A comparative environmental impact analysis of H_2O electrolysis technologies under different energy scenarios

Bortolini M., Cafarella C.*, Ferrari E., Guzzini A., Manieri R., Pellegrini M., Ventura V.

Department of Industrial Engineering, Alma Mater Studiorum – University of Bologna, Viale del Risorgimento 2, 40136 – Bologna – Italy

(marco.bortolini3@unibo.it, cristian.cafarella2@unibo.it, emilio.ferrari@unibo.it, alessandro.guzzini2@unibo.it, riccardo.manieri6@unibo.it, marco.pellegrini3@unibo.it, valentina.ventura7@unibo.it)

Abstract: Both scientific community and politic institutions frequently stress the crucial role of energy and renewables as key-asset to reduce climate change and support the achievement of long-term sustainable development goals. Hydrogen supplying to industrial users is currently the major hydrogen business worldwide and the demand for hydrogen is almost entirely supplied from fossil fuels. In such a context, the use of hydrogen as energy carrier represents a sustainable pathway towards the energy transition and the decarbonization of the most energy-intensive sectors. The H_2O electrolysis technologies cope the challenges related to the balance of fluctuating electricity generation from renewables as backup power and energy storage. The three main H_2O electrolysis technologies commercially available are the alkaline electrolysis cell (AE/AEC), polymer electrolyte membrane electrolysis cell (PEM/PEMEC), and solid oxide electrolysis cell (SOE/SOEC). Several studies analyze the environmental impacts of the H_2O electrolysis technologies considering their main components and manufacturing processes in a life cycle perspective. Moreover, the hydrogen production process is often investigated comparing these technologies under different energy scenarios. Starting from the Life-Cycle-Impact-Assessment (LCIA) results in literature, this paper tries to contribute to this research stream focusing on the Global Warming Potential (GWP) of the low-temperature electrolysis technologies (AEC and PEM), by evaluating the effect of different Italian energy policies on the hydrogen production. The comparative analysis includes the impacts related to the stacks and to the operation phase of producing hydrogen, while those of Balance of Plant (BoP) are not included in the system boundaries. Overall, based on the results of this paper, PEM technology has a lower GWP than AEC. Moreover, future scenarios with a high share of renewables in the energy mix significantly reduce the GWP related with the operation phase of these electrolysis technologies.

Keywords: Hydrogen, Environmental impacts, CO2, Electrolysis, Renewable energy sources

I. INTRODUCTION

The International Panel on Climate Change (IPCC) recently clearly stated that intensive human activities have caused global warming and that global greenhouse gas (GHG) emissions have continued to increase over last decades with unequal historical contributions [1]. The energy sector is responsible for more than one third of net global GHG emissions and power generation is currently the largest source of carbon dioxide (CO_2) emissions globally. At the same time, energy sector is leading the energy transition through the rapid adoption of renewable energy sources, such as solar and wind [2,3,4]. Hydrogen is actually not a primary source and it is obtained through the conversion from other energy powers. The use of hydrogen as energy carrier constitutes a sustainable pathway towards the energy transition [5] and the decarbonization of the major energy-intensive sectors, including industry, transport and buildings. For long-term grid storage, hydrogen is produced from surplus production of intermittent sources, via water (H_2O) electrolysis, and help facing the balance of fluctuating electricity generation. Despite significant conversion losses, electrolysis from renewable electricity sources, i.e., green hydrogen, confers low-carbon characteristics to the hydrogen produced. Through the following conversion to electricity via fuel cells, this solution ensures with load-following on an annual timeframe by consuming minimal CO_2 emissions [6,7]. The three main H_2O electrolysis technologies commercially available are the alkaline electrolysis cell (AE/AEC), polymer electrolyte membrane electrolysis cell (PEM/PEMEC), and solid oxide electrolysis cell (SOE/SOEC). AEC is the most mature technology and, together with PEM, is based on a low-temperature process (below 100 °C). SOEC is the least evolved technology and requires further research to overcome some deployment barriers. In contrast to the others, SOEC operates at elevated temperature (600 – 900 °C) that strongly improves electrical efficiency. These technologies are not exempted from environmental burdens, mainly for the electricity supply needed during hydrogen production [8]. The Life-Cycle-Assessment (LCA) is an environmental management tool defined in ISO standards (ISO 14040 and ISO 14044) that identifies environmental impacts along the entire life cycle of a product or a process [9]. Several studies analyse the environmental impacts of the H_2O electrolysis technologies considering both the manufacturing and the operation phase in a life cycle perspective [10,11]. Moreover, the hydrogen production process is often investigated comparing the electrolysis technologies under different energy scenarios [12]. Starting from this background, this paper contributes to this research stream by evaluating the environmental impacts of two out of the three H_2O electrolysis technologies, i.e., the low-temperature technologies AEC and PEM. Firstly, the impacts of the manufacturing process for producing stacks components are analysed. Then, given the Italian energy mix as reference, the environmental assessment is carried out considering different future energy scenarios to fuel the stacks for hydrogen production during the operation phase. The remaining structure of this paper is as follows: Section 2 presents the methodology behind the environmental impact analysis, Section 3 reviews the results, while Section 4 draws the conclusion.

II. MATERIALS AND METHODS

The following sections are structured according to the four steps of LCA methodology: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and the final phase of interpretation of results.

A. Goal and scope definition

The objective of this study is to evaluate and compare the carbon footprint of AEC and PEM electrolysis technologies, considering both the stacks of the two technologies, i.e., raw materials and manufacturing, and the operation phase for the hydrogen production. The Functional Unit (FU) constitutes the basis for the calculations in the impact assessment [9]. In this study, for the evaluation of the stacks manufacturing process, 1 m^2 of the stack area is considered [8]. For the operation phase, 1 kg of H_2 is used [12]. Fig. A.1, in Annex A, shows the system boundary of the study. This includes the material and energy inputs used for the stack components and during the manufacturing process, as wells as the final treatment of the decommissioned stack. The operation phase, where the electrolysis process takes place, forms the central part of the system. Here, the electricity consumptions are considered with the energy mix from the grid, that forms the main disparity between the scenarios. The Balance of Plant (BoP) is not included in the system boundary at present. Concerning the hydrogen production, the impacts associated with electrolysis via AEC and PEM are evaluated using the Italian national electricity mix, considering the effect of different national energy policy on the carbon footprint. Five different future energy scenarios, provided by TERNA (the Italian transmission system operator), are considered [13]. Among them, the two scenarios for the time horizon of 2030 are:

- a policy scenario in line with the Fit-for-55 (FF55) objectives;
- a Late Transition (LT) scenario in line with the objectives of the National Energy and Climate Plan (NECP) of December 2019.

While over the 2040 time horizon the three scenarios are:

- a Distributed Energy Italy (DE-IT) scenario;
- a Global Ambition Italy (GA-IT) scenario;
- a LT scenario in line with that of 2030.

Table 1 shows the details of the energy balance for the different scenarios considered.

TABLE I
DETAIL OF ELECTRICITY BALANCE (FF55, LT, DE, GA) [13]

Electricity balance (TWh)	2019	2030 FF55	2030 LT	2040 DE	2040 GA	2040 LT
Electricity demand	*320*	*366*	*331*	*418*	*396*	*389*
National Production	*281*	*319*	*281*	*374*	*355*	*343*
Total renewable	*113*	*239*	*187*	*325*	*302*	*244*
Hydro	*46*	*51*	*52*	*51*	*51*	*51*
Solar	*23*	*101*	*69*	*157*	*138*	*102*
Wind	*20*	*68*	*46*	*108*	*99*	*71*
Other renewable	*23*	*23*	*23*	*25*	*25*	*24*
Overgeneration	*0*	*-5*	*-4*	*-16*	*-11*	*-5*
Total fossil fuels	*169*	*80*	*96*	*49*	*53*	*99*
Natural Gas	*138*	*75*	*91*	*46*	*50*	*94*
Other fossil fuels	*31*	*5*	*5*	*3*	*3*	*5*
Net import	*38*	*52*	*54*	*54*	*49*	*51*
Losses (storage)	*-1*	*-5*	*-3*	*-10*	*-8*	*-5*

Starting from Table 1, it is possible to define the contributions of the different energy sources in the Italian energy mix for the six scenarios considered. The AEC technology is the most developed, mature, and commercially available technology since decades [14]. The technology is available for large plant sizes and operates with a stack efficiency of up to 67% based on the Lower Heating Value (LHV) of the generated hydrogen [15]. The operating temperature is between 60 and 80 °C, the current density is around 0.2–0.4 A/cm^2, the cell voltage ranges from 1.8 to 2.4 V, the gas purity is higher than 99.5%, while the operating pressure is up to 30 bar [16,17,18]. The AEC stack lifetime ranges from 60.000 to 90.000 h [16]. In comparison to AEC electrolysers, PEM electrolysers are less mature [19]. The PEM technology is commercially available and operates with similar system efficiency to the AEC technology. However, the current density and the gas purity are higher compared to AEC, with values between 0.6 and 2.0 A/cm^2 for the current density and a gas purity of more than 99.99% [16]. Moreover, the operating pressure (below 200 bar) is significantly higher in comparison to AEC systems, while the operating temperature (50 °C to 80 °C) and the cell voltage (1.8 to 2.2 V) are similar to AEC systems [16,17,18]. The PEM stack lifetime ranges from 20.000 to 60.000 h [16].

Several studies about AEC and PEM electrolysis which include direct or indirect information about cell voltage, current density, cell efficiency range, and hydrogen yield are presented in [20]. Based on these data, the average electricity consumption for PEM technology is 45.44 kWh/kgH_2, and for AEC is 53.29 kWh/kgH_2. Assuming that the units are modular and that can be added together without any impact on performances, the active area for a given system capacity is calculated as in the following equation [20]:

$$Active\ area = System\ Capacity\ /\ Power\ Density \quad (1)$$

The following steps serve to achieve an estimation of the produced amount of hydrogen during the electrolyser lifetime, by assuming no conversion losses.

- The starting point of the calculation is the system electricity consumption required to produce 1 kg of hydrogen (kWh/kgH_2).
- In the next step, this value is divided by 11.2 Nm^3H_2/kgH_2 to obtain the value in kWh/Nm^3H_2.
- Then, the system size in kW is divided by this value to get the result in Nm^3H_2 per hour.
- Next, to reach the result in kgH_2 per hour, the value is multiplied with the density of H_2 under standard condition (1 bar, 15 °C) equal to 0.0893 kg/Sm^3 of H_2.
- Finally, the obtained value is multiplied with the operating hour over the system lifetime [12].

B. Life Cycle Inventory

The inventory of AEC and PEM technology considers both the usage of materials and energy consumption for stack production, and the main energy sources used for the operating phase of hydrogen production.

The input materials include also the resources used during the manufacturing process of the stacks, such as solvents, and the waste disposal. Each electrolysis stack consists of different components and specific chemicals elements which fall into the following parts of the stack: oxygen electrode, electrolyte, hydrogen electrode, interconnect, frame, manufacturing process and waste disposal. The LCI data for the stacks production is gathered from [8] and [11], based on the functional unit of 1 m^2 of the stack area.

Over the lifespan, every technology that produces energy impacts significantly the environment. The most serious damage is caused by fossil fuels, followed by natural gas. Despite renewable energy technologies have not negligible impacts, they remain the best available options on the market. In a life-cycle perspective, in addition to the usage of materials and energy for stack production, the energy absorption during the operating phase of producing hydrogen have to be assessed [6]. The energy consumption for the operation of AEC and PEM technologies is evaluated considering, firstly, the impacts of producing 1 kWh of electricity with different energy sources. Starting from this, the carbon footprint of a given energy mix can be assessed by weighting the incidence of the different energy sources. Data originates from [3], where the geographical area considered for assessing the impact of electricity generation options is Europe. Table 2 shows the GWP values for the main electricity generation options derived from [3].

TABLE II
GWP OF ELECTRICITY OPTIONS [3]

	GWP kgCO_2-eq/kWh
Natural Gas without CCS	0.4340
Hard Coal without CCS	0.9360
Wind onshore	0.0124
Wind offshore	0.0142
Solar PV (Poly_Si)	0.0370
Solar concentrated	0.0319
Hydro	0.0107
Nuclear	0.0051

C. Life Cycle Impact Assessment

The LCIA is employed to analyse potential environmental impacts and to select impact assessment categories. The impacts can be characterised either with mid-point or endpoint indicators [6]. GWP is the most widely adopted midpoint impact category and this study adopted it to evaluate the impacts of producing AEC and PEM stacks, and the impacts of the operating phase for producing hydrogen via electrolysis [10]. Both analyses take into account the midpoint impact of category of Climate change (GWP), expressed as kg of CO_2 equivalents.

III. RESULT AND DISCUSSION

In this section, the results of the environmental impacts analysis are discussed. In the first paragraph (A), the impacts related to the production of stacks (AEC and PEM) are presented, starting from [8]. After showing the results of the impacts analysis of different energy scenarios to fuel the hydrogen production processes (B), the overall results are described. In order to compare the GWP indicators for the two phases, i.e., manufacturing and operating, appropriate unit conversions are made, considering also the different functional units.

A. Stack production impacts

The potential environmental impact distribution of the five components, i.e., oxygen electrode, electrolyte, hydrogen electrode, interconnect, frame, and of the manufacturing and waste disposal according to the impact category of GWP, is shown in Table 3 for AEC and in Table 4 for PEM.

TABLE III
GWP OF AEC STACK [8]

	Unit	**AEC Stack**
GWP of the Stack	kgCO_2-eq/m^2	201.6
Oxygen electrode	%	12.22
Electrolyte	%	6.15
Hydrogen electrode	%	12.27
Interconnect	%	50.33
Frame	%	18.87
Manufacture process	%	0.01
Waste disposal	%	0.15

TABLE IV
GWP OF PEM STACK [8]

	Unit	PEM Stack
GWP of the Stack	$kgCO_2$-eq/m^2	1765.6
Oxygen electrode	%	47.66
Electrolyte	%	1.13
Hydrogen electrode	%	13.44
Interconnect	%	37.58
Frame	%	0.19
Manufacture process	%	0.001
Waste disposal	%	0.001

As evident, the major contributors to the GWP come from the interconnect and the frame for AEC, and from the oxygen electrode and the interconnect for PEM. In both of the technologies the share of manufacturing process and the waste disposal is not relevant in comparison to the share of stacks components. Nickel is responsible for the majority of impacts for AEC and, together with stainless steel, has a dominant influence in the GWP. Concerning PEM, the two materials that affect significantly the impacts are platinum and iridium. A reduction in the use of these noble catalysts can drastically reduce the overall GWP.

In general, comparing the kg of CO_2 equivalent per kg of H_2 produced of the two technologies, the result of GWP for PEM is around 3 times higher than that of the AEC stack, as highlighted in Fig. 2, i.e., 0.02 and 0.05 $kgCO_2/kgH_2$ (= 31.9 $kgCO_2$/kW and 55.0 $kgCO_2$/kW).

The chosen data for the current study for AEC and PEM technologies, relative to which results in Fig. 2 are scaled, are detailed in Table 5.

TABLE V
KEY PARAMETERS FOR AEC AND PEM TECHNOLOGY [8, 20]

	Unit	AEC	PEM
Current density	A/cm^2	0.4	1.8
Cell voltage	V	1.8	1.8
Lifetime	hour	85,000	50,000

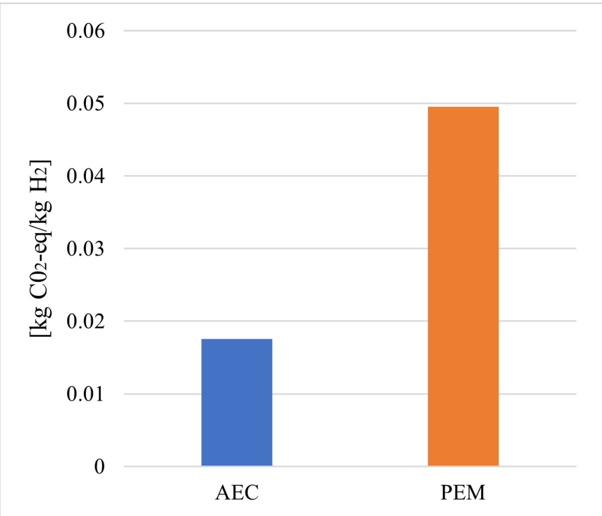

Figure 2. GWP results for AEC and PEM stacks.

B. *Hydrogen production process impacts*

As starting point, for this second part of the environmental assessment, the national energy mix is evaluated. The following assumptions are made:

- AEC and PEM electrolysers are fed only from the Italian energy mix and the impacts associated with the share of imported energy are excluded;
- The share of offshore wind energy is estimated from data reported in [13]
- Coal-fired plants are decommissioned from 2030 onwards [13].

The composition of the six energy scenarios taken into account for this study are detailed in Fig. A.2, in Appendix A.

To calculate the impacts of producing hydrogen through AEC and PEM technologies, the first step considers the kg of CO_2 equivalent for the production of 1 kWh of electricity with the different energy sources [6]. Once the GWP is calculated per 1 kWh of every source (kg CO_2-eq/kWh), the incidence of each electricity generation option is weighted according to the share in the selected energy mix.

The results of the GWP for AEC and PEM technology during the operation phase of producing hydrogen with the six energy mixes are shown in Fig. 3. The results shown in Fig. 3 are estimated starting from an average electricity consumption for PEM technology of 45.44 kWh/kgH2, and for AEC of 53.29 kWh/kgH_2, according to [20].

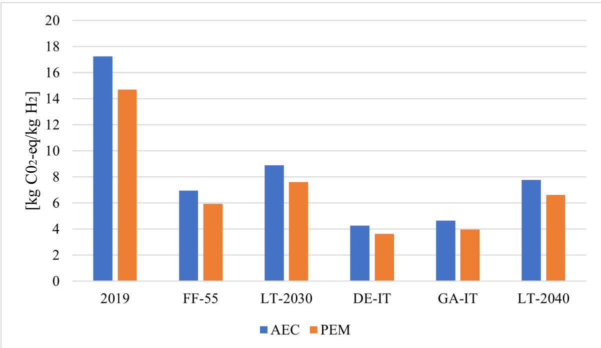

Figure 3. GWP results for hydrogen production via AEC and PEM.

Based on Fig. 3, PEM technology has an overall lower GWP than AEC. However, to date, both technologies would be responsible for greater CO_2 emissions than traditional steam methane reforming (10.9 $kgCO_2/kg_{H2}$ [21]), assuming the energy mix in 2019.

The future scenarios with a high share of renewables in the energy mix significantly reduce the GWP associated with these technologies. However, considering the recent rules for the production of renewable liquid and gaseous transport fuels of non-biological origin [22], no one of the investigated grid scenarios would allow the production of totally renewable hydrogen. Comparing GWP results for the stacks and for the operation phase, in the case of the grid-connected configuration, the electricity consumption for hydrogen production has the largest contribution of the total impacts for both electrolysers.

IV. CONCLUSION

Hydrogen represents a sustainable pathway towards the energy transition and the decarbonization of the most energy-intensive industrial sectors. Electrolysis technologies, i.e., alkaline electrolysis cell (AEC), polymer electrolyte membrane electrolysis cell (PEM), and solid oxide electrolysis cell (SOEC), are the main commercially available solutions to produce hydrogen (H_2). The environmental impacts of producing the stacks of these technologies and their operating phase to produce H_2 impact significantly on the carbon emissions in the atmosphere. This paper aims, firstly, to assess the impacts related to the materials and energy used during manufacturing of stacks, and, secondly, to evaluate the incidence of different energy sources for producing hydrogen through electrolysis technologies. The indicator used as reference to evaluate carbon emissions is the Global Warming Potential (GWP). GWP is the most widely adopted midpoint impact category in Life-Cycle-Impact-Assessment (LCIA) regarding hydrogen production via electrolysis.

The main results of this paper highlight that a high share of renewables in the energy mix can significantly reduce the GWP connected to hydrogen production for both electrolysis technologies considered (AEC and PEM). Considering the stack of the two technologies (raw materials and manufacturing) PEM technology has a higher GWP than AEC due to the use of noble catalysts, such as platinum and iridium. Based on the expected nominal installed capacity by 2030, i.e., 40 GW, the total carbon dioxide emission for the realization of the stack would result in the range between 1.3-2.2 million tons, i.e., 0.05% of the European carbon dioxide equivalent emissions in 2019 [23].

Moreover, the GWP results for hydrogen production via AEC and PEM show that PEM technology has an overall lower GWP than AEC due to the lower electricity consumption of PEM technology. Comparing GWP results for the stacks and for the operation phase in the grid-connected configuration, the electricity consumption for hydrogen production has the largest contributions of the total impacts for both electrolysers.

The study was limited to AEC and PEM electrolysis technologies assessing only the GWP related to the stack (raw materials and manufacturing) and the operational phase fed from the Italian energy mix (under different energy scenarios). Future research focuses on two directions of developments. The former deals with the extension of the system boundary and the inclusion of other impact indicators both mid-point and endpoint. The latter deals with further application to assess the potential of different energy policies and geographical contexts to reduce the environmental impacts related to the hydrogen production.

REFERENCES

[1] International Panel on Climate Change (2023). Synthesis Report of the IPCC Sixth Assessment Report (AR6). Longer Report.

[2] Bortolini, M., Cafarella, C., Galizia, F.G., Gamberi, M., Mora, C., Ventura, V.: The potential of Industry 4.0 toward smart grids: opportunities and challenges. In: Proceedings of the XXVII Summer School "Francesco Turco", pp. 1-7. AIDI - Italian Association of Industrial Operations Professors, Rome (2022).

[3] Bortolini, M., Cafarella, C., Ferrari, E., Galizia, F. G., Gamberi, M., Ventura, V. (2023). Assessing energy requirements in the European (EU-28) food sector. In: Accorsi R., Bhat B. (eds) Sustainable Development and Pathways for Food Ecosystems (pp. 259-272). Academic Press.

[4] Bortolini, M., Cafarella, C., Galizia, F.G., Gamberi, M. (2023). Energy System Optimization Modelling and Electrical Grid Management: The Case of Italy. In: Galizia, F.G., Bortolini, M. (eds) Production Processes and Product Evolution in the Age of Disruption. CARV 2023. Lecture Notes in Mechanical Engineering. Springer, Cham.

[5] Nedaei, M., Faccio, M., Bortolini, M., and Gamberi, M. (2022). Design and simulation-based optimisation of a renewable energy system consisting of wind and hydrogen for the purpose of reliable electrification. International Journal of Environmental Technology and Management, 25(5), 445-465.

[6] United Nations Economic Commission for Europe (2022). Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources. United Nations.

[7] Saccani, C., Pellegrini, M., Guzzini, A. (2020). Analysis of the existing barriers for the market development of power to hydrogen (P2H) in Italy. Energies, 13(18), p.4835.

[8] Zhao, G., Kraglund, M.R., Frandsen, H.L., Wulff, A.C., Jensen, S.H., Chen, M. and Graves, C.R. (2020). Life cycle assessment of H2O electrolysis technologies. International Journal of Hydrogen Energy, 45(43), pp.23765-23781.

[9] Hauschild, M.Z. (2018). Introduction to LCA methodology. Life cycle assessment: theory and practice, pp.59-66.

[10] Bhandari, R., Trudewind, C.A., Zapp, P. (2014). Life cycle assessment of hydrogen production via electrolysis–a review. Journal of cleaner production, 85, pp.151-163.

[11] Vilbergsson, K.V., Dillman, K., Emami, N., Ásbjörnsson, E.J., Heinonen, J. and Finger, D.C. (2023). Can remote green hydrogen production play a key role in decarbonizing Europe in the future? A cradle-to-gate LCA of hydrogen production in Austria, Belgium, and Iceland. International Journal of Hydrogen Energy.

[12] Gerloff, N. (2021). Comparative Life-Cycle-Assessment analysis of three major water electrolysis technologies while applying various energy scenarios for a greener hydrogen production. Journal of Energy Storage, 43, p.102759.

[13] TERNA. Documento di Descrizione degli Scenari 2022. https://download.terna.it/terna/Documento_Descrizione_Scenari_2022_8da74044f6ee28d.pdf, [Accessed 18 May 2023]

[14] Kreuter, W., & Hofmann, H. (1998). Electrolysis: the important energy transformer in a world of sustainable energy. International Journal of Hydrogen Energy, 23(8), 661-666.

[15] Schiebahn, S., Grube, T., Robinius, M., Tietze, V., Kumar, B., & Stolten, D. (2015). Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany. International journal of hydrogen energy, 40(12), 4285-4294.

[16] Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., & Few, S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. International journal of hydrogen energy, 42(52), 30470-30492.

[17] Zeng, K., & Zhang, D. (2010). Recent progress in alkaline water electrolysis for hydrogen production and

applications. Progress in energy and combustion science, 36(3), 307-326.

[18] Carmo, M., Fritz, D. L., Mergel, J., & Stolten, D. (2013). A comprehensive review on PEM water electrolysis. International journal of hydrogen energy, 38(12), 4901-4934.

[19] Zhang, X., Chan, S. H., Ho, H. K., Tan, S. C., Li, M., Li, G., ... & Feng, Z. (2015). Towards a smart energy network: The roles of fuel/electrolysis cells and technological perspectives. International Journal of Hydrogen Energy, 40(21), 6866-6919.

[20] Aghakhani, A., Haque, N., Saccani, C., Pellegrini, M. and Guzzini, A. (2023). Direct carbon footprint of hydrogen generation via PEM and alkaline electrolysers using various electrical energy sources and considering cell characteristics. International Journal of Hydrogen Energy.

[21] Reiter G, Lindorfer J. (2015). Global warming potential of hydrogen and methane production from renewable electricity via power-to-gas technology. International Journal of Life Cycle Assessment.

[22] European Commission. (2023). Supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin.

[23] Parlamento Europeo. Emissioni di gas serra nell'UE per paese e settore: Infografica. https://www.europarl.europa.eu/news/it/headlines/society/20180301STO98928/emissioni-di-gas-serra-per-paese-e-settore-infografica.

Appendix A. SUPPLEMENTARY MATERIALS

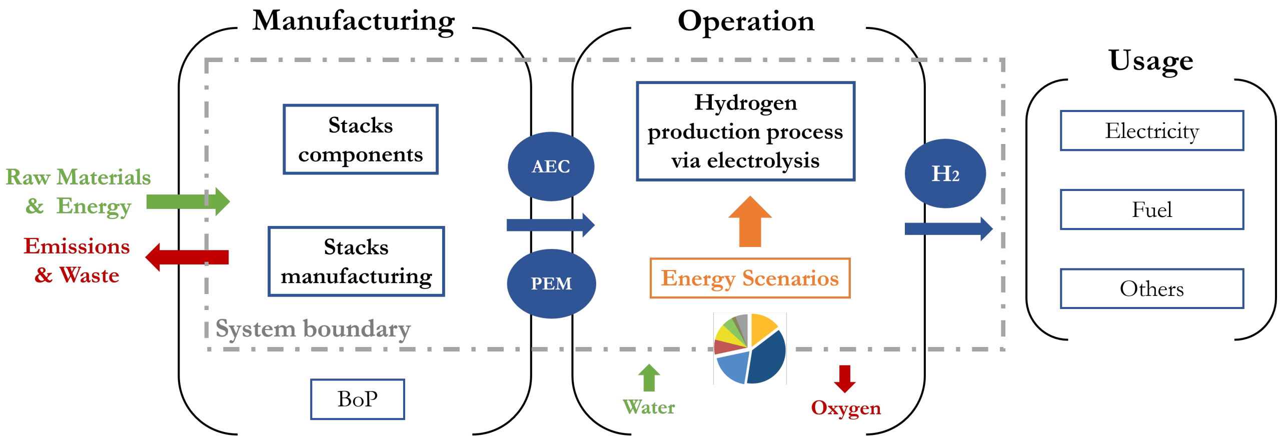

Figure A.1. System boundary of the study.

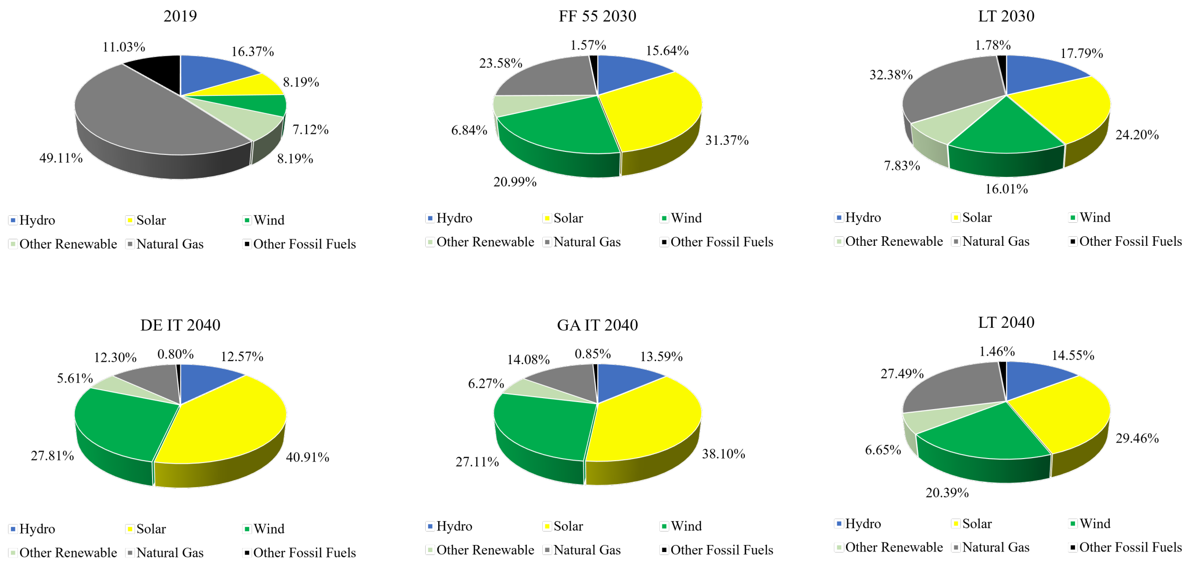

Figure A.2. Energy scenarios.