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Life cycle analysis of hydrogen production by different alkaline electrolyser technologies sourced with renewable energy

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ABSTRACT

Green hydrogen has been considered a promising alternative to fossil fuels in chemical and energy applications. In this study, a life cycle analysis is conducted for green hydrogen production sourced with a mixture of renewable energy sources (50 % solar and 50 % wind energy). Two advanced technologies of alkaline electrolysis are selected and compared for hydrogen production: pressurised alkaline electrolyser and capillary-fed alkaline electrolyser. The different value chain stages were assessed in SimaPro, enabling the assessment of the environmental impacts of a green hydrogen production project with 60 MW capacity and 20 years lifetime. The results evaluate the environmental impacts depending on the components, construction and operation requirements. The results demonstrated that capillary-fed alkaline electrolyser technology has lower potential environmental impacts by around 17 % than pressurised alkaline electrolyser technology for all the process stages. The total global warming potential was found to be between 1.98 and 2.39 kg of carbon dioxide equivalent per kg of hydrogen. This study contributes to the electrolysers industry and the planning of green hydrogen projects for many applications towards decarbonization and sustainability.

1. Introduction

Mitigating greenhouse emissions and finding alternative clean energy sources of fossil fuels have become trend goals for the international industrial community [1]. Renewable energy resources (RES) such as wind and solar are commonly used and continue developing toward higher efficiency, electricity storage solutions and minimising their costs [2]. Electricity produced from RES can be converted to chemical products and biofuels required in many applications using green hydrogen [3], since hydrogen can be produced by the electrolysis process [4] and then used to provide chemical products such as methanol synthesis and ammonia [5]. In addition, hydrogen has been considered an important gas material for energy storage and use, such as for power conversion to fuels [6] and aviation [7]. The carbon-free combustion of hydrogen (without carbon dioxide emission) [8] makes it an important energy form and advanced solution for decarbonising in industry and other applications related to transportation and domestic needs, whether the hydrogen in the usage stage is green (e.g. produced based on renewable energy) [9] or blue hydrogen (e.g. produced by steam methane reforming) [10]. RES now reached a development stage in terms of reducing the levelized cost of energy (LCOE) and becoming comparable to the cost of fossil fuels [11]. The enhancement of the hydrogen production methods and RES technologies inspires and leads to their integration to produce green hydrogen toward sustainability and a clean environment without the need for fossil fuel [12]. Therefore, now is an appropriate time to apply RES to produce Green hydrogen (GH_2) taking advantage of its environmental features [13], as well as improving the GH_2 feasibility and system performance to the highest levels by tools such as Artificial Intelligence models [14]. The same happened in the context of Portugal, where the roadmap of the EU for Carbon Neutrality (RNC 2050) and the National Energy and Climate Plan (NECP) have set the pathways for decarbonisation for the next decades presenting hydrogen as a multi-functional form of green energy based on several production methods [15]. The most widely used hydrogen across applications worldwide comes from fossil fuels-based production methods, mainly the steam reforming of methane (SMR) [16]. Although hydrogen production through fossil fuels methods such as SMR, coal, and biomass gasification has been a commercially feasible procedure, it involves significant challenges related to environmental impacts [17]. The

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Nomenclature

ALE	Alkaline electrolysis.
ALE-C	pressurised alkaline electrolysis.
ALE-P	capillary-fed alkaline electrolysis.
AP	Acidification.
CAPEX	capital expenditure.
EP ter	Terrestrial eutrophication.
EP fw	Freshwater eutrophication.
EP sw	Marine eutrophication.
FEW	Freshwater ecotoxicity.
GH_2	Green hydrogen.
GWP	Global warming potential.
HTnc	Human toxicity, non-cancer effects.
HTc	Human toxicity, cancer effects.
IRH	Ionizing radiation HH.
IRE	Ionizing radiation E (interim)
KOH	Potassium.
LCA	Life Cycle Analysis.
LU	Land use.
MFRDP	Mineral, fossil & ren resource depletion.
NaOH	sodium hydroxide.
OPEX	The annual operational expenditures.
ODP	Ozone depletion.
OH−	hydroxide ions.
PEMEL	proton-exchange membrane electrolysis.
PES	Porous polyether sulfone.
PM	Particulate matter.
POF	Photochemical ozone formation.
Pt/C	carbon- platinum np catalyst.
RES	Renewable energy sources.
SMR	steam methane reforming.
SOEL	oxide electrolysis.
WRD	Water resource depletion.

overall greenhouse gas (GHG) emissions of the total hydrogen production plant using the SMR method were estimated to be around 11.89 kg CO_2 eq./kg H_2, as reported by NERL [18]. In this, 8.9 of 11.89 kg CO_2 eq./kg H_2 was mainly caused by the SMR process [19]. Also, Khojasteh et al. [20] reported a value of 11.7 kg CO_2 eq./kg H_2 using the SMR method for hydrogen production. It should be mentioned that these reported GHG values are for the SMR process without carbon capture, caused mainly by the system operation requirements [21].

Therefore, several technologies have been presented to produce hydrogen-based RES while the electrolysis process of water demonstrated effective implementation [22]. So far, the electrolysis process used several technologies mostly, alkaline electrolysis (ALE), proton-exchange membrane (PEM) and solid oxide (SO) based on the application requirements, available materials and costs [23], as well as recent electrolysis technology known as anion exchange membrane [24]. It should be mentioned the importance of using a RES mix to feed the hydrogen electrolysis system with stable power performance to avoid the low energy feeds that can happen sometimes during the day due to the environmental factors of the location such as the sunny hours for photovoltaic (PV) solar [25], especially for ALEs that are usually operated in stable conditions [26].

ALE generally has two Nickel electrodes parted by a membrane layer and an alkaline electrolyte liquid [27]. The hydroxide ions (OH−) are created at the cathode side and move via the membrane to the Anode side realizing the hydrogen [28]. The alkaline electrolysis method works at relatively low temperatures from 30 to 80 ∘C and features available and low-cost materials for its components of the electrolyte solution, electrodes and the different membrane composites such as titanium [29] and polysulfone composite [30]. A recent ALE type with high-pressure operation (pressurised) showed a promising performance compared to atmospheric ALE [31], especially for applications that require compressed hydrogen [32]. Nevertheless, there is still continuous research to develop ALE technology to overcome the negative characteristics such as enhancing the current density, working pressure, lifetime and energy efficiency [33], for instance, developing electrocatalysts [34]. Also, the optimization of the operating conditions significantly contributes to the advancement of ALE that can be achieved using high current density (above 1 A cm^{-2}), zero-gap design, less membrane thickness (Zirfon), higher temperature and operating pressure that was found to be preferably below 8 bar [35]. The development of ALE performance requires deep attention to the design of the electrodes, particularly the electrocatalysts, where several aspects affect the performance such as charge transmission, mass transport, electrochemical erosion and gas bubbles [36]. Advanced materials-based series of polymers were suggested by Marinkas et al. [37] to develop anion exchange membranes (AEM) to enhance ALE technology towards membranes with high anionic conductivity, strength and thermal and chemical stability. Moreover, low-cost materials of manganese oxide ($Na_{0.44}MnO_2$) were investigated as a solid-state redox method for the production of hydrogen and O_2 in ALE to obtain high levels of hydrogen purity and energy efficiency without the need for any membrane [38]. Also, Hnat et al. [39] investigated a new catalyst coating of platinum-free for AEM in ALE with several thicknesses and advanced performance and stability were demonstrated with a reduction of the used catalyst load compared to conventional catalyst materials. Furthermore, Khalil and Dincer [40] investigated the use of coated 3D-printed electrodes for ALE, and the highest hydrogen production rate was found for Ni-Cu (nickel-copper) electrodes coated by Nickel conductive paint (NCP), with values of about 2.48×10^{-10} kg/s during the initial operation 15 min and reduced to 1.38×10^{-10} kg/s after 30 min of the operation.

Recently, a capillary membrane consisting of porous polyether sulfone was tested for ALE and demonstrated a promising performance reaching 98 % energy efficiency with only 40.4 kWh/kg H_2 power consumption [41], which was set under the goal of the International Renewable Energy Agency (IRENA) for 2050 to reduce the power consumption in hydrogen production to less than 42 kWh/kg [42]. The provided capillary membrane prevents the forming of bubbles that cause energy losses on the surfaces of the electrodes in the electrolysis process and directly converts the water to bulk hydrogen and oxygen [43]. The negative impacts of bubble creation in electrolysis systems were previously discussed and several approaches were investigated to avoid the resulting power losses including the capillary porous hydrophobic materials that can extract the produced [44]. However, the enhancement in energy efficiency mostly leads to a reduction in the levelized cost of hydrogen production, while further investigations are still required for the environmental impacts caused by the newly used materials and methods in the systems.

Therefore, life cycle analysis (LCA) studies that can provide data about the developed hydrogen electrolysis technologies, considering the newly added materials to the manufacturing of the electrolier system, are essential to reach the goal of energy industry decarbonisation. Sadeghi et al. [45] evaluated the life cycle of hydrogen production-based solar power compared to SMR and coal gasification. The results demonstrated a value of the Global warming potential (GWP) of 3.08 kg CO_2 eq./kg H_2 when PV solar electrolysis is used, as well as a reduction in GHG costs by 1.37$/kg CO_2 compared to the conventional hydrogen production method (based fossil fuel). In another study, Sadeghi et al. [46] carried out a LCA on the integrated solar copper-chlorine fuel production process for hydrogen generation. Their findings highlighted several significant factors that influence the environmental impacts.

These include solar irradiation, the system's lifetime and the conversion energy efficiency. On the other hand, a study by Zhang et al. [47] discovered that an extension in the lifetime of the PV solar-based electrolysis system from 30 to 60 years resulted in a significant reduction in the Global Warming Potential (GWP). Specifically, the GWP decreased from 8.67 to 4.33 kg CO_2 per kg of H_2 produced. This underscores the environmental benefits of enhancing the longevity of such systems.

Furthermore, Koj et al.[48] found that the conditions of the location of the electricity mix supply for 6 MW ALEs system capacity played a significant role in affecting the environmental impacts when comparing three sites (Austria, Spain and Germany), resulting in a better environmental performance for the scenario in Austria. Even though the operation of hydrogen electrolysis methods powered by RES is green and environmentally friendly, the establishment and component production of the electrolysis system and renewable plants are still causing environmental impacts [49]. Numerous ecological indicators for the LCA approaches of the electrolysis systems were mentioned in previous studies to evaluate the ecology performance of hydrogen production systems such as Climate change (GWP), Eutrophication, abiotic depletion potential (ADP), freshwater eutrophication potential (FEP), and Ionizing radiation (IRP) [50]. However, the assumptions considered for LCA studies on hydrogen production should be selected carefully when there is a lack of information regarding some important parameters of the project such as the site conditions, lifetime of the cycle, construction components, energy consumption and materials. An accurate analysis of the hydrogen production technology will aid in establishing a guideline for the optimisation of operational rules and material usage. This is aimed at enhancing overall efficiency and improving the management of natural resources within the plant. Such enhancements can elevate the plant's economic and societal benefits, thereby creating a more sustainable and beneficial operation [51]. Furthermore, more investigations are still required for the environmental impacts caused by the newly used materials and methods for developing the hydrogen electrolysis systems in different locations, considering novel technologies for minimizing the environmental impacts such as miniaturization and recycling of the components.

The current study conducts an LCA for GH_2 production with a high capacity of 60 MW based on both PV solar and wind energy sources in Portugal. The study follows the objectives defined in Portugal (and Europe) to support reasonable decisions on the hydrogen technological path [52] and the incorporation of hydrogen into each value chain [53], that best matches the national requirements supervised by a deep scientific and technical discussion. Also, two recent ALE technologies are examined and compared for hydrogen production, mainly the capillary-fed alkaline electrolyser (ALE-C) and pressurised alkaline electrolyser (ALE-P). The results evaluate the environmental impacts depending on various factors such as the operation, requirements, construction components and ALE technology. Therefore, to the authors' knowledge, the comparative LCA of the pressurised and capillary ALE technologies addressed in this study is novel and there is no similar study in the literature. In addition, the comprehensive LCA of GH_2 production is performed for specific system boundaries selected in the present study, e.g. the site in Portugal, a substantial capacity of 60 MW, 50 % PV and 50 % wind energy, manufacturing and importing the ALEs from two different regions (Northern Europe and South Asia).

2. Materials and methods

SimaPro software is used for the modelling, where the available data are collected from different confidential sources in literature, the project site, the company producers, experts and the SimaPro inventory. SimaPro was selected for its unique impact assessment capabilities, enabling systematic evaluation of life cycle inventory data across various stages of a process or system. Moreover, SimaPro tools have shown suitable usage for analysing hydrogen production processes and have been extensively employed for similar processes by researchers in the field. The methods of the current LCA study followed the ISO 14044 requirements [54] and relevant guideline documents for hydrogen production systems [55], including the four stages: the goal and scope definition stage, inventory analysis stage, impact assessment stage, and interpretation stage. The next sections present descriptions of the methods in detail.

2.1. Goal and scope

The goal of this study is to define the most appropriate and environmentally friendly electrolysis hydrogen production among two advanced ALE technologies (ALE-P and ALE-C) based RES for Portugal location in a comparative way. The ALE-C technology was chosen from the literature as a promising technology. The new technology of ALE-C that achieves 40.4 kWh/kg H_2 power consumption [41] and falls within the goal of IRENA for 2050 for less energy consumption for hydrogen production (under 42 kWh/kg) [42]. This LCA study focuses mainly on the electrolysis hydrogen production phase and the effects of the advanced used materials (the study does not take into account the subsequent application of the produced hydrogen), in addition to testing the use of PV and Wind energy to power the hydrogen production. Additionally, Portugal was chosen as a case study since it is a country with a high penetration of RES in electricity generation. Nowadays, electricity production in Portugal is based on multiple energy resources (including fossil fuel and RES) with rapid progress toward the use of RES (specifically political target for penetration of RES in electricity), mainly wind and solar resources which represents a promising wide range of environmental features. Therefore, the environmental impacts listed in Table 1 are analysed for each ALE technology for the same system boundaries and powered by the same capacity of PV solar and wind energy.

The assessment process used in the LCA study is based on the International Reference Life Cycle Data (ILCD) following the European Commission recommendations [56]. The ILCD 2011 Midpoint method (available in SimaPro) is a proper calculation method as it accurately applies characterization factors for impact evaluation, drawing from existing environmental impact assessment models like EC-JRC. Also, the adoption of the ILCD 2011 method aligns harmoniously with prior LCA studies undertaken within the domain of electrolytic hydrogen production [48 5758], facilitating comparison and enhancing the reliability of the findings within the broader research context. The results are intended to be analysed for the production of 1 kg hydrogen as a functional unit with pressure of 33 bar, temperature of 40 ∘C, and 99.8 % purity. In addition, a normalization analysis is carried out by benchmarking the resulting environmental impacts to a standard system for a

Table 1
The analysed environmental impacts with their abbreviations and units.

Environmental Impact	Abbreviation	Unit
Global warming potential	GWP	kg CO_2 eq
Ozone depletion	ODP	kg CFC-11 eq
Human toxicity, non-cancer effects	HTnc	CTUh
Human toxicity, cancer effects	HTc	CTUh
Particulate matter	PM	kg PM2.5 eq
Ionizing radiation HH	IRH	kBq U235 eq
Ionizing radiation E (interim)	IRE	CTUe
Photochemical ozone formation	POF	kg NMVOC eq
Acidification	AP	molc H+eq
Terrestrial eutrophication	EP ter	molc N eq
Freshwater eutrophication	EP fw	kg P eq
Marine eutrophication	EP sw	kg N eq
Freshwater ecotoxicity	FWE	CTUe
Land use	LU	kg C deficit
Water resource depletion	WRD	m^3 water eq
Mineral, fossil & ren resource depletion	MFRDP	kg Sb eq

CFC-11 = trichlorofluoromethane; 2 NMVOC=non-methane volatile organic compound.

better understanding of the results. The normalization analysis is based on the EU Product Environmental Footprint (PEF) considering EC-JRC Global as a referenced standard system [59].

2.2. Life cycle inventory

The characterization of the system boundaries is essential as it includes the inputs and the process phases. The main life cycle stages and system boundary examined in this study are shown in Fig. 1. The construction of the two main units in the system are for the energy sources (PV solar and Wind) and hydrogen production through water electrolysis. Each unit includes raw materials, manufacturing, transport, operation and maintenance, dismantling, and waste treatment.

Throughout the inventory of the current LCA study, the total defined inputs and outputs from the electrolysis process of the system were evaluated and categorized according to environmental impacts considered using SimaPro software (version 9.3.0.3). The data adopted for the current LCA study were collected from project partners, producer companies, experts and related literature to be implemented based on the database of SimaPro (such as power supply, materials, and processes).

Moreover, for an accurate analysis of the environmental impacts, the data modelled for the operation supplies (such as water, potassium hydroxide, cleaning, maintenance, solar irradiation and wind location conditions) of the energy plant and electrolyser system are based on Portuguese datasets when it is available if not European datasets are evaluated. In addition, the production of the two ALE technologies is modelled (ALE-P and ALE-C) and the corresponding materials, energy, and processes were modelled in SimaPro software.

2.2.1. Electricity supply and operation

The main scenario of the current study is established considering the power supply to the electrolysis system from RES, based on 50 % power from wind turbines and 50 % power from solar PV in Portugal (described in Fig. 2), taking into account the annual yield ranges and the lifetime. The consideration of wind and PV energy sources and the selected percentages (50/50) comes for various reasons. Firstly, the selected location of the hydrogen project located in the south of Portugal, where the data regarding the total generated electricity in Portugal refers to around 27 % of electricity generated by wind turbines and 11 % by solar energy [60], with increasing the electricity generated solar percentage in the southern areas of Portugal. Also, it can be found by analysing the recent data provided by the National Laboratory of Energy and Geology in Portugal (LNEG) regarding the potential areas for the installation of solar and wind electricity units [61], the existing areas with possible installation of 50 % wind and 50 % solar units that can provide approximately equal electricity capacity to the grid. Secondly, having two different RES (solar and wind) suppliers enables the electrolysers to operate continuously, thereby boosting the overall efficiency of the hydrogen plant through increased operational hours and reduced expenses [62]. In this regard, solar and wind sources are usually preferred to be integrated for operating an H_2 production system, while other RES (such as hydropower) are preferable for grid base load usage without the need to balance their input sources [63]. Thirdly, GH_2 production is proposed as an optimal solution for utilizing RES in situations where there is a gap between electricity demand and production, particularly in instances of limited available storage capacity, where it is particularly relevant for solar and wind energy due to their dependence on weather conditions [64].

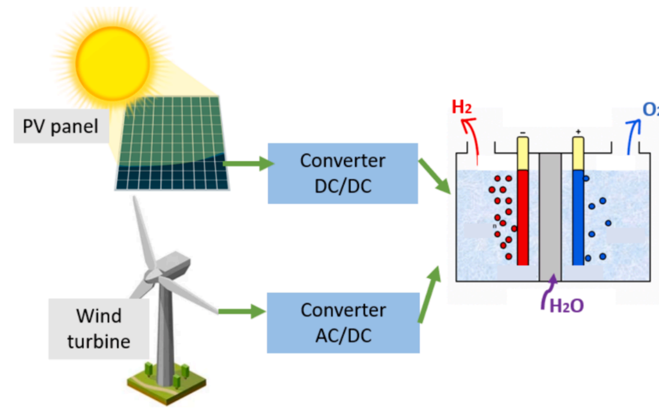


Fig. 2. GH_2 production-based hybrid solar and wind energy sources.

Moreover, a capacity of 60 MW by the wind/PV power plant is needed to power the electrolysis process in the Alkaline stacks. The data for power harvesting are all based on ecoinvent version 3 from the SimaPro database, corresponding to the conditions and performances of RES (wind and PV) in Portugal (as the location of the electrolysis system is in Portugal). It is assumed that wind/PV power plant with a capacity of more than 60 MW (e.g. up to 340 MW) is needed for the hydrogen production project. The wind/PV power plant should be capable of

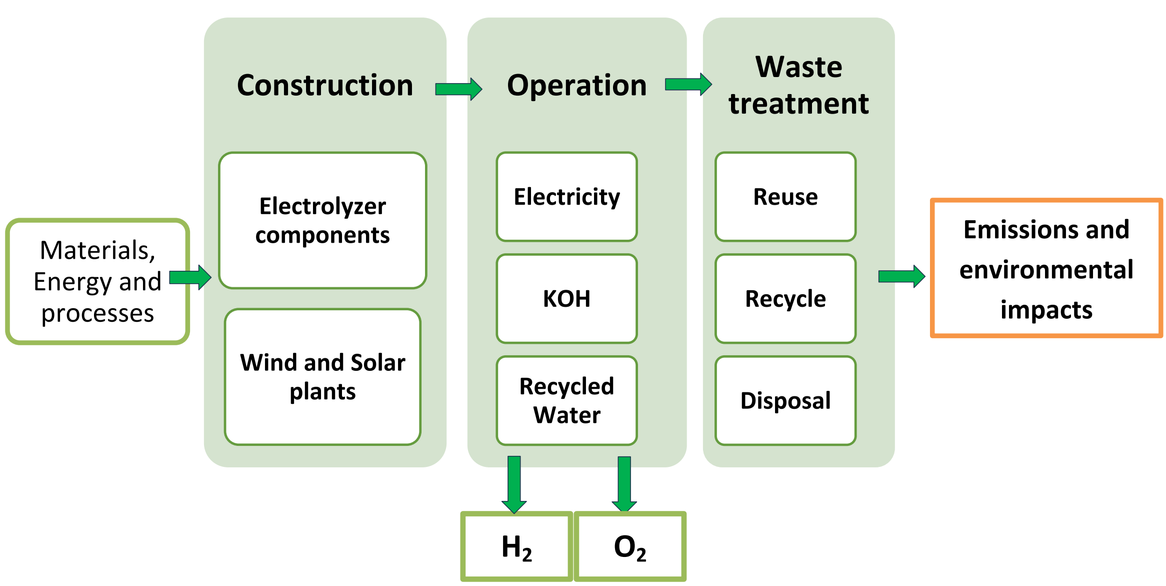


Fig. 1. Processes and components of the life cycle for ALE hydrogen production.

maintaining stable proportions of wind and solar energy at 50 %/50 % throughout the year regardless of fluctuations in power generation caused by weather conditions, as well as provide the additional electricity requirements on the site such as compressing and storage of hydrogen. In this regard, there are plans for future green hydrogen projects in Portugal such as the Green H_2 Atlantic with a 100 MW production capacity in Sines, Portugal [65]. Additionally, similar green hydrogen projects with wind/PV power plants already exist in locations in Spain with similar conditions to the studied project location here (south Portugal) such as the Teruel-Endesa hydrogen production project with 60 MW capacity for the electrolyser system associated with 334 MW Wind/Solar power plant [66].

Therefore, the onshore wind turbines were selected from the SimaPro database with a capacity of 4.5 MW for each (Enercon E-112 type), containing the infrastructure elements for the wind turbine (e.g. rotor, tower, blades and base foundation) and the electricity grid elements (e.g. voltage converter, connections and cables) [67]. In addition, the PV solar panels were selected for low voltage electricity with a 570 kWp open ground plant (multi-Si PV panels type). Also, the plant includes an inverter to convert the low voltage DC into AC power and the water used for cleaning. The inventory in SimaPro of the wind turbines and PV panels were modelled for Portugal considering the production of high voltage 1kWh of electricity distributed to the electricity grid, the operation and maintenance, replacement of materials (e.g. the lubricating oil is replaced every one year). In general, the GHG emissions for wind turbines can range between 8 and 62 g CO_2-eq per kWh, and for PV can be up to 132 g CO_2-eq per kWh [68]. A study by Schleisner [69] for offshore and onshore wind turbines reported data for GHG emissions of 16.5 and 9.7 g $CO_{2\text{-eq}}$/kWh respectively. Recently, the production of PV panels technology showed enhancement regarding GHG emissions reaching the range between 12 and 17.6 g CO_2-eq per kWh in the EU (excluding the balance of the system) with a lifetime between 25 years and 30 with high performance [70]. The modelled wind turbines and PV panels in the current study presented GHG emissions values of 16.7 g CO_2-eq/kWh for the PV and 9.8 g CO_2-eq/kWh for wind turbines which match the reported improvements in the literature.

Besides the electricity supply assessment of the ALE hydrogen project, the operation also includes the supply of deionized water and potassium hydroxide solution (25 % KOH v/v). The water is derived from a nearby wastewater treatment plant (recycled water), as an optimal water option for augmenting the environmental performance of the hydrogen production project. A lifetime of 10 years is considered for the KOH and the ALE stacks which require a replacement after its lifetime end. The total lifetime of the studied hydrogen production system is considered to be 20 years with an operation period of 8300 h per year. Hence, a single replacement was considered for the KOH and ALE stacks, entailing the doubling of the associated material quantities for the simulation inputs within the SimaPro database. Also, it is considered that the production of each 1 kg of hydrogen consumes around 10 L of deionized water in the total system (including the BoP). Also, steam and nitrogen are used for cleaning purposes of the ALE system during the operation period of the system. It should be also mentioned that purification and storage of the produced hydrogen are not considered into the boundary conditions of the studied system.

2.2.2. Technical scope and components of the electrolysers

The water electrolysis system is a popular procedure to produce hydrogen started in the early 19th century [71]. The electrolyser is composed of united cells of cathodes and anodes connected to DC voltage power, where hydrogen is released on the cathodes and oxygen on the anodes. Also, electrolytes and electrocatalysts are used for the electrolysis process to enhance the electrolyser efficiency and costs [23]. The two electrodes in ALE are separated by a membrane and enclosed in an electrolyte solution of KOH. The hydroxide ions (OH −) initially generate from the cathode and then transfer through the membrane layer to the anode, producing hydrogen at the cathode first [28]. Then the O_2 and H_2 gases are released by the oxidization of water molecules. Generally, ALE is operated at temperatures between 30 and 80 ℃, and is characterized by the low-cost materials used, for example, the electrolyte, asbestos for the membrane and the nickel electrodes [29]. In contrast, SO electrolyser technology works at high-temperature conditions above 700 ℃ which requires an extra heat energy source [72], along with other challenges of using SO electrolyser technology related to instability and degradation conditions of the materials [73]. The latter makes SO electrolyser technology unsuitable for joining with intermittent energy sources such as PV solar and Wind energy, but favourable with nuclear energy [74]. Moreover, PEM electrolyser is still seen as requiring higher expenses compared to ALE [75], because of the costly materials primarily composed of palladium/platinum for the cathode and ruthenium/iridium for the anode [76].

The big capacity of the investigated hydrogen project (60 MW ALE) in this study is still not in industrial operation yet. A commercial model was chosen as the maximum available capacity of around 15 MW for each unit which includes 10 stacks for each unit and 139 cells for each stack [77]. Therefore, four units of 15 MW capacity were considered for the project to obtain the required total 60 MW capacity, considered to be produced in Northern Europe. The needed information (especially the mass of used materials in the ALE production and operating requirements) were collected from the producers companies and by upscaling available data for lower project capacities such as 6 MW ALEs [48]. Moreover, the technical characteristics of the two ALE technologies in this study were defined based on the information found in the related publications and producer companies.

The performance of the capillary-fed ALE (ALE-C) has been improved, by using the technique of capillary membrane [41], by controlling the supply of the water directly through the membrane to the cathode and the anode side, avoiding the forming of bubbles on the electrodes during the electrolysis process [78], reaching the efficiency of 97.5 % based on the high heating value (HHV) of hydrogen. Based on studies and evaluations related to ALE-C, its characteristics can be determined as presented in the following Table 2. It should be mentioned that the PES material of the membrane has a porosity with a micrometre scale for the average pore diameter [41]. Furthermore, the characteristics of the pressurized ALE (ALE-P) have been reported by several research studies (an efficiency of 80.05 % HHV, for the ALE was defined) for similar investigations or in commercial documentation [79], as presented in Table 2.

Table 2
Characteristics of the two ALE technologies used for hydrogen production, the pressurized ALE (ALE-P) and capillary-fed ALE (ALE-C).

Characteristics	ALE-P [48,57,79]	ALE-C [41,80]
Membrane type	Zirfon	Porous polyether sulfone (PES)
Electrolyte	25 wt% aqueous KOH	27 wt% aqueous KOH
ALE Electricity to H_2 efficiency	80.5 %	97.5 %
Total efficiency with BoP 5.5 kWh	72.4 %	87.5 %
Energy consumption at stacks	48.8 kWh/kg H_2	40.4 kWh/kg H_2
Energy consumption at BoP	5.5 kWh/kg H_2	5.5 kWh/kg H_2
Total system Capacity	60 MW of 4 units	60 MW of 4 units
Capacity of each unit	15 MW	15 MW
System Lifetime	20 years	20 years
Number of stacks	40 (10 stacks for each unit)	40 (10 stacks for each unit)
ALE stack lifetime	10 years	10 years
Number of cells per stack	139	139
Annual operation	8300 h	8300 h
Operating pressure and temperature	33 bar and 85 ∘C	33 bar and 85 ∘C
The hydrogen production rate for a unit (15 MW)	307.4 kg H_2/h	371.3 kg H_2/h
Power of KOH cycle pump	1.5 KW	Capillary without pump

According to the information collected, the two technologies of ALE (ALE-C and ALE-P) share the same mass of materials (coloured with black in Fig. 3) for the cell frame, gasket, anodes and cathodes (Nickl, Steel, Aluminium, Copper etc.), while it differs with the materials of membrane (coloured with blue for ALE-P and orange for ALE-C) and the additional two catalysts of carbon- platinum np catalyst (Pt/C) and nickel–iron oxyhydroxide (NiFeOOH) were used for the ALE-C type, as shown in Fig. 3. The components and construction materials of the two ALE electrolysers in the current study are summarised in Fig. 3.

However, investigating the environmental impacts of replacing the membrane materials of a commercial ALE system (ALE-C type) with an advanced PES method (suggested recently by researchers for ALE-C type [41,80]) adding the catalysts (Pt/C and NiFeOOH) is considered one of the novelties and innovations of the current study presented here.

In addition to the stack components, the Balance of Plant (BoP) is considered in the current LCA which consists of tanks, heat exchangers, pumps, power electronics/inverter, potassium hydroxide filter and gas separator. The materials and mass of BoP were modelled based on the collected data from the producer company and related literature. In general, the environmental impacts of BoP are much lower than the ones caused by the electrolyser stacks. On another hand, the transportation used to bring the electrolyser systems to Portugal is considered and modelled as Container Ships in the LCA inventory considering the ALE-C system is produced in Northern Europe and the ALE-P system is produced in South Asia.

2.3. Waste treatment and reuse

One important way to reduce the environmental impacts and costs of hydrogen production with electrolysers is by reducing the amount of the used material throughout the system's entire life cycle. Therefore, recycling the components of the electrolysis while increasing the reuse rate and reducing the disposal to the landfill should be considered in an LCA study. A study by Ferriz [81] referred to strategies to recycle some components of ALE at its end of life, especially for Nickel and plastics. A hydrometallurgical process can be applied for the Raney Nickle, while the Polytetrafluoroethylene (PTFE) material can be grounded and mixed with pure PTFE. The other useful compounds can be recycled and cleaned from unwanted impurities to be suitable products in the industry. In the current study, the waste treatment (end-of-life) method of hydrogen production by the ALE system follows the strategy presented by Lotric et al. [82] where an inventory list was prepared for the recycling of the ALE system including the recovery rate and process. Therefore, the components of the system were considered to be manually dismantled. The rates of recycling for each material (steel, nickel, plastics, electronics) were estimated according to the recycling industry and available literature, as presented in Table 3 for some materials and as a 99 % recycling rate and 1 % rate for landfill for the rest of the used materials in the system.

The landfill disposal option was chosen only when the recovery or recycling of the materials was not feasible. In this, it should be mentioned that the majority of steel materials are mainly used as cell stack frameworks for house holding which can be reused for future projects and the rest of the steel is recycled.

3. Results and discussion

The environmental impacts of hydrogen production through the two ALE technologies are calculated and compared per 1 kg H_2 unit in this section.

3.1. Environmental impacts of the life cycle phases

The environmental impacts of the total life cycle phases including the construction, disposal and operation are presented in Fig. 4. The electricity supply and other operation requirements such as steam, KOH and nitrogen (discussed in section 2.2.1) are considered here when evaluating the overall hydrogen production system. The results show that the electricity supply (the energy mix of wind and solar supplies) of the ALE system occupies the major influence on the various environmental impacts with a contribution percentage of around 92 % for OPD, 96 % for MFRDP and 98 % for the rest of the categories (including GWP). Also, the impact values of the two ALE technologies are approximately similar in percentages for the total life cycle stages as presented in Fig. 4. The latter presents less importance of some operation requirements (steam, KOH and nitrogen) compared to the electricity supply.

Table 3
The considered waste treatment rates for some materials used in the system [82].

Material type	Reused	Recycled	landfill
Steel	60 %	35 %	5 %
Aluminium	0	96 %	4 %
N-methyl-2	0	84 %	16 %
Aniline	0	50 %	50 %
Pt/C	0	76 %	24 %

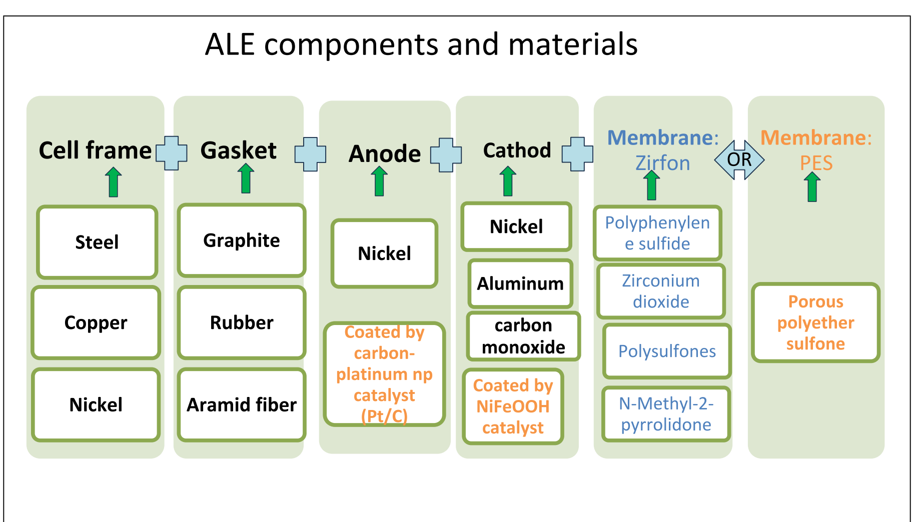


Fig. 3. Components and materials for the two ALE structures, distinguished by colours (the black materials are shared for both ALE, the blue materials are for ALE-P, and the orange materials are for ALE-C). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

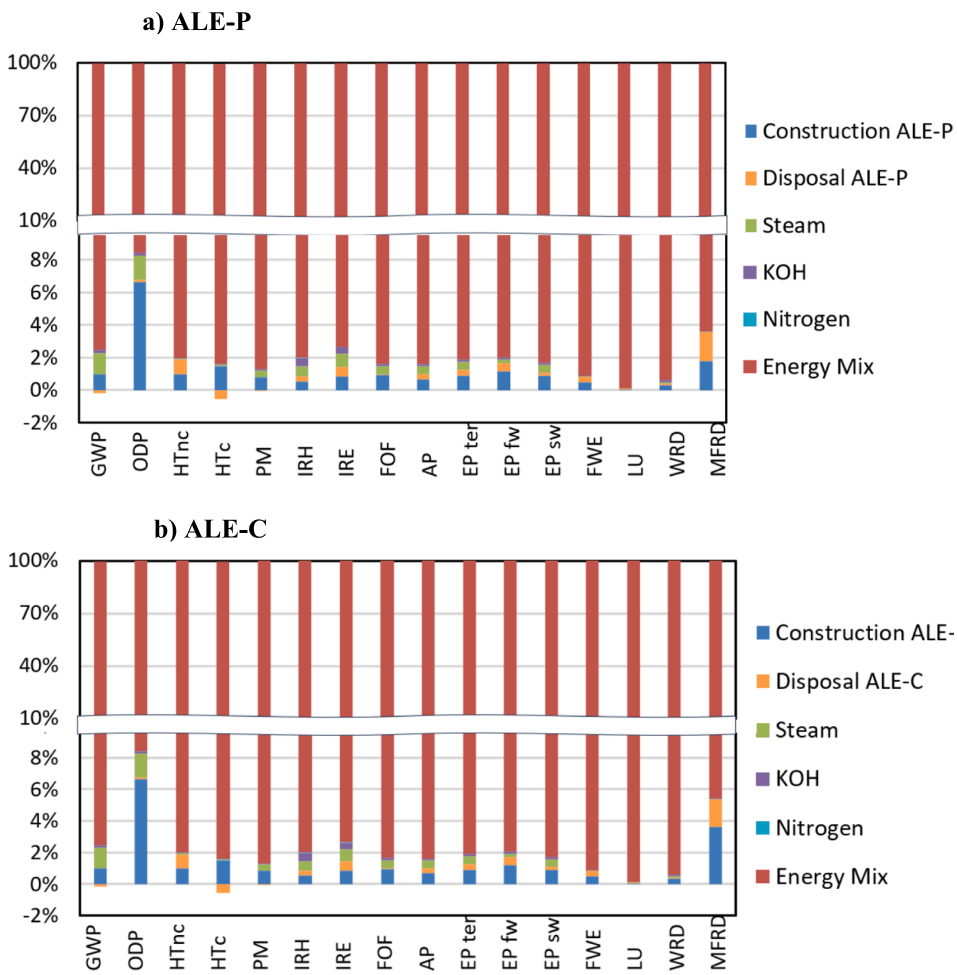


Fig. 4. Environmental impacts (per kg H_2) resulted from the total LCA of the value chain of the two electrolyser systems: a) ALE-P and b) ALE-C. Where: GWP: Global warming potential, ODP: Ozone depletion. HTnc: Human toxicity, non-cancer effects. HTc: Human toxicity, cancer effects. PM: Particulate matter. IRH: Ionizing radiation HH. IRE: Ionizing radiation E (interim). POF: Photochemical ozone formation. AP: Acidification. EPter: Terrestrial eutrophication. EPfw: Freshwater eutrophication. EP sw: Marine eutrophication. FEW: Freshwater ecotoxicity. LU: Land use. WRD: Water resource depletion. MFRDP: Mineral, fossil & ren resource depletion.

Moreover, as mentioned earlier, the electricity efficiency of the ALE system was improved by using the new ALE-C technology (replacing the membrane materials) to be around 87.5 % compared to 72.4 % for the ALE-P technology (including the BoP electricity requirements). Therefore, the used amount of energy will lead to a difference in the amount of hydrogen produced during the considered lifetime of the system (20 years), which affects the environmental impact values for each ALE technology (per kg H_2). Therefore, Table 4 summarises the

Table 4
Environmental impacts (per kg H_2) for the total LCA by using ALE-C instead of ALE-P.

Environmental Impact	Abbreviation	Unit	Total LCA		
			ALE-P	ALE-C	Decreases %
Global warming potential	GWP	kg CO_2 eq	2.396	1.980	17.3 %
Ozone depletion	ODP	kg CFC-11 eq	2.6E-07	2.1E-07	17.4 %
Human toxicity, non-cancer effects	HTnc	CTUh	2.9E-06	2.4E-06	17.4 %
Human toxicity, cancer effects	HTc	CTUh	1.0E-06	8.5E-07	17.4 %
Particulate matter	PM	kg PM2.5 eq	2.6E-03	2.2E-03	17.4 %
Ionizing radiation HH	IRH	kBq U235 eq	2.1E-01	1.8E-01	17.4 %
Ionizing radiation E (interim)	IRE	CTUe	7.7E-07	6.4E-07	17.4 %
Photochemical ozone formation	POF	kg NMVOC eq	1.0E-02	8.5E-03	17.3 %
Acidification	AP	molc H+eq	2.1E-02	1.7E-02	17.4 %
Terrestrial eutrophication	EP ter	molc N eq	3.3E-02	2.7E-02	17.4 %
Freshwater eutrophication	EP fw	kg P eq	1.6E-03	1.3E-03	17.3 %
Marine eutrophication	EP sw	kg N eq	3.1E-03	2.6E-03	17.3 %
Freshwater ecotoxicity	FWE	CTUe	7.1E+02	5.8E+02	17.4 %
Land use	LU	kg C deficit	1.7E+02	1.4E+02	17.4 %
Water resource depletion	WRD	m^3 water eq	2.1E-02	1.7E-02	17.4 %
Mineral, fossil & ren resource depletion	MFRDP	kg Sb eq	5.4E-04	4.5E-04	15.8 %

changes of all environmental impacts by using the new ALE-C technology (using PES membrane) compared to ALE-P technology for all the stages (operation, construction and disposal). The results indicate a decrease of around 17.4 % for most environmental indicators by using the new ALE-C technology. Furthermore, the results indicate high variation in the actual values from environmental indicator to other (e.g. 7.1E+02 for few and 2.6E-07 for ODP), as presented in Table 4.

In addition, as GWP has been considered a significant impact in LCA studies Fig. 5 presents the results of GWP for both ALE technologies. The total GWP of the total LCA using ALE-C technology is demonstrated to be lower than the one using ALE-P technology by around a 17.3 % decrease, which can be explained by the higher energy efficiency of ALE-C (97.5 % reported previously). The results confirmed the greater contribution of the used energy mix supply to the GWP values in both technologies.

It should be mentioned that the found value of GWP in the current study is 1.98 kg CO_2 eq./kg H_2 for ALE-C and 2.39 kg CO_2 eq./kg H_2 for ALE-P, which is lower by 83 % for ALE-C and by 79.8 % for ALE-P than the common hydrogen production method of SMR (around 11.89 kg CO_2 eq./kg H_2 [18]). Furthermore, the GWP results found by Ghandehariun and Kumar [83] for hydrogen production based only on the wind energy source was around 0.68 kg CO_2 eq./kg H_2). Also, Sadeghi et al. [45] found a GWP value of 3.08 kg CO_2 eq./kg H_2 for a hydrogen production system using PV solar power. On the other hand, Zhang et al. [47] found a GWP value ranges between 8.67 and 4.33 kg CO_2 eq/kg H_2 (change with the lifetime of the system from 30 to 60 years) of the electrolysis system-based PV power source. To compare of the ALE used in the current study to other electrolyser technologies, a study by Henriksen et al. [84] investigated H_2 production through PEM and SO electrolysis technologies in the United States case. The results reported GWP emissions of 2.8 CO_2-eq/ kg H_2 for PEM and 2.9 kg CO_2-eq/ kg H_2 for SO using renewable energy supply, in higher GWP values than the one found for ALE-C in this study. This represents the benefit of using the new advanced ALE-C technology compared to not only the conventional ALE but also to other electrolyser technologies such as SO and PEM. In the same sense, Zhao et al. [85] compared the use of the three electrolysis technologies and conventional ALE technology achieved lower GWP values compared to the use of SO and PEM electrolysers by 41 and 63 CO_2-eq/FU, respectively. Therefore, it can be concluded that ALE technology, in general, is achieving lower environmental impacts compared to other technologies (SOEL and PEM electrolysers), when ALE is chosen for the proper operation conditions and boundaries (such as temperature), and using an advanced version of ALE (such as ALE-C used in this study) will exceed the environmental advantages.

However, environmental impact values of hydrogen production mostly differ between conducted research to date, due to numerous issues such as the system capacity, energy supply type, location conditions, and used materials of the electrolysis technology. In general, previous studies in the field have reported data related to the environmental impacts of the total LCA of hydrogen production. In contrast, no detailed study focusing on the environmental impacts of the construction materials used for the ALE system could be found (to the best of the authors' knowledge), which is addressed in the current study in the next section.

3.2. Environmental impacts of the production phase of the electrolyser system

Through an individual analysis of the production phase of the ALE system, the influence of the material used on the environment can be assessed in detail regardless of the dominance of energy supplies in the operating phase. Therefore, the contributions of the materials in the ALE construction phase are subdivided and presented in Fig. 6 for the two ALE technologies.

As previously mentioned in section 2.2.2, the electrolyser system involves the components of the cells (the framework, electrodes, gasket and membrane), and BoP. The results in Fig. 6 show that steel and nickel, used mainly for constructing the cell components, cause the largest environmental impacts in most categories (e.g. around 65 % of GWP and 38 % of IRH for steel). At the same time, the results of the ODP category referred to a large contribution of the TFE materials used in the production of the gasket (around 97 % of ODP). Nickel is abundant in the electrodes and the cell frames, and its industrial process releases phosphorus and nitrogen emissions. Also, copper has a considerable contribution to most environmental impact categories (less than steel and nickel), especially for HTnc and AP. The membrane materials in both ALE technologies, Zirfon composites for ALE-P and PES of ALE-C, contribute in similar percentages of the total environmental impacts (the yellow part in Fig. 6). Furthermore, the catalysts used for the ALE-C,

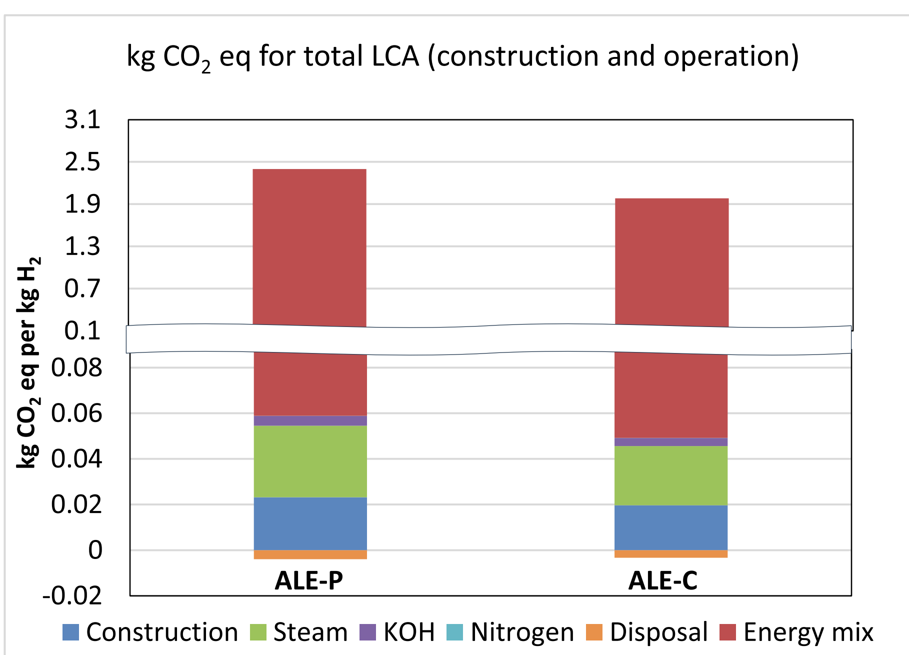


Fig. 5. GWP (kg CO_2 eq per kg H_2) for the total LCA of the value chain for ALE-C and ALE-C.

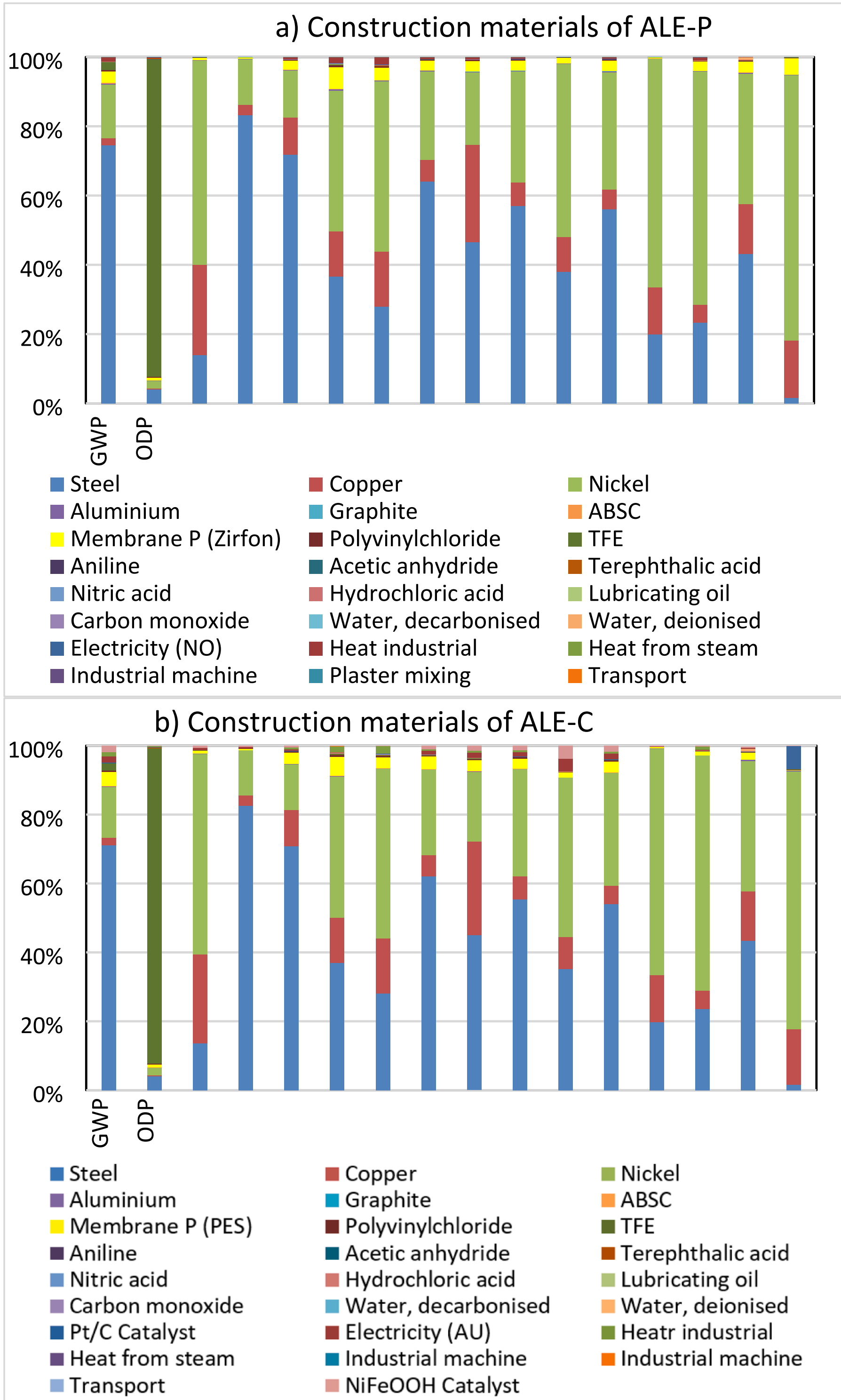


Fig. 6. Environmental impacts (per kg H_2) for the construction materials for: a) ALE-P and b) ALE-C. Where, GWP: Global warming potential, ODP: Ozone depletion. HTnc: Human toxicity, non-cancer effects. HTc: Human toxicity, cancer effects. PM: Particulate matter. IRH: Ionizing radiation HH. IRE: Ionizing radiation E (interim). POF: Photochemical ozone formation. AP: Acidification. EP ter: Terrestrial eutrophication. EP fw: Freshwater eutrophication. EP sw: Marine eutrophication. FEW: Freshwater ecotoxicity. LU: Land use. WRD: Water resource depletion. MFRDP: Mineral, fossil & ren resource depletion.

mainly Pt/C and NiFeOOH, caused additional small contributions to the various environmental impacts (e.g less than 3 %) due to the minimum amount used as a coating for the surfaces of the electrodes. It should be mentioned that the results presented in Fig. 6 were intended to show the contribution of each material (the materials used in the construction of the electrolyser technology) to the environmental impact categories in percentages, therefore it is necessary to present the absolute values for these categories per kg of hydrogen produced to compare the two ALE technologies. Thus, Table 5 summarises the changes of all environmental impacts per kg of hydrogen produced by using the new ALE-C technology (with PES membrane and the additional catalysts Pt/C and NiFeOOH) compared to ALE-P technology for the construction stage.

Table 5
The environmental impacts (per kg H_2) for the construction stage by using ALE-C instead of ALE-P (units are in Table 1).

Environmental Impact	Abbreviation	Unit	Construction phase		
			ALE-P	ALE-C	Decrease %
Global warming potential	GWP	kg CO_2 eq	2.32E-02	1.97E-02	15.1 %
Ozone depletion	ODP	kg CFC-11 eq	1.71E-08	1.41E-08	17.6 %
Human toxicity, non-cancer effects	HTnc	CTUh	2.86E-08	2.38E-08	16.6 %
Human toxicity, cancer effects	HTc	CTUh	1.56E-08	1.30E-08	17.0 %
Particulate matter	PM	kg PM2.5 eq	2.18E-05	1.82E-05	16.4 %
Ionizing radiation HH	IRH	kBq U235 eq	1.19E-03	9.72E-04	18.1 %
Ionizing radiation E (interim)	IRE	CTUe	6.72E-09	5.53E-09	17.6 %
Photochemical ozone formation	POF	kg NMVOC eq	9.82E-05	8.28E-05	15.7 %
Acidification	AP	molc H+eq	1.43E-04	1.21E-04	15.7 %
Terrestrial eutrophication	EP ter	molc N eq	2.90E-04	2.44E-04	15.9 %
Freshwater eutrophication	EP fw	kg P eq	1.87E-05	1.61E-05	13.9 %
Marine eutrophication	EP sw	kg N eq	2.77E-05	2.34E-05	15.6 %
Freshwater ecotoxicity	FWE	CTUe	3.55E+00	2.94E+00	17.1 %
Land use	LU	kg C deficit	7.34E-02	5.99E-02	18.5 %
Water resource depletion	WRD	m^3 water eq	7.02E-05	5.75E-05	18.1 %
Mineral, fossil & ren resource depletion	MFRDP	kg Sb eq	9.72E-06	8.24E-06	15.3 %

The results showed a reduction of the environmental indicators by using the new ALE-C technology ranging between 18.5 % for LU and 13.9 % for EP-fw. These results (the reduction in the environmental impacts in Table 5) are mainly due to the lower energy efficiency (Electricity to H_2 efficiency) and lower energy consumption at stacks of the ALE-C technology compared to the ALE-P technology, which appemidars when counting per kg H_2 produced. Furthermore, the actual values for each total environmental impact (caused by all the materials together) for each ALE technology are presented in Table 5 which refers to high relative values for FWE and low values for IRE.

However, the critical GWP impacts are usually proportional to the steel mass used in the ALE construction, as steel being the major cause of GWP among the electrolyser components. Fig. 7 presents the results of GWP for the construction of both ALE technologies per kg H_2. The GWP is decreased by 15.1 % when the ALE-C technology is used compared to ALE-P due to the energy efficiency enhancement of ALE-C.

3.3. Environmental impacts of the disposal phase

The possibility of recycling the components of both ALE systems for the reuse of the system after the considered project lifetime (20 years) may cause additional increases/decreases for the potential environmental impacts due to the manufacturing requirements (such as energy inputs). Therefore, this section discusses the environmental impacts

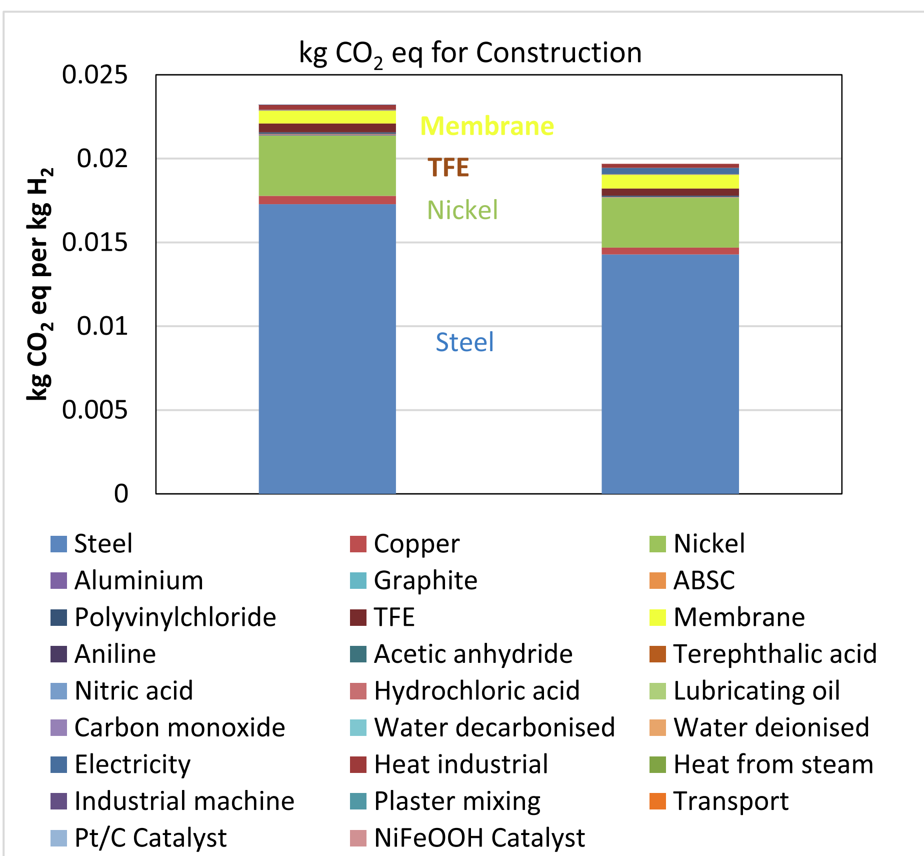


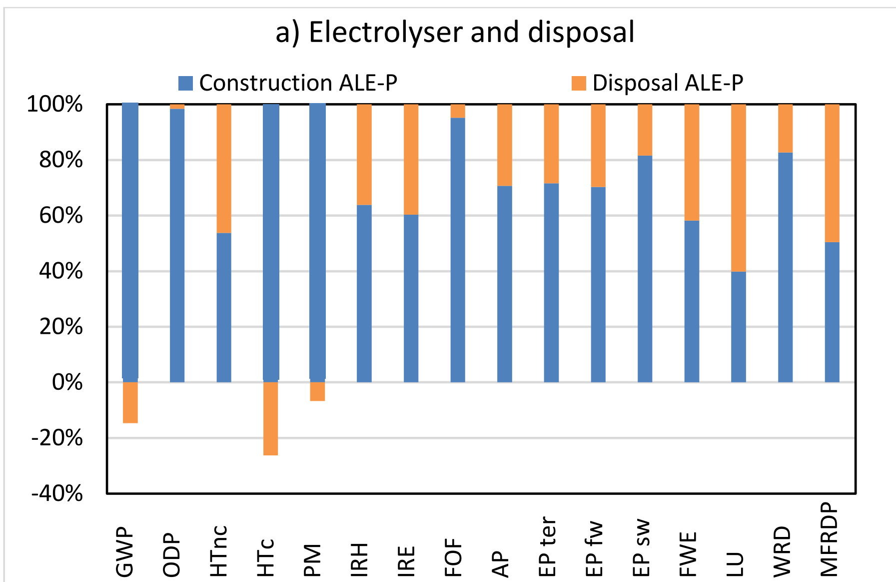
Fig. 7. GWP (kg CO_2 eq. per kg H_2) for the LCA of the construction materials for ALE-C and ALE-C.

caused by the waste disposal stage for both ALE systems, as presented in Fig. 8 (the orange part). The results show a decrease in GWP, HTc and PM caused by the waste treatment stage by about 18 %, 22 % and 6 %, respectively. In contrast, the remaining 13 environmental impacts increased for both ALE systems due to the recycling process.

These increases in environmental impacts are due to the manual dismantling and recycling processes due to the additional energy used and associated emissions. Reusing the steel in the cell stacks has also caused a reduction in the environmental impacts. However, due to the high energy efficiency of the ALE-C system, the energy recovery process is not considered for this study. However, the applied end-of-life processes (recycling, reuse, and landfill) caused extra energy and materials spending, increased emissions, and raised the environmental impact. On the other hand, the reuse of some materials led to a decrease in the environmental impacts.

3.4. Normalization

The normalization step is carried out and the results for both ALE technologies are presented in Fig. 9 for the construction stage and the total stages. The normalization analysis compares the 16 environmental impacts. ALE-C system yields the best results by allowing the smallest normalized values which were found to be 0.24 for the total stages (Fig. 9 a) and 0.0021 for the construction stage (Fig. 9 b), compared to ALE-P causes normalized impacts of 0.29 for the total stages (Fig. 9 a) and 0.0024 for the construction stage (Fig. 9 b). Also, the results show that GWP contributes the highest values to the normalized environmental impacts in both ALE systems. Also, Human toxicity impacts (HTc and HTcn) considerably contribute to the overall normalized results (with less than 8 % of the annual impacts of the average EU citizen Fig. 9 a). However, the life cycle of the total system of H_2 production in 20 years accounts for less than 30 % (the maximum obtained value, Fig. 9 a) of the annual impacts of the average EU citizen (EU Product



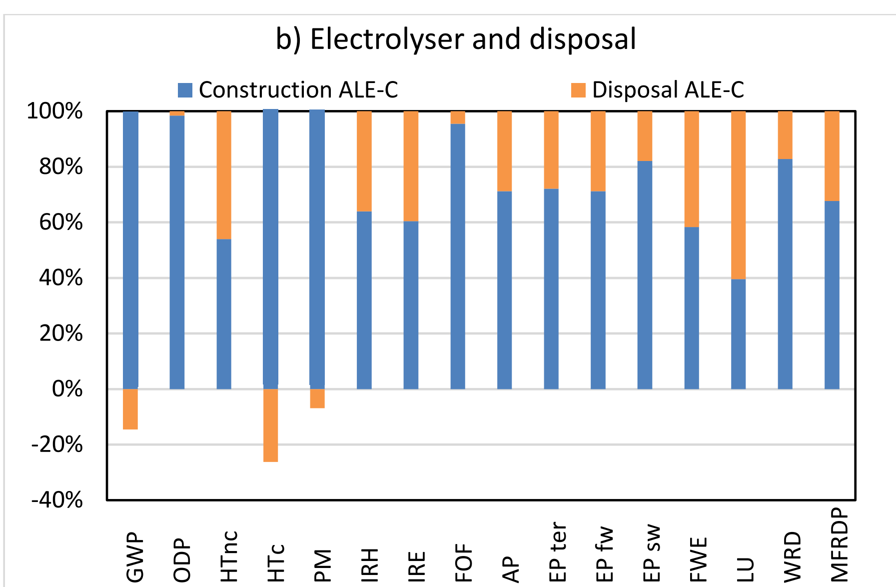


Fig. 8. Environmental impacts (per kg H_2) of the construction and the disposal for: a) ALE-C and b) ALE-C. Where, GWP: Global warming potential, ODP: Ozone depletion. HTnc: Human toxicity, non-cancer effects. HTc: Human toxicity, cancer effects. PM: Particulate matter. IRH: Ionizing radiation HH. IRE: Ionizing radiation E (interim). POF: Photochemical ozone formation. AP: Acidification. EP ter: Terrestrial eutrophication. EP fw: Freshwater eutrophication. EP sw: Marine eutrophication. FEW: Freshwater ecotoxicity. LU: Land use. WRD: Water resource depletion. MFRDP: Mineral, fossil & ren resource depletion.

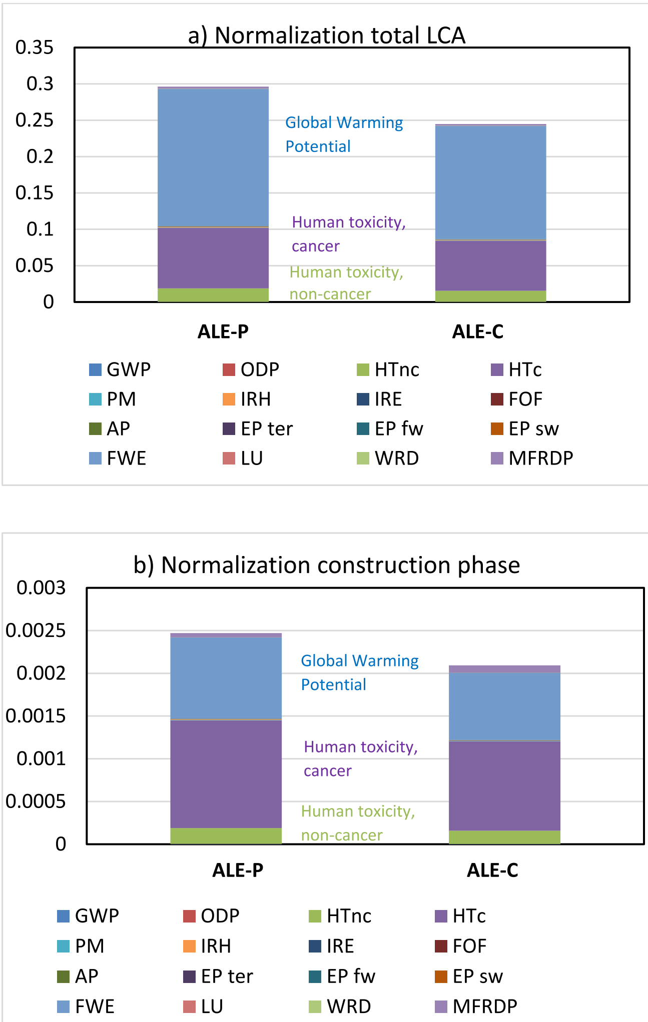


Fig. 9. Th normalization of environmental impacts per kg H_2 for: a) total LCA and b) construction phase. Where, GWP: Global warming potential, ODP: Ozone depletion. HTnc: Human toxicity, non-cancer effects. HTc: Human toxicity, cancer effects. PM: Particulate matter. IRH: Ionizing radiation HH. IRE: Ionizing radiation E (interim). POF: Photochemical ozone formation. AP: Acidification. EP ter: Terrestrial eutrophication. EP fw: Freshwater eutrophication. EP sw: Marine eutrophication. FEW: Freshwater ecotoxicity. LU: Land use. WRD: Water resource depletion. MFRDP: Mineral, fossil & ren resource depletion.

Environmental Footprint (PEF)), which is an acceptable value.

3.5. Sensitivity analysis

In this section, a sensitivity analysis is conducted to assess the data uncertainties associated with the newly proposed ALE-C technology for hydrogen production, encompassing all stages, namely operation, construction, and disposal. Therefore, the sensitivity analysis considers the ALE system boundaries that may change based on the operation conditions, mainly significant boundaries such as lifetime and energy efficiency. Furthermore, the results of this study (e.g. Fig. 4) showed the electricity supply (50 % PV and 50 % wind power) to have a contribution of about 98 % for most environmental impact categories (including GWP), therefore it is intended to also perform a sensitivity analysis for the ratio between wind and PV, considering the two ratios 75/25 % and 25/75 % for PV/wind power. In addition, it is intended to compare the PV/wind ratios against Portugal's national grid electricity (considered as an additional scenario), providing a thorough comprehension of how various electricity supply scenarios influence the environmental impacts of the ALE system. Therefore, the grid electricity in Portugal is modelled in SimaPro software based on the data collected in 2023, where the grid was supplied by 92 % of electricity generated within Portugal involving 24 % wind power, 9 % PV solar, 28 % hydropower, 7 % bioenergy, 20 % natural gas, and 4 % other fossil fuels [60], and 8 % of electricity is imported from Spain (92 % from Portugal and 8 % from Spain) [86]. Thus, the Tornado chart is established for the total GWP (Global warming potential) indicator that has been chosen for the sensitivity analysis as the most critical and known parameter among the 16 environmental impacts. The variations of the input boundary parameters are presented in Table 6. The ranges shown for parameters 1 and 2 in Table 6 come from the fact that ALE-C technology is still new and not thoroughly experienced for long periods (such as 20 years), in contrast to ALE-P technology systems. Therefore, the uncertainty of the energy efficiency is assumed here as $\pm$ 1.5, while the uncertainty of the lifetime is assumed here to be between −8 years and + 4 years. The latter assumptions of the uncertainty ranges are based on the authors' logical expectations, as changes in the lifetime and the energy efficiency of the ALE electrolyser system may happen when the capillary membrane materials (PES) are used (where there isn't available information about the operation of ALE-C for the total lifetime of the project, such as 20 years).

The resulting Tornado chart in Fig. 10 displays the range of the GWP changes according to each associated boundary parameter value. It can be observed that the hydrogen production-based ALE-C technology can be derived the most by the lifetime uncertainty of the project. The total GWP environmental impact varies between 1.70 and 2.97 kg CO_2 eq./kg H_2 based on the system lifetime, and between 1.94 and 2.02 kg CO_2 eq./kg H_2 based on the energy efficiency. For the PV and wind ratio analysis, the total GWP varies between 1.73 (for 25 % PV and 75 % wind) and 2.23 (for 75 % PV and 25 % wind) kg CO_2 eq./kg H_2, which refers to the advantages of using higher percentages of wind power (to lower the GWP impact) for the electricity supply for hydrogen electrolysis production. On the other hand, employing grid electricity in Portugal scenario (100 %) for the ALE system to produce hydrogen (not green hydrogen) yielded a large GWP value of 6.25 kg CO_2 eq./kg H_2 compared with the analysed PV and wind ratios (25/75, 50/50, 75/25). However, the found range of the GWP for green hydrogen production supplied by PV and wind ratios, in the current study, is larger than the GWP determined by Ghandehariun and Kumar [83] for hydrogen production based only on the wind energy source (around 0.68 kg CO_2 eq./kg H_2) and lower than the GWP determined by Sadeghi et al. [45] for hydrogen production systems using PV solar power (3.08 kg CO_2 eq./kg H_2) as well as lower than the GWP determined by Zhang et al. [47] for the electrolysis system-based PV power source (8.67 and 4.33 kg CO_2 eq/kg H_2).

4. Conclusions

The current study has conducted a thorough analysis of the life cycle for GH_2 production-based PV solar and wind energy in Portugal with a capacity of 60 MW, comparing two recent advanced ALE technologies using SimaPro software. The LCA results demonstrated that ALE-C technology has lower potential environmental impacts than ALE-P technology in the examined 16 environmental categories. The electricity supply (provided by solar and wind energy sources) occupies

Table 6
Variation of the boundaries' parameters for sensitivity analysis.

Parameters	Unit	Ranges
1- ALE-C system lifetime	y	12—24
2- ALE-C system energy efficiency	%	96—99
3- PV and wind power ratio, compared to Grid electricity	%	75/25 % – 25/75 %, and grid electricity 100 %.

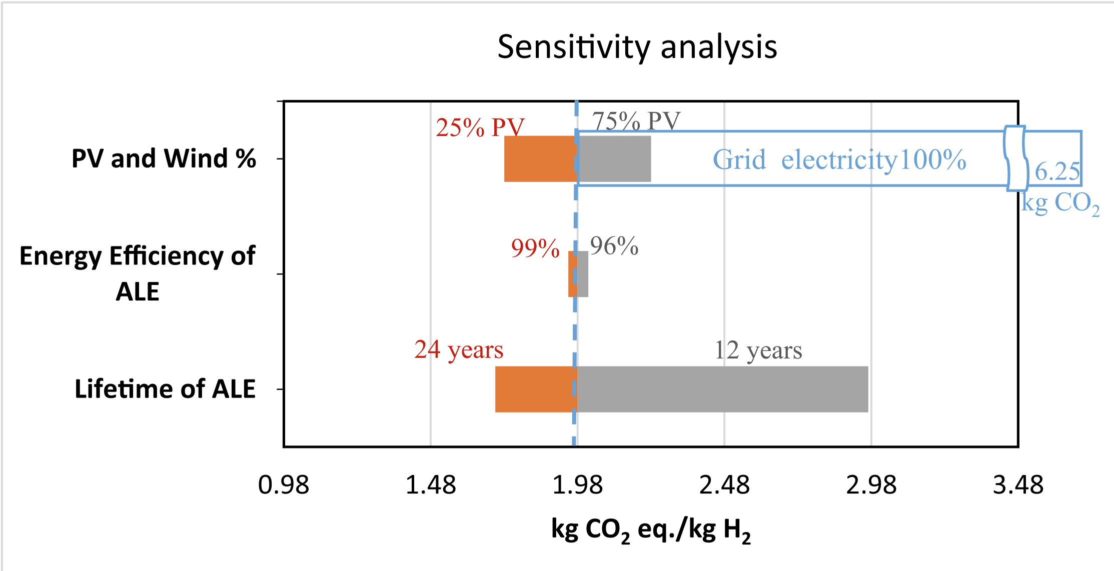


Fig. 10. Tornado chart for GWP environmental impact of the hydrogen production-based ALE-C technology.

around 98 % of the impacts on the various environmental categories. Also, a decrease of around 17.4 % was found for most environmental indicators (including the Global warming potential indicator) by using the new ALE-C technology for the total process.

For the construction stage of the ALE, steel and nickel presented the largest contributions to the environmental impacts in most categories e.g. around 65 % of GWP and 38 % of IRH for steel. Also, TFE materials used for the gasket part caused around 97 % of ODP impact. The impact of the membrane materials was similar in percentage in both ALE technologies (Zirfon composites for ALE-P and PES for ALE-C). Additionally, the catalysts used for the ALE-C, mainly Pt/C and NiFeOOH, caused a contribution lower than 3 % to the various environmental impacts. Moreover, the use of new ALE-C technology reduces environmental impacts in the ranges between 18.5 % for LU and 13.9 % for EP-fw (for the construction phase per kg H_2). For the GWP (Global warming potential), a decrease of 15.1 % was found when the ALE-C technology was compared to ALE-P.

For the waste disposal stage, decreases in GWP (Global warming potential), HTc (Human toxicity, cancer effects) and PM (Particulate matter) categories were found by about 18 %, 22 % and 6 % respectively, whereas the remaining 13 environmental categories increased for both ALE systems due to the additional energy input for the recycling process.

During the normalization analysis, it was observed that ALE-C yielded the lowest normalized values, 0.24 for the total stages and 0.0021 specifically for the construction stage, when compared to ALE-P.

Furthermore, the sensitivity analyses referred to an estimated variation in the total GWP (Global warming potential) between 1.7 and 2.9 kg CO_2 eq./kg H_2 based on the system lifetime (range 12 to 24 years), 1.73 and 2.23 kg CO_2 eq./kg H_2 based on PV/wind ratio (25/75 and 75/25), and between 1.94 and 2.02 kg CO_2 eq./kg H_2 based on the energy efficiency of ALE-C (range 96 %-99 %). However, the standard value of GWP found in this study was found to be 1.98 kg CO_2 eq./kg H_2 for ALE-C and 2.39 kg CO_2 eq./kg H_2 for ALE-P, which is lower than using grid electricity scenario in Portugal (found in this study with value of 6.25 kg CO_2 eq./kg H_2) and much lower (by 83 % for ALE-C and by 79.8 % for ALE-P) than the common hydrogen production method of SMR (around 11.89 kg CO_2 eq./kg H_2).

Moreover, advancements in electrolyser systems technology present additional opportunities for enhancing system efficiency and minimizing energy and materials usage. The ALE-C technology, as proposed, demonstrates the potential for increased hydrogen productivity and decreased environmental impacts compared to conventional methods. Future research should focus on optimizing various stages of the hydrogen value chain, such as distribution, storage, and utilization across diverse applications. Additionally, exploring the feasibility of utilizing multi-power distribution networks for cost reduction and improved energy consumption in hydrogen production projects, including thermal management strategies, could further improve total system energy efficiency and mitigate environmental impacts.

However, this study provides an important analysis of the environmental aspects needed for industrial electrolyser producers and planned projects to produce GH_2 needed in many applications, following the target for decarbonization the society for the next decades. The results of this study can be used alongside other categories such as economic and social aspects for creating appropriate decisions in the field of hydrogen production.

CRediT authorship contribution statement

Wagd Ajeeb: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Patrícia Baptista:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Conceptualization. **Rui Costa Neto:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation, Conceptualization.

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.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2024.118840.

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