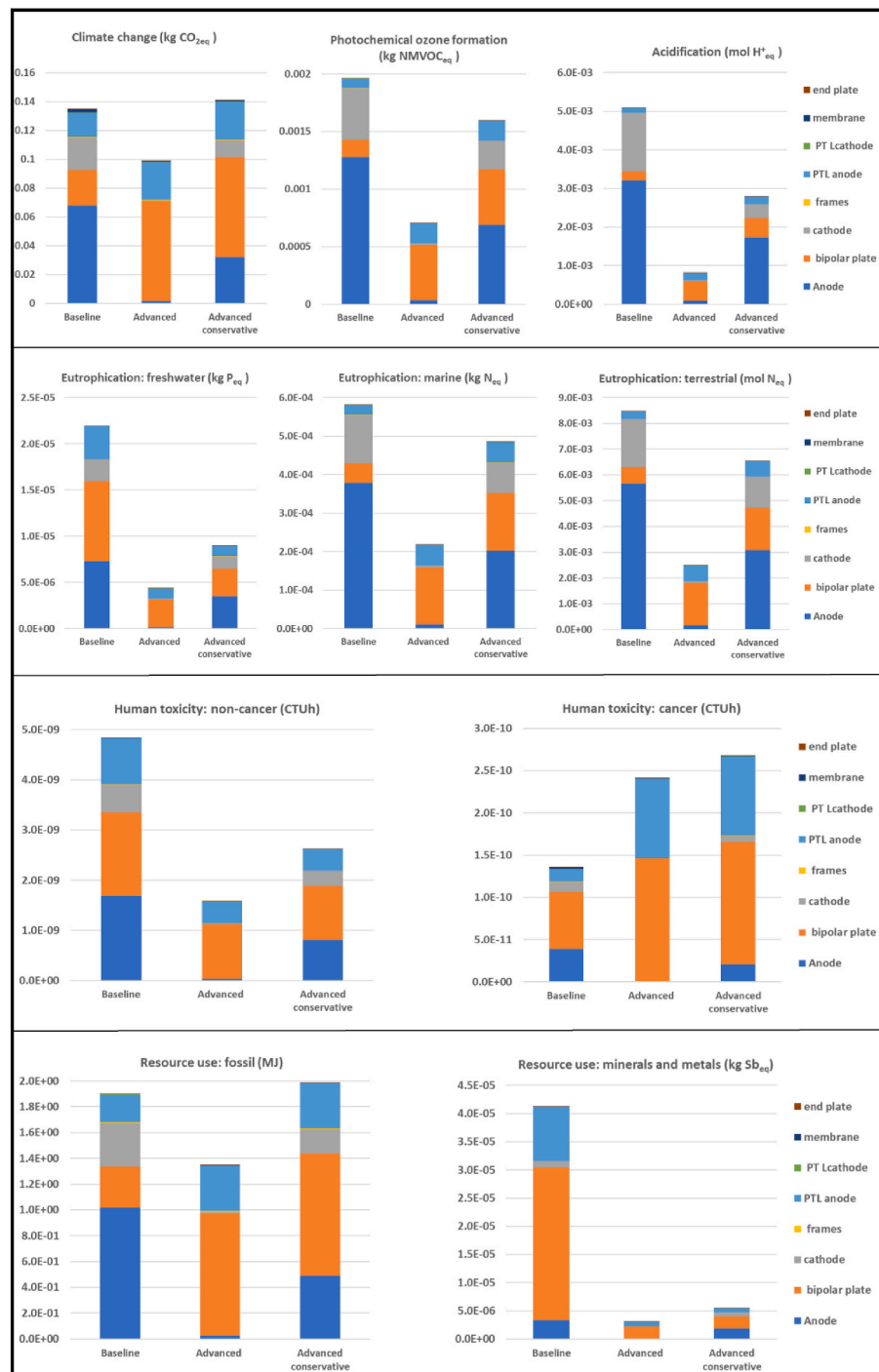


Fig. 9. Comparison of contribution of the conservative scenario with the baseline and advanced PEM stack to the assessed impact categories. Baseline and advanced conservative design Pt and Ir loading: 1.75 mg/cm² and 2 mg/cm², respectively.

exist, but technologies to remove metal coating from metal surfaces have not yet been technically proven. Laser ablation can be employed to possibly remove metal coatings from metal surfaces, but the coating layer is fully vaporized and therefore cannot be recovered from recycling [40].

The process of electrolysis produces hydrogen and oxygen. On a mass basis this ratio is 1:8. As mentioned in section 2.1, the current practice is to vent out the oxygen since it is not used by industry. In the future, if the uptake for oxygen by industry exists, then the system boundary (Fig. 1) needs to be expanded to include oxygen as a byproduct. The production of oxygen as a byproduct could be included in the LCA model by applying mass allocation but most of the impacts will be allocated to oxygen. Economic allocation would result in most of the impacts being allocated to hydrogen production since the average price of oxygen and green hydrogen is 0.016 €/kgO₂ and 5.45 €/kgH₂ [2] respectively. Both mass and economic allocation will skew the results. Alternatively: 1) looking at future demand for each (oxygen and hydrogen) from a holistic energy systems transition perspective (and as such how to distribute the upstream burden); or 2) allocating the environmental impact based on the volumetric output ratio of 2:1 could be more suitable. Ultimately choosing a particular allocation method could have a major impact on the environmental performance of green hydrogen.

5. Conclusion

We conducted a comprehensive environmental assessment of the current (baseline) AE and PEM electrolyser systems, and evaluated the potential reduction in environmental impact with advanced stacks that are expected to be commercially available within the next decade. Our analysis revealed that the primary contributors to the assessed impact categories are the electricity source and the stacks, while the BoP and PE have minimal impact. Notably, the advanced AE and PEM systems exhibited similar impacts.

In our comparison of green (advanced design), grey, and blue hydrogen at a midpoint level, we found that green hydrogen outperforms in the assessed impact categories, except Resource use, minerals and metals due to the use of rare earth metals in the electrolyser stacks. Blue hydrogen outperforms grey hydrogen only in one category Climate change. Therefore, from an environmental perspective, it might be better to directly transition from grey to green hydrogen by diverting investments from blue hydrogen into scaling up green hydrogen.

Regarding electricity use, the AE systems displayed higher impacts due to slightly lower efficiency (advanced design case) and their reliance on grid electricity to fulfill the higher minimal load requirement. To address this, it is crucial to focus on reducing the minimal load requirements for AE systems, thereby aligning their contributions with those of PEM systems in the assessed impact categories.

While most impacts associated with electricity use can be attributed to the grid electricity, the impact categories of Human toxicity and Resource use, minerals and metals were found to be connected with offshore wind, specifically copper mining and the treatment of copper slag. Implementing strategies that incorporate sustainable mining practices and improved waste treatment methods could effectively reduce the burden on Human toxicity and Resource use, minerals and metals arising from wind turbine manufacturing.

The primary cause of the observed impact reduction between the baseline and advanced designs is the increase in current density, as it directly influences the efficiency of stacks and systems. However, uncertainties persist regarding the achievability of such high current densities at the corresponding voltages (as shown in Table 1). Thus, it is essential to prioritize research and investment towards achieving the ambitious current density targets set for 2030 while concurrently reducing the use of materials associated with high environmental impacts.

The assessment of material usage in stacks reveals that carbon steel and platinum group metals (PGMs) significantly contribute to

environmental impacts. Since PGMs are rare with limited supply, it is crucial to research alternative materials in lab-scale and incorporate recycling and sustainable waste treatment strategies into electrolyser system designs to minimize environmental consequences until efficient recycling technologies become commercially available.

By addressing these critical areas and implementing appropriate measures such as reducing minimal load requirements, promoting sustainable mining practices, researching alternative materials, and improving waste treatment technologies, we can enhance the environmental performance of electrolyser systems and advance the transition towards a more sustainable energy future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijhydene.2023.10.192>.

References

- [1] IEA. Electrolysers. Paris: IEA; 2022. <https://www.iea.org/reports/electrolysers>. License: CC BY 4.0.
- [2] Bhandari R, Trudewind CA, Zapp P. Life cycle assessment of hydrogen production via electrolysis—a review. *J Clean Prod* 2014;85:151–63.
- [3] Valente A, Iribarren D, Dufour J. Life cycle assessment of hydrogen energy systems: a review of methodological choices. *Int J Life Cycle Assess* 2017;22:346–63. <https://doi.org/10.1007/s11367-016-1156-z>.
- [4] Valente A, Iribarren D, Dufour J. Harmonised life-cycle global warming impact of renewable hydrogen. *J Clean Prod* 2017;149:762–72.
- [5] Mehmehi A, Angelis-Dimakis A, Arampatzis G, McPhail SJ, Ulgiati S. Life cycle assessment and water footprint of hydrogen production methods: from conventional to emerging technologies. *Environments* 2018;5(2):24.
- [6] Kanz O, Bittkau K, Ding K, Rau U, Reinders A. Review and harmonization of the life-cycle global warming impact of PV-powered hydrogen production by electrolysis. *Frontiers in Electronics* 2021;11.
- [7] Bareiß K, de la Rua C, Möckl M, Hamacher T. Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. *Appl Energy* 2019;237:862–72.
- [8] Gerloff N. Comparative Life-Cycle-Assessment analysis of three major water electrolysis technologies while applying various energy scenarios for a greener hydrogen production. *J Energy Storage* 2021;43:102759.
- [9] Zhao G, Kraglund MR, Frandsen HL, Wulff AC, Jensen SH, Chen M, Graves CR. Life cycle assessment of H₂O electrolysis technologies. *Int J Hydrogen Energy* 2020;45(43):23765–81.
- [10] Lotrič A, Sekavčnik M, Kuštrín I, Mori M. Life-cycle assessment of hydrogen technologies with the focus on EU critical raw materials and end-of-life strategies. *Int J Hydrogen Energy* 2021;46(16):10143–60.
- [11] Mori M, Stropnik R, Sekavčnik M, Lotrič A. Criticality and life-cycle assessment of materials used in fuel-cell and hydrogen technologies. *Sustainability* 2021;13(6):3565.
- [12] ISO 14044. Environmental management – life cycle assessment – requirements and guidelines. Geneva, Switzerland: International Organization for Standardization; 2006.
- [13] Valente A, Iribarren D, Dufour J. End of life of fuel cells and hydrogen products: from technologies to strategies. *Int J Hydrogen Energy* 2019;44(38):20965–77.
- [14] Lozanovski A, Schuller O, Faltenbacher M. Guidance document for performing LCA on hydrogen production systems FCH JU. 2011 [Brussels, Belgium].
- [15] Fc Hyguide. Guidance document for performing life cycle assessment (LCA) on fuel cells (FCs) and hydrogen (H₂) technologies. In: A Project Funded by Fuel Cell and Hydrogen e Joint Undertaking. EU; 2011.
- [16] ISPT, Institute for Sustainable Process Technology. Hydrohub GigaWatt scale electrolyser. <https://ispt.eu/projects/hydrohub-gigawatt/>.
- [17] de Groot MT, Kraakman J, Barros RL. Optimal operating parameters for advanced alkaline water electrolysis. *Int J Hydrogen Energy* 2022;47(82):34773–83.

- [18] ISO 22734. Hydrogen generators using water electrolysis-Industrial, commercial, and residential applications. 2019.
- [19] Krishnan S, Koning V, de Groot T, de Groot A, Mendoza P, Junginger M, et al. Present and future cost of alkaline and PEM electrolyser stacks. *Int J Hydrogen Energy* 2023;48(83):32313–30.
- [20] Fuel cells and hydrogen 2 Joint undertaking (FCH JU). Multi-Annual Work Program; 2018.
- [21] TenneT. Monitoring Leveringszekerheid 2022 (2025-2030). 2022. TenneT TSO B.V. Monitoring Leveringszekerheid 2022_12JAN2023.pdf (tennet-drupal.s3.eu-central-1.amazonaws.com).
- [22] Mann M, Spath P. *Life cycle assessment of renewable hydrogen production via wind/electrolysis: Milestone completion report* (No. NREL/MP-560-35404). Golden, CO. (US): National Renewable Energy Lab.; 2004.
- [23] Battelle Memorial Institute. Manufacturing cost analysis of PEM fuel cell systems for 5- and 10-kW backup power applications/DOE contract No. DE-EE0005250. https://www.energy.gov/sites/prod/files/2016/12/f34/fcto_cost_analysis_pem_fc_5-10kw_backup_power_0.pdf; 2016.
- [24] In Lee H, Dung DT, Kim J, Pak JH, Kim SK, Cho HS, Kim CH. The synthesis of a Zirfon-type porous separator with reduced gas crossover for alkaline electrolyzer. *Int J Energy Res* 2020;44(3):1875–85.
- [25] IEA. The role of critical minerals in clean energy transitions. Paris: IEA; 2021. <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transition>. License: CC BY 4.0.
- [26] IEA. China power system transformation. Paris: IEA; 2019. <https://www.iea.org/reports/china-power-system-transformation>. License: CC BY 4.0.
- [27] IEA. An energy sector roadmap to carbon neutrality in China. Paris: IEA; 2021. <https://www.iea.org/reports/an-energy-sector-roadmap-to-carbon-neutrality-in-china>. License: CC BY 4.0.
- [28] IEA. Iron and steel technology roadmap. Paris: IEA; 2020. <https://www.iea.org/reports/iron-and-steel-technology-roadmap>. License: CC BY 4.0.
- [29] Janjua R. Energy use in the steel industry Brussels: world steel association. Available online: https://iea.blob.core.windows.net/assets/imports/events/185/8_Session2_B_WorldSteel_231014.pdf; 2014.
- [30] Hermesmann M, Müller TE. Green, turquoise, blue, or grey? Environmentally friendly hydrogen production in transforming energy systems. *Prog Energy Combust Sci* 2022;90:100996.
- [31] Ghandehariun S, Kumar A. Life cycle assessment of wind-based hydrogen production in Western Canada. *Int J Hydrogen Energy* 2016;41(22):9696–704.
- [32] Zhao G, Pedersen AS. Life cycle assessment of hydrogen production and consumption in an isolated territory. *Procedia CIRP* 2018;69:529–33.
- [33] IEA. Offshore wind outlook 2019. Paris: IEA; 2019. <https://www.iea.org/reports/offshore-wind-outlook-2019>. License: CC BY 4.0.
- [34] Somers J. Technologies to decarbonise the EU steel industry. Luxembourg: EUR 30982 EN, Publications Office of the European Union; 2021. <https://doi.org/10.2760/069150.978-92-76-47147-9>.
- [35] Mattress for Electrochemical Cells. Patent: EP 0 726 971 B1. Dow Chemical Company; 1998.
- [36] Hydrogen Europe Position Paper on PFAS.. The importance of fluoropolymers across the hydrogen value chain, and impacts of the proposed PFAS restriction for the hydrogen sector. Avenue Marnix 23, Brussels/Belgium, https://hydrogeneurope.eu/wp-content/uploads/2023/02/Hydrogen-Europe-position-paper-on-PFA-S-ban_v12_FINAL.pdf; 2023.
- [37] Henry BJ, Carlin JP, Hammerschmidt JA, Buck RC, Buxton LW, Fiedler H, Seed J, Hernandez O. A critical review of the application of polymer of low concern and regulatory criteria to fluoropolymers. *Integrated Environ Assess Manag* 2018;14(3):316–34.
- [38] Korzeniowski SH, Buck RC, Newkold RM, Kassmi AE, Laganis E, Matsuoka Y, Dinelli B, Beauchet S, Adamsky F, Weilandt K, Soni VK, Kapoor D, Gunasekar P, Malcasi M, Brinati G, Musio S. A critical review of the application of polymer of low concern regulatory criteria to fluoropolymers II: fluoroplastics and fluoroelastomers. *Integrated Environ Assess Manag* 2023;19(2):326–54.
- [39] Moschovi AM, Zagoraiou E, Polyzou E, Yakoumis I. *IOP Conf Ser Mater Sci Eng* 2021;1024:012008.
- [40] Westing EV, Savran V, Hofman J. Recycling of metals from coatings. Materials innovation institute M2i. Stichting Kennisplatform Oppervlaktetechnologie. <http://kpot.nl/recycling.pdf>.