Fuel 390 (2025) 134749

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Life cycle analysis of hydrotreated vegetable oils production based on green hydrogen and used cooking oils

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ARTICLE INFO

Keywords:
HVO
Green hydrogen
Life cycle analysis
Renewable energy
Used cooking oils

ABSTRACT

Hydrotreated Vegetable Oils (HVOs) have won significant attention worldwide as a viable alternative to fossil diesel in transportation. In the present study, a life cycle analysis (LCA) of the production of HVO is conducted, focused on HVO in the case of Portugal. The production process considered exploits used cooking oils (UCOs), alongside green hydrogen (GH_2). SimaPro software is used to analyse the environmental impacts of the entire value chain associated with the production of GH_2 and HVO. The resulting environmental impacts are also compared with other conventional scenarios that include using virgin oils and the grid mix electricity. The LCA results demonstrated that the HVO produced using GH_2 and UCO has a reduction in environmental impacts by around 0.23 to 0.45 kg CO_2 eq./kg HVO compared to the conventional scenarios. The lowest GWP level observed is in the UCO with PV/Wind electricity scenario at 0.304 kg CO_2 eq/kg HVO, While the highest GWP is for using Palm Oil with grid mix at 0.748 kg CO_2 eq/kg HVO. These findings underscore the significant influence of electricity sources and feedstock type on the GWP values in HVO production.

1. Introduction

In the modern era, energy demand and climate change represent pressing challenges, highlighting the urgent need for a sustainable energy transition in the transport sector. Growing awareness about the environmental impacts of greenhouse gases (GHG) is increasingly driving the search for innovative solutions. In this context, the importance of renewable fuels like Hydrotreated Vegetable Oils (HVO) becomes crucial for many applications, particularly the HVO produced based on used cooking oils (UCO) [1]. In terms of liquid fuels, HVOs have gained special attention in recent years due to their quality performance in existing diesel engines, their low pollutant emissions and their renewable nature [2]. HVO can be considered a superior alternative to fossil diesel in various applications since it has similar chemical characteristics to fossil diesel but can improve the GWP emissions due to its renewable nature [3]. HVOs can be obtained from the hydrotreatment of different raw materials such as vegetable oils, animal fats, sewage sludge, nut shells, biomass fraction of wastes and residues from forestry and forest-based industries [4,5]. The use of waste materials, particularly UCO, as sustainable feedstocks for the production process of those renewable fuels increased their advantages in terms of costs and environmental aspects. Also, transforming used oils into fuels originates better yields in biofuel production and can help alleviate the energy crisis [6,7].

In addition, HVO usage leads to a notable decrease in the GWP emissions in internal combustion engines when contrasted with the use of fossil diesel, particularly in the context of transitioning towards ultra-low emission vehicles [8]. Moreover, HVO features high reactivity that enables increasing combustion efficiency and achieves ultra-low emissions when exhaust gas recirculation strategies are employed [9]. This approach using HVO effectively mitigates emissions in usage and production stages such as nitrogen oxides and others [10]. On the other hand, HVO can also be blended with fossil diesel to contribute towards reducing fuel consumption [11,12].

Furthermore, by-products of the production process of HVO such as propane, liquefied petroleum gas and naphtha can also be sold on the market, adding economic value to the process [13]. The advantages of hydrotreatment in relation to transesterification (for example the process used to produce Biodiesel) include the possibility of achieving a greater percentage of blending with fossil fuels and greater flexibility in the selection of raw materials [14]. In this process, hydrogen is used to remove oxygen atoms and double bonds from the triglyceride structure through decarbonylation, decarboxylation and hydrodeoxygenation

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https://doi.org/10.1016/j.fuel.2025.134749
Received 8 July 2024; Received in revised form 26 January 2025; Accepted 14 February 2025
Available online 18 February 2025

Nomenclature

ALE	Alkaline electrolysis
ALE-P	capillary-fed alkaline electrolysis
AP	Acidification
EP ter	Terrestrial eutrophication
EP fw	Freshwater eutrophication
EP sw	Marine eutrophicatio
FEW	Freshwater ecotoxicity
GH_2	Green hydrogen
GHG	greenhouse gases
GWP	Global warming potential
HTnc	Human toxicity, non-cancer effects
HTc	Human toxicity, cancer effects
HVO	Hydrotreated vegetable oils
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
ODP	Ozone depletion
OH−	hydroxide ions
PEM	proton-exchange membrane
PM	Particulate matter
POF	Photochemical ozone formation
PTFE	Polytetrafluoroethylene
RED II	Renewable Energy Directive (2018)
RED III	Renewable Energy Directive (2023)
RES	Renewable energy sources
SMR	steam methane reforming
UCO	used cooking oil
WRD	Water resource depletion

[12]. Additionally, the composition of HVOs is mainly based on a mixture of paraffinic hydrocarbons that do not contain sulfur or aromatics, which enable them to have a high cetane number and properties like those observed in traditional diesel produced from fossil materials [15]. It can also have better storage properties [16] and greater lubricity than fossil diesel [17] while helping to reduce different types of emissions when used in internal combustion engines such as CO_2 (up to 4 % of reduction) and NO_x (up to 25 % of reduction) [4]. Therefore, the use of green hydrogen, produced by water electrolysis [18], has appeared to be the most effective way to maximize the advantages of HVO (as hydrogen is considered an essential component of the production process). Thus, renewable fuels have been used for some years as a very viable option to meet energy demand in a sustainable way.

In this regard, the importance of employing life-cycle analysis (LCA) studies of these fuels appeared not only to address their role in climate change mitigation but also to help promote cleaner and more sustainable mobility, triggering significant advances in the transition to a more efficient future in the transport sector [19]. Therefore, a LCA of the total value chain of HVO provides an overall context for improving energy efficiency and adjusting the environmental impacts of the system. A study by Concas et al. [20] analysed the hydrogen electrolysis production powered by wind and PV energy sources for fuel cells and methane production applications. A significant enhancement for environmental impacts was found for the use of PV in the hydrogen production and using hydrogen for fuel cell application with 2.4 kg CO_2/kg H_2 (compared to 11.8 kg CO_2/kg H_2 by steam methane reforming (SMR)). Moreover, Wang et al. [21] studied the hydrogen electrolysis production and its usage for fuel cells ships in China, and promising performance was found regarding the environmental advantages. Sadeghi et al. [22] reported an enhancement of the lifetime (by 5 years) and a decrease in global warming potential (GWP) by 26 %, due to the use of solar compared to the SMR process for hydrogen production. In this, the site conditions (related to sun radiation or wind speed) play an important role in the electricity supply by renewable energy sources, influencing the environmental impacts [23].

Renewable energies are used to produce green hydrogen mainly by the effective water electrolysis process [24]. Several electrolysis processes (different electrolysers) have been used such as alkaline electrolyser (ALE) [25], proton-exchange membrane (PEM) and solid oxide (SO) that differ in the operation conditions and materials for their construction [26]. Using multi-renewable energy sources for the green hydrogen production process helps to overcome the power supply instability caused by the factors related to the location, e.g., the variable sun radiation and wind velocity during the day [27,28]. One of the common electrolysis methods is ALE which consists of two electrodes made of Nickel, a membrane and an electrolyte solution that is considered low-cost in the case of materials and it is operated at low temperatures (30–80 C°) [25,27]. However, the water electrolysis method is still in continuous development mainly to enhance the current density and operation conditions such as temperature and pressure, lifetime and energy consumption [32,33]. Also, the produced hydrogen from different electrolysis technologies, mainly AWE, PEM and SOEC in addition to Anion Exchange Membrane (AEM), are used in further power to gas/liquid processes to produce products such as Syncrude and Synthetic Natural Gas (SNG) [34].

Therefore, it becomes good timing to implement green hydrogen (produced by water electrolysis powered by renewable energy) in the process of HVO production to mitigate the environmental impacts (mainly caused by conventional hydrogen production methods such as SMR). However, the hydrogen electrolysis production process is still causing environmental impacts due to the needed production of the components of the electrolysis system and linked renewable sources should be considered and optimised [35,36]. The hydrogen electrolysis process and renewable fuels production should be evaluated regarding the environmental performance using some environmental indicators [37,38] such as GWP, eutrophication, abiotic depletion potential (ADP), freshwater eutrophication potential (FEP), and ionizing radiation (IRP), for example.

The current study conducts a LCA for HVO production based on GH_2 produced from renewable energies (both PV solar and wind energy sources) and UCOs as feedstock, in Portugal. This study follows the objectives defined in Europe for climate neutrality and decreasing greenhouse gas emissions, such as the targets defined in the “Fit for 55 package” [39] and “RED II and III” [40], and to support reasonable decisions on the hydrogen technological path and the incorporation of hydrogen into each value chain, that best matches the national requirements supervised by a deep scientific and technical discussion [41,42]. Additionally, this LCA study uses a comprehensive approach that considers several environmental impacts (such as GWP, ODP, AP, and other toxicity categories). In contrast, most previous LCA studies on H_2 and HVO have predominantly focused solely on only GWP. Furthermore, the specific conditions of this study distinguish it from previous papers: geographical scope and case study in Portugal, the capacity of 305 kt UCO, powered by 50 % solar and 50 % wind energy, using green hydrogen and comparing four different scenarios. These factors make the current study a novelty in the literature.

2. Methodology

It becomes clear that the environmental impacts correlated with

HVO production are required to be properly assessed concerning all stages of the life cycle to provide appropriate comparisons between different possible scenarios of energy sources and input materials. In this meaning, the LCA methodology has been widely performed to evaluate the ecological performance of the HVO production process during its total life cycle. Therefore, the methodology adopted for this LCA research is following the ISO 14044 conditions [43] and the related instructions for production systems associated with hydrogen [44], mainly defining the goal and scope, analysing the inventory, impact assessment stage and interpreting the final results.

Moreover, SimaPro software is used for the modelling, where the available data are collected from different confidential sources in literature, different companies, experts and the SimaPro inventory. The results evaluate the environmental impacts depending on various factors such as the operation, requirements, and construction components for the stages of the total value chain from the feedstocks collection to the hydrogen electrolysis process to the HVO production. The presented system boundaries of this study encompass a location in Portugal, a conversion capacity of 305 k tons of UCO per year and a renewable energy supply (50 % PV and 50 % wind energy). Furthermore, additional three scenarios, involving the use of conventional feedstock (virgin palm oil) and the electricity grid mix in Portugal as a power supply to the hydrogen and HVO production processes, are examined and compared with the main scenario of using UCO and PV/Wind energy supply.

Furthermore, a normalization assessment is performed by comparing the resulting environmental impacts against a reference system to enhance the interpretation of the findings. This assessment utilizes the EU Product Environmental Footprint (PEF), with the EC-JRC Global framework serving as the benchmark reference [45]. Also, sensitivity analysis is conducted to assess the data uncertainties associated with HVO production, encompassing all life cycle phases. This analysis employs a Tornado chart based on the GWP indicator. Key parameters considered include critical boundaries such as electricity and steam usage during the production phase, as well as possible variations in the collection and transportation of UCO feedstock required for the process.

2.1. Goal and scope

The target of the current LCA study is to predict the environmental performance of the production process of HVO using GH_2 and UCOs as feedstocks in Portugal. The pressurised Alkaline electrolyser (ALE-P) technology was chosen for this study because of its technological maturity. The produced GH_2 is supplied with the pre-treated raw materials to the reactors and the operation requirements of temperature, pressure and other inputs are applied to produce the HVO and byproducts. Furthermore, this study analyses the implementation of a mixed PV and wind energy plant in Portugal to provide the needed electricity for the different processes. Currently, the grid electricity in Portugal is supplied by multiple sources such as fossil fuels and renewable energies. Although, the progress towards the change of using fossil fuels for the use of renewable energies is going rapidly, mainly wind and solar PV which correspond to significant environmental advantages. Thus, this study considers 16 environmental impacts presented in Table 1 using the ILCD 2011 Midpoint evaluation method recommended by the European Commission [46].

Also, the functional unit selected for the HVO production is 1 kg of HVO. The UCOs used in the operation were collected mostly from Portugal, Spain, Netherlands and Malaysia. This information will be discussed in more detail in section 2.2.4.

Additionally, for a better understanding of the results and the advantages associated with producing HVO based on UCO as feedstock and PV/Wind energy supply, three additional scenarios are considered for comparison with the main scenario. The three scenarios are mainly to examine the use of virgin vegetable oil (Palm Oil) as a feedstock and the grid electricity mix in Portugal for the energy supply. Therefore, the main scenario and the other three scenarios considered in the current study are summarised in Table 2 as follows:

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; **NMVOC: non-methane volatile organic compound.

2.2. Life cycle inventory

Firstly, it is important to present the elements and boundaries of the HVO production system for a proper LCA study, considering the production stages from the electricity supply to the hydrogen production and the reactor process including the processes' inputs and outputs. The process stages and boundaries of the current study are presented in Fig. 1. The construction processes include the requirements for two main units: the water electrolysis system for hydrogen production and the reactor systems for HVO production. Also, the construction stage of each unit (as presented in Fig. 1) should contain the inputs of materials, fabrication, transportation, operation requirements, maintenance, dismantlement and end-of-life waste treatment. It should be mentioned that the electricity supply sources, and their construction stage (PV solar panels and Wind turbines) are also modelled using the database of Simapro and validated with correlated literature.

In this section of the inventory, the whole input and output parameters of the current LCA study were evaluated and categorized to environmental impacts considered, using SimaPro software (version 9.3.0.3). The used data and values were collected from manufacturer companies, experts and found correlated literature (e.g. energy sources, materials and processes). Besides, the input data regarding the operation supplies and requirements (e.g. raw materials pre-treatment, water, cleaning, maintenance, solar irradiation, and wind location conditions) of the energy plant, electrolyser and HVO reactor system are accurately modelled relying on datasets from Portugal or Europe (according to the availability). In addition, the production of the electrolyser technology and HVO reactor is modelled (in SimaPro software) based on the conditions of the producer's regions (the input materials, energy, and processes). Furthermore, a waste treatment stage is considered for the current LCA study involving the components recycling and the reuse of some materials in order to reduce the disposal to the landfill, following the end-life methodology reported by Lotric et al. [47] for systems related to hydrogen electrolyser production.

Table 2
The main scenario and the other three scenarios considered in the current study.

	Feedstock	Electricity supply
Scenario 1	UCO	PV/Wind
Scenario 2	UCO	Grid mix
Scenario 3	Palm oil	PV/Wind
Scenario 4	Palm oil	Grid mix

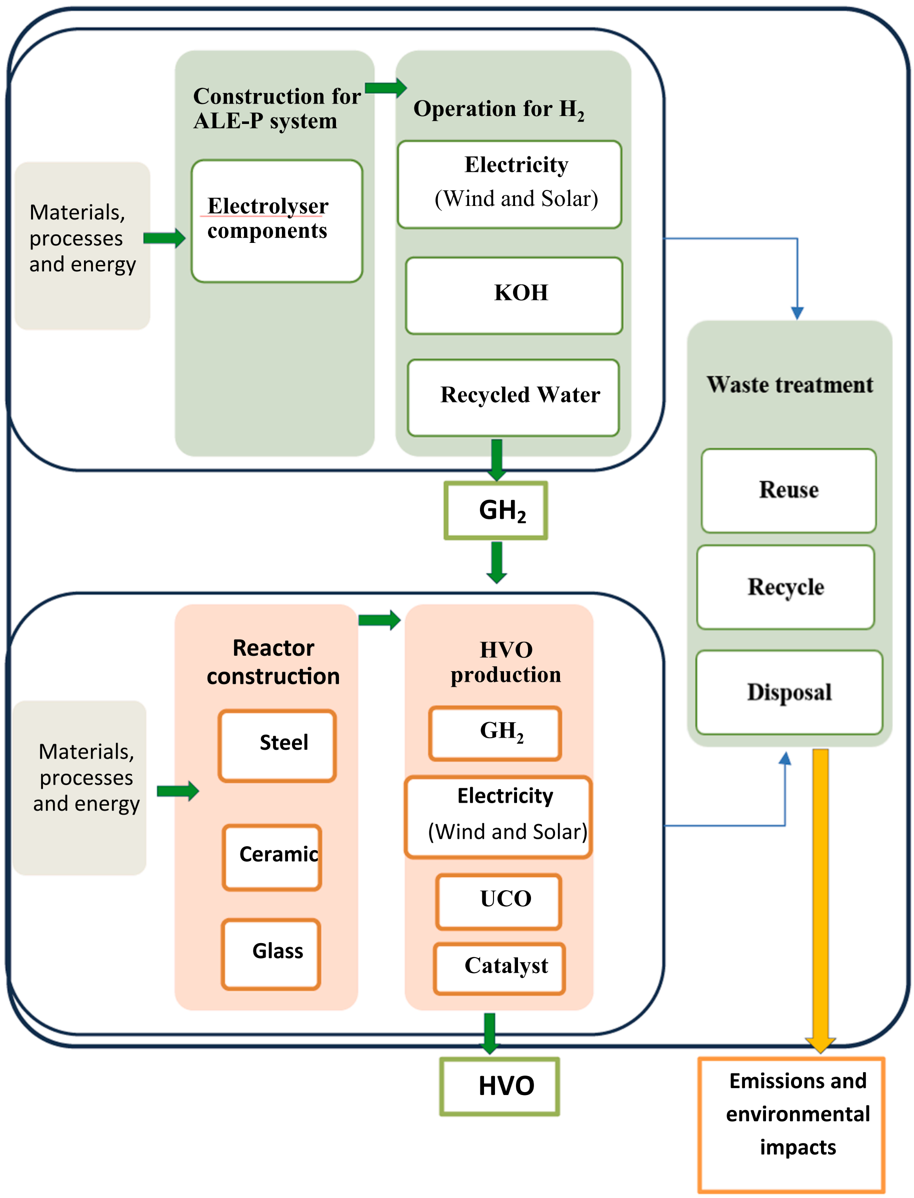

Fig. 1. System boundaries of the life cycle for HVO production.

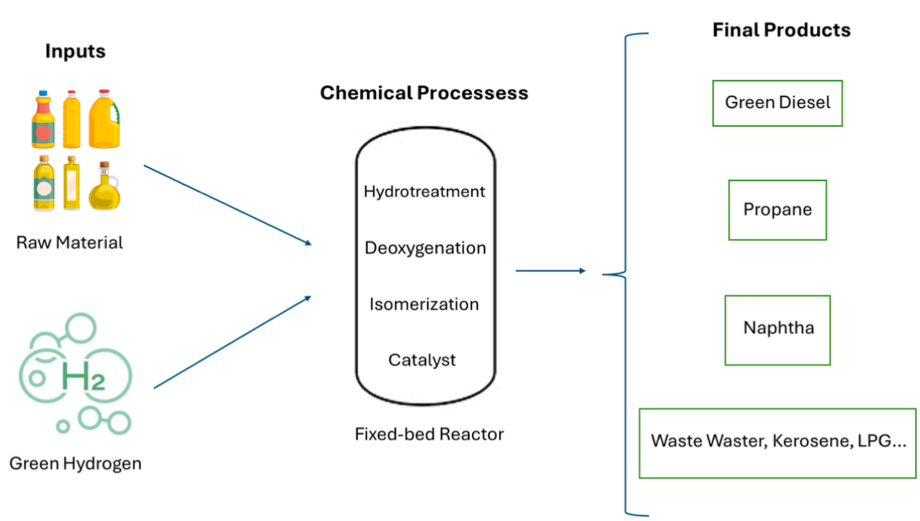

Fig. 2. Schematics of the HVO production process.

2.2.1. The HVO production system

As mentioned earlier, HVO shows similar characteristics (such as cetane number, density, etc), chemical composition and heating value (around 43 to 44 MJ/kg) to those of fossil diesel [48]. HVO is produced by the hydrotreatment, deoxygenation and isomerization chemical reactions under suitable conditions, and it is composed of paraffinic materials. In general, the main stages to produce HVO are the pre-treatment of the feedstocks (oils), the chemical reactions mentioned above inside two reactors (in the presence of the treated feedstock materials, green hydrogen and a catalyst) and final separation [49], as shown in Fig. 2. Furthermore, propane and naphtha are common by-products of this process and can also be sold in the market [50]. Normally, the UCOs are collected from restaurants or other food establishments and points of collection around cities and municipalities, where people can drop their bottles of UCO. The hydrogen should be supplied to the process in a pressure condition between 3 and 20 MPa [9], which is mainly responsible for removing oxygen atoms and double bonds from the triglyceride structure [51]. Here, the crucial chemical reaction (for the oxygen-free condition) is the deoxygenation reaction (which includes decarboxylation and decarbonylation) [52]. Finally, the used type of catalyst, the UCO (or virgin oil) properties and the reactor operation conditions of temperature and hydrogen pressure have a significant impact on the properties of the obtained HVO [53].

HVO production results in a green drop-in diesel fuel, stable in terms of oxidation, with a high cetane number, excellent energy density and lower cloud and pour points. The typical value chain of HVO produced from UCO and green hydrogen is clarified in Fig. 3.

In addition, it should be mentioned that different kinds of reactors can be used to produce HVO such as Trickle-Bed reactors [54] which are normally used in the petrol industry when a reaction that involves hydrogen occurs. Other types of reactors that can be used to produce HVO are Batch reactors or Fixed-Bed reactors [55].

2.2.2. Operation and input data for the HVO production process

The operation that produces HVO needs a specific amount of pre-treated feedstock material, hydrogen and energy as inputs for each kg of HVO produced. Some related input data found in the literature are presented in Table 3.

The inputs/outputs for the current HVO production (adopted in the current study) are presented in Table 4. These inputs/outputs values have been defined based on previous related studies and information collected from industries such as Neste [61] and other references [56–59,62] as have been analysed in Table 3. Also, the selected catalysts are NiMo/γ-Al_2O_3 (Nickel Molybdenum with gamma-alumina) for the hydrotreatment process (in the first reactor) and Pt/SAPO-11/Al_2O_3 (Platinum/SAPO-11/Aluminum Oxide) for the isomerization process (in the second reactor). NiMo/γ-Al_2O_3 exhibits significant features for processing triglyceride feedstock to generate decarboxylated hydrocarbon products [63,64]. The weight of the catalyst used is calculated based on the Weight Hourly Space Velocity (WHSV) factor, considered here equal to 2 h^{-1} associated with the feedstock volumetric flow rate in the reactor [63] and the replacement of the catalyst every 3 years, resulting in 2217 tons of NiMo/γ-Al_2O_3 and 975 tons of Pt/SAPO-11/Al_2O_3 for the total lifetime considered in the current study (20 years). Moreover, the hydrotreatment process in the reactor is considered to be under temperature from 300 to 450 °C and hydrogen pressure from 3 to 20 MPa as stated by Lorenzi et al. [65].

In addition, the environmental impacts results obtained in the current study are analysed considering the production of 1 kg of HVO and its associated by-products (Propane and Naphta) as presented in Table 4, avoiding the allocation methods (the allocation methods for the by-products are not used in the current study). However, different allocation methods (energy, market and mass allocations) can be found in a study by Xu et al. [58] to define the attribution in the energy use and emissions for HVO and the by-products resulting from the reactor system. It was reported that the by-products occupied 8.8 % in the energy-based allocation method, 4.9 % in the market-based allocation method and 9 % in the mass-based allocation method [58].

In the current study, two Trickle-Bed reactors were considered for the HVO production process, where the materials to build the reactors are considered in the LCA approach by Simapro. A Trickle-Bed reactor is a common type used for the hydrotreatment of vegetable oils [54] and in petrol manufacturing, mainly for reactions with hydrogen [66]. This type of reactor was also used by Srifa et al. [67] for the hydrodeoxygenation of palm oil at 573 K and 5 MPa. The components and materials used to build this type of reactor are described in detail by Herskowitz et al. [68], where the main component is stainless steel. Also, the BOP-linked components of a feedstock (e.g. UCO) tank include gas cylinders, gas/liquid separator, flowmeters, heating pump (for high-temperature feedstock) and controllers for the pressure and temperature with a suitable safety arrangement to ensure the safe procedure of the reactor [68]. The process starts by mixing the raw material (e.g. UCO) with hydrogen (under high temperature), followed by feeding the hydrogen/oil mixture to the reactor in the presence of a catalyst where the decarboxylation, decarbonylation and deoxygenation processes happen [65]. Then, the products are cooled down by a heat exchanger and derived to the separation stage where the by-products and extra hydrogen (unreacted in the process) are removed from the resulting final liquid biofuel [7]. Then, the final result is directed to a suitable container [69].

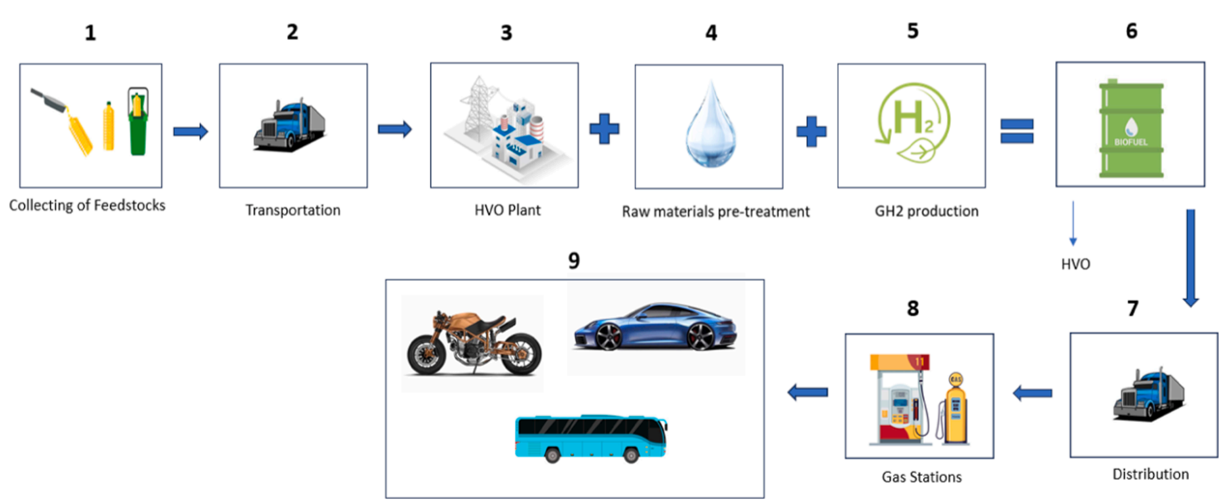

Fig. 3. The typical value chain of HVO produced from GH_2 and UCO.

Table 3
Reactor operation inputs and outputs for the HVO production process.

Input type	Kalnes et al. [56]	Roque et al. [9] and [57]	Xu et al. [58] (2022)	Gehrer et al. [59]	Xu et al.[60] (2020)	Neste Oil [61]	Sierk de Jong et al. [62]
Feedstock (t/t RD)	1.02–1.14	1.19	1.26	1.22	1.18	1.21	1.17
Hydrogen (kg/t RD)	17–38	42	34	32	38	38	47
Electricity (MJ/t RD)		107	430	220	382		224
Steam (MJ/t RD)		29		196			
Water (kg/t RD)		29			208		
Output type							
HVO	✓	✓	✓	✓	✓	✓	✓
Propane	✓	✓	✓	✓	✓	✓	✓
Naphtha	✓		✓		✓	✓	✓
Fuel Gas			✓				
Gasoline		✓					
Kerosene	✓						

Table 4
The operation inputs and outputs for the HVO production process in the current study based on previous studies [56–59,61,62].

Current study Input type	Input value per kg HVO	Output type	Output value per kg HVO
UCO Feedstock	1.2 kg	Renewable Diesel (RD)	1 kg HVO
Hydrogen	0.042 kg	Renewable Propane	0.058 kg
Electricity	0.272 MJ	Renewable Naphtha	0.011 kg
Steam	0.1125 MJ	Water	0.14 kg
Distilled water	0.116 kg	Other	0.13 kg

2.2.3. *Feedstock supply*

Different raw materials can be used to produce HVO such as virgin oils, UCO, animal manure and sewage sludge, nut shells, biomass fraction of wastes and residues from forestry, forest-based industries and animal fats [70]. In this study, UCO is considered as feedstock for the main scenario of the HVO production process, with a capacity of 305 k tons of feedstock supply per year for the total project assumed in the current study. Additionally, the use of virgin oil is also examined for comparison with the UCO scenario.

2.2.3.1. UCO feedstock. In general, the providers of UCOs are, for example, restaurants, nutrient industries, and oil recycling centres. UCO comes from the wasted vegetable oils (e.g. soybean, corn, olive, sesame oils, etc.) after frying in restaurants, houses, and other sources. After collecting, the feedstock material is stored and then sent to the HVO production plant by suitable transportation such as trucks, ships or rail. Then, the feedstock material is stored at the HVO place facility for the pre-treatment process. Therefore, the boundaries of the HVO production system, particularly regarding the UCO, involve the pre-treatment process of the oils (energy and materials needed) and the requirements of transportation (collecting) the mentioned amount of UCO. However, it is considered for this study that the UCO supply is coming from different locations to the proposed project site in Portugal (for the current study), mainly 30 % of UCO from Portugal, 40 % from Spain, 10 % from Rotterdam Seaport in Netherlands and 20 % from Malaysia. These four destinations for oil imports are determined based on Portuguese national data, which identifies the countries that supply the highest amount of UCO to Portugal [71]. The distances considered for the transport stage of the UCO to the HVO plant were 626 km from Madrid to Lisbon (Spain case), 200 km from Aveiro to Lisbon (Portugal case), 2000 km from the seaport of Rotterdam to Lisbon (Netherlands case) and 13000 km from Malaysia to Lisbon (Malaysia case). The transport cases of Spain and Portugal are executed by road transport in a lorry with 7,5 to 16 metric tons of capacity. The transport cases of Netherlands and Malaysia are made by sea transportation, in a container ship.

Furthermore, the main known steps for UCO pre-treatment are filtration, degumming, bleaching and final washing [72–74]. First, the UCOs are often filtered to remove solid impurities and contaminants. Sodium Hydroxide (NaOH) and Phosphoric Acid (H_3PO_4) were used for degumming where occurs a reaction with the phospholipids in the oil to form soaps, which are then removed along with other impurities during subsequent washing steps. Next, the activated carbon, which features a high surface area and pore structure is used for bleaching which allows the adsorption of a wide range of impurities, including colour pigments and odours. In the end, water is applied for the final washing. Also, it should be mentioned that, in this study, all the energy used for the pre-treatment process of the UCO feedstock comes from RES for the main scenario.

2.2.3.2. Virgin oil feedstock (Palm oil). In this study, Palm oil, which is a virgin vegetable oil feedstock, is chosen for comparison purposes with the use of UCO as one of the most used raw materials to produce biofuels. Palm oil features a higher production yield compared to other virgin vegetable oils, and it requires less fertilizers, water and pesticides for its planting and cultivation [75]. Palm oil production also requires less sunlight and can achieve an average annual yield of 4220 kg/ha [9,76]. For its production, fresh fruit bunches are harvested, sterilized and dismembered into empty fruits. The result is then pressed, giving rise to palm oil [49]. From 2000 to 2020, the global palm oil harvested area increased from 10,40 to 28,74 million hectares at a rate of around 0,92 Mha (million hectares) per year but despite this and considering its economic benefits, its production is associated [77] with deforestation, huge fires, greenhouse gas emissions, soil erosion and the consequent loss of biodiversity and fertility, as well as the loss of animal biodiversity [78]. The use of palm oil for the production of biofuels is often criticized due to the competition that exists with food agriculture and the consequent use of large areas of land for its cultivation and extraction.

However, after the cultivation and extraction of Palm oil, it is also collected, stored and sent to the HVO production plant by suitable transportation. Then, similar to UCO, the Palm oil is driven to the HVO place facility for the pre-treatment process. In this study, considering the Portugal case, Palm oil supply is transported to the proposed project site (of the current study) by sea in a container ship from Indonesia through a distance of 16,000 km.

2.2.3.3. Electricity supply. The electricity supply to the total systemis powered by renewable energy sources (50/50 wind/PV sources in Portugal), described in Fig. 4. The total capacity of the wind/PV power plant is 180 MW. The input data for the renewable energy harvested are

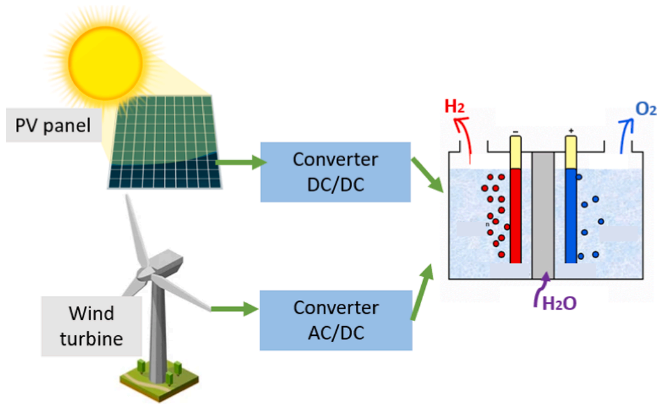

Fig. 4. Hybrid solar and wind electricity sources for GH_2 production.

found in the ecoinvent version 3 in the SimaPro database. Also, the location of the suggested project in Portugal (in the current study) is considered for conditions such as wind velocity, solar radiation variation, and lifetime for their influence on the environmental categories of the total renewable diesel production system.

For the electricity grid mix from Portugal, 2023 data were considered and applied in SimaPro software. Knowing that Portugal imports some electricity from Spain, 8 % of the mix was considered regarding Spain data and the rest (92 %) is from Portugal generation. Below, in Tables 5 and 6, are presented the values of the generation of electricity in each country in the year 2023 by fuel.

2.2.3.4. The electrolyser system for hydrogen production. So far, hydrogen has been recognized as an important energy carrier, and ongoing advancements in its production, storage, and utilization technologies are underway, underscoring its significance [81]. The water electrolysis process has been commonly used to produce hydrogen since the beginning of the 19th century [82]. In general, the electrolyser system consists of merged cells of electrodes linked to DC voltage electrical energy. The electrodes are the cathodes where hydrogen is released and the anodes where the oxygen is released. Also, electrolytes and catalyst materials are employed in the electrolysis procedure to increase the hydrogen production efficiency [26]. The electrodes are parted by a layer of membrane-bounded into a liquid electrolyte of Hydroxide Potassium (KOH), mainly 25 wt% aqueous KOH for the current study. The working principle is mainly that the hydroxide ions ($OH-$) are firstly created at the cathode and across the membrane material to the anode side, resulting in hydrogen at the cathode side [83]. In the second step, the oxygen and hydrogen bubbles are emitted by the oxidization reaction of the water particles [90]. However, the features of ALE are mainly that it requires low operating temperatures from 30 to 80 °C, and the cheaper materials of its components (e.g. asbestos membrane and nickel electrodes) [29–31].

The hydrogen project presented in this study is designed with a power capacity of 60 MW, categorizing it as a large-scale facility. This 60 MW capacity, generated by the wind/PV power plant, is required to sustain the electrolysis process, enabling the production of hydrogen at a rate sufficient to meet the demands of the HVO production process. The electrolysis model was selected to be four units of 15 MW capacity each. The unit involves 10 stacks with 139 cells [84]. The lifetime of the stack is considered 10 years. The information regarding the materials mass of the ALE components and operating inputs was gathered from the manufacturers and through upscaling data inputs for other conducted projects for ALE systems [23]. Furthermore, the technical description of the ALE system was specified relying on correlated publications and manufacturers. The used electrolyser in this study is the pressurized ALE which has been showing good performances with a maximum efficiency of 80.05 % [23,85,86]. The components like the cell frame, gasket, anodes, and cathodes and their materials such as Nickel, Steel, Aluminium, Copper etc, are summarised in Fig. 5.

Additionally, the Balance of Plant (BoP) for the electrolysis system contains the tanks, heat exchangers, pumps, electronic equipment and filters that are considered in the current study, where the total energy efficiency of the electrolysis system including BoP becomes 72.4 %.

Table 5
2023 Portugal electricity generation mix.

2023 Portugal electricity generation [79]	TWh	Percentage
Other fossil fuels (Petroleum)	1,53	3,1%
Wind onshore	13,48	27,2%
Solar	5,21	10,5%
HydroPower	15,03	30,3%
Bioenergy	3,85	7,8%
Natural gas	10,3	20,8%
Other renewables	0,2	0,4%
Total	49,6	100 %

Table 6
2023 Spain electricity generation mix.

2023 Spain Electricity Generation [80]	TWh	Percentage
Other fossil fuels	12,16	4,44 %
Wind onshore	62,97	22,97 %
Solar	42,23	15,41 %
HydroPower	31,04	11,32 %
Bioenergy	4,67	1,70 %
Nuclear	57,74	21,07 %
Natural gas	59,9	21,85 %
Coal	3,38	1,23 %
Total	274,09	100 %

2.2.3.5. Waste treatment. To lessen environmental impact and costs in HVO and GH_2 production, it is crucial to minimise material usage across the system's life cycle. This involves recycling the components used in the reactor and electrolysis systems, particularly steel, copper, nickel and plastics, as outlined in Ferriz's study [87]. Techniques like hydrometallurgical processes for Raney Ni and grinding Polytetrafluoroethylene (PTFE) for reuse are viable. Lotric et al. [47] suggested a strategy for waste treatment in hydrogen production that is followed here, involving manual dismantling and material recovery. Therefore, recycling, reused and landfill rates are three approaches to treat the waste materials at the end of the life of system components. In this study, steel, copper, nickel and plastics are estimated to be treated as presented in Table 7, based on industry standards and literature. At the same time, most other materials are targeted for 99 % recycling and 1 % disposal in landfills. The landfills scenario is used as an inert waste for final disposal without further treatment. For example, 60 % of the steel will be reused in other cases, 35 % will be recycled to be transformed into other equipment and the remaining 5 % will be disposed of in the landfill.

Landfill disposal was only considered when material recovery or recycling was not viable. It's worth noting that most steel materials that serve as frameworks and householding can be reused in future projects, while any remaining steel is recycled.

3. Results and discussion

In this section, the environmental impacts of the life cycle stages of HVO production are assessed in detail per 1 kg of HVO unit basis.

3.1. Environmental impacts of the total life cycle stages

Fig. 6 presents the environmental impacts across the total life cycle stages of HVO production (UCO case with RES and Grid mix), encompassing construction, disposal, and operation. This evaluation includes the electricity supply requirements and other operational necessities like

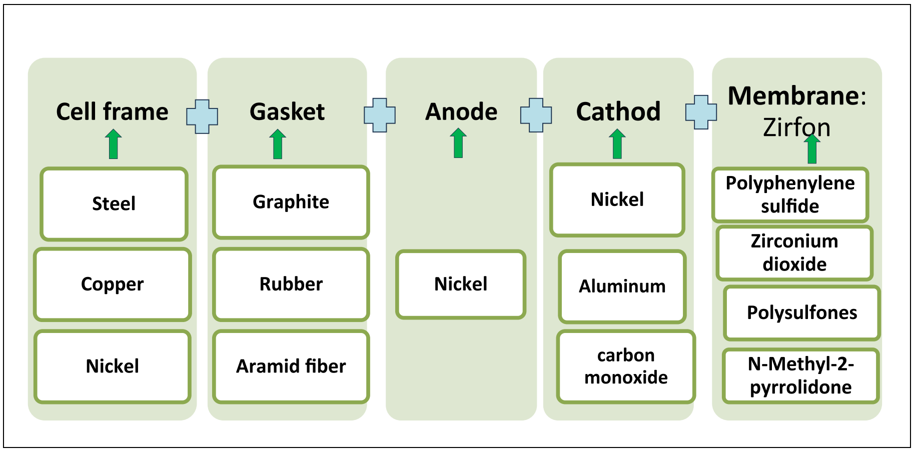

Fig. 5. Components and input materials for the water electrolysis system.

Table 7
The waste treatment rates for select materials utilised in the system [47].

Material	Reused	Recycled	Landfill
Steel	60 %	35 %	5 %
Aluminium	0	96 %	4 %
Copper	0	97 %	3 %
N-methyl-2	0	84 %	16 %
Aniline	0	50 %	50 %

steam, water and materials, as discussed in section 2.2 for HVO production, also feedstock pre-processing, electricity supply and electrolyser systems. The results indicate that the transport of feedstocks exerts the most significant influence on environmental impacts for UCO case which is mainly due to the use of fossil fuel for transportation over long distances. Transportation contributed around 37 % of the total GWP for UCO with PV/Wind electricity source and 20 % for UCO with grid mix electricity source, where the transport contribution to the GWP is because of the use of fossil fuels in trucks and ships needed. Those

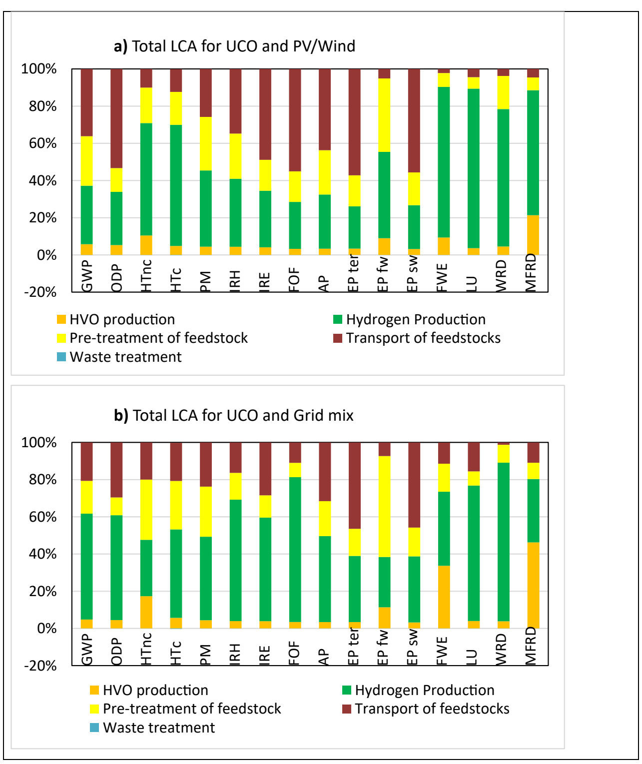

Fig. 6. Environmental impacts (per kg HVO) for the total LCA of HVO production for UCO case using electricity from a) PV/Wind, b) Grid mix, Where: GWP: Global warming potential, ODP: Ozone depletion. HTnc: Human toxicity, non-cancer effects. HTc: Human toxicity, cancer effects. PM: Particulate matter. 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.

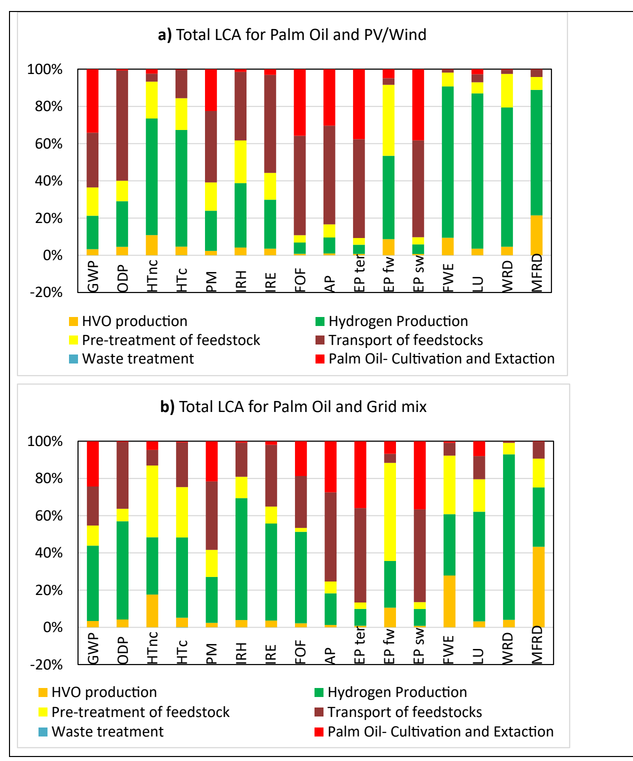

Fig. 7. Environmental impacts (per kg HVO) for the total LCA of HVO production for Palm Oil case using electricity from a) PV/Wind, b) Grid mix, Where: GWP: Global warming potential, ODP: Ozone depletion. HTnc: Human toxicity, non-cancer effects. HTc: Human toxicity, cancer effects. PM: Particulate matter. 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.

impact percentages associated with the transportation stage become lower in the case of Palm Oil, as presented in Fig. 7, as an additional stage of cultivation and extraction of the feedstock was added.

Additionally, the impact values of using two different electricity sources show different percentages across the total life cycle stages, as depicted in Fig. 6 for the UCO case and Fig. 7 for the Palm Oil case, because of changing the electricity input option (firstly the PV/Wind and second the Grid-mix) required in the stages of Pre-treatment of feedstock, Hydrogen production and HVO production. Moreover, the waste treatment stage shows negligible impacts with less than 1 % of the total life cycle stages, as can be seen in Figs. 6 and 7 (in blue colour).

Moreover, the four scenarios adapted for considering two different feedstocks and two electricity sources will lead to obtaining different final absolute values of the resulting 16 environmental impacts, as presented in Table 8. In the case of UCO and PV/Wind (Scenario 1), the results of environmental impacts showed the lowest values compared to the other three scenarios. Also, it can be seen that using PV/Wind as an electricity source lowers the environmental impact values for both UCO and Palm Oil cases. Furthermore, having an additional stage required for the cultivation and extraction of Palm Oil led to higher environmental impacts for the scenarios involving Palm Oil compared to UCO, reaching the maximum impact values for Scenario 4.

Furthermore, given that GWP holds considerable importance in LCA investigations, Fig. 8 illustrates the GWP outcomes for the four scenarios of HVO production. The total GWP of the entire LCA employing UCO with PV/Wind electricity exhibits the lowest GWP value of 0.304 kg CO_2 eq/kg HVO, followed by UCO with Grid mix electricity for a value of 0.5319 kg CO_2 eq/kg HVO. Next, the Palm Oil case with PV/Wind electricity for a value of 0.533 kg CO_2 eq/kg HVO, and the largest value for the Palm Oil with Grid mix electricity of about 0.748 kg CO_2 eq/kg HVO. These findings confirm the substantial influence of the electricity source and feedstock type on GWP values across the four scenarios. The results of our LCA analysis highlight significant differences in the GWP of HVO production depending on the feedstock and energy source used. The scenario utilizing UCO with PV/Wind electricity achieved the lowest GWP value of 0.304 kg CO_2 eq/kg HVO, aligning well below the RED II and RED III (European Renewable Energy Directives of 2018 and 2023, respectively) [40] thresholds for advanced biofuels, which mandate a minimum of 65 % (fossil diesel normally emits around 1.18 kg CO_2 eq/kg diesel) GHG savings compared to fossil fuels. In contrast, UCO with grid mix electricity showed a slightly higher GWP of 0.5319 kg CO_2 eq/kg HVO but remains competitive and within the sustainability benchmarks.

However, the scenarios using palm oil as feedstock demonstrate considerably higher GWP values, with 0.533 kg CO_2 eq/kg HVO for PV/Wind electricity and 0.748 kg CO_2 eq/kg HVO for grid mix electricity.

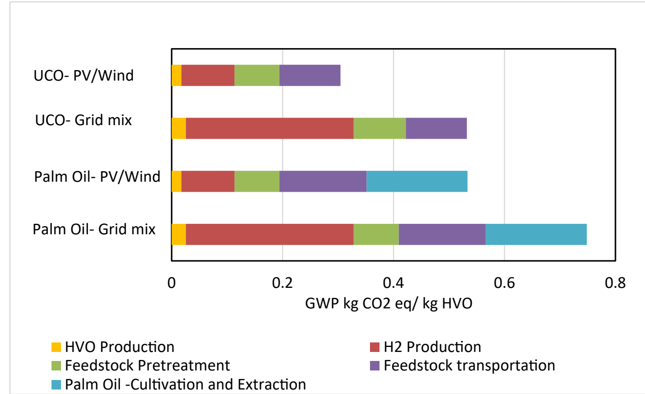

Fig. 8. GWP (kg CO_2 eq per kg HVO) for the total LCA of the value chain of HVO production for the four scenarios.

These figures may struggle to meet the RED III requirements, especially given the directive's stricter sustainability criteria and focus on minimizing indirect land-use change impacts. These results underscore the importance of feedstock selection and renewable energy integration in ensuring compliance with European targets and maximizing the environmental benefits of HVO production.

Also, the results in Fig. 8 show that the Pre-treatment stage of the feedstock results in here 0.081 kg CO_2 eq/kg HVO for the use of PV/Wind electricity source, and 0.093 kg CO_2 eq/kg HVO for the use of grid electricity source that it is almost equal for UCO and Palm Oil feedstock types. Those obtained values for the Oil feedstock pre-treatment process are close to the findings in the literature for HVO production [72]. Also, the HVO production stage presented a 0.0175 kg CO_2eq./kg HVO for the use of PV/Wind electricity source, very close to the values found by Roque et al. [9] (0.018), Xu et al. (0.029 kg CO_2/kWh) [58] and Sierk De Jong et al. (0.025 kg CO_2/kWh) [62]. Related to the extraction stage of palm oil, the high contribution to the GWP (0.18 kg CO_2 eq per kg HVO) was mainly due to the use of fossil fuels in the machinery used for the cultivation and extraction of vegetable oils.

In this regards, Roque et al. [9] conducted a LCA of HVO production based on soybean and palm oil. The hydrogen used for production was obtained by natural gas reforming process. The results showed great contributions to GWP in the stages of cultivation and extraction (350 kg CO_2 eq./1000 kWh for soybean and 100 kg CO_2 eq./1000 kWh for palm) of the vegetable oils and in the transport stage (90 kg CO_2 eq./1000 kWh for Soybean and 15 kg CO_2 eq./1000 kWh for Palm in land transportation and 60 kg CO_2 eq./1000 kWh for both Soybean and Palm in sea transportation). The GWP of soybean cultivation was four times

Table 8
Environmental impacts (per kg of HVO) for the total LCA of HVO production.

			Scenario 1	Scenario 2	Scenario 3	Scenario 4
Environmental Impact	Abbreviation	Unit	Total LCA UCO and PV/Wind	Total LCA UCO and Grid mix	Total LCA Palm oil and PV/Wind	Total LCA Palm oil and Grid mix
Global warming potential	GWP	kg CO_2 eq	3.0E-01	5.32E-01	5.33E-01	7.5E-01
Ozone depletion	ODP	kg CFC-11 eq	3.6E-08	6.5E-08	4.2E-08	6.9E-08
Human toxicity, non-cancer effects	HTnc	CTUh	1.9E-07	9.5E-08	1.8E-07	9.3E-08
Human toxicity, cancer effects	HTc	CTUh	6.3E-08	3.7E-08	6.6E-08	4.1E-08
Particulate matter	PM	kg PM2.5 eq	2.6E-04	2.8E-04	4.9E-04	5.1E-04
Ionizing radiation HH	IRH	kBq U235 eq	2.3E-02	5.0E-02	2.5E-02	5.0E-02
Ionizing radiation E (interim)	IRE	CTUe	1.0E-07	1.7E-07	1.2E-07	1.9E-07
Photochemical ozone formation	POF	kg NMVOC eq	1.6E-03	8.2E-03	6.8E-03	1.3E-02
Acidification	AP	molc H+eq	2.9E-03	3.9E-03	9.7E-03	1.1E-02
Terrestrial eutrophication	EP ter	molc N eq	5.7E-03	7.0E-03	2.6E-02	2.8E-02
Freshwater eutrophication	EP fw	kg P eq	1.4E-04	9.5E-05	1.4E-04	1.0E-04
Marine eutrophication	EP sw	kg N eq	5.3E-04	6.5E-04	2.4E-03	2.5E-03
Freshwater ecotoxicity	FWE	CTUe	3.5E+01	6.8E+00	3.5E+01	8.2E+00
Land use	LU	kg C deficit	7.7E+00	2.2E+00	8.0E+00	2.7E+00
Water resource depletion	WRD	m^3 water eq	1.3E-03	3.4E-03	1.1E-03	3.3E-03
Mineral, fossil & ren resource depletion	MFRDP	kg Sb eq	3.2E-05	1.3E-05	3.2E-05	1.4E-05

bigger when compared to palm. In the step of hydrogen production based on natural gas reforming, carbon emissions are associated too and were an important contribution to the GHG emissions (15 kg CO_2 eq./ 1000 kWh for both palm and soybean).

However, the variation in emissions results of different vegetable oils (from different LCA studies) is due to carrying emissions from various inputs such as chemicals, diesel, electricity, and water used during the cultivation stage of the crops. The latter was discussed by R. Chatterjee et al. [75] for the use of rapeseed oil, palm oil and *jatropha* as feedstocks to produce HVO. The resulting GWP was lower for HVO produced from Palm oil (380 g CO_2 eq./kWh) and higher for HVO produced from Rapeseed and Jatropha (700 g CO_2 eq./kWh and 590 g CO_2 eq./kWh respectively). In addition, Sierk de Jong et al. [62] focused on the production of renewable jet fuel (SAF – Sustainable Aviation Fuel, also a HVO). The hydrogen considered for the SAF production process was achieved by the steam methane reforming process. UCOs, Jatropha and Camelina were the feedstocks considered. The results showed that the GHG emissions reductions exceeded 60 % compared to fossil jet fuel. Jatropha (30 g CO_2 eq./MJ) and camelina (20 g CO_2 eq./MJ) showed particularly high cultivation emissions.

Also, hydrogen production is found to be an important contributor to the overall GHG emissions. Furthermore, using the UCO (from waste residues) shows better emission mitigation potential than virgin oils (e.g. food crops that interfere with agriculture), because of low emissions related to fertilizer use, feedstock cultivation or feedstock collection.

3.2. Environmental impacts of the H_2 production stage

The results presented in Table 9 illustrate the environmental impacts encompassing the entire life cycle of hydrogen production, including the construction, disposal, and operation stages. In this evaluation of the overall hydrogen production system, factors such as electricity supply and additional operational necessities like steam, KOH, and nitrogen are taken into account. Nitrogen is utilized for washing the electrolyser system during its working phase. It can be also noticed from Table 9 higher environmental impacts for the use of the Grid mix option compared to PV/Wind case.

Also, the results presented in Fig. 9 for the contribution of each operation factor (steam, nitrogen, electricity input, KOH, ALE Construction and Disposal stage) reveal that the PV/Wind electricity supply exerts the most significant influence on various environmental impacts, contributing approximately 98 %. This underscores the lesser significance of certain operational requirements (steam, KOH, and nitrogen) compared to electricity supply.

Table 9
Environmental impacts (per kg H_2) for the H_2 production.

Environmental Impact	Abbreviation	Unit	PV/ Wind	Grid mix
Global warming potential	GWP	kg CO_2 eq	2.4E+00	7.6E+00
Ozone depletion	ODP	kg CFC-11 eq	2.6E-07	9.1E-07
Human toxicity, non-cancer effects	HTnc	CTUh	2.9E-06	7.2E-07
Human toxicity, cancer effects	HTc	CTUh	1.0E-06	4.5E-07
Particulate matter	PM	kg PM2.5 eq	2.6E-03	3.1E-03
Ionizing radiation HH	IRH	kBq U235 eq	2.1E-01	8.1E-01
Ionizing radiation E (interim)	IRE	CTUe	7.7E-07	2.4E-06
Photochemical ozone formation	POF	kg NMVOC eq	1.0E-02	1.6E-01
Acidification	AP	molc H+eq	2.1E-02	4.6E-02
Terrestrial eutrophication	EP ter	molc N eq	3.3E-02	6.3E-02
Freshwater eutrophication	EP fw	kg P eq	1.6E-03	6.4E-04
Marine eutrophication	EP sw	kg N eq	3.1E-03	5.7E-03
Freshwater ecotoxicity	FWE	CTUe	7.1E+02	6.8E+01
Land use	LU	kg C deficit	1.7E+02	4.0E+01
Water resource depletion	WRD	m^3 water eq	2.1E-02	7.3E-02
Mineral, fossil & ren resource depletion	MFRDP	kg Sb eq	5.4E-04	1.1E-04

In addition, the results of GWP presented in Fig. 10 for the hydrogen production stage show that the total GWP using PV/Wind (with the value of 2.34 kg CO_2 eq/Kg H_2) is demonstrated to be lower than the use of grid mix electricity supply option (with the value of 7.51 kg CO_2 eq/ Kg H_2) by around 5.17 kg CO_2 eq/Kg H_2 decrease (69 % decrease). The results confirmed the good choice of using PV/Wind for electricity supply for better environmental performance compared to the electricity grid mix.

The present research reveals a GWP value of 2.34 kg CO_2 eq./kg H_2 for ALE hydrogen production, marking a significant 80 % decrease compared to the conventional method of steam methane reforming, which stands at around 11.89 kg CO_2 eq./kg H_2 [88]. However, the GWP value of hydrogen production varies notably across different studies due to factors such as total capacity, energy source, location, and materials used in electrolyser systems. For instance, Sadeghi et al. [22] identified a GWP value of 3.1 kg CO_2 eq./kg H_2 for a hydrogen production system utilizing PV solar power. Also, Zhang et al. [89] noted a fluctuating GWP value ranging between 8.67 and 4.33 kg CO_2 eq./kg H_2, depending on the system's lifetime changing from 30 to 60 years, for an electrolysis system based on PV power.

3.3. Environmental impacts of only the HVO production stage

The results regarding only the HVO production stage are presented in Fig. 11, considering only the scenarios involving UCO utilization – a) UCO with PV/Wind energy supply and b) UCO with grid mix energy supply. It can be seen that, in the first case, steam is responsible for the bigger part of the environmental impacts. In the case of the grid mix energy supply, the energy input is also a big part of the environmental contributions, reaching a similar value like steam. The catalyst shows a very low value in this contribution and the reactor materials (for the construction of the systems) are almost insignificant in the total landscape.

3.4. Normalization

The process of normalization is executed, and the outcomes for HVO production, utilizing UCO feedstock and electricity from Photovoltaic (PV)/Wind sources, are depicted in Fig. 12. This figure represents the stages of the entire process. The normalization analysis takes into account 16 different environmental impacts. Very low normalized values can be observed of about 0.043 (the sum of the 16 environmental impacts) for all stages. The results indicate that FWE has the most significant contribution to the normalized environmental impacts with around 0.02 value. Additionally, Human Toxicity impacts (both cancerous, HTc, and non-cancerous, HTcn) also make a substantial contribution to the overall normalized results, accounting for approximately 0.022 (for the sum of both HTc and HTcn) of the annual impacts of an average EU citizen. However, the life cycle of the entire HVO production system over 20 years represents less than 4.5 % (the highest value obtained) of the annual impacts of an average EU citizen, according to the EU Product Environmental Footprint (PEF), which can be considered a good outcome.

3.5. Sensitivity analysis

In this section, a sensitivity analysis is performed to check the data uncertainties for the HVO production process based on the UCO and PV/ Wind electricity supply scenario, including all the stages (operation, construction, and disposal). Therefore, the sensitivity analysis considers the HVO system boundaries that may change based on the operation

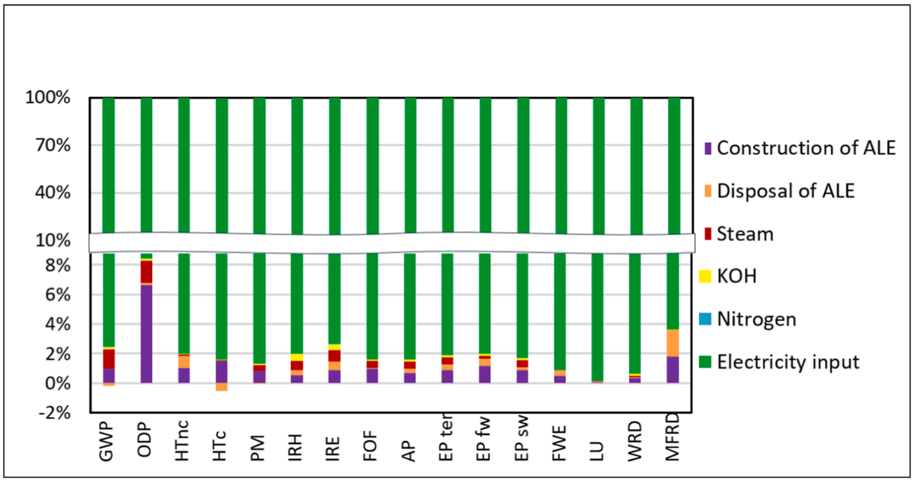

Fig. 9. Environmental impacts per kg H_2 of the hydrogen production stage using PV/wind power. Where: GWP: Global warming potential, ODP: Ozone depletion. HTnc: Human toxicity, non-cancer effects. HTc: Human toxicity, cancer effects. PM: Particulate matter. IRH: Ionizing radiation HH. IRE: Ionizing radiation 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.

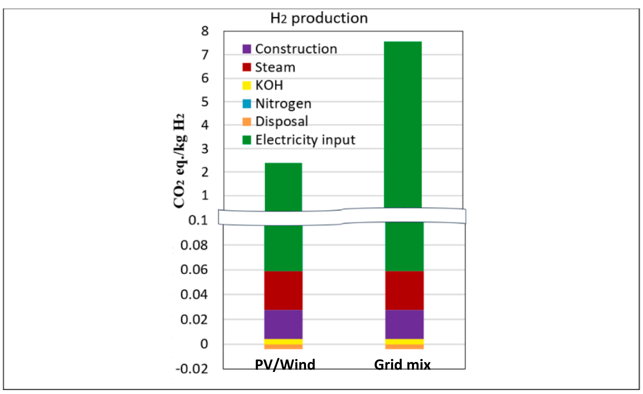

Fig. 10. GWP of the hydrogen production stage for electricity input from PV/wind power compared to Grid mix.

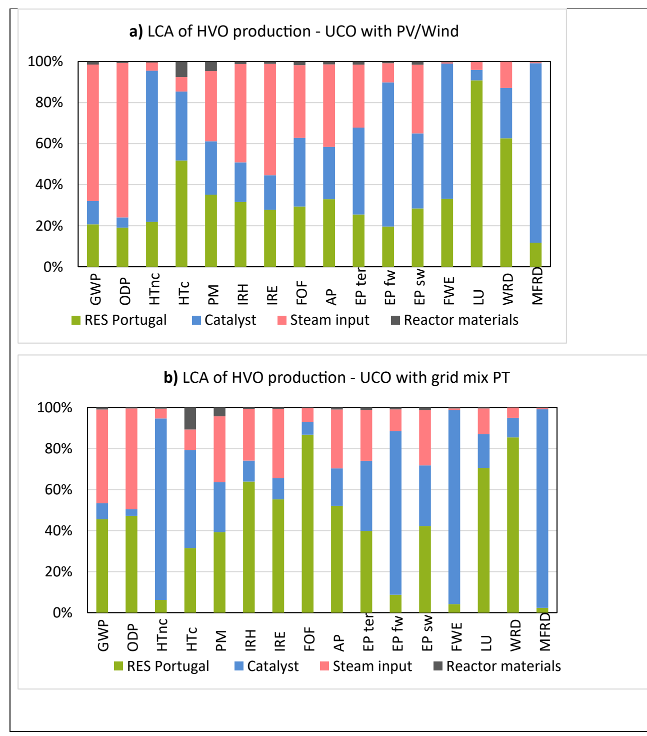

Fig. 11. Environmental impacts (per kg HVO) for the HVO production stage for UCO using electricity from a) PV/Wind, b) Grid mix. Where: GWP: Global warming potential, ODP: Ozone depletion. HTnc: Human toxicity, non-cancer effects. HTc: Human toxicity, cancer effects. PM: Particulate matter. IRH: Ionizing 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.

conditions, mainly significant boundaries such electricity and steam. Also, sensitivity analysis considers the change that may happen in the collection of UCO feedstock, where it is considered here that all the UCO are collected from Portugal, thus the transportation stage is analysed. Thus, a Tornado chart is created for the total GWP 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 10. The ranges shown for parameters 1 and 2 in Table 10 are due to the variation of the data obtained for the HVO production stage (presented in Table 3). Therefore, the uncertainty of the electricity consumption is assumed here to range between 100 and 400 MJ/t HVO, while the uncertainty of the steam input is assumed here to be between 20 and 200 MJ/t HVO. In addition, another transportation scenario of having 100 % of UCO collected in Portugal is considered for the sensitivity analysis and compared to the transportation scenario previously conducted (30 % of UCO from Portugal, 40 % of UCO from Spain, 10 % of UCO from Rotterdam Seaport in the Netherlands and 20 % of UCO from Malaysia).

The resulting Tornado chart in Fig. 13 displays the range of the GWP changes according to each associated boundary parameter value in Table 10. It can be observed that the HVO production can be derived the most by the new transportation scenario of UCO collected totally in Portugal up to 0.048 kg CO_2 eq./kg HVO (with a final value of 0.256 kg CO_2 eq./kg HVO). Also, the steam uncertainty required in the HVO production stage showed a range of variation between 0.313 and 0.295 kg CO_2 eq./kg HVO. Furthermore, the GWP showed a range between 3.06 and 3.02 kg CO_2 eq./kg HVO based on the electricity consumption in the HVO production stage.

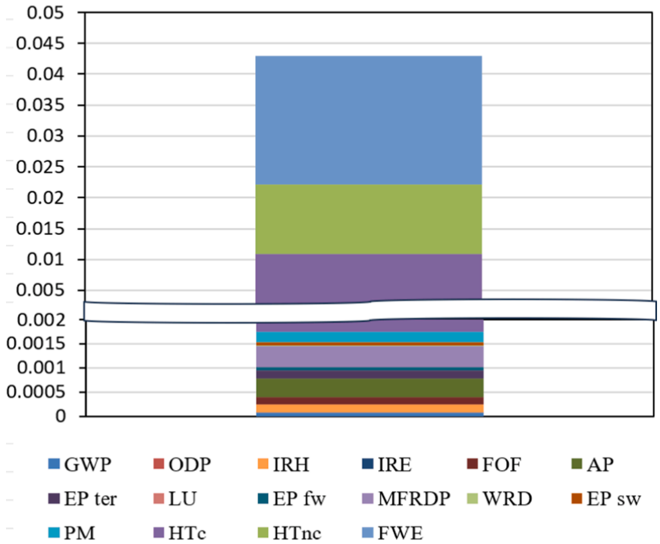

Fig. 12. The normalization of environmental impacts per kg HVO for total LCA for the scenario UCO and PV/Wind. Where, GWP: Global warming potential, ODP: Ozone depletion. HTnc: Human toxicity, non-cancer effects. HTc: Human toxicity, cancer effects. PM: Particulate matter. IRH: Ionizing radiation HH. 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.

Table 10
The ranges of parameters for sensitivity analysis.

Parameters	Unit	Ranges
Electricity	by year	100–400 MJ/t HVO
Steam	–	20–200 MJ/t HVO

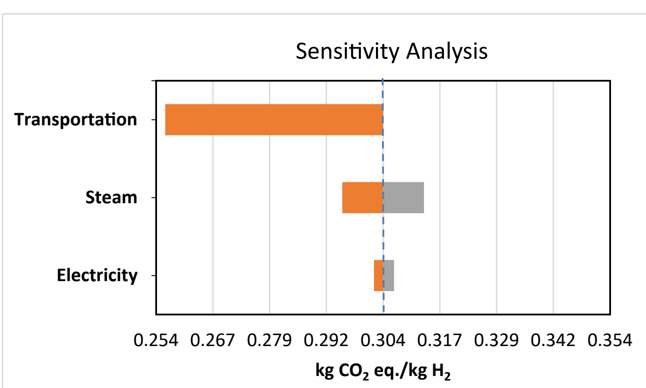

Fig. 13. Sensitivity analysis for GWP of the HVO production.

4. Conclusions

In this study, a LCA for HVO production based on GH_2 and UCOs as feedstock is conducted for the Portugal case. The environmental impacts were evaluated based on the operation, requirements, and construction components for the procedure stages of the feedstock collection, pre-treatment, transportation, hydrogen electrolysis production and HVO production. The scenario of using UCO and PV/Wind energy supply for GH_2 and HVO production is compared with the additional three scenarios involving the use of virgin palm oil and the electricity grid mix in Portugal.

The LCA results demonstrated that the transportation stage, primarily due to fossil fuel use in trucks and ships, constitutes about 37 % of the total GWP (with the most significant influence on environmental impacts) for UCO with PV/wind electricity case and 20 % for UCO with grid mix electricity case. Furthermore, in Scenario 1 where UCO is combined with PV/Wind energy, the environmental impacts are the lowest among the four scenarios. Additionally, utilizing PV/Wind energy reduces the environmental impacts for both UCO and Palm Oil cases. However, the extra stage needed for the cultivation and extraction of Palm Oil results in higher environmental impacts for scenarios involving Palm Oil compared to UCO. The LCA reveals the lowest GWP at 0.304 kg CO_2 eq/kg HVO for UCO with PV/Wind electricity scenario. UCO with grid mix follows at 0.532 kg CO_2 eq/kg HVO, then Palm Oil with PV/Wind at 0.533 kg CO_2 eq/kg HVO, and the highest is Palm Oil with grid mix at 0.748 kg CO_2 eq/kg HVO. This emphasizes the critical impact of electricity sources and feedstock on GWP values of HVO production.

For the hydrogen production stage, the PV/Wind electricity supply is the dominant factor in environmental impacts, contributing about 98 %, overshadowing other operational inputs like steam, KOH, and nitrogen. The research shows that ALE GH_2 production achieves a GWP of 2.34 kg CO_2 eq./kg H_2, which is an 80 % reduction from the SMR method.

For the HVO production stage, steam contributes the most to environmental impacts in the UCO with PV/Wind energy scenario, while in the grid mix energy scenario energy input similarly matches steam in its environmental contribution. The catalyst has a minimal impact, and reactor materials are nearly insignificant.

The normalization analysis across 16 environmental impacts shows consistently low values around 0.043 for all stages, with FWE contributing the most at approximately 0.02.

The sensitivity analysis demonstrated that the new transportation scenario for UCO collected entirely in Portugal results in lower HVO production emissions of 0.256 kg CO_2 eq./kg HVO. Also, uncertainty in steam usage during HVO production varies between 0.313 and 0.295 kg CO_2 eq./kg HVO. Additionally, GWP ranges from 3.06 to 3.02 kg CO_2 eq./kg HVO based on electricity consumption in the production stage.

Our study focuses on the LCA of HVO production in Portugal, highlighting its importance in addressing global decarbonization efforts. As a renewable diesel fuel produced from waste feedstocks like UCO, HVO offers significant greenhouse gas emission reductions, aligning with EU targets such as the Fit for 55 package and RED II and III. By conducting an LCA, our research evaluates the environmental impacts across the entire production process, providing transparency and identifying opportunities for optimization, particularly in leveraging local feedstocks and renewable energy sources like PV and wind.

This study is especially relevant for Portugal, where HVO production could reduce fuel import dependency, create circular economy opportunities, and integrate emerging technologies like green hydrogen. On a broader European scale, our findings contribute to harmonized biofuel assessment methods, fostering collaboration and investment in advanced biofuels. In 2024, as decarbonization deadlines approach, this work empowers stakeholders with the insights needed for evidence-based policies and sustainable energy decisions.

Future studies on HVO production could explore innovative opportunities, such as optimizing decentralized facilities to reduce logistics-related carbon footprints. Research could assess trade-offs between waste-based feedstocks like used cooking oils and animal fats to improve supply chain strategies. Co-locating HVO plants with renewable energy facilities offers potential synergies for efficiency and cost savings, while analysing social and economic benefits in rural areas could further support policy development.

Other promising avenues include advanced carbon capture integration for emission reductions, emerging catalytic technologies to enhance production efficiency, and evaluating the long-term impacts of large-scale production on feedstock availability and land use. Comparative studies with other advanced biofuels and exploring circular economy frameworks, such as repurposing industrial by-products, could also drive innovation and sustainability in HVO production.

CRediT authorship contribution statement

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

Acknowledgements

This work has been supported by the Fundação para a Ciência e Tecnologia (FCT), Portugal through IN+, under the M-ECO2 project, contract nr. C632471917- 00467009, co-funded through the Resilience and Recovery Plan (PRR-IAPMEI).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fuel.2025.134749.

Data availability

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

References

[1] No SY. Application of hydrotreated vegetable oil from triglyceride based biomass to CI engines - A review. Fuel 2014;115:88–96. https://doi.org/10.1016/j.fuel.2013.07.001.

[2] Yadav J, Deppenkemper K, Pischinger S. Impact of renewable fuels on heavy-duty engine performance and emissions. Energy Rep 2023;9:1977–89. https://doi.org/10.1016/j.egyr.2023.01.016.

[3] Szeto W, Leung DYC. Is hydrotreated vegetable oil a superior substitute for fossil diesel? A comprehensive review on physicochemical properties, engine performance and emissions. Fuel 2022;327(July):125065. https://doi.org/10.1016/j.fuel.2022.125065.

[4] Pinto GM, et al. Experimental investigation of performance and emissions of a CI engine operating with HVO and farnesane in dual-fuel mode with natural gas and biogas. Energy 2023;277(August 2022):127648. https://doi.org/10.1016/j.energy.2023.127648.

[5] Pinto F, Varela FT, Gonçalves M, Neto André R, Costa P, Mendes B. Production of bio-hydrocarbons by hydrotreating of pomace oil. Fuel 2014;116:84–93. https://doi.org/10.1016/j.fuel.2013.07.116.

[6] Sonthalia A, Kumar N. Comparison of fuel characteristics of hydrotreated waste cooking oil with its biodiesel and fossil diesel. Environ Sci Pollut Res, 2021;28(10):11824–34. https://doi.org/10.1007/s11356-019-07110-w.

[7] Sonthalia A, Kumar N. Hydroprocessed vegetable oil as a fuel for transportation sector: A review. J Energy Inst 2019;92(1):1–17. https://doi.org/10.1016/j.joei.2017.10.008.

[8] Di Blasio G, Ianniello R, Beatrice C. Hydrotreated vegetable oil as enabler for high-efficient and ultra-low emission vehicles in the view of 2030 targets. Fuel 2022;10(PB):122206. https://doi.org/10.1016/j.fuel.2021.122206.

[9] Roque LFA, et al. Experimental analysis and life cycle assessment of green diesel (HVO) in dual-fuel operation with bioethanol. J Clean Prod 2023;389(September 2022):135989. https://doi.org/10.1016/j.jclepro.2023.135989.

[10] Hunicz J, Matijošius J, Rimkus A, Kilikevičius A, Kordos P, Mikulski M. Efficient hydrotreated vegetable oil combustion under partially premixed conditions with heavy exhaust gas recirculation. Fuel 2020;268(January):117350. https://doi.org/10.1016/j.fuel.2020.117350.

[11] Napolitano P, Guido C, Beatrice C, Pellegrini L. Impact of hydrocracked diesel fuel and hydrotreated vegetable oil blends on the fuel consumption of automotive diesel engines. Fuel 2018;222(July 2017):718–32. https://doi.org/10.1016/j.fuel.2018.02.097.

[12] Suarez-Bertoa R, et al. Impact of HVO blends on modern diesel passenger cars emissions during real world operation. Fuel 2019;235(March):1427–35. https://doi.org/10.1016/j.fuel.2018.08.031.

[13] S1876610219304886.

[14] Lorenzi G, Mignini L, Venezia B, Silva C, Santarelli M. Integration of high-temperature electrolysis in an HVO production process using waste vegetable oil. Energy Procedia 2019;158:2005–11. https://doi.org/10.1016/j.egypro.2019.01.465.

[15] Aatola H, Larmi M, Sarjovaara T, Mikkonen S. Hydrotreated vegetable Oil (HVO) as a renewable diesel fuel: Trade-off between NOx, particulate emission, and fuel consumption of a heavy duty engine. SAE Int J Engines 2009;1(1):1251–62. https://doi.org/10.4271/2008-01-2500.

[16] Dimitriadis A, et al. Improving PM-NOx trade-off with paraffinic fuels: A study towards diesel engine optimization with HVO. Fuel 2020;265(December 2019). https://doi.org/10.1016/j.fuel.2019.116921.

[17] Pechout M, Kotek M, Jindra P, Macoun D, Hart J, Vojtisek-Lom M. Comparison of hydrogenated vegetable oil and biodiesel effects on combustion, unregulated and regulated gaseous pollutants and DPF regeneration procedure in a Euro6 car. Sci Total Environ 2019;696:133748. https://doi.org/10.1016/j.scitotenv.2019.133748.

[18] Razmi AR, Sharifi S, Gholamian E, Arabkoohsar A, Shahbakhti M, "15 - Green hydrogen," in Future Grid-Scale Energy Storage Solutions, 2023, pp. 573–619. [Online]. Available: https://doi.org/10.1016/B978-0-323-90786-6.00006-6.

[19] Ajeeb W, Costa R, Baptista P. Life cycle assessment of green hydrogen production through electrolysis : A literature review. Sustain Energy Technol Assessments 2024;69(May):103923. https://doi.org/10.1016/j.seta.2024.103923.

[20] Concas G, Cocco D, Lecis L, Petrollese M. Life Cycle Analysis of a Hydrogen Valley with multiple end-users. J. Phys. Conf. Ser. 2022;2385(1). https://doi.org/10.1088/1742-6596/2385/1/012035.

[21] Wang Z, et al. Life cycle framework construction and quantitative assessment for the hydrogen fuelled ships: A case study. Ocean Eng 2023;281(April):114740. https://doi.org/10.1016/j.oceaneng.2023.114740.

[22] Sadeghi S, Ghandehariun S, Rosen MA. Comparative economic and life cycle assessment of solar-based hydrogen production for oil and gas industries. Energy 2020;208:118347. https://doi.org/10.1016/j.energy.2020.118347.

[23] Koj JC, Wulf C, Schreiber A, Zapp P. Site-dependent environmental impacts of industrial hydrogen production by alkalinewater electrolysis. Energies 2017;10(7). https://doi.org/10.3390/en10070860.

[24] Shiva Kumar S, Lim H. An overview of water electrolysis technologies for green hydrogen production. Energy Rep 2022;8:13793–813. https://doi.org/10.1016/j.egyr.2022.10.127.

[25] Ajeeb W, Baptista P, Costa R. Life cycle analysis of hydrogen production by different alkaline electrolyser technologies sourced with renewable energy. Energy Convers Manag 2024;316:118840. https://doi.org/10.1016/j.enconman.2024.118840.

[26] Schmidt O, Gambhir A, Staffell I, Hawkes A, Nelson J, Few S. Future cost and performance of water electrolysis: An expert elicitation study. Int J Hydrogen Energy 2017;42(52):30470–92. https://doi.org/10.1016/j.ijhydene.2017.10.045.

[27] Li R, et al. Capacity optimization of a wind-photovoltaic-electrolysis-battery (WPEB) hybrid energy system for power and hydrogen generation. Int. J. Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.08.029.

[28] Brauns J, Turek T. Alkaline water electrolysis powered by renewable energy: A review. Processes 2020;8(2). https://doi.org/10.3390/pr8020248.

[29] Seetharaman S, Balaji R, Ramya K, Dhathathreyan KS, Velan M. Graphene oxide modified non-noble metal electrode for alkaline anion exchange membrane water electrolyzers. Int J Hydrogen Energy 2013;38(35):14934–42. https://doi.org/10.1016/j.ijhydene.2013.09.033.

[30] Shiva Kumar S, Ramakrishna SUB, Krishna SV, Srilatha K, Devi BR, Himabindu V. Synthesis of titanium (IV) oxide composite membrane for hydrogen production through alkaline water electrolysis. South African J Chem Eng 2018;25:54–61. https://doi.org/10.1016/j.sajce.2017.12.004.

[31] Burnat D, et al. Composite membranes for alkaline electrolysis based on polysulfone and mineral fillers. J Power Sources 2015;291:163–72. https://doi.org/10.1016/j.jpowsour.2015.04.066.

[32] Pozio A, Bozza F, Nigliaccio G, Platter M, Monteleone G. Development perspectives on low-temperature electrolysis. Energia, Ambient. e Innov. 2021;(July):66–71. https://doi.org/10.12910/EAI2021-014.

[33] Anwar S, Khan F, Zhang Y, Djire A. Recent development in electrocatalysts for hydrogen production through water electrolysis. Int J Hydrogen Energy 2021;46(63):32284–317. https://doi.org/10.1016/j.ijhydene.2021.06.191.

[34] Gao R, et al. A life cycle exergy-based analysis of Power-to-liquid/Power-to-gas hybrid processes coupled with different water electrolysis technologies. Fuel 2024;357(PC):130040. https://doi.org/10.1016/j.fuel.2023.130040.

[35] Suleman F, Dincer I, Agelin-Chaab M. Comparative impact assessment study of various hydrogen production methods in terms of emissions. Int J Hydrogen Energy 2016;41(19):8364–75. https://doi.org/10.1016/j.ijhydene.2015.12.225.

[36] Zhang X, Bauer C, Mutel CL, Volkart K. Life cycle assessment of power-to-gas: Approaches, system variations and their environmental implications. Appl Energy 2017;190:326–38. https://doi.org/10.1016/j.apenergy.2016.12.098.

[37] Gerloff N. Comparative Life-Cycle-Assessment analysis of three major water electrolysis technologies while applying various energy scenarios for a greener hydrogen production. J Energy Storage 2021;43(May):102759. https://doi.org/10.1016/j.est.2021.102759.

[38] Delpierre M, Quist J, Mertens J, Prieur-Vernat A, Cucurachi S. Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis. J Clean Prod, 2021;299:126866. https://doi.org/10.1016/j.jclepro.2021.126866.
[39] European Union, "Fit for 55 package." https://www.consilium.europa.eu/en/policies/fit-for-55/.
[40] European Union, "RED II," 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC.
[41] A. e A. C. República Portuguesa and Direção Geral de Energia e Geologia, Roteiro e plano de ação para o hidrogénio em portugal. 2019.
[42] Ministério do Ambiente e Ação Climática, "EN-H2 Estratégia Nacional Para O Hidrogénio Versão Draft," República Port., 2020.
[43] "International Organization for Standardization (ISO). Environmental management e life cycle assessment e principles and framework," 2006. https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en.
[44] A. Lozanovski, O. Schuller, M. Faltenbacher, M. Fischer, K. Sedlbauer, and Fraunhofer-Institut für Bauphysik, Guidance document for performing LCA on hydrogen production systems, 9; 2013.
[45] L. Zampori, E. Saouter, E. Schau, J. Cristobal, V. Castellani, and S. Sala, "Guide for interpreting life cycle assessment result," 2016. doi: 10.2788/171315.
[46] European Comission, "Recommendations for Life Cycle Impact Assessment in the European context - Based on existing environmental impact assessment models and factors," 2011.
[47] Lotrič A, Sekavčnik M, Kuštrin I, Mori M. Life-cycle assessment of hydrogen technologies with the focus on EU critical raw materials and end-of-life strategies. Int J Hydrogen Energy 2021;46(16):10143–60. https://doi.org/10.1016/j.ijhydene.2020.06.190.
[48] Vonortas A, Papayannakos N. Comparative analysis of biodiesel versus green diesel. Wiley Interdiscip Rev Energy Environ 2014;3(1):3–23. https://doi.org/10.1002/wene.78.
[49] Arvidsson R, Persson S, Fröling M, Svanström M. Life cycle assessment of hydrotreated vegetable oil from rape, oil palm and Jatropha. J Clean Prod 2011;19 (2–3):129–37. https://doi.org/10.1016/j.jclepro.2010.02.008.
[50] Torres-Ortega CE, Gong J, You F, Rong BG. Optimal synthesis of integrated process for coproduction of biodiesel and hydrotreated vegetable oil (HVO) diesel from hybrid oil feedstocks. Comput Aided Chem Eng 2017;40:673–8. https://doi.org/10.1016/B978-0-444-63965-3.50114-8.
[51] Dimitriadis A, et al. Evaluation of a hydrotreated vegetable oil (HVO) and effects on emissions of a passenger car diesel engine. Front Mech Eng 2018;4(July):1–19. https://doi.org/10.3389/fmech.2018.00007.
[52] Oh YK, Hwang KR, Kim C, Kim JR, Lee JS. Recent developments and key barriers to advanced biofuels: A short review. Bioresour Technol, 2018;257(February): 320–33. https://doi.org/10.1016/j.biortech.2018.02.089.
[53] Di Vito Nolfi G, Gallucci K, Rossi L. Green diesel production by catalytic hydrodeoxygenation of vegetables oils. Int. J. Environ. Res. Public Health 2021;18 (24). https://doi.org/10.3390/ijerph182413041.
[54] R. Kiefel and J. T. Lüthje, "Conceptual Process Design: Production of Hydrotreated Vegetable Oil as an Additive for Petro-Diesel," 2018.
[55] Kurian V, Gill M, Dhakal B, Kumar A. Recent trends in the pyrolysis and gasification of lignocellulosic biomass. Biofuels Bioenergy A Techno-Economic Approach 2022:511–52. https://doi.org/10.1016/B978-0-323-90040-9.00028-X.
[56] Kalnes T, Shonnard DR, Marker T. Green diesel: A second generation biofuel green diesel. Int J Chem React Eng 2017;5.
[57] S. Nikander, "Greenhouse gas and energy intensity of product chain: case transport biofuel," 2008. [Online]. Available: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:GREENHOUSE+GAS+AND+ENERGY+INTENSITY+OF+PRODUCT+CHAIN+:+CASE+TRANSPORT+BIOFUEL#0.
[58] Xu H, Ou L, Li Y, Hawkins TR, Wang M. Life cycle greenhouse gas emissions of biodiesel and renewable diesel production in the United States. Environ. Sci. Technol. 2022;56(12):7512–21. doi: 10.1021/acs.est.2c00289.
[59] Gehrer M, Seyfried H, Staudacher S, Life Cycle Assessment of Btl As Compared To Hvo Paths in Alternative Aviation Fuel Production, pp. 1–10, 2014.
[60] Xu H, Lee U, Wang M. Life-cycle energy use and greenhouse gas emissions of palm fatty acid distillate derived renewable diesel. Renew Sustain Energy Rev 2020;134. https://doi.org/10.1016/j.rser.2020.110144.
[61] Neste Oil, "NExBTL ® Renewable Diesel Singapore Plant," 2009. [Online]. Available: https://www.neste.com/about-neste.
[62] De Jong S, et al. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. Biotechnol Biofuels 2017;10(1):1–18. https://doi.org/10.1186/s13068-017-0739-7.
[63] Hsu KH, Wang WC, Liu YC. Experimental studies and techno-economic analysis of hydro-processed renewable diesel production in Taiwan. Energy 2018;164:99–111. https://doi.org/10.1016/j.energy.2018.08.208.
[64] Srifa A, Faungnawakij K, Itthibenchapong V, Viriya-empikul N, Charinpanitkul T, Assabumrungrat S. Production of bio-hydrogenated diesel by catalytic hydrotreating of palm oil over NiMoS2/γ-Al2O3 catalyst. Bioresour Technol, 2014; 158:81–90. https://doi.org/10.1016/j.biortech.2014.01.100.
[65] Lorenzi G, Baptista P, Venezia B, Silva C, Santarelli M. Use of waste vegetable oil for hydrotreated vegetable oil production with high-temperature electrolysis as hydrogen source. Fuel 2020;278(December 2019):117991. https://doi.org/10.1016/j.fuel.2020.117991.
[66] Satterfield CN, Trickle-Bed Reactors 21(2);1975:209–228.
[67] Srifa A, Viriya-Empikul N, Assabumrungrat S, Faungnawakij K. Catalytic behaviors of Ni/γ-Al2O3 and Co/γ-Al2O3 during the hydrodeoxygenation of palm oil. Catal Sci Technol 2015;5(7):3693–705. https://doi.org/10.1039/c5cy00425j.
[68] Herskowitz M, Landau MV, Reizner Y, Berger D. A commercially-viable, one-step process for production of green diesel from soybean oil on Pt/SAPO-11. Fuel 2013; 111:157–64. https://doi.org/10.1016/j.fuel.2013.04.044.
[69] Bezergianni S. Catalytic hydroprocessing of liquid biomass for biofuels production, liquid gaseous and solid biofuels. Convers Tech 2013:299–326.
[70] REDII - Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance.), 2024.
[71] UCO data from Portugal - COMPLIANCE WITH THE CRITERIA OF SUSTAINABILITY IN PRODUCTION AND IMPORT OF BIOFUELS IN PORTUGAL, 2024.
[72] Talens Peiró L, Lombardi L, Villalba Méndez G, Gabarrell i Durany X. Life cycle assessment (LCA) and exergetic life cycle assessment (ELCA) of the production of biodiesel from used cooking oil (UCO). Energy 2010;35(2):889–93. https://doi.org/10.1016/j.energy.2009.07.013.
[73] Cárdenas J, Orjuela A, Sánchez DL, Narváez PC, Katryniok B, Clark J. Pre-treatment of used cooking oils for the production of green chemicals: A review. J. Clean. Prod. 2021;289. https://doi.org/10.1016/j.jclepro.2020.125129.
[74] Yano J, Aoki T, Nakamura K, Yamada K, Ichi Sakai S. Life cycle assessment of hydrogenated biodiesel production from waste cooking oil using the catalytic cracking and hydrogenation method. Waste Manag 2015;38(1):409–23. https://doi.org/10.1016/j.wasman.2015.01.014.
[75] Chatterjee R, Sharma V, Mukherjee S, Kumar S. Life cycle assessment of bio-diesel production—A comparative analysis. J Inst Eng Ser C 2014;95(2):143–9. https://doi.org/10.1007/s40032-014-0105-5.
[76] Soam S, Hillman K. Factors influencing the environmental sustainability and growth of hydrotreated vegetable oil (HVO) in Sweden. Bioresour Technol Reports 2019;7(March):100244. https://doi.org/10.1016/j.biteb.2019.100244.
[77] Chrisendo D, Siregar H, Qaim M. Oil palm cultivation improves living standards and human capital formation in smallholder farm households. World Dev 2022; 159:106034. https://doi.org/10.1016/j.worlddev.2022.106034.
[78] Yu H, et al. Regimes of global and national oil palm cultivations from 2001 to 2018. Glob Environ Chang 2024;86(March):102845. https://doi.org/10.1016/j.gloenvcha.2024.102845.
[79] Eurelectric - Portugal 2023 Electricity Generation by Fuel, 2023.
[80] Eurelectric - Spain 2023 Electricity Generation by Fuel, 2023.
[81] Zhang L, et al. A comprehensive review of the promising clean energy carrier: Hydrogen production, transportation, storage, and utilization (HPTSU) technologies. Fuel 2024;355(August 2023). https://doi.org/10.1016/j.fuel.2023.129455.
[82] Hnát J, Paidar M, Bouzek K. Hydrogen production by electrolysis. Curr. Trends Futur. Dev. Membr. New Perspect. Hydrog. Prod. Sep. Util. 2020;V:91–117. https://doi.org/10.1016/B978-0-12-817384-8.00005-4.
[83] Abe I. Alkaline water electrolysis. In energy carriers and conversion systems. UNESCO–Encyclopedia Life Support Syst. Chiba 2009;I.
[84] Nel Hydrogen, "The World's Most Efficient and Reliable Electrolysers," Nel Hydrog., p. 16, 2020, [Online]. Available: https://nelhydrogen.com/wp-content/uploads/2020/03/Electrolysers-Brochure-Rev-C.pdf.
[85] Koj JC, Schreiber A, Zapp P, Marcuello P. Life cycle assessment of improved high pressure alkaline electrolysis. Energy Procedia 2015;75:2871–7. https://doi.org/10.1016/j.egypro.2015.07.576.
[86] Correas L, Improvements to Integrate High Pressure Alkaline Electrolysers for Electricity/H2 production from Renewable Energies to Balance the Grid, no. 1, pp. 1–12, 2014.
[87] Férriz AM, Bernad A, Mori M, Fiorot S. End-of-life of fuel cell and hydrogen products: A state of the art. Int J Hydrogen Energy 2019;4:12872–9. https://doi.org/10.1016/j.ijhydene.2018.09.176.
[88] P. L. Spath and M. K. Mann, "Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming," Golden, Colorado (US), 2000. [Online]. Available: https://www.nrel.gov/ docs/fy01osti/27637.pdf.
[89] Zhang J, Ling B, He Y, Zhu Y, Wang Z. Life cycle assessment of three types of hydrogen production methods using solar energy. Int J Hydrogen Energy 2022;47 (30):14158–68. https://doi.org/10.1016/j.ijhydene.2022.02.150.
[90] Assunção R, Ajeeb W, Eckl F, Gomes DM, Neto RC. Decentralized hydrogen-oxygen co-production via electrolysis for large hospitals with integrated hydrogen refueling station. Int. J. Hydrogen Energy 2025;103:87–98. https://doi.org/10.1016/j.ijhydene.2025.01.169.