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Prospective Life Cycle Inventory Data Of Hydrogen Production For Aviation

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Abstract

Hydrogen (H_2) fuels are seen as alternative propulsion fuels to reduce aviation's contribution to climate change as it does not produce carbon dioxide upon combustion. One major challenge for this transition is that hydrogen production routes often entail emissions that drastically reduce the environmental benefits of adopting the technology. Low-impact H_2 production is associated with three processes; electrolysis powered by renewable energy, biological fermentation and biomass gasification. Impacts of the latter two can potentially be further reduced by carbon capture and storage. Several datasets to support life cycle assessments (LCAs) of mentioned H_2 production routes exist, but are limited by different temporal and geographical scopes. Future changes in energy systems as well as technology developments will have a major effect on the long-term impacts of hydrogen production. Not considering these changes will distort decision-making based on prospective assessments. This study addresses this gap by harmonizing existing data for the three most prominent water electrolysis technologies and developing prospective H2 production life cycle inventory datasets for Europe. Only the production of hydrogen itself is considered, excluding liquefaction, storage and distribution to the aircraft refueling point. We consider the technological changes that are partially expected to lead to dramatic reductions in material intensities of the electrolysers. By harmonizing regionally specific background data, this work contributes to a clearer understanding of the conditions under which green H2 fuels can deliver substantial climate benefits as future aviation fuels.

Keywords: Life cycle inventory data, hydrogen production, technological learning, prospective LCA

1. Introduction

Aviation accounts for around 3% of global CO_2 emissions from fossil fuel combustion [1] and more than 14.4% of EU transport emissions [2]. Although new technologies aim to reduce this impact, global air transport demand is still increasing by about 2% per year, and emissions could potentially triple by 2050 [3]. Particularly in-flight effects and the environmental burdens of fuel production represent major contributors to future aviation's climate impact.Research on new aircraft concepts is therefore mainly focusing on alternative energy carriers and associated propulsion systems. Among these, hydrogen and power-to-liquid (PtL) fuels are increasingly discussed as potential options for sustainable long-distance air travel [4]. Hydrogen (H2) is promoted as a pathway to decarbonize aviation under the EU's 'Fit for 55' programme [2], as it enables zero CO_2 emissions during combustion. Nevertheless, the diversity of hydrogen production routes makes environmental assessments highly complex; 96% of hydrogen production was still based on fossil-fuels in 2019 [5]. Similarly, PtL, which are synthetic fuels that are produced from renewable electricity and carbon sources [6], is often described

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as one of the most compatible options for civil aviation [7,8]. Yet, relatively few studies have assessed its impacts in detail [9]. As PtL fuels require substantial amounts of hydrogen, sufficient, flexible and reliable H2 production is a key enabling factor for both liquid hydrogen (LH2) and PtL [6]. In an aircraft hydrogen can be used for direct combustion through a turbine or in conjunction with oxygen through a fuel cell that generates electricity for propulsion or on-board power supply [10].

There are multiple production routes for hydrogen [11]. Grey hydrogen, produced via steam methane reforming, is still associated with a high carbon footprint. Blue hydrogen relies on the same process but integrates carbon capture and storage. The most promising renewable pathway with the potential to substantially mitigate aviation's climate impact is green hydrogen, which is produced through water electrolysis powered by renewable energy. However, the availability linked to large-scale production of green hydrogen remains critical, especially for the application in aviation. Electrolysis powered by renewable energy is currently only implemented at comparatively small scale and requires large development efforts, which could potentially lead to unexpected and undesired environmental impacts, but also to significant efficiency improvements [12,13]. For the use in aircraft, hydrogen must be converted to liquid hydrogen (LH2), as only the liquid state provides a feasible energy density. This requirement introduces significant design challenges, including cryogenic storage, integration of LH2 tanks into the airframe, and the development of dedicated safety concepts [14].

Hydrogen production is very energy-intensive. Green hydrogen production that depends on renewable energy sources is likely to be concentrated in specialized production and import hubs. In Europe, centralized hydrogen hubs are planned in coastal areas and industrial clusters with access to wind, solar, or hydropower resources. From there, distribution to airports could occur via pipelines, trucks, or ships. Based on the H2inframap [15] and IEA [16], likely future hubs include the North Atlantic region (Netherlands, Northern Germany, Denmark), Scandinavia, and the Mediterranean area. Although nuclear energy is not classified as renewable, some studies propose using surplus nuclear energy for hydrogen production in France [17]. As a consequence, regional factors and energy sources are expected to strongly shape the environmental profile of hydrogen production.

Given these challenges, this study reviews the main green hydrogen production pathways reported in the literature and evaluates their environmental implications, with particular consideration of aviation-specific constraints. Three electrolysis processes; proton exchange membrane (PEM), alkaline water electrolysis (AWE), and solid oxide electrolysis (SOE) are considered for green hydrogen production. A literature review of life cycle inventories (LCIs) reveals substantial variation regarding electricity demand and materials used. As Aviation is highly globalized, in this study production scenarios are compared for five different hydrogen hubs in Europe. Furthermore, learning rates are applied to account for efficiency gains expected from technological development by 2050 [18,19]. The aim of this study is to provide a foundation for future research on hydrogen use in aviation and to support the implementation of hydrogen datasets in prospective life cycle assessments of emerging aviation concepts.

2. Fundamentals

To assess the future impacts of hydrogen production pathways in different locations, we give a brief overview of the assessed technologies and method.

2.1 Hydrogen production pathways

As water electrolysis is the main technology that supports green hydrogen production based on renewable energy, we investigate the three different production methods that are discussed in literature. They are distinguished primarily by the electrolyte that is used.

Alkaline water electrolysis

The process of AWE is enabled by a liquid electrolyte, a solution of water and potassium hydroxide. The electrolyte is added into two chambers that are separated by a diaphragm, while one chamber contains the cathode, the other one the anode. At the cathode, water splits into H_2 and OH^- ions. Nickel and nickel alloys are preferably used as electrode materials. The diaphragm mostly consists of zirconium oxide and polysulfone [20]. AWE is currently the most efficient but also the most mature electrolysis technology, improvements are expected to be less significant than for the other technologies. Nonetheless, under future scenarios analysed (e.g., in Wei et al. [19]), AWE contributes to the decline in average life cycle GHG emissions of water electrolysis technologies globally.

Proton-exchange membrane

The name for this technology stems from the used electrolyte, a proton-conducting polymer membrane, usually Nafion. Similar to AWE, hydrogen is formed at the cathode side, while water is split at the anode. Contrary to AWE, the electrolyte is not liquid, which is why the membrane is directly connected to the electrodes. Next to the membrane, the most relevant materials are platinum as anode and iridium as cathode material [21]. Design improvements are expected to drastically reduce material intensities, next to the critical raw material contents in the electrode for example for stainless steel and titanium [12].

Solid-oxide electrolysis

The electrolyte for this technology is a layer of a solid oxide mineral. Typically, to date that is zirconium oxide (ZrO_2) with yttrium oxide (Y_2O_3) as stabilizer, while nickel is used as catalyst [20]. SOE operates at high temperatures, usually more than 700º C, allowing for higher efficiency and potentially lower electricity demand [18] at the cost of additional heat demand. From a life cycle perspective, SOEs promise a greater reduction in greenhouse gas emissions than low-temperature electrolysers if waste heat or renewable high-temperature heat is available and if issues of material and operational stability are resolved [19]. Due to its efficiency gains SOE is a promising hydrogen production method for the forthcoming energy system. Of the three alternatives SOE is at the lowest technology readiness level and still has a lot of potential to be improved. For example, Scandium as replacement for yttrium is discussed to increase efficiency further [22].

2.2 pLCA studies on hydrogen production

The environmental impacts of emerging aviation concepts are not straightforward to assess. As highlighted by Rahn et al. [9], accounting for impacts dynamically and spatially more accurately in the context of aviation can change the long-time effects dramatically. In line with the indicators of the pedigree matrix for uncertainty, temporal and geographical correlation are important factors to reduce uncertainty further [23].

Table 1. Parameters changing over time from excerpt of literature review, shown for baseline year (~2020)

Study	Delpierre et al. [24]		Wei et al. [19]			Koj et al. [20]			Ajeeb et al. [25]	
Technology	AWE	PEM	AWE	PEM	SOE	AWE	PEM	SOE	AWE	PEM
Lifetime [hr x10^3]	60-80	60-80	75	60	20	60	40	20	53-85	40-80
Electricity [kWh/kg H2]	50	50	50	57	43	55	55	38	50-66	50
Water [kg/kg H2]	9	9	12	12	12	9	9	9	9-10	10
Steel [kg/kW]	10-30	7-10	20	10	9	3.9	10	3.6	-	-

Thonemann et al. [18] and Cucurachi et al. [19] defined prospective or ex-ante LCA as an environmental evaluation conducted on technologies that are still in their early development stages, but modelled as if they were deployed at future scale. Its purpose is to anticipate potential environmental impacts, compare emerging options with established technologies, and guide design improvements before large-scale implementation. Because data for such technologies are often scarce and uncertain, prospective LCAs require careful definition of goals and scope, scaling methods to project future performance, and sensitivity or scenario analyses to address uncertainty. The prospective approach aims at helping researchers, engineers, and policymakers identify environmental hotspots early and make informed decisions that steer innovation towards more sustainable outcomes.

We reviewed 10 studies after conducting a scoping review to extract relevant parameters that change over time, as well as the LCI of Balance of plant (BoP) and stacks. If the sources provided a range of values for e.g. the lifetime or electricity consumption, we noted the minimum and maximum value. For our assessment we used the average values of the reviewed studies, excluding values that were highly irregular. The inventory data of *Wei et al.* [19] and *Gerloff* [26] was used for exchanges that do not change over time. The review revealed differences for multiple parameters, including efficiency, scaling factors and amount and type of materials used in BoP and stack production. Most studies base their inventories on the publications by *Gerloff* [26], *Bareiß et al.* [12] and *Lotriç et al.* [27], as also highlighted by *Ajeeb et al.* [25]. They have been extensively reviewed, often the assumed consumables and technological learning differ however.

3. Method

The prospective LCA (pLCA) is conducted using the activity browser [28], brightway2 [29] and premise [30]. We make use of the superstructure approach and combine the SSP2-NDC scenario from REMIND [31] with own scenarios for the changes per technology until the year 2050. These changes were modelled by averaging values from the literature review for 2020 and 2050. Values between those two years were interpolated with a sigmoid function, resembling hypothetical learning curves as introduced by *Koj et al.* [18].

3.1 Goal & scope

For the pLCA we define our functional unit as 1kg of gaseous H_2 produced by water electrolysis with different technologies. The scope is cradle-to-gate with the goal of developing H_2 production datasets as background for prospective dynamic LCA studies in the future. Within Europe five regions are assessed. Based on literature we assumed which energy production method is likely to be prominent in each particular region. We assess the time frame from 2020 to 2050 every five years.

Fig. 1 shows all foreground processes modelled indicating which processes change with time. Three different types of changes were modelled. Foreground temporal changes include efficiency improvements that result in decreasing material intensities and electricity demand. Background changes include the processes' supply chains, implemented through REMIND. Spatial changes refer to the five regions, with their simplified main electricity production method for water electrolysis. For the purpose of demonstrating the differences of distinct electricity production methods we assume that:

- In France, surplus nuclear electricity supports low-carbon hydrogen production [32]
- In the Mediterranean region, hydrogen production is primarily supported by photovoltaic-based electricity [33,34]
- In Scandinavia, the surplus of renewable energy generated by hydropower is used [35]
- In the North Atlantic Region, parts of the offshore wind energy produced in the North-Sea is used [36]
- In Central Europe, a mix of 11% photovoltaic, 65% wind (onshore), 5% wind (offshore) and 19% hydropower with Germany as placeholder is used [37]

While liquefaction, storage and transportation of hydrogen are important parts of the supply chain for hydrogen fuels in aviation, we exclude these in this study because data availability covering technology improvement was not sufficient and unclear infrastructure and transport distances for future airports would distort the pLCA results, further increasing the uncertainty.

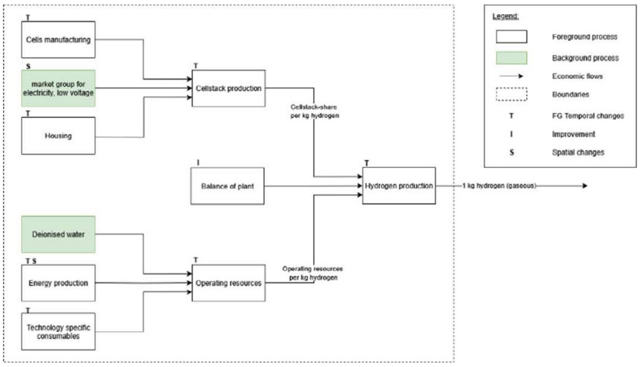

Fig. 1. Flowchart of assessed system including the different changes over time

3.2 Life cycle inventory

The assumptions based on the reviewed literature and own calculations for the development of selected parameters are shown in Table 2. All changes in materials and consumables can be found in Appendix A.1.

Table 2. Excerpt of expected changes from 2020 to 2050

per kg H_2	AWE	PEM	SOE
BOP share	2.9e-7 → 9.7e-8	3.5e-7 → 2.3e-7	2.6e-7 → 1.7e-7
Stack share	8.9e-7 → 3e-7	5.7e-7 → 1.9e-7	2.3e-6 → 2.3e-6
Electr. [kWh]	53.7 → 48.3	54 → 47	43 → 37
per stack			
Steel [t]	16.5 → 7.8	0.1 → 0.04	3.56 → 0.78
Titanium [kg]		528 → 37	
Yttrium [kg]			15.4 → 0.58
Lanthanum [kg]			15.9 → 0.6

4. Results

4.1 Prospective assessment with technological learning

The prospective impacts of hydrogen production through electrolysis were assessed in five regions, with and without technological advancements. Fig. 2 shows these impacts for the three technologies in 13 impact categories of the EF v3.1 method [38]. The transparent bars represent the reduction in environmental impacts when technological learning is considered. The opaque bars show the reduction in impacts when only supply chain changes, modelled through the REMIND SSP2-NDC scenario, are implemented. The regions correspond to the previously described simplified energy supply scenarios.

4.2 Importance of green hydrogen production for aviation

To illustrate the importance of prospective datasets, we demonstrate a rough estimation of the use of hydrogen in aviation. Based on a whitepaper of the international council on clean transportation [39], a hydrogen-powered aircraft in the size of an A320 would consume around 1,850 kg hydrogen on a medium mission of 1,500 km. Assuming around 1,600 flights per year [9], a single aircraft would therefore require roughly 2,960 tonnes of hydrogen annually. Taking the PEM electrolysis in the Mediterranean region as example, this demand could, for instance, lead to roughly 8,283 tCO2-eq. in 2020 versus only 1,984 tCO2-eq. in 2050 with an optimized technology and material factors. This simplified example highlights that even moderate fleet sizes would lead to significant hydrogen demand, and that the chosen production pathways can strongly influence the global warming potential. In addition to that, this estimation assumes that all hydrogen is produced in a single location. In reality, aircraft operate globally, and hydrogen would need to be sourced from different regions depending on departure and arrival airports. This highlights the multifaceted nature of hydrogen supply chains in aviation. Using regionally resolved, prospective LCA datasets can thus provide more realistic environmental assessments, potentially avoiding overestimation of impacts and thereby supporting continued development and deployment of advanced hydrogen technologies for aviation.

5. Discussion

Our results show that hydrogen production pathways are expected to substantially differ in their environmental impacts in the future depending on the production technology and energy source. This has particular relevance for aviation, as hydrogen offers better combustion properties compared to kerosene, meaning that a significant share of its overall environmental impact arises during fuel production. By examining the production processes in detail and considering the constraints associated with aviation our analysis reveals potential burden-shifting effects. The choice of electrolysis technology and regional energy mix strongly influences environmental performance, highlighting the need for technology- and location-specific strategies. These insights are not only important for selecting suitable hydrogen production routes but also for informing aircraft design, infrastructure planning, and policy development.

By reviewing existing literature and synthesizing life cycle inventories, we identified knowledge gaps and uncertainties in current assessments of hydrogen production. Especially the electrolysis process PEM, considering its technological advancements is promising. PEM’s global warming potential is lowest in Scandinavia, where the electricity is produced by hydro-power. The difference between the impact reduction with technological learning and without it, is also most noticeable in this region. The reduction of materials used for the manufacturing of the components leads to significant distinctions in most impact categories. However, the effect on climate change is comparatively low, the determining factor remains the energy production method.

The assessment conducted in this study is limited by the fact that system boundaries and functional unit of the reviewed literature were not always the same, which increases the uncertainty when aligning the values.

Assumptions about e.g. efficiency and operation factor had to be made to calculate the materials used per functional unit and perform the physical allocation of components to the functional unit.

The location of the introduced hydrogen hubs is very simplified, other studies are investigating the complexity of introducing hydrogen production into national and international energy systems. As the stacks endure for their respective lifetime (see Table 1) efficiency improvements will only be implemented after they have been replaced, this is not modelled here.

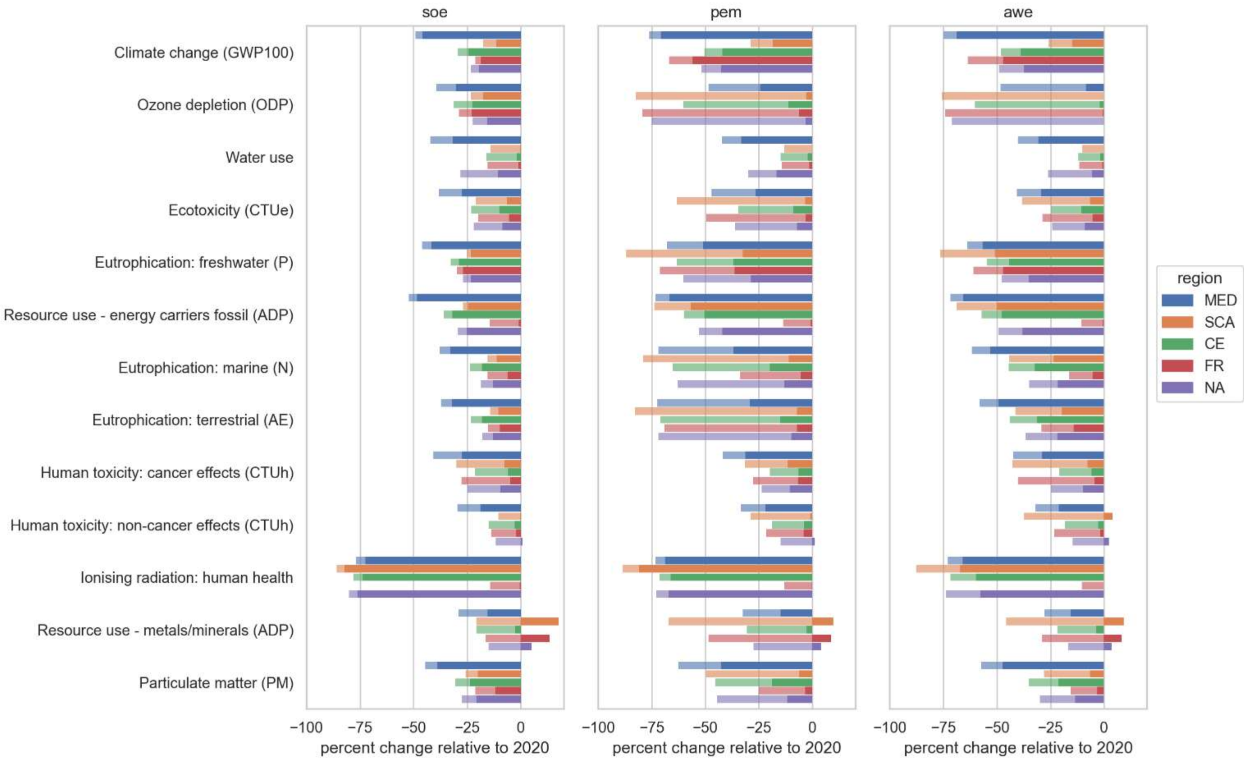

Fig. 2. Percent change from 2020 to 2050 for the three assessed electrolysis technologies; Solid Oxide Electrolysis (SOE), Proton Exchange Membrane (PEM) and Alkaline Water Electrolysis (AWE) in five different regions: MED – Mediterranean, SCA – Scandinavia, CE – Central Europe, FR – France, NA – North Atlantic; transparent bars: with technological learning, opaque bars: without learning

With omitting liquefaction, transportation, storage and the related infrastructure, important aspects of the supply chain for hydrogen as PtL or LH2 fuels in aviation are not considered in this assessment, as well as end-of-life strategies for the materials and components used. Future studies should expand the system boundaries and include these processes to give a more complete picture of the impacts. However, the gaseous hydrogen produced by the technologies that were assessed in this study is fed into the infrastructure in the same way. Therefore, the comparison with the used system boundaries still provides insights into future developments. Fig. 2 shows that with the reviewed data points, technology developments would not as drastically reduce the impacts of SOE in comparison to PEM and AWE. This result contradicts studies that have SOE in focus, we attribute it to the many unknown variables that might change with time. Replacing yttrium with scandium is one example of the research developments that have not been modelled, but could lead to significant efficiency and lifetime improvements.

We have not conducted a sensitivity or uncertainty analysis in this study. In the framework of developing prospective datasets these are important steps to ensure documenting the multifold possible outcomes of a highly uncertain future.

6. Outlook

The inclusion of prospective technology learning curves allows for the creation of forward-looking datasets, enabling an evaluation of benefits and drawbacks per production technology in the context of long-term environmental impacts. Given that aviation is planning to operate with hydrogen within the next decades and aircraft have long service lifetimes, considering future-oriented aspects may facilitate the adoption of hydrogen technologies and support informed decision-making for both industry and policymakers [11].

The results show that the abiotic depletion potential for metals and minerals is changing from increasing to decreasing when considering technological learning over time. That highlights the importance of addressing the future raw material demand in enabling technologies. Analysis of future material flows can enable circular strategies, which in turn can improve strategic autonomy and supply chain resilience [37, 38]. The hydrogen production site is also important for strategic resilience, an interesting approach for the future would be to consider the supply chain per location of hydrogen hubs.

The location is also important, because the electrolysis technologies are embedded into the industrial context of their respective hub. PEM benefits from a dynamic power response and is more flexible than AWE, making it suitable to deal with intermittent electricity production from renewable sources [24]. SOE might thrive in industrial symbiosis, when access to a waste heat source from nearby plants, for example nuclear power plants, can be connected. Further research could apply the prospective datasets to real application use-cases like a hydrogen powered aircraft and provide clear criteria for determining under which regional and energy mix conditions each electrolysis technology delivers the greatest environmental benefits.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT in order to improve the writing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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