Identify Parameters Hindering Renewable Hydrogen Production in France: Life Cycle Sensitivity and Uncertainty Analysis

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Abstract. Flourishing green hydrogen economy worldwide serves as a pillar for global energy transition and carbon-neutral targets. However, rare researches on the environmental impact of green hydrogen production have focused on national average resource availability and technology market share. Nor a detailed and holistic sensitivity and uncertainty analysis regarding both foreground and background parameters in the green hydrogen production life cycle could be found. To fill these gaps, we present this study as a comprehensive environmental impact investigation of renewable-electricity-based water electrolysis H_2 production in France, in terms of average resource availability and technology market share in France in 2019. Water electrolysis H_2 production with average French wind electricity through proton exchange membrane electrolysis unit was identified as the most environmentally-beneficial option among all pathways studied. By building the corresponding French national benchmark parametric life cycle model, the key parameters that determine the environmental impact of green hydrogen in France were revealed. Under current French context, environmental impact's uncertainty for solar-to-H_2 and wind-to-H_2 pathways is between 19%-26% and 8%-11%, respectively. Based on the unit process contribution investigation and further scenario analyses, we propose the guidelines and suggestions on improving life cycle renewability and sustainability to French green H_2 production.

1 Introduction

In the current global techno-economic context, fossil fuels, e.g., coal and natural gas, cover 80 % of global energy consumption[1]. The ever-increasing energy demand worldwide, especially the fossil fuel demand, becomes the primary driver of global warming[1], environment degradation[2, 3], and human disease[4, 5], pressuring the world's sustainable development[6]. Aiming for global decarbonization of energy services, hydrogen energy (H_2), a potentially green and renewable energy vector, gives a cross-boundary opportunity for the sustainable and renewable global energy landscape transition[7-10].

1.1 Hydrogen and hydrogen sector in France

As the lightest element in Mendeleev's periodic table, hydrogen is present from the first moment of the universe, taking around 75 % of the contemporary universe's total mass[11]. Colorless, odorless, and non-corrosive, hydrogen gas, i.e., the hydrogen molecule, is a suitable energy carrier on earth, with a much higher mass-energy density (120MJ/kg) than fossil fuels[11, 12].

At present, Europe currently consumes 339 TWh H_2 per year[13], of which around 90.6 % is fossil-based hydrogen[14]. In Europe 2018, only two hydrogen production plants (fossil-based) were equipped with carbon capture (CCS) facilities. For France, the country produced around 920,000 metric tons (Mt) H_2 in 2008[15], while the H_2 production capacity raised to 2088.8 Mt/day in 2019[16]. Besides, almost all merchant H_2 is produced from steam methane reforming and, to a lower extent, autothermal reforming and less commonly partial oxidation, both in Europe[7, 13] and France[15, 16]. Regarding water electrolysis H_2 based on low carbon or renewable electricity, their total installed capacity of electrolysis unit is around 58MW in EU27 2018[17], half of which is produced in Germany. The 58 MW electrolyzer generates less than 0.1 % of the total H_2 production in Europe.

One obvious thing is that the ambitious in hydrogen production sector decarbonization[18] is the crucial and inevitable step to fulfill the carbon emission reduction target and climate change goals announced by the French government successfully: 36 % CO_2 emission reduction by 2030 compared to 2005[19] in the National energy and climate plans of France; achieving a carbon-neutral

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society by 2050[20]. Remarkably, the water electrolysis H_2 production based on renewable power and biomass sourced H_2 production draws the main focus of French society and government due to their renewable and sustainable potential, e.g., the negative-carbon effect of biomass sourced H_2 generation[21, 22].

The French government has established the "hydrogen deployment plan for the energy transition"[23, 24] to facilitate renewable & low carbon H_2 permeation. According to this plan, France will switch 20 % to 40 % fossil-based hydrogen nationwide consumed to renewable hydrogen electrolyzed from low carbon electricity or recovered from biomass by 2028[8]. The Multiannual Energy Program (la programmation pluriannuelle de l'énergie 2020, PPE 2020), released on 23rd April 2020 (for the period s of 2019 - 2023 and 2024 - 2028), provides a basket of policies adding financial support for hydrogen sector development[25]. Under the instruction of the PPE 2020, guarantees of origin scheme and Guarantees of Traceability, as has already been applied to the French biogas market, will also be developed[25]. French Ordinance No. 2021 - 167[26] defines the future context of the country's renewable & low-carbon hydrogen market. All these measures will finally standardize the co-financing models promoting the H_2 ecosystem deployment integrating different uses (mobility, industry, etc.) up to the local level in France. Besides, France also participated in the HyLaw project, IPCEI projects[27-30], etc., to identify, assess, and find prioritizing measures to the significant regulatory barriers, and thus to accelerate the development of a global hydrogen market.

Table 1. Critical advance in demonstration and commercialization of renewable and low-carbon H_2 in France.

Location and time	Responsible parties	Novelty and Significance
Vitry-le-François, Strasbourg 2019	Haffner Energy	Commercialization of the first highly efficient biomass sourced H_2 production recovering up to 70 % of the biomass energy with a relatively low price: € 6/kg[31].
Brittany, Normandy, and Loire 2020	Lhyfe	VHyGO project: Building a completely renewable H_2 ecosystem for west France region[32].
South region of Provence-Alpes-Côte d'Azur 2021	TotalEnergies, ENGIE	Masshylia project: Start design, develop, build, and operate France's currently largest renewable hydrogen production program[33].
Le Croisic 2022	Lhyfe, Chantiers de l'Atlantique	Start operation of first commercialized off-shore wind hydrogen production plant worldwide[34].

The nationwide favorable policies promotion has enabled France to become a thriving economy for sustainable hydrogen. Numerous robust actors in the fields of renewable & low-carbon hydrogen and fuel cells from both industries (Lhyfe[34, 35], ENGIE[36], TotalEnergies[33], etc.) and academia bring lots of new hydrogen production projects, and technologies come into being. Recent renewable & low-carbon H_2 production projects across Europe and France can be found from Fuel Cell and Hydrogen Joint Undertaking[37], International Energy Agency (IEA)[38], and EU Commission[39]. Several landmark project that marked critical advance in democratization and permeation of renewable & low-carbon H_2 for France is shown in Table 1 below.

1.2 Hydrogen production environmental impact

Serving as the basic for H_2 production sector decarbonization, identifying sustainable H_2 production pathways through environmental impact assessment of H_2 production has long been a hot spot for researchers. Life cycle assessment (LCA) methodology, which aims for assessing potential environmental impacts associated with all life cycle stages (e.g., extraction and processing of raw material, manufacture, distribution, and use, recycling or end-of-life treatment) of a commercial product, process, or service, is widely accepted and developed by researchers working on environmental impact assessment of H_2 production.

In terms of methodological innovation, Valente et al.[40-42] developed a harmonized approach to estimate the environmental impacts of different H_2 production technologies, currently focusing on three impact categories: global warming potential (GWP), cumulative energy demand (CED), and acidification potential (AP). Their harmonized LCA method has been applied to a vast of electrochemical[43], thermochemical[41], nuclear[44], and biological[45] H_2 production pathways. Their harmonization protocol to refine cradle-to-gate system boundaries suggests a functional unit of 1 kg industrial-grade hydrogen (purity >99 %) and compressed to 200 bars. To increase comparability of the results, they recommend using system expansion or economic allocation in the attributional LCA assessment when hydrogen is the main product or by-product, respectively[40].

However, for a region or country like France that aims to implement a highly sustainable H_2 sector, massive implementation for different renewable and low-carbon H_2 production technologies fed by various feedstocks is inevitable, along with continuous industry development. Current environmental impact assessment of H_2 production technologies rarely focuses on the average resource availability and technological market shares at the national or regional level. While such results could, however, provide the scientific basis to guide one nation's financing policy formulation[26], subsides determination[46], and tender process[47] to promote the renewable and low-carbon H_2 penetration.

Regarding specific technologies, embodied with huge sustainability potential, the environmental performance of water electrolysis H_2 production has been extensively studied[48-51]. The source of electricity used in the water electrolysis is the determining factor for the environmental impact of the H_2 produced[40, 49, 52, 53]. The majority of the research agrees that H_2 from wind, solar, and hydro electrolysis generally has a lower GWP, CED, and AP than the biomass sourced H_2 and much lower than the fossil-based H_2 without CCS[40-42, 49, 50]. In terms of GWP, CED, and AP, hydro electrolysis ranked as the best among water electrolysis H_2 pathways, followed by wind electrolysis, photovoltaic solar electrolysis, and thermal solar ranked as the worst[40, 42, 49, 50]. Nevertheless, some critical impact categories that are not supposed to be neglected, e.g., eutrophication potential human toxicity potential, ionizing radiation, photochemical Oxidation Potential, are seldomly discussed in the existing literature, which is the same for resources use mineral and metals, abiotic Depletion Potential[49].

Regarding the uncertainty (UA) and sensitivity analysis (SA), a detailed review of UA and SA in H_2 production LCA hasn't appeared yet. Most UA and SA for H_2 production focus on the techno-economic context[54-64], and only a few studies focus on the UA and SA of H_2 production on LCA. Furthermore, the little research available concentrates only on the UA and SA of foreground life cycle parameters related to H_2 production facilities and processes.

UA and SA towards the following foreground life cycle parameters have been carried out: reduction and recycling rate of electrolysis stack material[65]; electrolyzer efficiency[66]; energy mix applied during H_2 production[67], allocation strategy[68], and treatment of H_2 production by-product[67]; H_2 production catalyst & chemical consumption rate[69]; weighting factors among economic, social, environmental influence[70, 71]; pollutant emission ratio during facility installation[72]. However, regarding the LCA result, some upstream or downstream parameters may have much more influence than the foreground parameters related to H_2 production facilities[73]. According to the author's best knowledge, no research could be found that performs a detailed and holistic SA and UA regarding all the foreground and background life cycle parameters involved in renewable-electricity-based water electrolysis H_2 production life cycle. Only Yadav et al.[73] perform the SA and UA of several upstream parameters involved in solar electricity plant (e.g., PV plant performance ratio, PV plant efficiency, Global horizontal irradiation) in the life cycle CED and GWP analysis to solar-based high-temperature water electrolysis system.

Facing and looking forward to complementing the existing research gaps stated above, the main objective of this research is a comprehensive environmental impact investigation and comparison among renewable-electricity-based water electrolysis H_2 production pathways. This study highlights the following specific research objectives:

1) From the angle of average French resource availability and technology market share, build corresponding French national benchmark parametric life cycle model for wind electricity-based (wind-to-H_2) and solar electricity-based (solar-to-H_2) water electrolysis H_2 production pathways through proton exchange membrane electrolyzer (PEM) and alkaline electrolyzer (AE).

2) Calculate the multi-environmental impacts for all H_2 production pathways analyzed and identify the corresponding main contributors and hotspots, e.g., foreground and background activities and emissions, to 11 impact categories studied.

3) A detailed and holistic SA and UA regarding all the foreground and background life cycle parameters by propagating the uncertainties of each life cycle parameter into corresponding parametric life cycle models. And testing the importance of each parameter uncertainty in each impact categories' global uncertainty for all H_2 production pathways.

4) Based on further scenario variation and comparison, we put forward the guidelines and suggestions towards improving the life cycle renewability and sustainability to renewable-electricity-based water electrolysis H_2 production.

The following paper is structured as follows: Section 2 elaborates the life cycle assessment methodology applied by this research, where the goal and scope definition, hypothesis and method for life cycle inventory analysis; life cycle impact assessment; and life cycle result interpretation (methodology for holistic SA and UA included) for each H_2 production pathway analyzed were elaborated.

Section 3 systemically present and discuss the result obtained: environmental impact categories score hotspot unit process contribution; findings discovered from further scenario variation and comparison; as well as impact category score's sensitivity to life cycle parameters and corresponding uncertainty. Based on the research performed, Section 3 finished with the detailed guidelines and suggestions towards improving the life cycle sustainability of French green hydrogen production. Major conclusions of this research are extended into the Conclusion section.

2 Materials and Methods

2.1 LCA methodology

The 14000 series of environmental management standards of the International Organisation for Standardisation (ISO), in particular, ISO 14040[74] and ISO 14044[75], provide detailed and worldwide accepted procedures for conducting LCA studies.

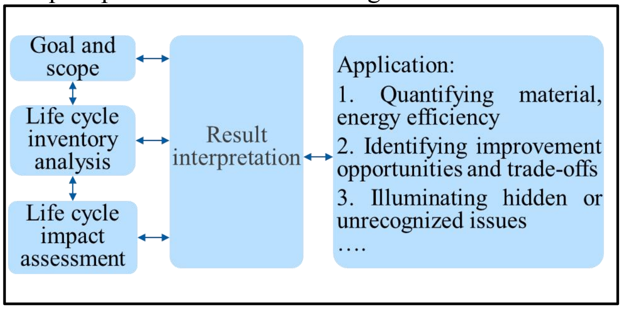

Fig. 1. General phases of life cycle assessment.

As pointed out by ISO, LCA can fulfill several goals: quantifying material and energy efficiency for a system; identifying improvement opportunities and trade-offs; highlighting hidden or unrecognized issues; promoting a wider communication about how to compare and improve highly complex industrial systems.

There are four general phases when conducting an LCA as shown in Fig. 1: Goal and scope definition; Life cycle Inventory analysis; Life cycle impact assessment (LCIA); Result interpretation.

2.2 Goal and scope definition

The goal of this work is to better understand the environmental sustainability of renewable-electricity-based water electrolysis H_2 production (RE-to-H_2) in France around 2019, from the angle of national average resource availability and technology market share, overcoming the existing limitation as stated above. The research result could serve as a basis and reference for governmental officials, policymakers, and companies, assisting in financing policy formulation to promote renewable & low-carbon H_2 penetration in France.

As mentioned in the Introduction section, the main tasks of this LCA research are, for each H_2 production pathway analyzed: 1) to build the corresponding French national benchmark parametric life cycle model, 2) to calculate the potential multi-environmental impacts, 3) to locate the primary hotspot of each impact categories studied, 4) to analyze the uncertainties and variability in the LCA results, thus becoming the first paper that performs a detailed and holistic SA and UA regarding both foreground and background life cycle parameters in RE-to-H_2 life cycle.

The functional unit of the research, common to all analyzed RE-to-H_2 pathways, is “1 MJ H_2 produced and being compressed to 200 bar”. As indicated in Fig. 2 below, the life cycle boundaries of cradle-to-grave assessment include:

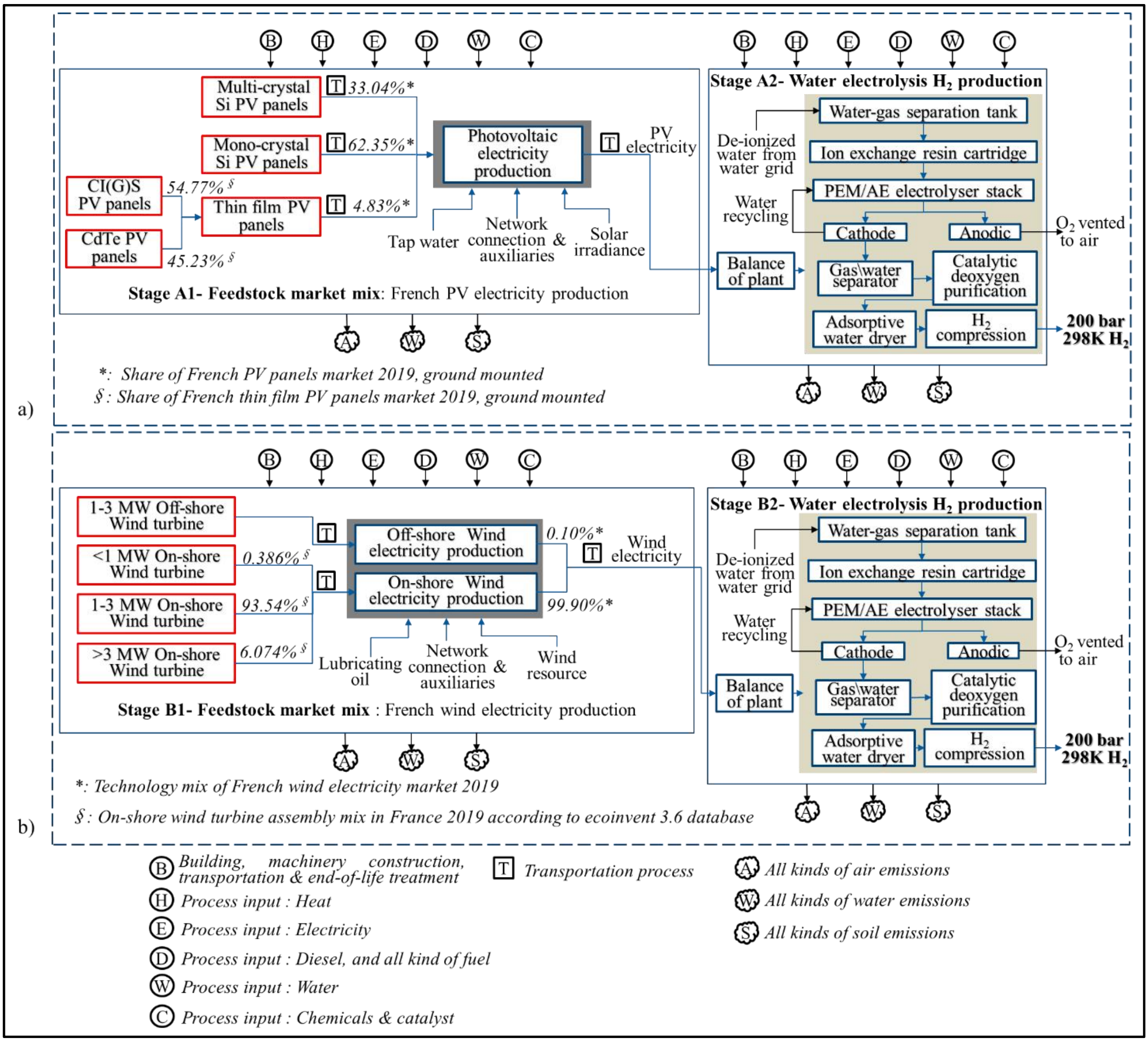

Fig. 2. Flowchart and life cycle boundaries of a) solar-to-H_2 pathways b) wind-to-H_2 pathways.

1) Photovoltaic solar electricity production market mix in France 2019, unified processes to each solar electricity production technologies clarified by ecoinvent v3.6 database, i.e., construction (material extraction,

transport, and end-of-life treatment) of PV panels and PV power plant network connection & auxiliaries; PV electricity production process.

2) mix of wind electricity production market in France 2019, unified processes to each wind electricity production technologies clarified by the ecoinvent v3.6 database, i.e., construction (material extraction, transport, and end-of-life treatment) of wind turbine assembly and wind power plant network connection & auxiliaries; wind electricity production process.

3) facility construction (material extraction, transport, and end-of-life treatment) of the water electrolysis unit (H_2 compression unit included).

4) water, energy & chemical consumption (related transport and end-of-life treatment included) during water electrolysis H_2 production, purification & compression process.

In each RE-to-H_2 pathway, the electricity generated by the PV panel or the wind farm will fulfill all the electricity demand of the water electrolysis unit (both the electrolyzer stack and all the auxiliaries included in the balance of plant, BOP), and the H_2 compressor.

Besides, in each pathway, the oxygen produced by the electrolysis unit is vented to the environment without a subsequent utilization and thus is considered environmental burden-free. Furthermore, after purification, the H_2 produced with a purity larger than 99.9 % is compressed to the standard H_2 transport pressure nowadays in Europe to ensure comparability to other studies.

The feedstock market mix, e.g., solar or wind electricity production market mix presented in Fig. 2 within the blue square, is embodied with high complexity under average resource availability and technology market share in France 2019. One obvious point is that the life cycle environmental impact for PV panels will vary based on PV panel types imported from different countries[76]. And according to different installation locations and applications, e.g., ground centralized PV panels, façade panels, and slanted or flatted mounted panels on the roof, the annual solar irradiation available on PV panels and the PV plant auxiliaries transportation distance will change. On the other hand, based on different technological details (e.g., rotor size, turbine capacity, tower type and size), more than 2000 wind turbine models are available and used in France. And the timely evolution of the technological specificities to PV and wind power plant components' production and installation will consume electricity under a very different electricity grid mix.

Thus, special attention should be paid when refining the life cycle boundaries and corresponding life cycle inventory (LCI) parameters. For the feedstock production market in each H_2 production pathway, this research follows the protocol and logic shown in Fig. 3 to define the life cycle boundaries, obtain corresponding LCI and parameters data. Thus, building the comparable French national benchmark parametric life cycle model best represents the reality, namely, France's average resource availability and technology market share.

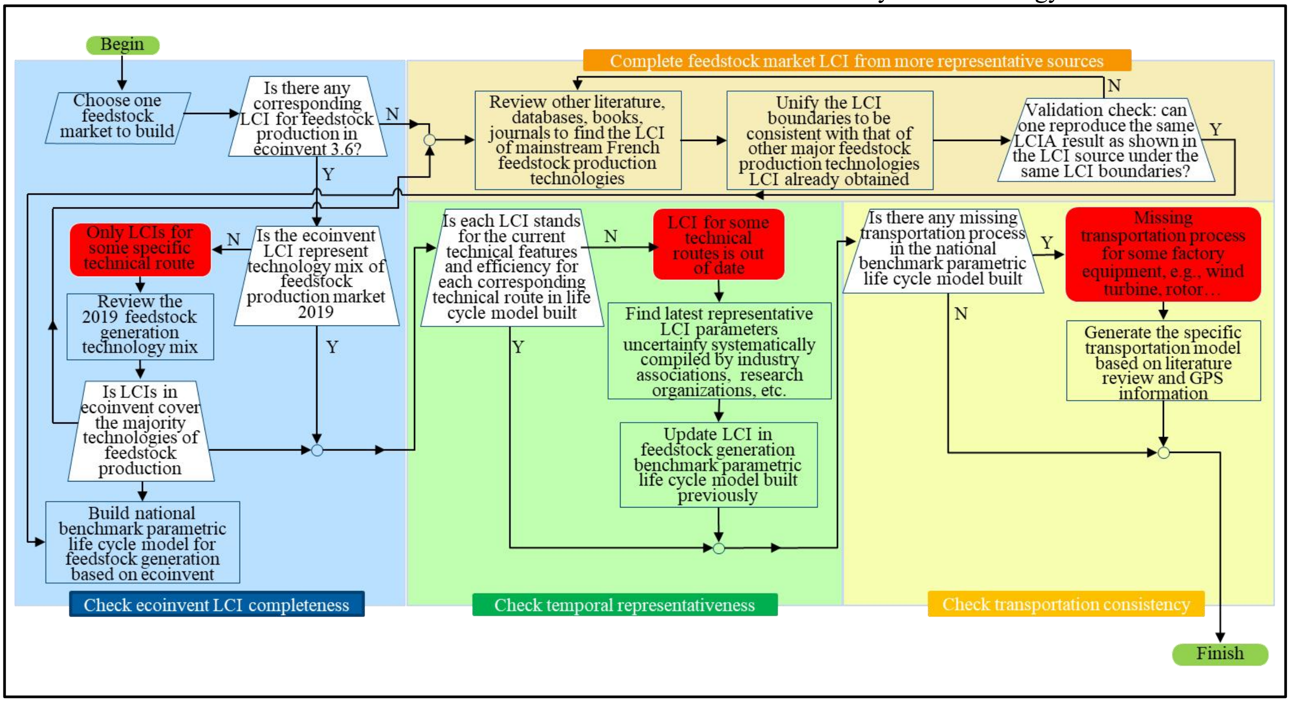

Fig. 3. Decision diagram for French national benchmark parametric LCA model harmonization regarding feedstock market mix.

As shown in Fig. 2 and Fig. 3, the French national benchmark parametric LCA models comprise the detailed modeling of the related transportation processes for each RE-to-H_2 pathway studied. In consist with methodology in the ecoinvent v3.6 database, all the transportation processes included in each RE-to-H_2 pathway are measured as metric ton*km (t*km hereafter).

2.3 Life cycle inventory

This section gives a detailed description of LCI for each RE-to-H_2 pathway studied, e.g., the data and hypothesis we collected and harmonized based on the new findings of the current H_2 production situation from various data sources and previous research. Corresponding French national benchmark parametric life cycle model, which integrated detailed LCI data of each pathway studied, is shown in Supplementary Materials. The ecoinvent database (version v3.6) “Allocation, cut-off by classification” is the primary source for the 2019 background LCI used in this research.

2.3.1 French solar electricity production market mix

2.3.1.1 PV plant construction: PV panels market mix in France

In this research, the solar electricity generation mix in mainland France 2019 mainly stands for the centralized photovoltaic electricity from on-ground mounted PV panels. Science large-scale captive H_2 production through centralized PV panels installed on the ground has long been drawing the main interest of the French government and companies[46, 77]. And due to data unavailability, the distributed & semi-centralized solar electricity generation is not included in the scope of this report. And it’s hereby not included in the French national benchmark parametric LCA model. This research assumes a PV plant with 100 m^2 total area powered by the national level PV panel mix (one unit of French national benchmark PV plant).

As shown in Fig. 2 a), according to IEA’s report on Task 12: PV Sustainability Activities[78-80], the open ground PV panels market mix in France 2019 is shared by three types of PV panels: multi-crystal Si PV panel (average, 62.35 %), mono-crystal Si PV panel (average, 33.04 %), and thin-film PV panel (average, 4.83 %). And the thin-film PV panel market of France in 2019 comprises mainly Cadmium telluride PV panels (CdTe, 54.77 %) and Copper indium gallium selenide PV panels (CIGS, 45.23 %). The PV panel production market has ushered in tremendous technological progress and efficiency improvement since 2005, namely, the time node in ecoinvent v3.6 database, as discussed in detail by Besseau[81] and the Methodology Guidelines for PV LCA released by IEA[82]. The latest LCI database for PV panels released by IEA[78] is used in this report to overcome the time hysteresis of the ecoinvent v3.6 database.

2.3.1.2 PV plant construction: network connection & auxiliaries

Following the protocol in Fig. 3, the network connection unit & auxiliaries apply the identical life cycle boundaries and LCI as defined in the ecoinvent v3.6 database, where the site preparation process, PV panel installation service, PV mounting system, and the DC/AC inverter, tap water consumption during PV plant installation and operation should be taken into consideration:

The DC\AC inverter used has a rated capacity of 500 kW. The LCI of the inverter, the PV panel installation service, and the tap water supplement are directly taken from the ecoinvent v3.6 database. The LCI of the PV mounting system used in this research is derived from IEA’s report on Task 12: PV Sustainability Activities[78], overcoming time hysteresis of the ecoinvent v3.6 database as stated above. The requirement of the site preparation process (including mainly the diesel consumption for land preparation), PV panel installation service, tap water consumption during PV plant operation was recalculated from the data in the ecoinvent v3.6 database to match the installed capacity of the PV plant to satisfy the FU. The installed capacity of the inverter equals the PV model’s installed capacity.

The amount of the PV mounting system, in m^2, equals the land area needed for the PV electricity plant, which is 100 m^2 as assumed. Equation (1) below calculates the 100 m^2 PV plant’s installed capacity accessed in the solar-to-H_2 pathway.

$$P_{\mathrm{PVplant}} = P_{\mathrm{peak}} \times \mathrm{A}_{\mathrm{PVplant}} \times GCR \tag{1}$$

Where,

P_{PVplant} : Nominal maximum power of the 100 m^2 French national benchmark PV plant.

P_{peak} : Nominal maximum capacity of the PV panels per m^2 under Standard Test Condition (STC), 115.06 Wp/m^2 on average[81].

$\mathrm{A}_{\mathrm{PVplant}}$: Land area for the PV plant, 100 m^2.

GCR : Ground cover ratio, which refers to the size of net PV modules, divided by the equivalent ground area of the PV power plant, under specific tilt and azimuth[83]. Besides PV panels, there should also be space dedicated to fire prevention and self-shading prevention in the PV plant. *GCR* is 36 % on average as calculated by Blondel Paul[84], under 30° tilt.

2.3.1.3 PV plant construction: transportation process

IEA’s report on Task 12[78] includes detailed transportation requirements for each process involved in LCI of all kinds of PV panel production until the PV panel is transported from the production countries to European regional storage. In solar-to-H_2 pathway, to cover PV panel transportation from European regional storage to their installation site in mainland France, based on the transportation scenario of Romain Besseau[81], Celik et al.[85], and the road information on Google map, a two-stage land transportation process was modeled here:

All PV panels are first transported by train (700 km, average) and then by lorry (300km, average). The two-stage land transportation process was also applied to all the other components involved in the PV plant construction and operation, e.g., each component in the PV plant network connection unit & auxiliaries (PV panel mounting and installation system, DC/AC inverter, etc.). The mass of each component involved, e.g., PV panels mix, network connection unit & auxiliaries, can be found in their corresponding LCI as shown in supplementary materials.

2.3.1.4 PV plant operation: solar irradiance and PV electricity generation mix in France

The daily or yearly solar irradiance determines the PV electricity generation. The accumulative yearly solar irradiance (Wh/m^2) for 13 administrative regions of mainland France 2019 are taken from the CAMS radiation service dataset "AGATE" with McClear version 3 and CAMS radiation bias correction[86], as shown in the supplementary materials. To utilize the maximum annual solar irradiance potential, the tilt angle is fixed at 30 ° and azimuth at 180 ° for PV panels installed in the French national benchmark PV plant.

With France's yearly solar irradiance data, we can calculate the total electricity production during the whole PV power plant lifespan with Equation (2), as standardized by IEA[76].

$$Elec_{\mathrm{PV}} = P_{\mathrm{PVplant}} \times \frac{Irr}{I_{\mathrm{HTC}}} \times PR \times Life_{\mathrm{PV}} \times ALR \qquad (2)$$

Where,

$Elec_{\mathrm{PV}}$: Accumulative electricity generation within the whole PV power plant lifespan, in kWh.

Irr : Annual solar irradiance at the PV power plant location under specific tilt and azimuth in kWh/m^2/yr. Maximum value[86] among 13 administrative regions in France 2019 as 1900.59 kWh/m^2/yr.

I_{HTC} : Solar irradiance under STC[87], which is 1 kW/m^2.

PR : Performance ratio (average, 0.8[78]), which indicates the efficiency of the PV power plant studied, namely the difference between the actual energy output and the theoretical energy output due to losses during PV electricity generation such as thermal and conduction losses[88].

$Life_{\mathrm{PV}}$: PV power plant lifespan in years, 30 years on average[82], which equals PV panels lifespan.

ALR : Average loss ratio describes the PV panel's average efficiency loss among the system's lifespan. Based on the yearly loss ratio[89, 90], it should be calculated with Equation (3).

$$ALR = \frac{1}{Life_{\mathrm{PV}}} \sum_{i=1}^{Life_{\mathrm{PV}}} \frac{100 - YLR \times (i-1)}{100} = \frac{200 - YLR \times (Life_{\mathrm{PV}} - 1)}{200} \quad (3)$$

Where,

YLR : Yearly loss ratio (average, 0.7 %[82]), which indicates PV panel efficiency loss each year.

2.3.2 French wind electricity production market mix

2.3.2.1 Wind plant construction: wind turbine assembly market mix in France

To represent the national average wind electricity generation mix in mainland France 2019, in the wind-to-H_2 pathway, we assumed one unit of French national benchmark wind farm shared by the off-shore wind farm and onshore wind farm mix based on the reality summarized below and as shown in Fig. 2b).

French wind power observatory[91, 92], Offshore Wind in Europe 2020[93], etc., detailed illustrate the current wind electricity market (production, new installations, financing activity, etc.) in France. The national average wind electricity generation market in mainland France 2019 is distinguished between off-shore wind (average, 0.1 %) and onshore wind (average, 99.90 %) electricity production. One can calculate the specific ratio from France's annual total wind electricity production and the production amount by type. The annual accumulative wind electricity production in France 2019 is 34.1 TWh from both off-shore and onshore wind power[94]. And total off-shore wind electricity production can be calculated by Equation (4) below. Besides the off-shore wind electricity, other electricity comes from the onshore wind turbines.

Wind Power Database (28th July 2021 last version)[95] summarized the technical details for all wind power plants (farm location, turbine model and capacity, hub height, turbine number, etc.) in France. On average, the market share of onshore wind turbine assembly mix is 11.27 % (<1MW wind turbine): 82.16 % (1-3 MW wind turbine): 6.568 % (>3 MW wind turbine). Following the off-shore wind electricity market in France around 2019[93], in this research, the capacity of all French off-shore wind turbines fulls between 1-3MW. For both onshore and off-shore wind turbine assembly in each corresponding wind farm, this study took their LCI from the ecoinvent v3.6 database.

2.3.2.2 Wind plant construction: plant network connection & auxiliaries

Based on the capacity level of the wind turbine and onshore/off-shore features, the types and amount of network connection unit & auxiliaries needed, i.e., the DC\AC transformer, cables, tower, foundation, lubricating oil, will vary. In the wind-to-H_2 pathway, the LCI of network connection & auxiliaries to each corresponding wind turbine assemblies under different capacity levels are exported from the ecoinvent v3.6 database. We can directly find the amount needed for 1 kWh wind electricity production.

Table 2. Components in one unit of French national benchmark wind farm covered by the predefined two-stage transportation process.

Components	Internal parts
Rotor	Rotor blades, rotor hub, extender
Nacelle	Nacelle cover, gearbox, generator, shaft, yaw system, flanges, etc.
Tower	All kinds of steel, epoxy resin, and paint

Control electronics	All kinds of electronics in the nacelle
Network connection	Cables, transformer, sub-station with the circuit breaker, electricity meter, etc.

2.3.2.3 Wind plant construction: transportation process

Transportation of all components involved in wind plant construction and operation, e.g., wind plant network connection & auxiliaries, each type of wind turbine assembly, as shown in Table 2, from the production site to the installation site, are not covered by the ecoinvent database. Thus, following the logic of Fig. 3, to cover the transportation from the production site to the installation site, this research applied the same two-stage land transportation process as defined in Section 2.3.1 of each component involved, as shown in Table 2. For off-shore wind turbine assembly, this research applies overseas transportation to 10 km (on average). The mass of each component summarized in Table 2 can be found in their corresponding LCI shown in the supplementary materials.

2.3.2.4 Wind plant operation: wind electricity generation mix in France

In the wind-to-H_2 pathway, we can calculate the total electricity production during the whole lifespan of one unit of French national benchmark wind farm with Equation (4) below.

$$Elec_{\text{wind}} = Cf_{\text{turbine}} \times P_{\text{Windplant}} \times 8760 \times Life_{\text{wind}}$$

(4)

Where,

$Elec_{\text{wind}}$: Accumulative electricity generation within the whole wind farm lifespan, in kWh.

Cf_{turbine} : Capacity factor for off-shore or onshore wind turbine assembly, which equals the annual wind turbine net electricity output divided by turbines' maximum power capability (net energy output under turbine's rated power, 8760-hour uninterrupted annually working). On average, 24.50 % for onshore wind turbines[96] and 38 % for off-shore wind turbines[97, 98] in France 2019.

$Life_{\text{wind}}$: Wind farm lifespan in years, 20 years on average[81], which equals wind turbine lifespan.

$P_{\text{Windplant}}$: The total installed capacity of one unit 2019 French national benchmark wind farm, in kW, which can be calculated with Equation (5) below.

$$P_{\text{Windplant}} = R_{\text{offshore}} \times P_{\text{offshore},1-3\text{MW}} + R_{\text{onshore}} \times \sum_i \left(R_{\text{turbine},i} \times P_{\text{onshore},i} \right) \quad (5)$$

Where,

R_{offshore} : Ratio of off-shore wind electricity to total wind electricity generated in France 2019, 0.1 % as calculated.

$P_{\text{offshore},1-3\text{MW}}$: Representative capacity of off-shore wind turbine assembly under 1-3 MW capacity level in France 2019, which is 2 MW as calculated in ecoinvent 3.6 database.

R_{onshore} : Ratio of off-shore wind electricity to total wind electricity generated in France 2019, 99.90 % as calculated.

i : Different wind turbine capacity levels, e.g., <1 MW, 1-3 M, >3 MW.

$R_{\text{turbine},i}$: Market share of different capacity level turbine assembly in French onshore wind turbine assembly mix 2019. For turbine assembly with a capacity level of <1MW, 1-3MW, >3MW, on average, the ratio is 11.27 %, 82.16 %, 6.57 %.

$P_{\text{onshore},i}$: Representative capacity for each onshore turbine capacity level as calculated in ecoinvent 3.6 database. For turbine assembly with a capacity level of <1MW, 1-3MW, >3MW, it is 800KW, 2MW, 4.5MW, respectively.

2.3.3 Water electrolysis unit

2.3.3.1 Water electrolysis unit and electrolysis H_2 production

As shown in Fig. 2, this research compares two types of water electrolysis units: proton exchange membrane electrolyzer and alkaline electrolyzer. For both the PEM and AE unit, balance of plant (BOP) system voltage adapting or rectifying the electricity from the PV or wind plant into proper DC electricity required by the electrolyzer stack (where the water electrolysis reaction takes place). The stack electrolyzes the French average water grid's deionized water into H_2 and O_2.

Bareiß et al.[99] give a detailed technical description of the PEM unit under France's present market situation, from where this research cited the LCI of PEM electrolysis unit (both the BOP and stack) per kW. The LCI to AE unit electrolyzer stack per kW is diverted from the parameterized model developed by Romain Besseau[81].

As pointed out by Bareiß et al.[99], it can be challenging to give a sound estimation for LCI of electrolysis unit BOP. Considering the similarity between BOP for both alkaline and PEM stack[100-102], and due to data limitation, LCI of BOP in both PEM and AE unit in this research is cited from Bareiß et al., which is identical to each other[99]. Equation (6) clarifies the electrolysis unit capacity calculation installed in each RE-to-H_2 pathway.

$$P_{\text{electrolyzer}} = \frac{\dfrac{Elec_{\text{H2}}}{\eta_{\text{unit}}}}{\dfrac{Elec_{\text{H2}}}{\eta_{\text{unit}}} + Elec_{\text{compress}}} \times P_{\text{REplant}} \quad (6)$$

Where,

$P_{\text{electrolyzer}}$: Capacity of electrolysis unit installed in the solar-to-H_2 pathway or wind-to-H_2 pathway, in kW of stack and BOP.

$Elec_{\mathrm{H2}}$: Net water splitting electricity demand with a 100 % efficiency in LHV kWh/ kg H_2, which is 33.3 kWh/kg H_2 (literally equals LHV of 1 kg H_2)[103].

η_{unit} : Water electrolysis unit global efficiency covering all facilities in the system, e.g., stack, electronics, pumps, safety equipment, infrastructure. Both for PEM, AE unit (average, 60 %) are summarized based on data from Bareiß et al.[99] and ecoinvent v3.6 database.

$Elec_{\mathrm{compress}}$: Compressor electricity demand for compressing H_2 from stack outlet pressure (30 bar) to 200 bar, which is 3.91 kWh/kg H_2 as maximum[104].

P_{REplant} : Total installed capacity of one unit 2019 French national benchmark wind farm or PV plant, in kW, which equals to P_{PVplant} or $P_{\mathrm{Windplant}}$ in Equation (2) and (5), respectively.

The electrolyzer stack efficiency and electrolysis unit global efficiency determine H_2 productivity. One can calculate the total H_2 production amount in the RE-to-H_2 pathway, e.g., total H_2 produced during the entire lifespan of one unit French national benchmark wind farm or PV plant utilizing Equation (7).

$$H_{2yield_{\mathrm{LHV}}} = H_{2yield_{\mathrm{kg}}} \times LHV_{\mathrm{H2}} = \frac{Elec_{gen}}{\frac{Elec_{\mathrm{H2}}}{\eta_{\mathrm{unit}}} + Elec_{\mathrm{compress}}} \times LHV_{\mathrm{H2}} \quad (7)$$

Where,

$H_{2yield_{\mathrm{LHV}}}$: Accumulative H_2 production amount within one unit of French national benchmark wind farm or PV plant whole lifespan, in MJ, based on low heating value (LHV).

$\mathrm{LHV_{H2}}$: LHV of H_2 in MJ/ kg H_2, which is 120 MJ/kg and equals 33.3 kWh/kg[12].

$Elec_{gen}$: Accumulative electricity generation within one unit of French national benchmark wind farm or PV plant whole lifespan, in kWh, e.g., $Elec_{\mathrm{PV}}$ or $Elec_{\mathrm{wind}}$ in Equation (2) and (4).

$H_{2yield_{\mathrm{kg}}}$: Accumulative H_2 production amount within one unit of French national benchmark wind farm or PV plant whole lifespan, in kg.

2.3.3.2 H_2 compressor and compression process

This research uses the most common H_2 compressor type, the diaphragm compressor, to model the H_2 compression process in the RE-to-H_2 pathway.

LCI per unit diaphragm compressor can be found in the premise database[105]. Since no exact data for diaphragm compressor lifespan inconsistent with the diaphragm compressor LCI is found during the research. To better represent the actual situation in France 2019, we estimate the diaphragm compressor unit needed in the RE-to-H_2 pathway with Equation (8).

$$Compressor_{\mathrm{unit}} = \frac{Life_{sys}}{Life_{\mathrm{Compressor}}} = \frac{Life_{sys}}{\frac{H_{2\mathrm{unit}}}{H_{2yield_{\mathrm{kg}}}} \times Life_{sys}} = \frac{H_{2yield_{\mathrm{kg}}}}{H_{2\mathrm{unit}}} \quad (8)$$

Where,

$Life_{sys}$: Lifespan of one unit French national benchmark wind farm or PV plant, which equals to $Life_{\mathrm{PV}}$ and $Life_{\mathrm{wind}}$ in Equation (2) and Equation (4), respectively.

$Life_{\mathrm{Compressor}}$: Lifespan of the diaphragm H_2 compressor.

$H_{2\mathrm{unit}}$: Total amount of H_2 can be compressed during the entire lifespan of one compressor unit, which is 5906475.3 kg/unit on average, as shown in the premise database[105, 106].

Furthermore, this research applies the two-stage transportation process defined above to each component involved in the AE and PEM electrolysis unit (e.g., the electrolysis stack, BOP, and H_2 compressor) to cover the transportation process from the component production site to the installation site. The mass of each component can be found from their corresponding LCI as shown in the supplementary materials.

2.3.4 Parametric LCA model & scenarios analyzed

Compared with other LCA software, due to their open-sourced features, the Python framework for LCA: Brightway2 (BW2) and the algebraic parametrization BW2 layer: *lca_algebraic* library[107, 108] enable a more flexible environment for LCA research innovation, e.g., dynamic LCA, life cycle model simplifying[108], as well as the quick check for impact categories correlation[107]. To perform a complete and systematic life cycle interpretation, thus meeting the goal and scope of the research, this research builds the French national benchmark parametric LCA model of all the pathways studied together with the corresponding LCI and data source in BW2 based *lca_algebraic* library. The LCA results and the related interpretation are then generated by simulating the parametric LCA model. To summarize, as shown in Fig. 4, based on the renewable electricity type (wind or solar electricity) and electrolysis unit type (AE or PEM unit), four RE-to-H_2 pathways were analyzed in this research.

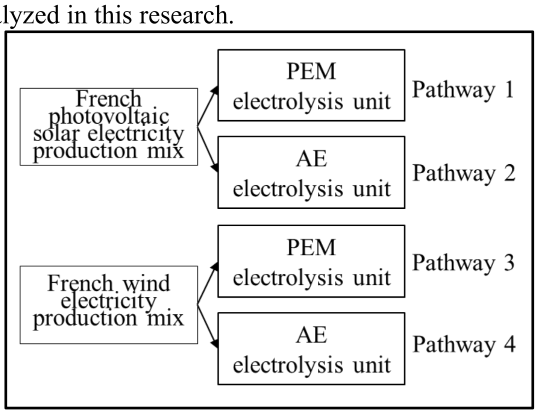

Fig. 4. RE-to-H_2 pathways analyzed in this research.

2.4 Life Cycle Impact Assessment

2.4.1 Life cycle impact categories

The choice of LCIA categories varies among different H_2 production LCA research, as pointed out by some H_2 production LCA overviews[49]. Based on the highest suggestion from the EU Joint Research Centre (climate change, ozone depletion, respiratory inorganics)[109], previous research[49], and the specific patterns of H_2 production pathway this research studied, the following 'ILCD 2.0 2018 midpoint' impact categories in Table 3 were analyzed by this research. Normalization, grouping, and weighting of the LCIA score are not included in the goal and scope of this research.

Table 3. LCIA categories analyzed in this research.

ILCD midpoint analyzed	Corresponding LCIA endpoint
Climate change total (GWP)	Climate change
Freshwater and terrestrial acidification (FTA)	Ecosystem quality
Carcinogenic effects (CE)	Human health
Ionizing radiation (IR)	Human health
Ozone layer depletion (OLD)	Human health
Photochemical ozone creation (POC)	Human health
Respiratory effects, inorganics (REI)	Human health
Fossils (FD)	Resources
Land use (LU)	Resources
Minerals and metals (MD)	Resources
Dissipated water (DW)	Resources

2.5 Life cycle result interpretation

2.5.1 Sensitivity and Uncertainty analysis

SA and UA can reveal the robustness of LCIA results in an LCA study (e.g., their sensitivity to the uncertainty of life cycle parameters). This research paid great attention to data uncertainty collection when building the French national benchmark parametric life cycle model for each pathway studied following the goal and scope.

Information and data collected enable us to define the probability distributions (PD) for every upstream parameter (e.g., parameters determining H_2 production feedstock market) and downstream parameter (e.g., electricity demand during H_2 compression) involved in each RE-to-H_2 pathway studied best representing French resource availability and technology market share.

Then, the uncertainty, e.g., PD, for each life cycle parameter is propagated holistically into the corresponding parametric LCA model to each pathway studied. Thus, becoming the first detailed and holistic SA and UA for renewable-electricity-based water electrolysis H_2 production LCA. The PD type, PD definition value, and PD representativeness for several most critical life cycle parameters in all RE-to-H_2 pathways identified by this research are illustrated in Table 4 below.

Table 4. PD model for critical life cycle parameters in RE-to-H_2 pathway.

Parameter	PD model	PD representativeness
Annual solar irradiance among France mainland (Irr , kWh/m^2/yr)	PD type: BETA Min: 1.365 E+06 Max: 2.401 E+06 α =1.735 β =6.822	Min, Max, α , β fitted by oracle crystal ball software based on data from AGATE dataset as stated above.
Performance ratio of the PV panels (PR , %)	PD type: Triangle Min: 50 Default: 80 Max: 90	Estimated based on IEA PV guideline[82, 112]. 50 %- 75 % for PV model installed in 1980s; 70 %- 80 % for 1990s; 80 %- 90 % for newly installed PV.
PV power plant lifespan ($Life_{PV}$, years)	PD type: Triangle Min: 20 Default: 30 Max: 40	Thirty years for model installed during the 1990s until now[82]. Fourth years for the very new model[82]. Twenty years[82] to cover the possibility of accident or overuse.
Onshore wind turbine capacity factor ($Cf_{onshore}$, %)	PD type: Normal Default: 25 Std: 0.01	Default and Std fitted by oracle crystal ball software based on capacity factor from Statista dataset[96] and corresponding land area[113] of 13 administrative regions in France.
Wind farm lifespan ($Life_{wind}$, year)	PD type: Triangle Min: 15 Default: 20 Max: 25	Default stands for the average[81]. Min[81] stands for frequently overload turbine with long working time. Max[81] stands for turbine under good maintenance.

Water electrolysis unit global efficiency (η_{unit} , %)	PD type: Triangle Min: 50 Default: 60 Max: 70	The stack efficiency for both the PEM and AE units was approved to be identical[99, 114]. Default stand for the average[99, 114]. The mix and Max were estimated based on the reference literature[99, 114].
BOP lifespan ($Life_{\text{BOP}}$, year)	PD type: Triangle Min: 18 Default: 20 Max: 22	Default stands for average[99]. Min stands for often overload facilities with long working time[99]. Max stands for the situation under good maintenance[99].

And the PD type and PD definition value for all the remaining background and foreground life cycle parameters is summarized in Table 5 and Table 6 below. Besides, the parameterized LCA model built in the *lca_algebraic* library applies the Sobol indices analyzing theory[110], namely the variance-based sensitivity analysis[111] as the SA method for LCIA results obtained.

The Sobol indices analyzing is a form of global sensitivity analysis that can decompose and attribute the variation and uncertainty of model output to each input's uncertainty. For one life cycle parameter, the closer its Sobol indices to 1 (or 100 %), the more uncertainty of one specific LCIA score is induced by this life cycle parameter's uncertainty[111].

The UA and SA for impact category LCIA score are performed through running Monte Carlo simulation (10,000 iterations) for each parametric LCA model. The Monte Carlo simulation simultaneously obtains the standard deviation (SD), and the arithmetic mean value (μ) for each LCIA score. This research chooses the coefficient of variation (CV, SD divided by μ) as indices for consistent uncertainty comparison of LCIA scores with different units.

Table 5. PD model for life cycle parameters studied in RE-to-H_2 pathway feedstock market mix.

Parameter and PD model
Nominal maximum power of PV panels (P_{peak} , Wp/m^2) PD type: Triangle, Min: 86.3, Default: 115.1, Max: 131.5
PV panels yearly loss ratio (YLR , %) PD type: Triangle, Min: 0.5, Default: 0.7, Max: 0.9
Electricity consumption during Mono Si ingot production, Czochralski process ($Elec_{\text{s-ignot}}$, kWh /Kg Si ingot) PD type: Triangle, Min: 10, Default: 32, Max: 150
Electricity consumption during Multi Si ingot production, casted ($Elec_{\text{m-ignot}}$, kWh /Kg Si ingot) PD type: Triangle, Min: 7, Default: 7, Max: 15
PV plant ground coverage ratio (GCR , %) PD type: Triangle, Min: 36, Default: 36, Max: 45
Market share of monocrystalline silicon panel in total French PV panel installed 2019 (R_{monoSiPV} , %) PD type: Triangle, Min: 30.1, Default: 33.04, Max: 49
Market share of the thin-film panel in total French PV panel installed 2019 (R_{filmPV} , %) PD type: Triangle, Min: 4.83, Default: 4.83, Max: 10
Off-shore wind turbine installed capacity in France 2019 ($P_{\text{offshore,total}}$, GW) PD type: Linear, Min: 0.01, Default: 0.01, Max: 0.48
Share of <1MW capacity level turbine assembly in total French onshore wind turbine assembly installed 2019 ($R_{\text{turbine,<1MW}}$, %) PD type: Linear, Min: 6, Default: 11.27, Max: 11.27
Share of >3 MW capacity level turbine assembly in total French onshore wind turbine assembly installed 2019 ($R_{\text{turbine,>3MW}}$, %) PD type: Linear, Min: 0.4, Default: 6.57, Max: 6.57
Off-shore wind turbine capacity factor in France 2019 (Cf_{offshore} , %) PD type: Triangle Min: 33 Default: 38 Max: 55

3 Results & Discussion

3.1 Multi-environmental influence

3.1.1 Unit process contribution of LCIA result

The representative patterns of unit process contribution to LCIA result for each RE-to-H_2 pathway are shown in Fig. 5. Histogram height stands for the arithmetic mean value obtained through Monte Carlo simulation, while the LCIA score uncertainty is shown in the corresponding box plot (e.g., P10, P25, P50, P75, P90). The corresponding graph of unit process contributions of the LCIA categories remaining is shown in the supplementary materials.

● *Global warming potential, Photochemical ozone creation*

The production, transportation, and construction of electrolysis unit plant infrastructure (e.g., the electrolyzer BOP, H_2 compressor) are the most critical contributor to GWP and POC for all the RE-to-H_2 pathways studied, which contribute 58.9 %- 70.5 %, 53.5 %- 62.9 % to GWP and POC respectively. This high contribution can be furtherly attributed to the massive concrete consumption during electrolysis unit foundation construction, where industrial concrete with 40 MPa compressive strength is applied. And the production of clinker (primary raw material for electrolysis unit concrete foundation) is very CO_2 and NO_x emission-intensive under the current French national context[115].

The remaining GWP and POC score for the solar-to-H_2 pathway and wind-to-H_2 pathway mainly contributed from the French national average solar and wind electricity supply chain. Under the current French context, most multi-Si and mono-Si PV panels are produced and imported from China[78], which are still CO_2 and NO_x emission-intensive due to the current fossil-based Chinese energy structure 2019. Besides, PV panel mounting system production contributes equally to Si PV panels production and transportation due to the production of aluminum wrought alloy massively consumed in PV panel mounting system. Under the current French and average European context, aluminum wrought alloy production is very electricity-intensive, e.g., CO_2 and NO_x emission[115].

Inside the wind electricity supply chain, GWP and POC mainly come from the construction process of 1-3 MW wind turbine assemblies, which produce most onshore wind electricity under the current French context. This high contribution comes from the massive low-alloyed steel consumed during wind turbine assembly construction. Since the dominant steel production technology in France, e.g., converter steel production, is still CO_2 and pollutant emission-intensive under massive production. Besides, most wind farms are located in remote areas with low population density under the current French context. To access the wind farm site, specific roads should be built. The road construction process is another crucial contributor to GWP and POC scores. Since a large amount of diesel and petroleum is consumed for road construction and extensive road construction material transportation. Among the four pathways studied, pathway 1 shows the highest GWP, and pathway 2 shows the highest POC, namely 5.46 E-02 kg $CO_{2\text{-eq}}$ /MJ H_2, 1.53 E-08 kg $NMVOC^-$ /MJ H_2, respectively. Pathway 3 indicates the lowest result for GWP and POC, namely 2.62 E-02 kg $CO_{2\text{-eq}}$ /MJ H_2, 1.03 E-04 kg $NMVOC^-$ /MJ H_2, respectively.

Table 6. PD model for other life cycle parameters studied in RE-to-H2 pathway.

Parameter and PD model
The lifespan of network connection & auxiliaries for PV plant, which equals to plant DC/AC inverter lifespan ($Life_{\text{solar,aux}}$, yr) PD type: Triangle Min: 10 Default: 15 Max: 30
The specific weight of PV plant DC/AC inverter (M_{inverter} , kg/KVA) PD type: Triangle Min: 1 Default: 2 Max: 4
The lifespan of network connection & auxiliaries for wind plant ($Life_{\text{wind,aux}}$, yr) PD type: Triangle Min: 15 Default: 20 Max: 25
PEM stack lifespan ($Life_{\text{PEM}}$, hour) PD type: Triangle Min: 40000 Default: 50000 Max: 60000
AE stack lifespan ($Life_{\text{AE}}$, hour) PD type: Triangle Min: 60000 Default: 75000 Max: 90000
The total amount of H_2 can be compressed during the lifespan of one H_2 compressor ($H_{2\text{unit}}$, kg/unit) PD type: Triangle Min: 5.021 E+06 Default: 5.906 E+06 Max: 6.792 E+06
H_2 compressor electricity consumption for 1 kg H_2 compression ($Elec_{\text{compress}}$, kWh/Kg) PD type: Triangle Min: 2.7 Default: 3.91 Max: 3.91
Lorry transport distance for each component in the two-stage transportation model ($Dist_{\text{lorry}}$, km) PD type: Triangle Min: 40 Default: 700 Max: 1400
Train transport distance in the two-stage transportation model ($Dist_{\text{train}}$, km) PD type: Triangle Min: 0 Default: 300 Max: 600
Oversea transportation distance for off-shore wind turbine component ($Dist_{\text{oversea}}$, km) PD type: Triangle Min: 0 Default: 10 Max: 100

● *Freshwater and terrestrial acidification, Ionizing radiation, Fossil resources depletion, Respiratory effects*

For FTA, IR, FD, and REI, French national average solar electricity supply chain, electrolysis unit plant infrastructure is the major contributor in the solar-to-H_2 pathway and wind-to-H_2 pathway, respectively. These two significant contributors take 44.95 %- 56.88 %, and 36.81 %- 56.95 % in all impact category scores among solar-to-H_2 and wind-to-H_2 pathways, respectively. The remaining half of FTA, IR, FD, and REI in solar-to-H_2 is mainly contributed by electrolysis unit plant infrastructure and French national average wind electricity supply chain in the wind-to-H_2 pathway. For FTA, the AE electrolysis stack contributes equally to the wind electricity supply chain, which is one-third of the contribution from the French national average solar electricity supply chain.

Like GWP, the production of aluminum wrought alloy used in PV panel mounting system; Chinese multi-Si and mono-Si PV panels production and transportation process is the main contributor to these four LCIA scores of French solar electricity supply chain., These LCIA scores for plant infrastructure mainly come from the clinker production process like GWP. And the contribution from hard coal & diesel burning during clinker and cement production; the cement transportation process is almost identical.

Besides, the electricity consumed by cement production under the current French context endows huge IR, contributing most of IR from electrolysis unit plant infrastructure. Since nuclear electricity contributes around 70 % of French electricity to the national electricity grid. And pressurized water reactors (PWR) generate almost all the nuclear electricity in France (as ecoinvent v3.6 database[115] indicated), which will produce a large pile of radioactive waste during PWR unit operation. Inside the wind electricity supply chain, the production process of copper (the primary component for 1-3 MW wind turbine assembly) is the main contributor to the FTA score. Under the current French context, major copper production technology is flash smelting furnaces reducing and refining, which is sulfur dioxide emission-intensive. The main contributor for IR can be further attributed to the production of electricity consumed during wind turbine assembling, mounting, and turbine end-of-life (EoL) removal. FD and REI mainly contributed from massive low-alloyed steel consumed during the construction of 1-3 MW wind turbine assembly. This low-alloyed steel consumption also ranked as the second significant contributor of IR and FTA. The production process of polyamide injection reinforced plastic glass fiber (main component of > 1 MW wind turbine blade[115]) is another significant contributor for FD. The primary raw material for glass fiber reinforced plastic production, Nylon6-6, is very fossil resources intensive during its production process[115]. The road-building process to access the wind farm is the third most significant contributor to FTA, IR, FD, and REI.

Pathway 2 shows the highest FTA, IR, FD, and REI results among each pathway studied, e.g., 3.61 E-04 mole H^+_{eq} /MJ H_2, 2.98 E-03 kg $U_{235\text{-}eq}$ /MJ H_2, 5.89E-01 MJ /MJ H_2, 3.16 E-09 disease i. /MJ H_2, respectively. Pathway 3 shows the lowest result of these LCIA scores, namely 1.37 E-04 mole H^+_{eq} /MJ H_2, 1.38 E-03 kg $U_{235\text{-}eq}$ /MJ H_2, 2.68 E-01 MJ /MJ H_2, 1.42 E-09 disease i. /MJ H_2, respectively.

● *Land use, Minerals and metals depletion, Dissipated water*

Regarding LU, MD, DW, the French national average solar electricity supply chain contributes around 62.20 %-89.66 % for the solar-to-H_2 pathway, ranking the most important contributor. Most of the LCIA score remained comes from the electrolysis unit plant infrastructure. However, for the wind-to-H_2 pathway, 42.21 %- 61.87 % of these 3 LCIA scores comes from electrolysis unit plant infrastructure, which is closely followed by the contribution from the French national average wind electricity supply chain.

Construction of PV panel mounting system will occupy large land areas[115], which contributes most of LU inside average French solar electricity supply chain. Besides, a lot of zinc is consumed during PV panel mounting system construction, which explains the MD score. The corresponding DW score is due to the massive multi-Si PV panel produced and imported from China[78]. Since current multi-Si wafer production in China is very water-consuming[78]. The road construction process occupies a large land area, which explains the LU score for the French national average solar electricity supply chain.

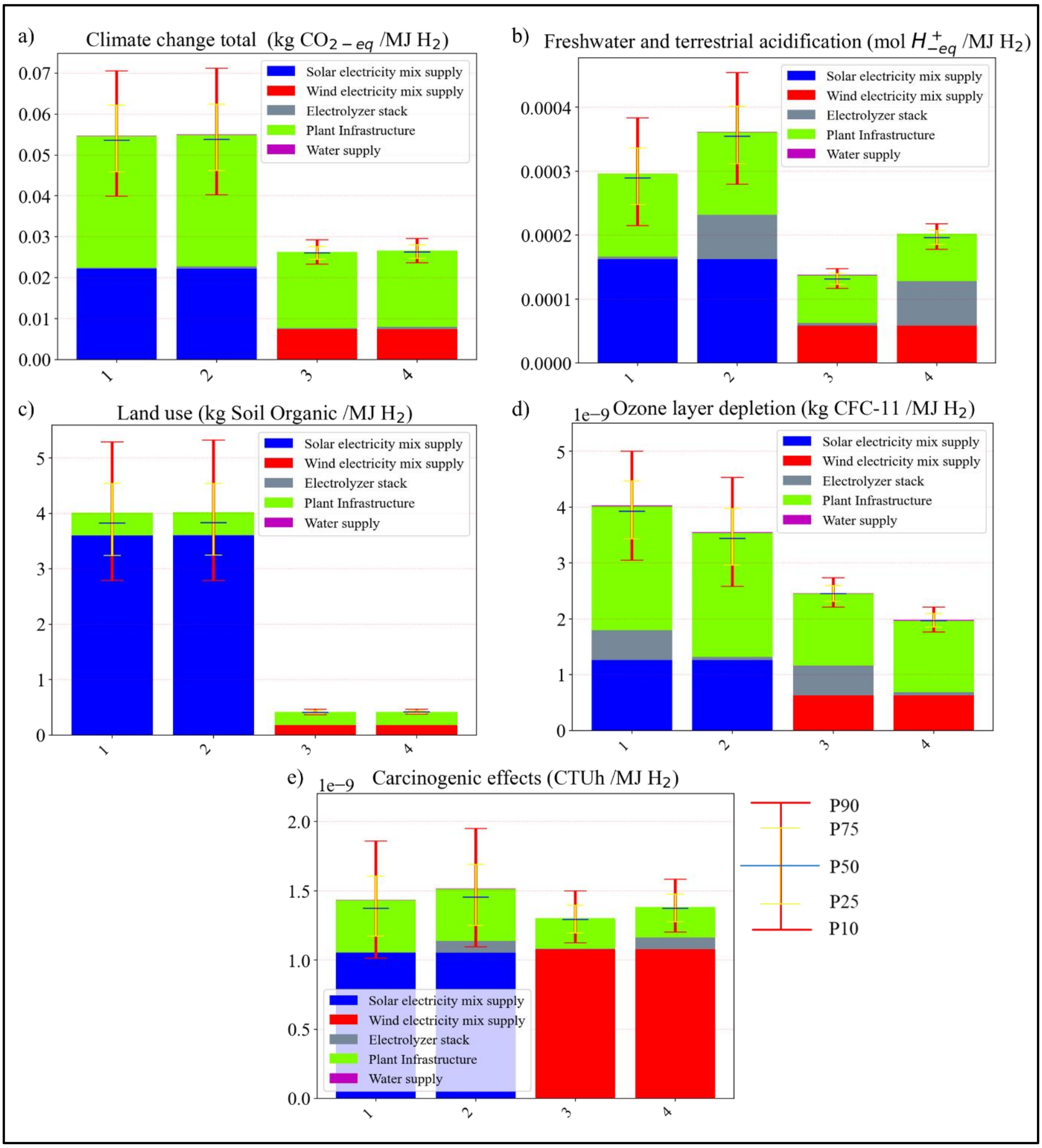

Fig. 5. Representative patterns of unit process contribution to LCIA result marked with uncertainty box plot. Pathway 1 to 4 corresponds to the rank in Fig. 4.

Under the current French context, Zinc coating is massively applied to wind turbine towers corrosion against, which contributes to most of the MD score. Regarding DW, the production of polyamide injection reinforced plastic glass fiber used in wind turbine blades and the low-alloyed steel used in the wind turbine tower contribute equally. Nylon6-6 for glass fiber reinforced plastic production is very water consumption intensive during its production process[115]. So is the same for the production process of low-alloyed steel production under the current French context[115].

Regarding the electrolysis unit plant infrastructure, most DW score is contributed from the concrete production process, which can be furtherly attributed to the water-intensive raw material extraction for cement production[78]: Clinker (Limestone rotary kiln calcination), gravel, and sand (extracted from river bed) production under current French context. Besides, the limestone rotary kiln calcination is limestone consumption intensive.

And this process will consume lots of zinc[78], which explains the corresponding MD score. The large amount of sand consumed in the electrolysis unit concrete foundation presents the most LU score, followed by the limestone consumption during clinker production and cement transportation.

Among each pathway studied, pathway 2 shows the highest result of LU, MD, DW, namely 4.02 kg Soil Organic /MJ H_2, 6.10 E-06 kg $Sb_{\text{-eq}}$ /MJ H_2, 3.11E-02 m^3 /MJ H_2, respectively. Pathway 3 shows the lowest result of these LCIA scores: 4.16 E-01 kg Soil Organic /MJ H_2, 2.11 E-06 kg Sb_{-eq} /MJ H_2, 5.79E-3 m^3 /MJ H_2, respectively.

●*Ozone layer depletion*

Regarding OLD, the electrolysis unit plant infrastructure contributes around 51.9 %- 64.3 % for all pathways studied. The remaining OLD in the solar-to-H_2 pathway and the wind-to-H_2 pathway is mainly contributed by the French national average solar and wind electricity supply chain, respectively. And in pathway 1 and pathway 3, where PEM electrolyzer is applied, 13.2 % and 21.6 % of OLD come from the production, transportation, and EoL of the PEM electrolysis stack.

Like GWP, the production of aluminum wrought alloy used in PV panel mounting system, Chinese multi-Si and mono-Si PV panels production and importation, contribute equally to OLD in French national average solar electricity supply chain. The electrolysis unit plant infrastructure's OLD score mainly comes from clinker production (primary raw material for electrolysis unit concrete foundation). And cement and clinker transportation process; the heavy fuel oil, petroleum coke, diesel burning during clinker and cement production rank as the main contributors.

Inside the wind electricity supply chain, the road construction process, with similar reason discussed in GWP, explain the OLD of the average French wind electricity supply chain. And low-alloyed steel consumed in wind turbine towers under the current French context is the second contributor to OLD of French national average wind electricity supply chain. Pathway 1 shows the highest OLD result among each pathway studied, 4.03 E-09 kg CFC-11 /MJ H_2. Pathway 4 indicates the lowest OLD result, namely 1.99 E-09 kg CFC-11 /MJ H_2.

●*Carcinogenic effect*

Regarding CE, the French national average solar and wind electricity supply chain contributes 69.4 % to 82.7 % for all pathways studied. The remaining CE is mainly contributed by electrolysis unit plant infrastructure.

The primary aluminum wrought alloy massively consumed by PV panel mounting system is mainly refined by aluminum oxide (mainly from red mud bauxite digestion) through the Hall-Héroult process[115]. The Hall-Héroult process is very electricity-intensive, and the bauxite digestion process is very pollutant emission-intensive, which explains most CE of the French average solar electricity supply chain. Besides, the PV panel mounting system consumed a lot of reinforcing steel mostly made from low-alloyed steel under the current French context, which explains most of the CE score remained.

Similarly, the production of low-alloyed steel and chromium steel used in the wind turbine tower is the main contributor to CE from the average French wind electricity supply chain. And clinker from limestone rotary kiln calcination is the main contributor of CE from the water electrolysis unit plant infrastructure. Among each pathway studied, pathway 2 shows the highest result of CE: 1.54 E-09 kg CTUh /MJ H_2. And pathway 3 indicates the lowest CE result, 1.30 E-09 kg CTUh /MJ H_2.

●*Particular focus: contribution from electrolysis stack*

Variation of environmental impact induced by different electrolysis stacks is illustrated in Fig. 6. Applying PEM electrolyzer stack has a much lower environmental impact than AE electrolysis stack for all impact categories studied, except OLD.

The production of manganese (the critical component of the cathode material), mainly through electrothermal and electrolysis treatment of manganese ore, is pollutant emission-intensive in terms of NH_3, HCl, VOC, as well as heavy metals[115]. This results in a higher CE score of the AE electrolysis stack than the PEM.

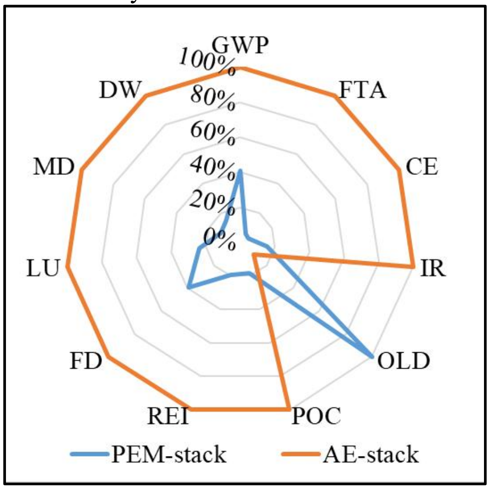

Fig. 6. Environmental influence difference between PEM stack and AE stack.

Besides, the production process of 99.5 % Nickel (another critical electrode material mainly comes from hydrometallurgical and pyrometallurgical nickel ore refining[115]) will emit large amounts of dust containing PM10 and VOC[115]. This will lead to a higher GWP, FTA, POC, and REI of AE electrolysis stack production.

The underground nickel ore mining infrastructure and heat consumption during the ore mining process explain the higher FD, LU, and MD for the AE electrolysis stack. Furthermore, a large amount of electricity is consumed during AE electrolysis stack assembling, explaining a higher IR and DW score. Regarding OLD, the solid polymer electrolyte production from trichloromethane is very CFC emission-intensive, explaining the higher OLD of the PEM electrolysis stack compared with the AE electrolysis stack.

3.1.2 Scenario variation and further comparison

Fig. 7 illustrated the LCIA result (arithmetic mean value obtained through Monte Carlo simulation) comparison among each RE-to-H_2 pathway studied. It's evident that whether from the view of comprehensive trade-off or only considering GWP, water electrolysis H_2 production with average French wind electricity through PEM electrolysis unit is the optional choice among all RE-to-H_2 pathways studied.

The total mass of the electrolysis unit (e.g., stack, electronics, pumps, safety equipment) is enormous, which can be up to 9.6 tonnes for a PEM electrolysis unit[99]. Thus, a foundation with high compressive strength is required for the stable installation of the electrolysis unit on the ground. And this research applies 40 MPa concrete when building the electrolysis unit foundation.

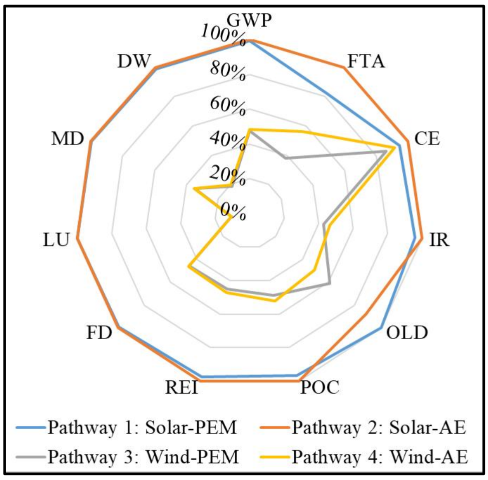

Fig. 7. LCIA result comparison among RE-to-H_2 pathways.

Fig. 8 a) illustrated RE-to-H_2 LCIA result variation among different electrolysis unit concrete foundations, various solar radiation, and wind energy availability conditions. Pathway 3 is compared with wind-to-H_2 applying PEM electrolysis unit built on 20MPa; wind-to-H_2 using PEM electrolysis unit under the maximum and minimum French wind turbine capacity factor. Pathway 2 is compared with solar-to-H_2 under maximum annual solar irradiance in France, applying PEM and AE electrolysis units, respectively.

The average capacity factor of the French wind turbine, both for onshore and off-shore applied in pathway 3 and pathway 4, is already close to the maximum capacity factor. Thus, wind-to-H_2 under the maximum capacity factor only reduces less than 7 % to each impact category compared to pathway 3.

But transferring the 40MPa concrete foundation to 20MPa concrete foundation will lead to a higher environmental impact reduction: 7.03 %-13.96 % reduction to GWP, FTA, IR, POC, FD, MD, and DW, as well as 1.47 %- 2.52 % reduction to CE, OLD, and REI. However, LU will increase around 10.68 % due to a higher sand consumption during 20MPa cement production[115].

An interesting result is revealed that while under maximum annual solar irradiance, all LCIA scores to solar-to-H_2 will be reduced around 20 % compared with pathway 2, but the environmental impact of solar-to-H_2 pathways is still more significant than the wind-to-H_2 pathways studied, as shown in Fig. 8 a).

Fig. 8 b) compares the environmental influence of RE-to-H_2 utilizing different electricity sources during the electrolysis process. RE-to-H_2 with PEM water electrolysis unit powered by electricity from Norwegian and French grid (94.1 % Norwegian electricity generated by hydropower and 70 % French electricity comes from PWR as stated above[115]), as well as European-average electricity from ENTSO-E is compared with pathway 2 and 3.

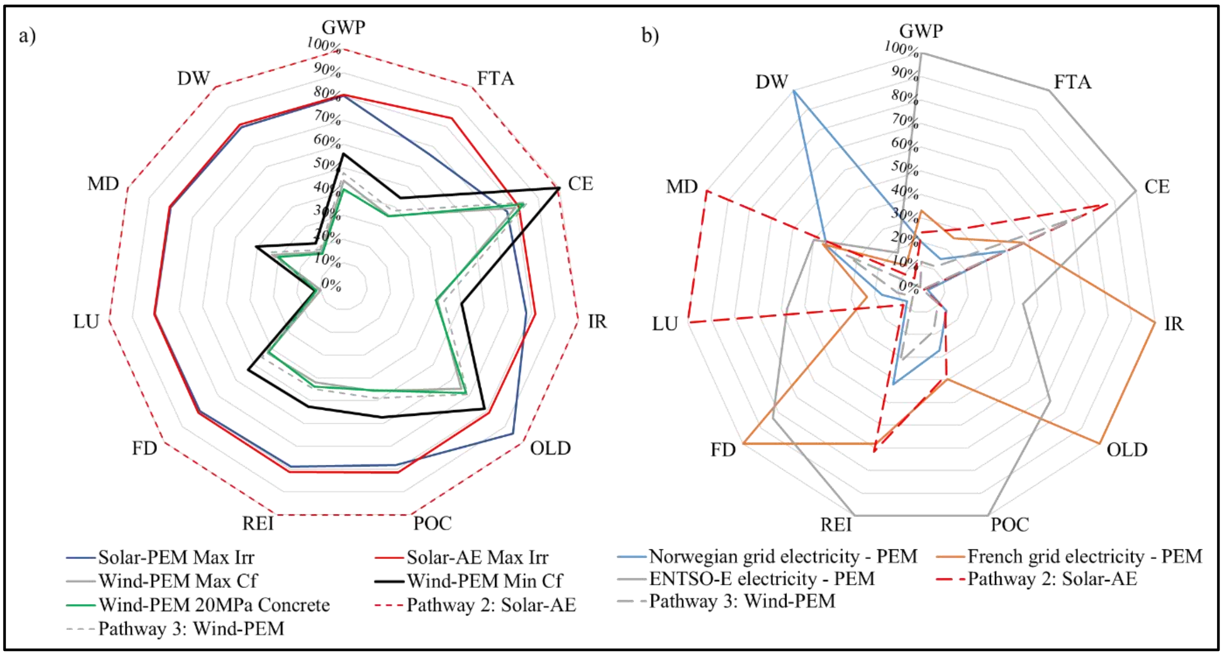

Fig. 8. LCIA score comparison of RE-to-H_2 pathways under scenario variation.

Compared with Norwegian, French, and ENTSO-E electricity, utilizing French national average wind electricity for water electrolysis H_2 production is still a wiser choice for most impact categories studied. Among them, PEM RE-to-H_2 through Norwegian electricity is most comparable to pathway 3 regarding most of the impact categories investigated. Despite the high water footprint of Norwegian electricity production, it will significantly reduce the CE compared with pathway 3. Applying the average French electricity will also reduce the CE (36.59 %) compared with pathway 3. However, it will induce a considerable increase in IR, OLD, REI, and

DW (981.52 %- 19188.59 %) and moderate to all the other categories (32.36 %- 190.22 %).

Applying the ENTSO-E electricity will increase the score of all the impact categories (34.32 %- 1688.00 %) compared with pathway 3. Another tricky point is that, for RE-to-H_2 with AE water electrolysis unit, applying the Norwegian, French, and ENTSO-E electricity will reduce the MD and LU (42.64 %- 76.78 %) significantly compared to pathway 2.

3.2 Sensitivity and uncertainty analysis

3.2.1 LCIA result sensitivity to life cycle parameter

Fig. 9 illustrated the SA result, i.e., First-order indices (S1 indices) of LCIA score to each life cycle parameter in pathway 3. For each impact category investigated, 33 %- 65 % LCIA score variation (or in another word, uncertainty) comes from the uncertainty of electrolysis unit global efficiency. Other critical life cycle parameters determining the LCIA score are wind turbine lifetime (contribute to 53 % CE variation, and 8 %- 29 % variation of all the other 11 impact categories), onshore wind turbine capacity factor (contribute 12 %- 19 % to score variation of all impact categories), electrolysis unit BOP lifetime (contribute 4 %- 11 % to score variation of all impact categories), and share of >3MW wind turbine assembly in French national average onshore wind turbine market (contribute 1 %- 9 % to score variation of all impact categories).

However, under the current French context, as shown in Fig. 9 b), uncertainty to each impact category score induced by all life cycle parameters' variation is relatively small. LCIA score uncertainty generated from electrolysis unit global efficiency variation is around 6-7 % regarding all impact categories.

Uncertainty of CE induced from wind turbine lifetime variation is about 8 %. Besides, uncertainty to each impact category score caused by the remaining life cycle parameters is below 5 %. Corresponding SA results for pathway 4 (in supplementary materials) are very close to pathway 3 as shown in Fig. 9.

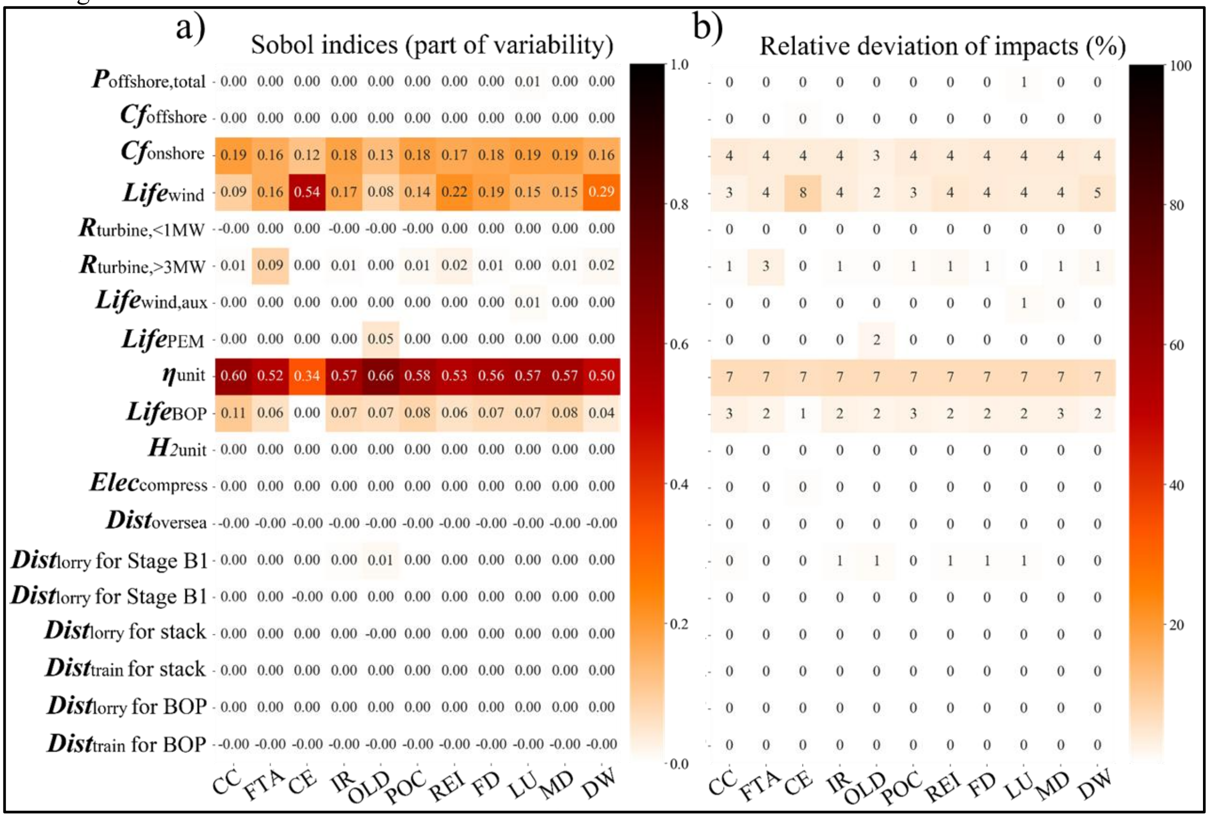

Fig. 9. Pathway 3 LCIA score sensitivity to life cycle parameters. Parameter names correspond to these in Table 4 and Table S1.

Fig. 10 a) shows the LCIA score S1 indices to each life cycle parameter in pathway 2. For each impact category studied, under French national average resource availability and technology mix 2019, around 38 %-50 % LCIA score uncertainty comes from the variation of French annual solar irradiation available on PV panels. 23 %-30 % LCIA score variation comes from the uncertainty of the PV panel performance ratio.

The remaining LCIA score variation mainly comes from PV panel lifetime uncertainty (contribute 19 %-28 % to the variation of CE, DW, and LU; 6 % to 16 % to variation of all the other eight impact categories), electrolysis unit global efficiency (6 %-12 % to variation of all impact categories), nominal maximum power of PV panels (1 %-6 % to the variation of all impact categories).

Inside the French national average solar electricity supply chain, critical life cycle parameters are identified with more considerable uncertainties than those in the French national average wind electricity supply chain. Thus, the LCIA score's uncertainty in the solar-to-H_2 pathway is more significant than the wind-to-H_2 pathway. For all impact categories, as illustrated in Fig, 10 b), LCIA scores uncertainty induced from French annual solar irradiation variation is around 13-16 %; Uncertainty caused from the PV panels performance ratio is 10-13 %; Uncertainty generated from PV panel lifetime is 6-13 %. Besides, uncertainty to each impact category induced by life cycle parameter remaining is below 7 %. Corresponding SA results for pathway 1 listed in the supplementary material are very close to these in Fig. 10.

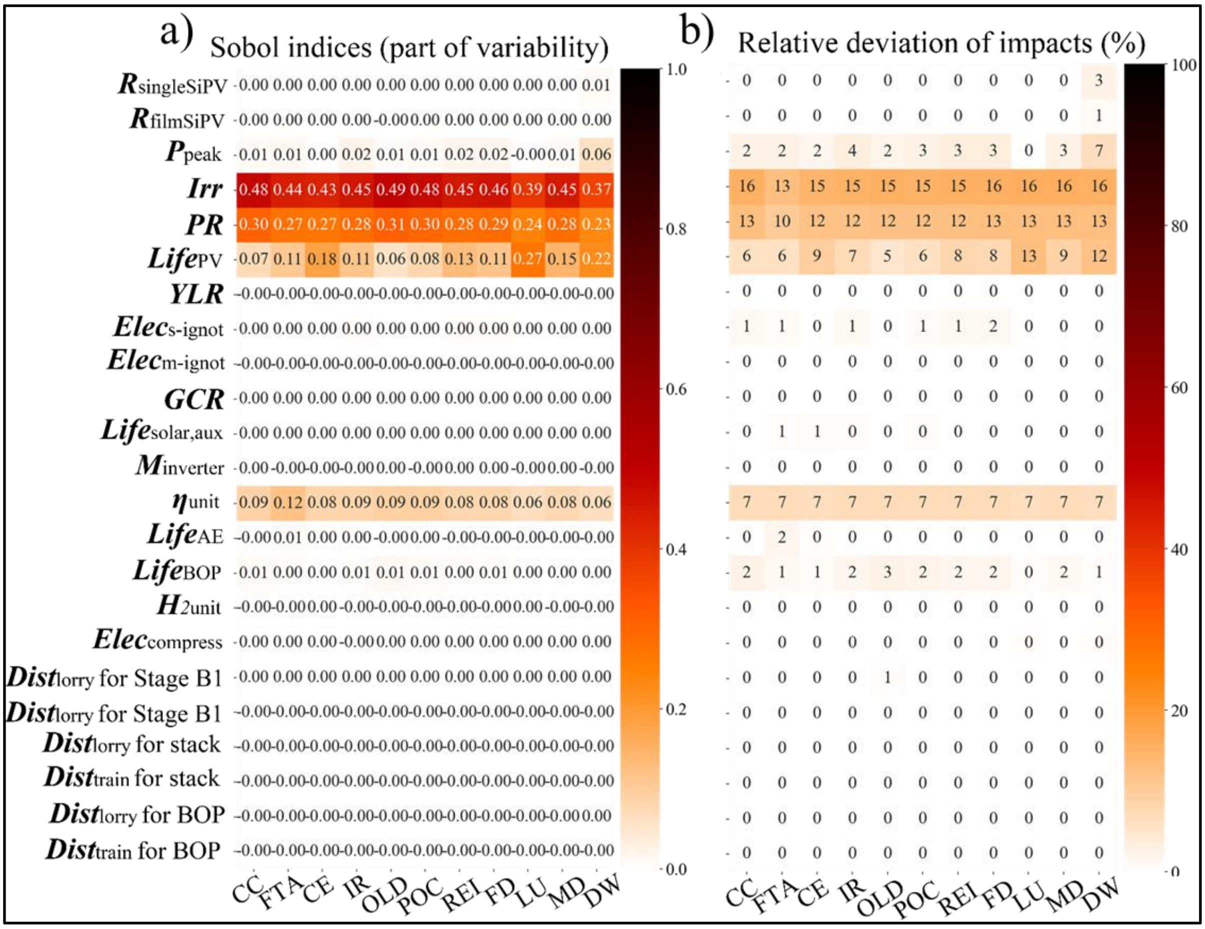

Fig. 10. Pathway 2 LCIA score sensitivity to life cycle parameters. Parameter names correspond to these in Table 4 and Table S1.

3.2.2 LCIA result uncertainty

Due to more life cycle parameters identified with relatively more significant uncertainties in French national average solar electricity supply chain stated above, as illustrated in Fig. 11, CV among all impact categories score of the solar-to-H_2 pathway is around 9.57 %-16.44 % higher, compared with the corresponding CV of the wind-to-H_2 pathway.

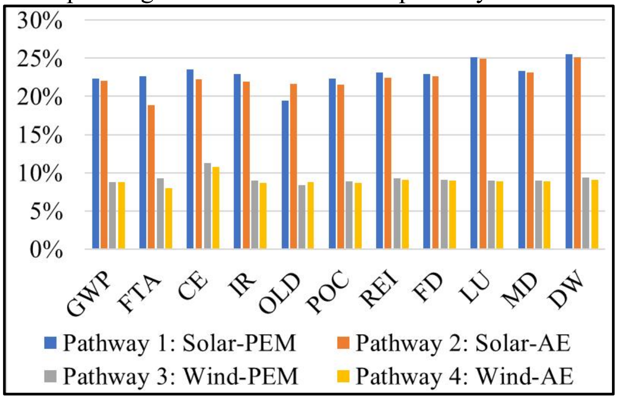

Fig. 11. LCIA results' uncertainty for each pathway.

Under the current French context, applying PEM electrolysis unit in the solar-to-H_2 pathway is embodied with more significant life cycle parameters uncertainty (especially the variation of stack lifespan[116]) than using the AE electrolysis unit. Thus, all impact categories CV for pathway 1 is 0.16 %- 3.76 % larger than those for pathway 2, except CV for OLD. OLD CV for pathway 1 is 2.21 % smaller than CV for pathway 2. LCIA results' CV for pathway 3 and pathway 4 is also comparable, where the difference among each impact category is smaller than 1.3 %.

3.3 Guidance for improving LCA sustainability

3.3.1 French solar electricity supply chain

As discussed above, in the current French context, many PV panels, especially the multi-Si and mono-Si panels, are manufactured and assembled in China, then imported to France and Europe. Manufacturing the Si PV panels related materials, e.g., solar gride silicon and silicon ingot, in China is very fossil energy, water, and emission (CO_2, NO_x, and other pollutants) intensive due to the current fossil energy-based Chinese energy structure. However, the renewable and sustainable energy transition is flourishing in China[117-119]. And remarkable technology advances have achieved in solar gride silicon production process depollution, attributed to the vigorous promotion and policy implementation of the Chinese government during last decade[120]. Besides, the gradual nationwide promotion of advanced technology, e.g., panel lead-free soldering, higher level automation production, has significantly improved the PV panel component manufacturing efficiency[121]. Thus, the environmental impact embodied in Chinese PV panels is visibly progressively decreasing[115]. This will continuously guarantee China as a primary PV panels provider for the French solar electricity market.

Regarding the PV mounting system, renewable energy-based zinc and aluminum refining should receive more research focus to reduce GWP, OLD, FTA, CE, and MD scores. And special attention should be paid to sustaining these materials' recycling process during PV mounting system EoL. Besides, bauxite digesters in Europe are still embodied with relatively large desulfurization and denitrification potential to reduce CE embodied in aluminium production.

Employees should receive qualified training regarding the PV plant operation phase to achieve a high enough PV panel performance ratio and lifetime under site-specific strategies. And innovation should primarily focus on irradiance tracing systems and PV panels site distribution optimization, which can achieve a lower LU.

3.3.2 French wind electricity supply chain

As mentioned above, chromium steel, low-alloyed steel, copper, and zinc coating are massively consumed in the wind turbine tower under the current French context. And the large-scale application of suitable & environmentally friendly metal alternatives (e.g., high-strength glass fibers, basalt, and aramid fibers[122]) is still far from strong enough economic competitiveness. Thus, improving the renewable energy permeation and material recycling ratio during the production of these metal materials is critical to bringing down the environmental influence of the French wind electricity supply chain in the foreseeable future. Besides, there is still enough improving space for desulfurization optimization to copper production in Europe to furtherly reduce the FTA embodied in copper production. Furthermore, more sustainable, e.g., biomass-based[123, 124], nylon 6-6 alternatives indicate significant DW and FD reduction potential during wind turbine blade production.

Innovation on less electricity-intensive wind turbine assembling, mounting, and EoL removal technology will achieve a lower DW and FTA. To fulfill more environmentally-friendly access to wind power plants in terms of OLD, LU, GWP, FTA, IR, FD, and REI, relative road building should highlight biomass-based alternatives[125, 126] to fossil asphalt.

And the particular focus should be paid on road construction raw material transportation distance management and diesel consumption efficiency during road construction. Operators should receive qualified training during the wind plant operation phase to achieve a high enough wind turbine lifetime, which is critical regarding all the impact categories studied.

3.3.3 Water electrolysis unit and operation

Similarly, to pursue a more environmental-friendly AE stack, improving the renewable energy permeation and material recycling ratio when producing the electrode material (manganese and 99.5 % nickel) is essential. And relatively high NH_3, HCl, VOC emission from the electrothermal manganese ore reforming (major manganese production technology) indicate the potential for further depolluting optimization. Meeting the huge heat requirement during manganese ore reforming from renewable biomass heat rather than fossil-based heat serves as another critical strategy. Similar regulations are also recommended for pyrometallurgical nickel ore refining, the primary technology for 99.5 % nickel production, to reduce PM10 and VOC emissions. Furthermore, attention should be paid to the innovation of more renewable solid polymer electrolytes, e.g., algal-based polysaccharides[127], to reduce the OLD score embodied in the PEM stack.

Furthermore, innovation on less electricity-intensive assembling, mounting, and EoL removal of AE electrolysis unit will achieve a lower DW and FTA sore. And the particular focus should be paid to improving stack efficiency, i.g., innovation on membrane temperature optimization technology[128], as well as the addition of more efficient electrolyte and electrocatalysts[129]. And during electrolysis unit operation, employees should receive qualified training to achieve higher electrolysis efficiency and BOP lifetime. Regarding BOP and H_2 compressor, compressive strength for qualified concrete that meets the electrolysis unit ground stabilization requirement should be as low as possible. To reduce GWP, POC, CE, OLD, and REI score, a high recycling rate of raw material (gravel and sand) and renewable electricity penetration during concrete production is indispensable.

Besides, innovation on improving the efficiency of significant clinker production technology in Europe, limestone rotary kiln calcination, should be highlighted. And renewable biomass sourced heat is a better choice rather than fossil-based heat during limestone rotary kiln calcination.

4 Conclusions

This study performs a comprehensive environmental impact investigation and comparison among renewable-electricity-based water electrolysis H_2 production in France, from the angle of average French resource availability and technology market share in 2019. With the corresponding French national benchmark parametric life cycle model built in BW2 based *lca_algebraic* library, this study becomes the first detailed and holistic SA and UA of RE-to-H_2 LCA both on the foreground and background life cycle parameters.

Four RE-to-H_2 pathways were analyzed based on different technical details and life cycle hypothesis. Based on the result and discussion discussed above, the following main conclusions are drawn:

1) The water electrolysis H_2 production with average French wind electricity via PEM electrolyzers is always the most environmentally-beneficial choice in all RE-to-H_2 pathways studied, whether in terms of impact categories comprehensive trade-offs or considering only GWP.

2) Compared with Norwegian, French, and ENTSO-E electricity, utilizing French national average wind electricity for water electrolysis H_2 production remains a more sensible option in terms of most impact categories studied.

3) Under the current French context, the uncertainty for solar-to-H_2 pathways is moderate, with CVs between 19% and 26% for all impact categories. LCIA score uncertainty primarily derived from variations of French annual solar irradiation available on PV panels; PV panel performance ratio; PV panel lifetime; electrolysis unit global efficiency; the nominal maximum power of PV panel.

4) In the current French context, the wind-to-H_2 pathway is embodied with relatively small uncertainties, with CVs between 8%-11% for all impact categories. Critical life cycle parameters determining the LCIA score are electrolysis unit global efficiency; wind turbine lifetime; onshore wind turbine capacity factor; electrolysis unit BOP lifetime; and share of >3MW wind turbine assembly in French national average onshore wind turbine market.

5) Several essential strategies should be highlighted to achieve a more renewable and sustainable RE-to-H_2 pathway. It's critical to improve the renewable energy permeation and material recycling ratio during the production of basic materials for infruscture construction (e.g., zinc, aluminum, copper, 99.5 % nickel, cement). Innovation in more sustainable substitution, such as biomass-based alternatives for infruscture materials and further depolluting optimization for infruscture materials production serve as other critical strategies. In addition, special emphasis should be placed on developing less electricity-intensive assembling, mounting, and EoL removal of both background and foreground infruscture (e.g., PV panels and mounting system, wind turbine assembly, and water electrolysis unit).

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Supplementary Materials

Other supplementary materials, e.g., the '.ipynb' jupyter notebook files contenting the French national benchmark parametric LCA model of all the pathways studied together with the corresponding LCI and data source; accumulative annual solar irradiance 2019 for French mainland's 13 administrative regions taken from the CAMS radiation service dataset "AGATE"; Unit process contribution to LCIA results with uncertainty box plot for each impact categories studied; the LCIA score S1 indices to each life cycle parameter and each impact category score's uncertainty for all pathway studied can be found at the authors' GitHub branch at:

github.com/ZHANG-Zongyue/FR_H2_LCA/tree/EREGCE-proceeding-2022.

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