Energy Conversion and Management: X 20 (2023) 100435

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

Resource requirements for the implementation of a global H_2-powered aviation

F. Schenke [a], J. Hoelzen [a], C. Minke [b], A. Bensmann [a,*], R. Hanke-Rauschenbach [a]

[a] Leibniz Universität Hannover, Institute for Electric Power Systems, 30167 Hanover, Germany
[b] TU Clausthal, Institute of Mineral and Waste Processing, Recycling and Circular Economy Systems, 38678 Clausthal-Zellerfeld, Germany

ARTICLE INFO

Keywords:
Hydrogen aviation
Liquid hydrogen
Synthetic aviation fuel
Critical raw materials
Desalination
Green hydrogen

ABSTRACT

In this paper, the resource requirements for the implementation of global H_2-powered aviation are investigated to answer one of the main questions asked by many stakeholders in the aviation industry: Are there any resource limitations for the implementation of H_2-powered aviation on a global scale? For this, the raw material, renewable energy and water demands for the deployment and operational phase are investigated on a global and regional perspective.

It is found that the iridium demand for a global hydrogen economy could be critical as it would exceed not only the current annual production by a factor of 11 but also the current reserves about 1.7 times. The H_2-powered aviation alone is not the main driver of iridium demand but could increase the limitations. With reduced specific raw material demands of further optimized electrolysis technologies and increased annual raw material production, the limitations especially for the iridium demand could be overcome.

Renewable energy capacities and water availability are sufficient for demands from H_2-powered aircraft on a global perspective. Nevertheless, the limited availability of renewable energy sources in some regions and regional water constraints may necessitate hydrogen import for certain airports.

While water desalination is likely to overcome water constraints in regions close to the sea, for airports located in regions with detrimental availability of renewable energy sources the import of hydrogen is the only way to ensure a hydrogen supply for H_2-powered aviation.

Introduction

This paper is about the analysis and evaluation of resource requirements for the implementation of hydrogen (H_2)-powered aviation. While critical raw materials are potentially limiting the deployment of an H_2 generation and supply infrastructure for the aviation sector, the operation of such infrastructure might require a vast amount of renewable energy and water. In this paper, the potential limitations and critical resources are identified based on selected scenarios and substitutions to deal with the limitations are evaluated.

Although aviation is responsible for only about 3% of the total CO_2 emissions, the full climate impact measured with the global warming potential (GWP) is estimated to be up to 5%, mainly due to NOx emissions and contrail formation [1,2]. For a reduction of the climate impact of aviation, the industry needs to introduce new technologies or fuels. Sustainable aviation fuels (SAF) such as biofuels or H_2-based synthetic fuels (synfuel), as well as carbon offsets, could play an important role in the next decades [1,3–5]. From a long-term perspective, most likely H_2-based synfuels produced with CO_2 from direct air capture (DAC) will be an important part of decarbonisation, although research indicates that H_2-propulsion might reduce more climate impacts than SAFs [1]. The use of H_2 in aviation can reduce the impact on the climate by 50–75% when combusted and 75–90% when a fuel cell is used [1]. The

Abbreviations: AWE, Alkaline Water Electrolysis; CO_2, Carbon Dioxide; DAC, Direct Air Capture; DERA, Deutsche Rohstoffagentur; EI, Economical Importance; EOL, End of Life; ETI, Energy Transition Index; FT, Fischer-Tropsch; GH_2, Gaseous Hydrogen; GHI, Global Horizontal Irradiation; GWP, Global Warming Potential; H2C, Hydrogen Council; H2, Hydrogen; IRENA, International Renewable Energy Agency; LH_2, Liquid Hydrogen; LHV, Lower Heating Value; LOHC, Liquid Organic Hydrogen Carrier; LPG, Liquid Propane Gas; NH_3, Ammonia; PEMWE, Proton Exchange Membrane Water Electrolysis; PGM, Platinum Group Metal; PTL, Power to Liquid; PV, Photovoltaic; RES, Renewable Energy Sources; RWGS, Reverse Water Gas Shift; SAF, Sustainable Aviation Fuel; SOE, Solid Oxide Electrolysis; SR, Supply Risk; SWRO, Seawater Reverse Osmosis; synfuel, Synthetic fuel.

* Corresponding author.
E-mail addresses: schenke@ifes.uni-hannover.de (F. Schenke), astrid.bensmann@ifes.uni-hannover.de (A. Bensmann).

https://doi.org/10.1016/j.ecmx.2023.100435
Received 30 May 2023; Received in revised form 22 July 2023; Accepted 4 August 2023
Available online 6 August 2023

Nomenclature

d	Transport distance in km
E	Energy demand in kWh
LHV	Lower heating value in kWh/kg
m	Mass in kg
$t_{fullloadhours}$	Electrolysis full load hours in h
$n_{technologyshare}$	Share of electrolysis technology used in %
P	Capacity in kW
Indices	
H2loss	Losses of hydrogen
i	Technology i
rm	Raw material
H2	Hydrogen
H2O	Water
s	Specific
synfuel	Synthetic fuels

development of H_2-powered aircraft advances with companies such as Airbus and ZeroAvia developing and testing H_2-powered aircraft [6,7]. The entry into service for large commercial short-range aircraft is expected to be in 2035 [8].

As the estimated demands for H_2-powered aviation could make up for a significant share of the expected future H_2 demand, the resources required for the deployment of H_2 infrastructure and supply of H_2 could be critical or in conflict with other decarbonization efforts in several applications. The scope of this study is on critical raw materials used for the construction of H_2 fuel supply infrastructure and on the availability of renewable energy sources (RES) and freshwater for water electrolysis.

In previous research, scenarios for decarbonization of the aviation sector were developed with a focus on the demand for H_2 and the required energy [1,9,10]. In a study by Clean Sky 2 JU and Fuel Cells and Hydrogen 2 JU, scenarios for the introduction of H_2-powered aviation have been developed [1]. Several H_2 supply chains were investigated and practical supply routes have been found but the research was rather concentrated on the environmental impact and economics [11–15]. Critical raw materials have been identified for large-scale water electrolysis, and several life cycle analyses have been carried out for selected H_2 supply chains [14,16–19]. Also, research reports can be found on the reduction of the specific raw material loading of the electrolyzers to reduce the overall demand for critical raw materials [20–22]. Several industry and academic research reports investigated the availability of RES from a global perspective [23,24] and for selected regions like Europe [25]. However, the potentials for RES diverge highly, as no consistent method is used for the calculation and the factors used differ, such as the space requirements and the suitable areas for RES [23]. In contrast to RES, water availability has been analysed with high resolution by the World Resources Institute with forecasting scenarios for the next two decades [26,27].

Although a lot of previous research has been conducted to develop scenarios for H_2-powered aviation, no comprehensive studies have been carried out to evaluate the raw material and water demands. There is also only little data on the raw material demands for a global H_2 economy. The potential of RES is much studied, with data for natural conditions freely available [28–30] and evaluations of H_2 production have been carried out [31]. However, these research efforts did not consider the high H_2 demand of aviation globally and also not at specific locations. Furthermore, the scenarios for global H_2 supply rarely include consideration of water availability [13,32–34].

In this paper, the identified research gaps are addressed to answer one of the main questions asked by many stakeholders in the aviation industry: Are there any resource limitations for the implementation of H_2-powered aviation on a global scale? Important aspects to answer this overarching question are indicated with the following three sub-questions:

1. What are the resource conflicts and scarcities caused by global H_2 production from a global and regional perspective?
2. Does the implementation of H_2-powered aviation enhance these conflicts and scarcities and what is the influence of synfuel production?
3. Are there any substitutions for identified critical resources to deal with the limitations?

To answer these questions, the paper is structured as follows. In Section 2, the methodology of the paper is introduced. The used model to determine the resource requirements is discussed and the scope of components as well as their description are presented. A basis for the comparison of the resource requirements for H_2-powered aviation and synfuel production is provided here.

Thereafter in Section 3, the resource requirements for the deployment phase of H_2 infrastructure – so, installing H_2 production and supply are evaluated. The raw material demands are compared to the annual production and available reserves and a sensitivity analysis is carried out for the relevant raw materials. At the end of the section, strategies are discussed to deal with the identified limitations.

In Section 4, the operational phase of H_2 supply for H_2-powered aviation and synfuel production for aviation is evaluated. The evaluation is focused on the renewable energy and water demands. For each of these, the availability is assessed from a global perspective and compared to the estimated future demands. As the global and regional perspective varies significantly, selected airports are evaluated to provide a general overview of the suitability of H_2 production directly at the airport. Then, strategies for regions with constraints in RES and water

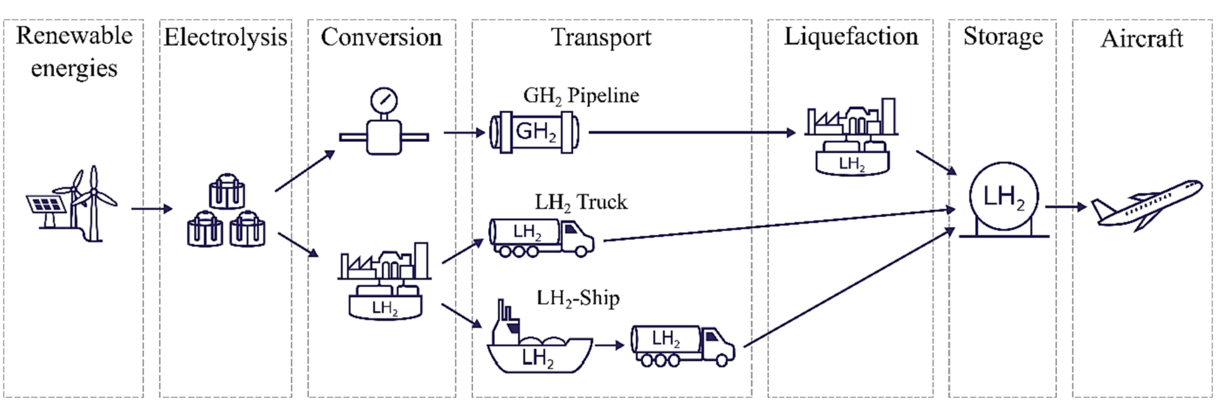

Fig. 1. Vestigated supply chains for h2-powered aviation.

are discussed.

Conclusions and recommendations are provided in Section 5 and the limitations of the study are outlined, as well as an outlook for further research opportunities is given.

Modelling the resource requirements for H_2-powered aviation

In this section, the methodology of this paper is outlined and the used components for the H_2 supply chain are investigated. The considered future H_2 demands and the relevant modelled components are discussed individually.

Methodology

This section shows the general methodology used including adapted component descriptions that match the level of relevant detail needed for the overall research objectives. As the posed research questions do not require detailed modelling of the individual components, a rather simple model is used to determine the resource requirements.

For this model, three supply chains shown in Fig. 1 are investigated. H_2 transport as ammonia (NH_3) or with liquid organic hydrogen carriers (LOHC) is not considered since these transport options require significantly more energy and cost more when the H_2 is required to be in a liquid state for the application [11,12,35]. For this evaluation, only green H_2 produced with RES is considered, since the goal of H_2-powered aviation is to lower aviation's climate impact as far as possible. Therefore, also other "low-carbon" H_2 for example produced with nuclear energy is not considered. Hydrogen is generated by means of water electrolysis, the exact technologies are discussed later in this section. Then, it is converted based on its way of transportation. For the pipeline route, H_2 is compressed, while it is liquefied for the transport via truck and ship. Since H_2 as a fuel for larger aircraft is required to be in a liquid state, H_2 liquefaction is part of every supply path [1]. At the airport, storage amounts of the liquid hydrogen (LH_2) are assumed to be designed to last for three days to ensure the LH_2 supply security at the airport [36]. For the comparison with synfuel, a shipping route is assumed for the import of synfuel using the conventional fuel infrastructure.

To determine the resource requirements, the future H_2 demand for global aviation is adopted form the literature. Two different demands for H_2-powered aviation are investigated based on scenarios by Clean Sky 2 JU and Fuel Cells and Hydrogen 2 JU [1]. The first demand scenario represents H_2 in aviation where it is the most cost effective means of decarbonization with 40% of all aircrafts converted to run on LH_2 by 2050. The second demand represents a maximum decarbonization scenario with ambitious assumptions leading to 60% of all aircraft powered by LH_2 in 2050. For a comparison to synfuel production, besides the H_2 for aviation scenarios, two synfuel scenarios are assumed with the same aircraft fleet share powered by synfuel as with H_2 in the equivalent scenarios. These scenarios serve as a direct comparison between H_2 and synfuel as a fuel. In contrast to the H_2 scenarios, the equivalent synfuel demands of the same fleet share as in the H_2 scenarios are not taken form the literature, but calculated based on the kerosene conversion factors from Hoelzen et al. [36]. As a reference for the required resources and to put the other scenarios into perspective, the forecasted total H_2 demand for all sectors by the Hydrogen Council (H2C) is given [37]. The main H_2 demand sectors in this scenario are already existing and new industry uses, building and industry heating, mobility and power generation. The investigated demands are shown in Table 1. For the calculation of the annual raw material demand, a linear increase in H_2 demand is assumed.

Based on these demands for the evaluation of RES availability, the total required energy E_{total} is calculated with

$$E_{\text{total}} = E_{\text{desalination}} + E_{\text{electrolysis}} + E_{\text{compression}} + E_{\text{transport}} + E_{\text{liquefaction}} \quad (1)$$

where $E_{\text{electrolysis}}$ is the required energy for the water electrolysis, $E_{\text{compression}}$ corresponds to the energy required for the compression if needed for the transport, $E_{\text{transport}}$ is the energy for H_2 transportation, $E_{\text{desalination}}$ the required energy for the desalinated water supply and $E_{\text{liquefaction}}$ the required energy for liquefying the H_2. The calculations of the individual energy requirements and the electrolyser capacity are shown in Appendix A.

Table 1
Considered global annual H_2 and synfuel demands for the shown years in Mton.

Scenario	2030	2035	2040	2050
H2C forecast for all sectors [37]	140	262	385	660
H_2 for aviation high [1]	0	5	40	130
Synfuel equivalent high	0	11.58	92.66	290.53
H_2 for aviation low [1]	0	2	10	40
Synfuel equivalent low	0	4.63	23.17	89.39

The individual raw material demands m_{rm} are calculated with

$$m_{\text{rm}} = m^s_{\text{rm}} \cdot P_{\text{electrolysis}} \cdot n_{\text{technologyshare}} \quad (2)$$

where m^s_{rm} is the specific raw material demand of the electrolyser, $P_{\text{electrolysis}}$ is the required electrolyser capacity and $n_{\text{technologyshare}}$ the share of used electrolysis technology for H_2 production.

The water demand $m_{\text{H2O,electrolysis}}$ is calculated with the total produced H_2 m_{H2} to

$$m_{\text{H2O,electrolysis}} = m_{\text{H2}} \cdot \sum m^s_{\text{H2O},i} \cdot n_{\text{technologyshare},i} \quad (3)$$

with the specific water demands $m^s_{\text{H2O},i}$ of the electrolysis technology i.

For comparison, also the resource requirements for synfuel are calculated. The amount of required synfuel is calculated with the fleet share and change of specific energy consumption based on Hoelzen et al. [36]. Based on these assumptions, the amount of required synfuel is 2.32 times the equivalent of H_2 demand. When producing synfuel in a Fischer-Tropsch process besides synfuel also by-products like naphtha and liquid propane gas are produced. Therefore, for 1 kg of synfuel for aviation, 1.28 kg of syncrude has to be produced. The H_2 demand for synfuel production $m_{\text{H2demand,synfuel}}$ is calculated with the total syncrude demand m_{syncrude} and the specific H_2 demand $m_{\text{H2/syncrude}}$ to

$$m_{\text{H}_2\text{demand,synfuel}} = m_{\text{syncrude}} \cdot m^s_{\text{H}_2/\text{syncrude}} \quad (4)$$

With the H_2 demand for synfuel production, the required raw materials can be calculated with Eq. (2). The total energy demand for the equivalent synfuel production is calculated with

$$E_{\text{total}} = E_{\text{desalination}} + E_{\text{electrolysis}} + E_{\text{DAC}} + E_{\text{FT+RWGS}} + E_{\text{transport}} \quad (5)$$

where E_{DAC} is the energy demand for CO_2 separation with DAC and $E_{\text{FT+RWGS}}$ is the energy demand for the Fischer-Tropsch process. The calculation of the individual energy and water demand for synfuel production can be found in Appendix A.

Technological description of the supply chain components

In this section, the modelled components for the H_2 supply chains shown in Fig. 1 are discussed briefly. The used input parameters for each component are shown in the Appendix in Table B.1. For the main comparison to synfuel production in Section 3 and 4, parameters are also discussed here.

Seawater desalination

If the required water for the water electrolysis cannot be supplied by conventional freshwater, desalinated seawater represents a viable alternative in regions close to the sea [38]. There are several technologies for seawater desalination of which seawater reverse osmosis (SWRO) is the most widely used [39]. This technology uses a semi-permeable membrane that allows water molecules to pass through and

Table 2
Specific energy and water demands for the different transport routes – see Appendix B for further information on energy requirements.

Pathway	LH_2: GH_2 pipeline transport	LH_2: LH_2 ship transport	LH_2: LH_2 truck transport	Synfuel: international shipping
Final output / end product	**1 kWh fuel (LH_2)**	**1 kWh fuel (LH_2)**	**1 kWh fuel (LH_2)**	**1 kWh fuel (Synfuel)**
Transportation	0.023 kWh	0.019 kWh	0.022 kWh	0.01 kWh
Storage	0.003 kWh	0.003 kWh	0.003 kWh	n/a – no losses
Liquefaction	0.21 kWh	0.21 kWh	0.21 kWh	n/a
H_2 generation incl. compression[1]	1.44 kWh	1.44 kWh	1.44 kWh	2.42 kWh
Seawater desalination	0.03 kWh	0.03 kWh	0.03 kWh	0.0015 kWh
Direct air capture	n/a	n/a	n/a	0.41 kWh
Fischer-Tropsch + RWGS	n/a	n/a	n/a	0.04 kWh
Total energy demand	**1.68 kWh (=59.63% efficiency)**	**1.67 kWh (=59.78% efficiency)**	**1.68 kWh (=59.67% efficiency)**	**2.89 kWh[2] (=36.31% efficiency)**
Total water demand	**0.3 l**	**0.3 l**	**0.3 l**	**0.51 l**

[1] Assuming the same electrolysis technologies for both LH_2 and synfuel production.
[2] If the LHV of all products of the FT process are considered as usable end product, then the requirements are reduced to 2.26 kWh energy and 0.4 l water demand.

blocks solids, and a high pressure pump to overcome the osmotic pressure [40]. In addition to the freshwater produced by SWRO, also brine is discharged which should not be returned to surface waters due to environmental concerns as increased salinity can negatively impact marine life and the ecosystem [41]. The SWRO is particularly suitable to supply water for H_2 production, as it has a comparably low energy demand (see Table 2) and adds only minor cost to the levelized H_2 costs [42]. The required raw material for SWRO is mainly steel [43].

H_2 production

For H_2 production, a combination of the most commonly used electrolysis technologies, alkaline water electrolysis (AWE), proton exchange membrane water electrolysis (PEMWE) and solid oxide electrolysis (SOE) is assumed. According to Smolinka et al. [44], all three technologies will be used in the future on different applications and based on the future technical and cost development none of the technologies can be identified as market dominating. The detailed technology share assumed in this study is shown in Table 7. Currently, AWE has the highest market share because it is the most mature and applied technology. An advantage of the AWE compared to other electrolysis technologies is the use of raw materials that are durable and comparably inexpensive. The relevant considered raw material of AWE in this study is nickel.

In the next 20 years, the PEMWE share is expected to grow with advantages in the design, significantly higher current densities and cost decreasing. Especially when coupled with RES, the PEMWE is advantageous because of its larger partial load range (lower minimum of ~5% of the nominal load) [45]. For electrolysis, platinum group metals (PGM) are often used as catalyst material. In this study, iridium, platinum and titanium are considered.

In 2050, the AWE and PEMWE are expected to have the same market share at each 40% [44]. The SOE is still in the development phase with some demonstration plants. It becomes particularly economically advantageous if the waste heat from external processes such as geothermal energy, solar thermal energy or power plant processes can be used. This could also be beneficial for synfuel production as waste heat from the Fischer-Tropsch process could be used. The expected SOE share is lower compared to the other technologies due to its late start into the market and limited external heat supply [44]. For the SOE lanthanum, nickel, and yttrium are considered in this study.

As shown in Table 2, the energy demand for H_2 production with electrolysis makes up for the largest share of the total energy demand in every investigated path.

H_2 compression

Because of the comparably low volumetric energy density of H_2 at atmospheric pressures, H_2 compressors are used to ensure more economic pipeline transportation [46]. There are different technologies available of which dry running piston compressors are the most establish in the industry and used for the model in this study. When multiple compression stages are used, high pressures can be achieved and the system is flexible in size and capacity [47]. The main material for manufacturing of piston compressors is steel.

H_2 liquefaction

As the H_2 is required to be in a liquid state for the assessed application in aviation, the H_2 needs to be liquefied. For the model, a hydrogen Claude cycle is assumed, as this process is discussed and used in most larger liquefaction plant concepts. This process consists of a combination of compression, recuperative cooling and expansion, for which the components mainly need steel as construction material. The liquefaction takes a minimum of 2.9 kWh/kg H_2 in a thermodynamic ideal process [48]. Currently, the energy demand is almost five times higher, but for future industrial plants, it is expected to go down to 6 kWh/kg H_2 [49,50]. H2 losses also occur in this model, 1.65% per kg H_2 feed are assumed [36].

LH_2 storage

LH_2 is stored at the airport to ensure supply security, a three days buffer of LH_2 can be found in previous studies [36,51]. The LH_2 is stored in heat-insulated tanks, which consist of an inner tank and an outer container made from stainless steel [52]. Between those are a vacuum and multilayer insulation made of several layers of aluminium foil alternating with fiberglass mats. The main losses during the storage are the boil-off losses, which decrease relative to the stored quantity with the container volume [53]. The boil-off rates at the airport are assumed 0.06% per day for vessels with a volume of over 20,000 m^3 [53,54].

H_2 transportation

There are several options to transport H_2. For the import of H_2 over longer distances, two alternatives are most prominent for a LH_2-powered end use: GH_2 pipelines or LH_2 vessels. The first make use of either existing pipeline infrastructure or the potential of building new pipelines. If a land routing is not possible or beneficial shipping LH_2 via ships can be another viable transport solution. For short distances the transport with a LH_2 truck is seen as most economic choice [55]. In the LH_2 transport scenarios, boil-off losses and the H_2 transfer losses occur, which lead to a higher energy demand. The energy demand for transporting H_2 is comparably low for the LH_2 transport scenario compared to the total energy demand and only slightly higher when transported with a pipeline due to the compressors as shown in Table 2. The same applies to water requirements. The energy and water demand of the transport make up for under 2% of the total demand with only minor differences in the form of transport.

Since this difference is negligible and to keep the model outcome simple, in the evaluation only the transport with LH_2-Tucks are considered. The raw materials required for the deployment of the H_2 transport infrastructure are difficult to predict and highly dependent on the specific technologies used like electric or H_2-powered trucks for instance, but most likely the largest share will be steel and aluminium. Because of this, in this study the raw material demands for H_2 transportation are not included.

Table 3
Results of the model for the assumed H_2 demands in 2050.

Demand scenarios in 2050	Total synfuel demand in Mt	Total produced H_2 in Mt[1]	Total electrolysis capacity in GW	Energy demand in PWh	Water demand in Mt
H2C forecast for all sectors	n/a	677.88	6,522.27	36.80	6.85
H_2 for aviation high	n/a	133.52	1,284.69	7.25	1.35
Synfuel equivalent high	290.53	178.50	1,717.47	10.26	1.80
H_2 for aviation low	n/a	41.08	395.29	2.23	0.41
Synfuel equivalent low	89.39	54.92	528.45	3.16	0.55

[1] The H_2 produced is calculated from the demands and the H_2 losses along the supply chain.

Table 4
Specific raw material demands for the evaluated electrolysis technologies.

Raw Materials	Specific raw material demand in kg/MW [44,59]
Titanium (PEMWE)	414
Platinum (PEMWE)	0.3
Iridium (PEMWE)	0.7
Nickel (AWE)	1000
Nickel (SOE)	150
Lanthanum (SOE)	20
Yttrium (SOE)	5

Synfuel production

As SAF is currently the only viable cleaner alternative besides H_2 for the larger commercial aviation, H_2-based power-to-liquid (PtL) fuel is considered to compare the resource requirements for H_2-powered aviation. Other SAF like biofuels could be an important part of decarbonisation in the near future but the scalability is limited due to the high space requirements for the production of the biomass feedstock.

For the synfuel, H_2 is also produced with the water electrolysis technologies introduced earlier in this section. The CO_2 necessary for synfuel production is provided by low temperature DAC plants as in a net zero future it is expected that not enough CO_2 is available form point sources. For the DAC mostly steel is used and no raw material limitations are expected [43]. The synfuel is produced by means of a Fischer-Tropsch (FT) process combined with a reverse water gas shift (RWGS) process. In this process, ruthenium can be used as a catalyst, which is assessed as critical by the European Commission [43,56]. When producing SAF with the Fischer-Tropsch process also by-products are produced like naphtha and LPG, which could be sold, but for this study are assumed losses for the energy efficiency. According to Haldor Topsoe and Sasol [57], the share of synfuel production is 78% per kg of produced syncrude. The calculation method and the assumed input parameters are shown in Appendix A and B. The specific energy demands for synfuel production are shown in Table 2.

Table 3 shows the results of the modelled H_2 and synfuel demands for the year 2050 with the LH_2 truck transport path. Based on these, the raw material demands are calculated as discussed at the beginning of this section.

Consideration of the deployment phase of H_2 supply infrastructure for H_2-powered aviation

In this section, the deployment phase of H_2 supply infrastructure for H_2-powered aviation is investigated in two steps. First, the required raw materials are analysed and the demands are compared to the annual production as well as current reserves to identify critical raw materials for H_2-powered aviation. Second, a sensitivity analysis is performed to investigate the influence of the share of electrolysis technologies and reduced specific raw material demands. Finally, substitutes for critical raw materials are discussed and strategies to deal with the limitations are evaluated.

Evaluation of raw material demands for H_2 supply infrastructure

As discussed in Section 2, each individual water electrolysis technology requires different raw materials, which are shown in detail in Table 4.

The relevant raw materials for this evaluation are selected based on supply risk (SR) and economical importance (EI). In addition, future trends are included, which could change the criticality of the raw materials. The raw materials required for the supply of renewable energy are not assessed, as this would exceed the scope of this study. Raw material returns gained through recycling of the electrolyzers are also

Table 5
Overview of the investigated raw materials in this paper.

Raw Material	Country concentration [43,60]	Applications [43]	Current reserves [61–65]	Annual production 2018 [43]	Estimated additional annual demand in 2040[2] [43]	Current EOL-RR [16,66,67]
Titanium	China 30%, South Africa 12%, Australia 10%	Paints and plastics	1,450 Mt	7.46 Mt	0,04 Mt	>50%
Platinum	South Africa 72%, Russia 12%, Zimbabwe 7%	Automotive, chemical industry, jewellery industry, banking sector	33 kt	0.19 kt	0.06 kt	60–70%
Iridium	South Africa 70%, Russia 11%, Zimbabwe 7%	Automotive, chemical industries	1070 t	6.8 t	0 t	20–30%
Nickel	Indonesia 38%, Philippines 12%, Russia 9%	nickel-bearing stainless steel, non-ferrous alloys, surface coatings	95 Mt	2.33 Mt	2.88 Mt	50–68%
Lanthanum	China 69%, Australia 10%, Myanmar 9%	Battery alloys, metal alloys, glass additives	28,550 kt[1]	25.8 kt	38.63 kt	<1%
Yttrium	China 69%, Australia 10%	high resistance ceramics, fluorescent tubes, flat panel displays, glass	500 kt	7.6 kt	1.8 kt	<1%

[1] Reserves calculated with the total rare earth element reserves and the ore composition (23.8 wt-%)[68].
[2] Without electrolysis technologies.

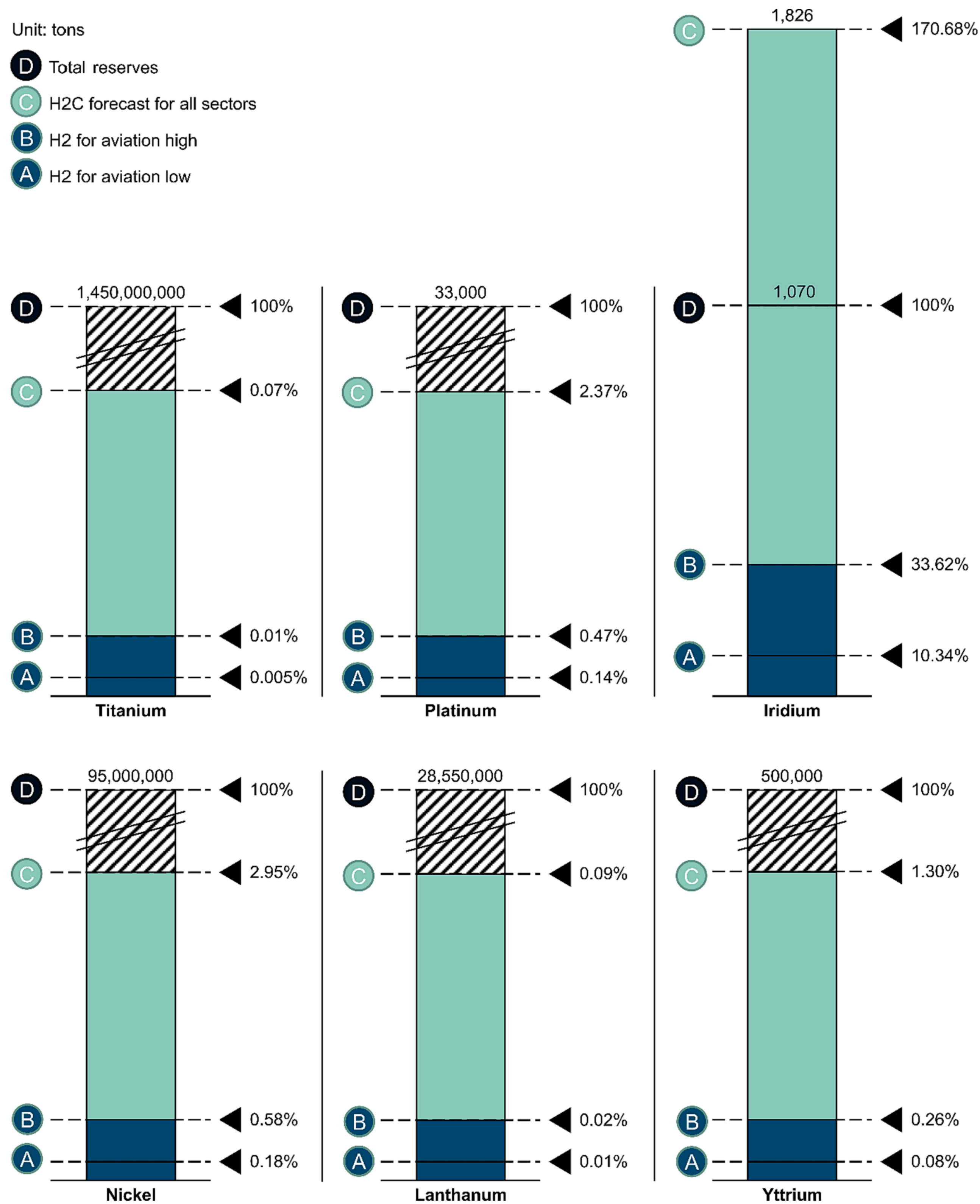

Fig. 2. Total raw material demands for H2 production until 2050 and current raw material reserves.

not considered since the amount of decommissioned electrolysis capacity is expected to be insignificant before 2050 [58].

In the following, the relevant raw materials for the evaluation are identified based on criticality and demand for the electrolysis technologies with the help of the EI and the SR [56]. The EI describes the importance of a raw material for related end-use applications and the performance of its substitutes in these applications. The SR reflects the risk of disruption in the supply of the assessed material. In this value, among others, the supply concentration, import reliance, governance performance and the existence and criticality of substitutes are assessed. The supply concentration, which is the share of the raw materials supplied by a single country, is an important factor for categorizing a raw material as critical. This applies to the share of mining, and the country concentration for the refinery. Based on the SR and EI, the raw materials iridium, platinum, titanium and yttrium are already identified as critical by the European Commission [56]. For this paper additional to the identified critical raw materials, lanthanum and nickel are also assessed. In Table 4, the investigated raw material quantities for H_2 production are shown.

Lanthanum currently has a low EI compared to the other raw materials but a high supply risk mainly due to the high supply concentration with China having a market share of 69% [43]. The EI could increase in the future due to its application in solid-state batteries. For a sustainable scenario, the German Mineral Resources Agency (German: Deutsche Rohstoffagentur = DERA) [43] expects a demand alone for future technologies in 2050 higher than the production in 2018. Nickel currently has a low SR but the demand is expected to rise significantly caused by the ramp-up of electro-mobility. Due to the high specific nickel demand for the AWE shown in Table 4, the demand for water electrolysis could lead to higher supply risk.

In Table 5, an overview of the investigated raw materials is shown with the country concentrations, main applications, current reserves, annual production, forecasted demands for future technologies and current end of life recycling rates (EOL-RR). The reserves are the known concentration of metal that are economically mineable under today's circumstances [59]. As shown in the table, the estimated annual demand for future technologies in 2040 for lanthanum and nickel exceed the annual production in 2018, which is considered critical by the DERA [43]. The low EOL-RR reinforces this, although it should be noted that these could increase in the future, if new recycling processes might have been developed.

Many of the raw materials have a high country concentration leading to a high supply risk. The current annual production is highly dependent on the demand and can adapt to future demands within certain limits. Based on the estimated demands for future technologies including H_2 production and with the development of current applications the annual production has to be adapted.

In the following, for each of the selected raw materials, the demands for the investigated H_2 and equivalent synfuel scenarios are determined as described in Section 2. For the evaluation, the annual and total demands until 2050 are compared with the current annual production and the current reserves.

As there are no reliable forecasts of future reserves and annual raw material productions, the calculated demands are compared to the current reserves and the current annual productions shown in Table 5. Fig. 2 shows the calculated total raw material demands and the share of the current reserves. The required raw materials for the H_2 demands for aviation are marked in blue ("A" and "B"), and in turquoise ("C"), the raw material demands for the H2C H_2 demand forecast for all sectors are shown. The percentages next to the bars indicate the share of the current reserves.

These demands are compared to the current reserves that make 100% of the graph and is labelled with a "D". If the demands ("A", "B", "C") exceed the reserves, then the graph reaches > 100%.

As shown in the figure, the iridium demands for H_2 in all sectors exceeds the current reserves, while the other H_2 demand scenarios still make up for a significant amount of the current iridium reserves. The reserve shares of the other assessed raw materials are significantly lower with shares under 3%. An important factor for the evaluation of the reserve share is the dynamic change of the reserves. The reserves can increase significantly due to economic, technological or regulatory reasons [69]. The consideration of future reserves is not within the scope of this study. Nevertheless, it is important to note that the current reserves are not definitive. As there is limited data on the iridium mining and reserves, the future reserves can only be estimated by comparing to other PGM like platinum of which iridium is a by-product. From 1997 to 2016, the relationship between annual reserve change and production was 0.75:1 [69]. That implies that the platinum reserves increased by 3 tons for every 4 tons mined. If this dynamic would be projected on the iridium reserves, the total iridium demands for the largest scenario "H_2 in all sectors" would account for 75.3% of the reserves in 2050.

Besides the reserves, the calculated demands are also compared to the current annual productions rates. The annual iridium demand for the H_2 demand forecast for all sectors in the year 2050 exceeds the current annual production by more than 11 times. For the high H_2 demand in aviation, the iridium demand in the year 2050 still exceeds the current annual production by more than 3.6 times. The other investigated raw material demands have significantly lower shares with only titanium having a 22.8% and platinum a 17.4% share of the current annual production.

Compared to H_2-powered aviation, the raw material demands for synfuel production with the same electrolysis technology share would be significantly higher with a factor of about 1.34 if the same fleet share would be powered by synfuel instead of H_2. This follows from higher H_2 demand for synfuel production mainly caused by the synfuel yield for aviation of the Fischer-Tropsch process as discussed in Section 2.2. If the SOE were used as the only technology for synfuel production, which could be beneficial due to waste heat recovery, the lanthanum and yttrium demands would increase significantly.

Sensitivity analysis

Because the share of water electrolysis technologies is uncertain and also the specific raw material demands of the electrolysers are expected to go down, in the following, a sensitivity analysis is performed.

There are three scenarios defined for each factor that will be considered now focusing on the used electrolysis technology and the underlying raw material demand per capacity installed.

For the specific raw material demands, the current raw material demands are used as the baseline scenario. The second resource scenario represents a scenario with a reduction of specific raw material demands while the third resource scenario represents an even higher reduction case based on estimates by the IEA [59]. For the technology scenario, there are two technology combinations from the literature and one scenario with a higher PEMWE share, to investigate the influence on the iridium demand, which is identified as the most critical raw material. The modelled scenarios are shown in Table 6 and 7 and are applied to both, the H_2 and synfuel scenarios.

Fig. 3 shows the iridium demand from the sensitivity analysis in comparison to the reserves, as iridium was previously determined as the

Table 6
Specific raw material demands assumed for the sensitivity analysis.

Specific raw material demand in kg/MW [44,59]	Baseline resource scenario	Mean resource scenario	Innovative resource scenario
Titanium (PEMWE)	414	223	32
Platinum (PEMWE)	0.3	0.165	0.03
Iridium (PEMWE)	0.7	0.385	0.07
Nickel (AWE)	1000	900	800
Nickel (SOE)	150	80	10
Lanthanum (SOE)	20	15	10
Yttrium (SOE)	5	3.75	2.5

Table 7
Electrolysis technology share assumed for the sensitivity analysis.

Electrolysis technology share in 2050	High PEMWE share	Mean PEMWE share (IndWEDe)[1] [44]	Low PEMWE share (DERA)[1] [43]
PEMWE	60%	40%	10%
AWE	20%	40%	85%
SOE	20%	20%	5%

[1] The technology shares from these studies are projected to the rest of the world.

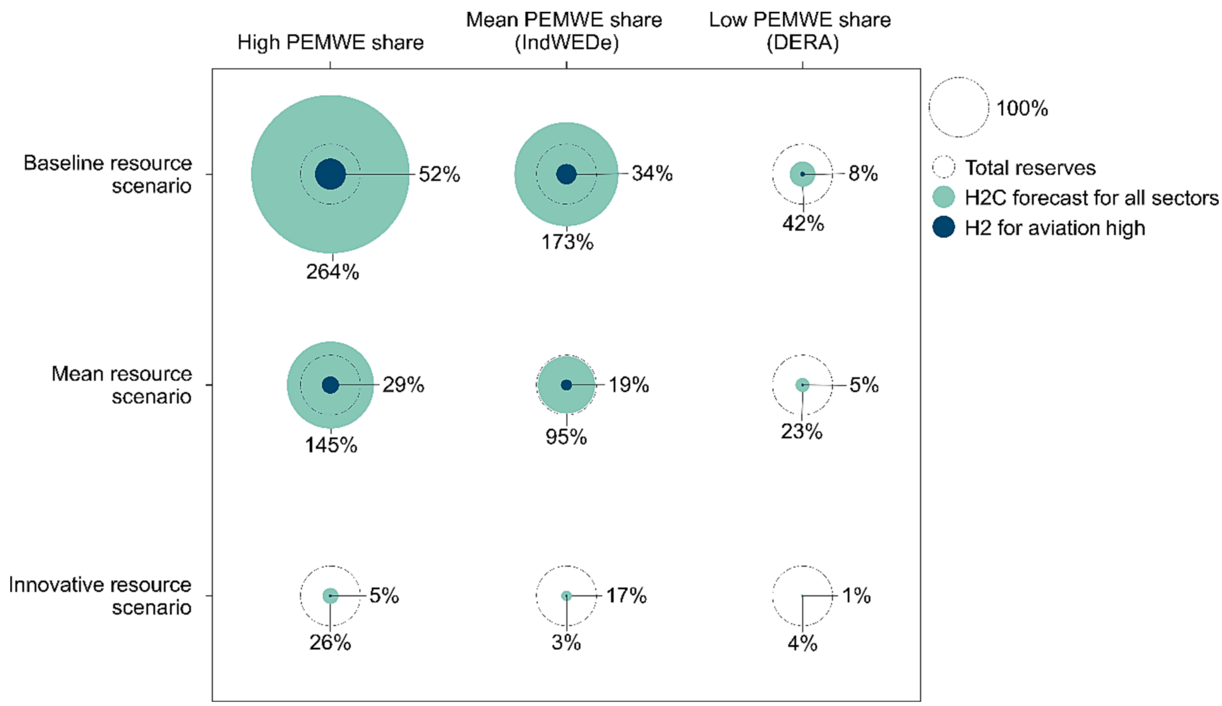

Fig. 3. Iridium demand depending on the different scenarios compared to the current reserves.

most critical raw material for larger H_2 demands. The dotted circle indicates the current iridium reserves, while the blue circles represent the high H_2 for aviation scenarios share of the reserve and the turquoise circle the H2C forecast for all sectors. As shown in the figure, the iridium demand for H_2 production for all sectors exceeds the current reserves in three scenario combinations. In the high PEMWE share scenario, the iridium demands are exceeding the reserves even in the mean resource scenario. The annual iridium demand for H2C forecast for all sectors in 2050 exceeds in all scenarios the current annual production except for the low PEMWE share and innovative resource scenario. When the specific iridium demand of the PEMWE or the share of used PEMWE is lowered, the share of the reserve is lowered significantly.

In the worst-case (high PEMWE share and baseline resource scenario), the annual iridium demand is more than 17 times higher than the current production (the annual production is not illustrated but shown in Table 5). For the other investigated raw materials, the share of the current reserves is comparatively low with shares of under 4% in the worst case.

When the change of reserves according to Rasmussen et al. [69] is assumed to be 0.75:1, for the worst case in Fig. 3, the share of total iridium reserves for all sectors would be significantly decreased to 88.6%.

The iridium demand for H_2-powered aviation on its own is not critical as shown in blue in Fig. 3, but could still be affected by the limited reserves. In addition, the annual production needs to be scaled up to meet the demands for H_2 production. When the specific iridium demand is lowered according to [59], the H_2 production with a high PEMWE share is viable.

For the other raw materials, the sensitivity analysis showed only low shares of the current reserves, with only nickel standing out as with lowered PEMWE share the AWE share rises which causes a higher nickel demand. So, in the highest demand scenario for nickel (low PEMWE share and baseline resource scenario), the total nickel demand is around 5.8% of the current reserves with only minor changes in the resource scenarios.

Substitutes for critical raw materials and dealing with the limitations

As the iridium demand for H_2 supply has been identified as critical, two obvious strategies for dealing with the possible limitations are evaluated.

The first strategy to deal with the limited iridium reserves is to lower the PEMWE share in the technology mix. This would lead to a higher nickel demand caused by a higher AWE share. As the nickel demand is expected to rise due to the ramp-up of electric mobility, this could also become a critical issue looking at overarching decarbonization efforts. As the PEMWE is advantageous when used in combination with RES, a high share is still seen favourable.

Consequently, a second strategy would be to lower the specific iridium demands or develop PGM-free electrolyzers. Especially for PEMWE, there is a lot of research to decrease the PGM demand with new manufacturing techniques like sequential electrodeposition [20]. In the field of PGM-free catalysts, progress has also been made. Moschkowitsch et al. [70] state that it is only a matter of time until new materials will be competitive for large-scale electrolyzers. Although new materials may enable water electrolysis to be completely free of critical raw materials, this is expected to be a lengthier process [71].

To realize the high demands for H_2 in the near future, the reduction of critical raw material loadings is crucial to achieving the targeted share of PEMWE. If a significant reduction or even a substitution of iridium in addition to the assumed reduction of the other raw materials can be accomplished, all investigated technology share scenarios are achievable regarding the raw material supply.

Consideration of the operational phase of H_2 supply for H_2-powered aviation

In this section, the resource requirements for the operational phase of the H_2 supply for H_2-powered aviation are investigated. For the evaluation, the availability of renewable energy sources (RES) and the water are assessed from a global perspective and for selected airports.

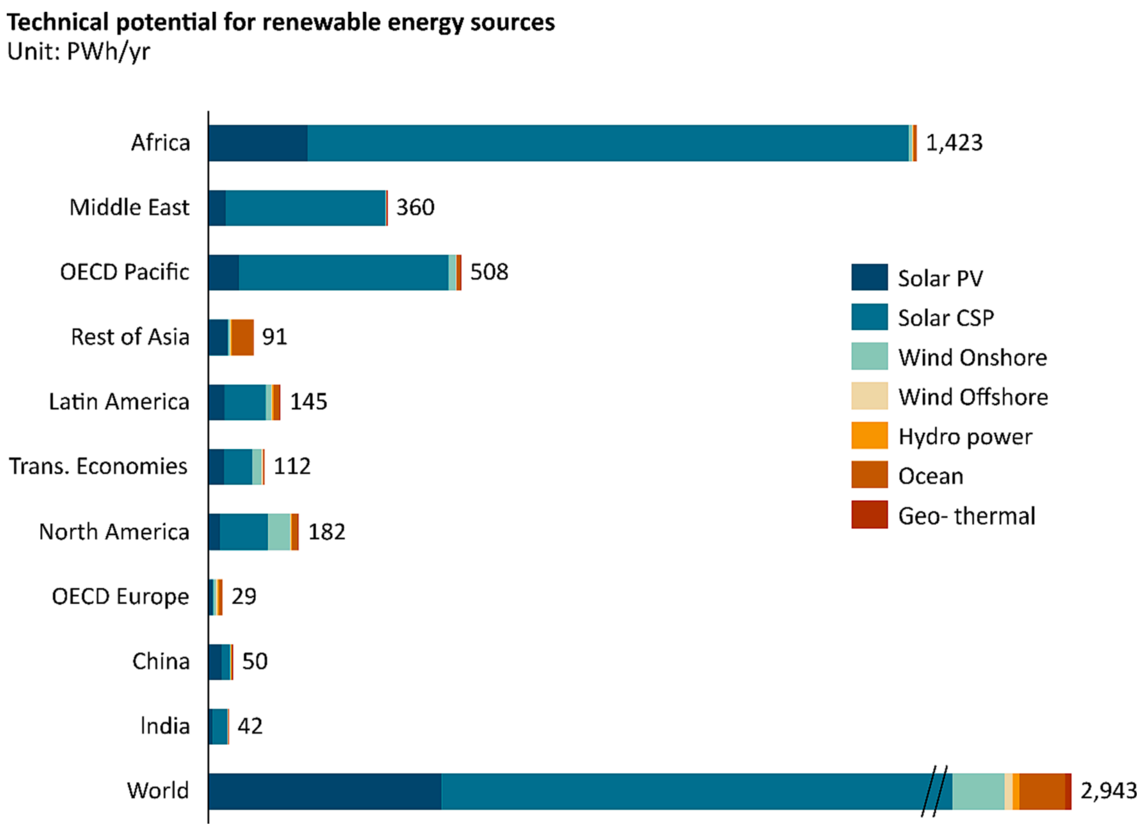

Fig. 4. Technical potential of RES divided into regions [23].

Evaluation of a global perspective

First, the availability of RES is assessed and compared to the expected energy demands. In 2020, the share of renewable energy in electricity generation worldwide accounted for 29% [72]. Including hydropower, the global renewable energy capacity was 2,838 GW. However, a forecast by Teske et al. shows that in a 1.5-degree future, a renewable energy capacity of 25,723 GW is needed in 2050 [73]. In such decarbonization scenarios, not only the electricity supply sector has to be powered by renewable energy as it only accounts for 30% of the global CO_2 emissions, but also other carbon-intensive sectors like the transport and heat sector [74].

The technical potential for RES is difficult to determine as it depends on many different factors besides natural conditions, for instance, land availability. The largest share of all the different RES for electricity generation is expected for wind and solar photovoltaic (PV) power, since capacity additions for hydropower is very limited [74]. In 2050, wind and solar PV power are expected to supply 63% of the total electricity needs [75]. The most relevant natural conditions for wind and PV power are solar irradiation and wind speed. The solar irradiation can be measured with the physical variable of global horizontal irradiation (GHI), which is the amount of direct and diffuse irradiation components that reach a horizontal surface [76]. For the practical solar PV potential, more factors have to be considered such as air temperature, terrain horizon, albedo and others that affect the system performance. The GHI is mainly determined by geographic latitude but also by the abundance of clouds, atmospheric aerosol concentration and moisture content [76]. The highest theoretical potential for PV power is located in the north and south of Africa, the Arabian Peninsula, Australia, Mexico and Chile. Around the equator, the potential is lower due to the frequent occurrence of clouds. In regions with lower temperatures, the potential is reduced due to a lower sun angle as well as a higher concentration of aerosols [76]. As for solar PV power, the technical wind power potential is depending on many different factors besides the mean power density such as land availability, distance regulations or slope inclination. The mean power density can be used to assess the wind energy potential in a region, as it not only includes wind speed but also the wind directions and atmospheric pressure. A low wind power density occurs around the equator and a higher power density around the poles. Also, the wind power density is higher at offshore sites [29].

Based on these factors, the potential for RES is determined. Fig. 4 shows the technical potential for RES based on an analysis from the German Environment Agency (Umweltbundesamt) [23], which estimates the global technical potential in 2050 at 2,942 PWh per year. Compared to other studies, this estimate is in the middle with the lowest estimate being 589 PWh per year and the highest up to 7,803 PWh per year [23]. The total world's primary energy demand in 2015 was about 154 PWh per year [73], which according to the IRENA [75], could rise to around 220 PWh per year in 2050. By just comparing the expected primary energy consumption to the technical renewable energy potential, even with the highest demand and the lowest estimates for the technical potential, the technical potential for renewable energies is more than twice as high.

As shown in Fig. 4, the largest potential of RES is located in Africa and consists mostly of PV power while Europe has a comparably low potential. When compared to the primary energy consumption, Africa has only one-third of the EU's demand but almost 50 times higher technical potential of RES [77]. This highlights the importance of evaluating the availability of renewable energy from a regional perspective.

In the following, the calculated energy requirements for the different H_2 and equivalent synfuel demands are compared to the technical potential of RES.

Fig. 5 shows the calculated energy and water demand for the different H_2 demand scenarios. The energy demand for the high H_2 demand in aviation with the baseline scenario calculates to 7.2 PWh,

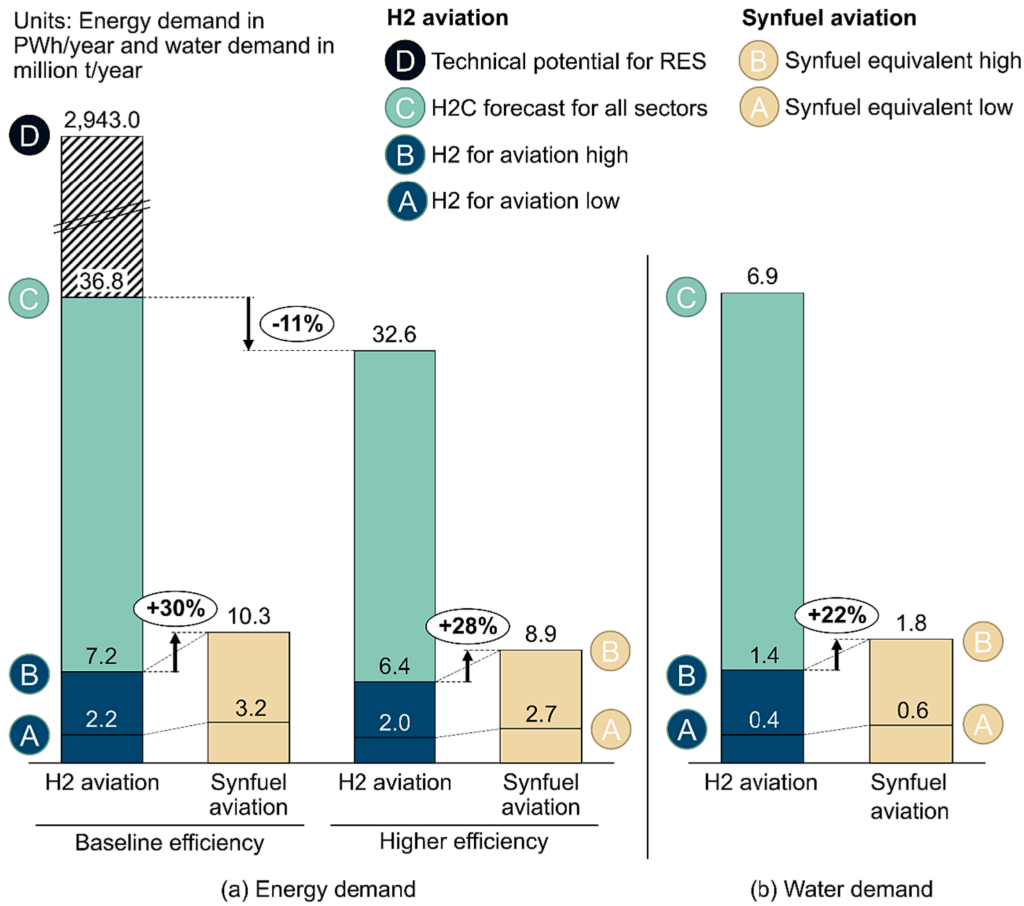

Fig. 5. Total annual energy (a) and water (b) demand for H2 and synfuel supply in 2050.

which makes up for 0.24% of the estimated global technical potential for RES. The energy demand corresponds to 4.2% of the current global energy demand [73] and to about 96.7% of the current renewable energy production including hydro power [78]. For comparison, the global kerosene demand in 2050 is estimated to 6.67 PWh [79]. While the energy demand seems feasible compared to the technical potential for RES, it still makes up for a large share of the current energy demand, which in a net-zero scenario needs to be supplied mostly by renewable energies in 2050. If the same aircraft fleet share as in the high H_2 for aviation scenario were to be powered by H_2-based synfuel, the energy demand would be 1.4 times higher. In the H_2 demand forecast for all sectors, the energy demand makes up for 1.3% of the technical potential.

When the efficiency of the electrolysis technologies increases as shown in Table B.1, the total energy demand is reduced by 11% as shown as "higher efficiency"-scenario in Fig. 5. The energy demand for synfuel production is reduced by almost 14% caused due to the higher electrolysis and DAC efficiency.

As the other main resource for the operational phase of H_2-powered aviation, the global water availability is assessed as well. Fig. 5 compares the modelled water demand for H_2 production to the current freshwater use, to evaluate the influence of H_2-powered aviation on the water demand.

The water stress, shown in Fig. 6(a), is particularly relevant for the implementation of H_2-powered aviation with H_2 produced by water electrolysis. The water availability is investigated based on the current water stress and the expected future change.

The water stress indicator, given in Fig. 6(a), compares water withdrawals with available renewable surface and groundwater resources. Water withdrawals in this case include consumptive and non-consumptive uses by households, industry, irrigation, and livestock. High water stress leads to environmental problems and can hinder the economic development of a country or region. Also, countries and regions with a water stress level above 40% are vulnerable to fluctuations such as droughts or increased water withdrawals [80]. As shown in Fig. 6(a), high and extremely high water stress occurs especially in regions with high population density. The global water stress level in 2019 was about 19%, which indicates that 19% of the world's renewable water is withdrawn after accounting for environmental flow requirements [81]. Currently, 2.3 billion people live in water-stressed countries of which 733 million live in countries with extremely high water stress [82].

Even if the water stress at a country level is low or low to medium, locally it can be high or even extremely high mostly in metropolitan regions. Future trends in water stress are subject to many uncertainties. In 60–75% of river basins, water stress is estimated to increase by 2050, while in a small part it will decrease or remain constant. Increasing water stress is mainly related to higher water withdrawals with the most important factor being the increase in household water use followed by increasing industrial and agricultural water use. Although population growth is an important factor, rising income has a higher impact on per capita household water use [27].

Fig. 6(b) shows the change of global water stress in 2040. When comparing the current water stress in Fig. 6(a) to the change of water stress, in many regions currently affected by high or extremely high water stress the level is expected to increase. The global Alliance Powerfuels states, that the water electrolysis should not increase the risk of declining water levels or negatively affect the existing water supply and therefore should not be installed in regions with "high" or "extremely high" water stress [38].

Again, the results of the demand modeling are compared to the

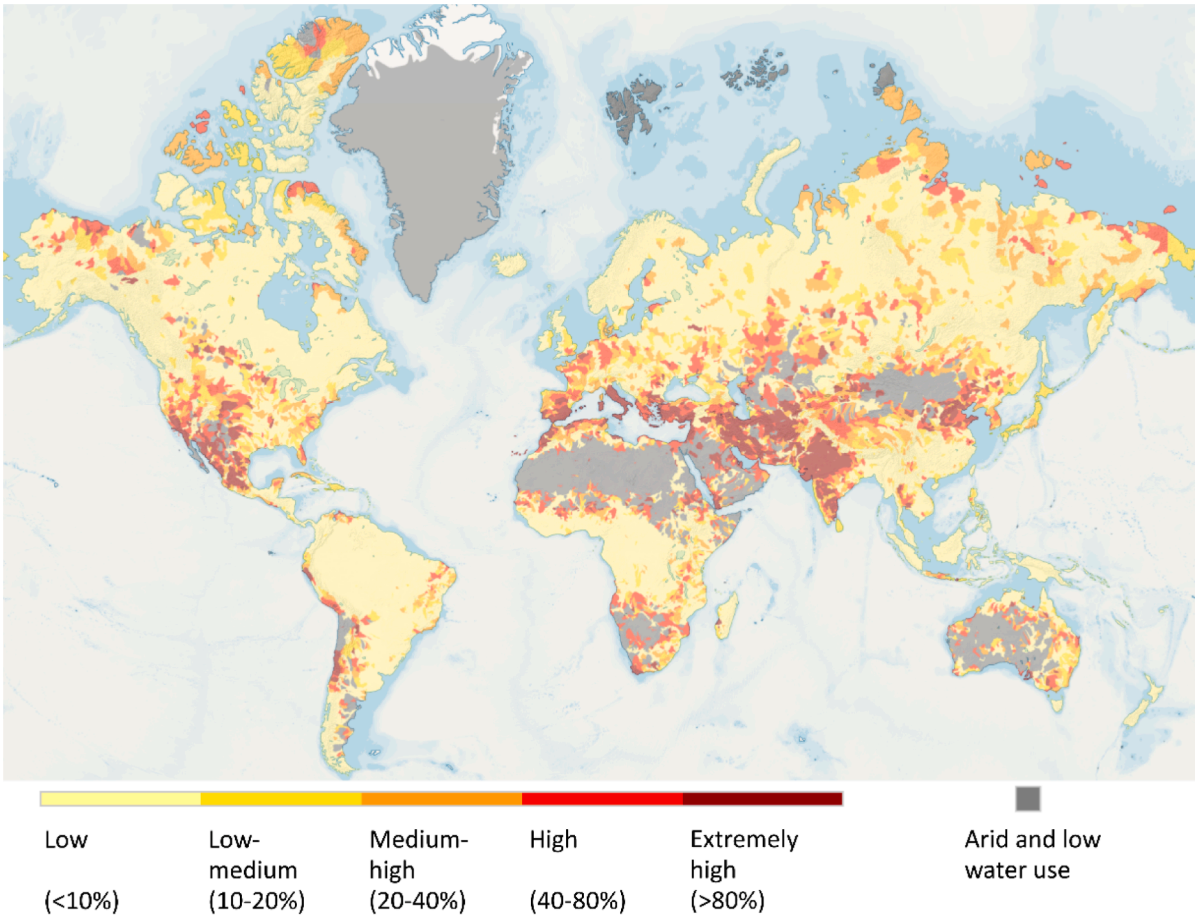

Fig. 6. Global water stress in 2019 in (a) and estimated change of global water stress 2040 in (b) [26].

current water use, to determine the influence of H_2 production for aviation. As shown in Fig. 5, in the high H_2 demand scenario for aviation, 1.4 billion m^3 of water are necessary in 2050. This would account for 0.04% of the global freshwater used in 2014, which was 3990 billion m^3. The water demand for the equivalent synfuel production is about 17.6% higher caused by a higher H_2 demand and water demand for the Fischer-Tropsch process.

Compared to the availabilities, water demand of H_2-powered aviation could be supplied by freshwater from a global perspective.

The sensitivity analysis carried out for the raw material evaluation has only minimal influence on the water demand, which is why it is not included for the evaluation of water availability. As H_2 production is dependent on the availability of RES in the region, the water stress has to be evaluated in combination with the availability of RES. As shown in Fig. 4 and Fig. 6, the regional availability of RES and freshwater varies significantly, which is why the conditions for H_2 production have to be evaluated individually from a regional perspective.

Evaluation of a regional perspective: selected airports

Finally, the implementation of H_2-powered aviation at selected airports is evaluated to derive general insights into the regional perspective. The water stress at the airports and the conditions for RES in the airport's countries are assessed to evaluate the potential for local H_2 production. The selection of airports was made to assess different airport scenarios, where these are located in areas with varying potential for RES, varying freshwater availability and distance to the sea.

First, the water stress and the distance to the sea of the selected airports are investigated.

The water availability for H_2 production with water electrolysis is highly dependent on the region. Even if the overall water stress in a country is at a low to medium level like for instance in the UK, the local water stress in the region around London is high. For over 600 large airports, the water stress has been evaluated based on the Aqueduct's water stress data [26]. Therefore, all airports with over a million passengers per year from scheduled commercial flights have been assessed. Due to a lack of data regarding the other considered conditions at the airport, the evaluation of these airports was limited to assessing only water stress. Of the assessed airports, 31.4% are located in regions with high or extremely high water stress. Of the biggest 30 airports ranked by passengers per year, 36.7% are located in regions with a high or extremely high water stress level (>40%).

The water stress in the regions of the selected airports is shown in Table 8. Five of the investigated regions have high or extremely high water stress. As discussed by Khan et al. [42] seawater desalination is a viable option for water electrolysis in regions with detrimental availability of freshwater. More than half of the largest 30 airports that are in water stressed regions are located 100 km or farther away from the sea,

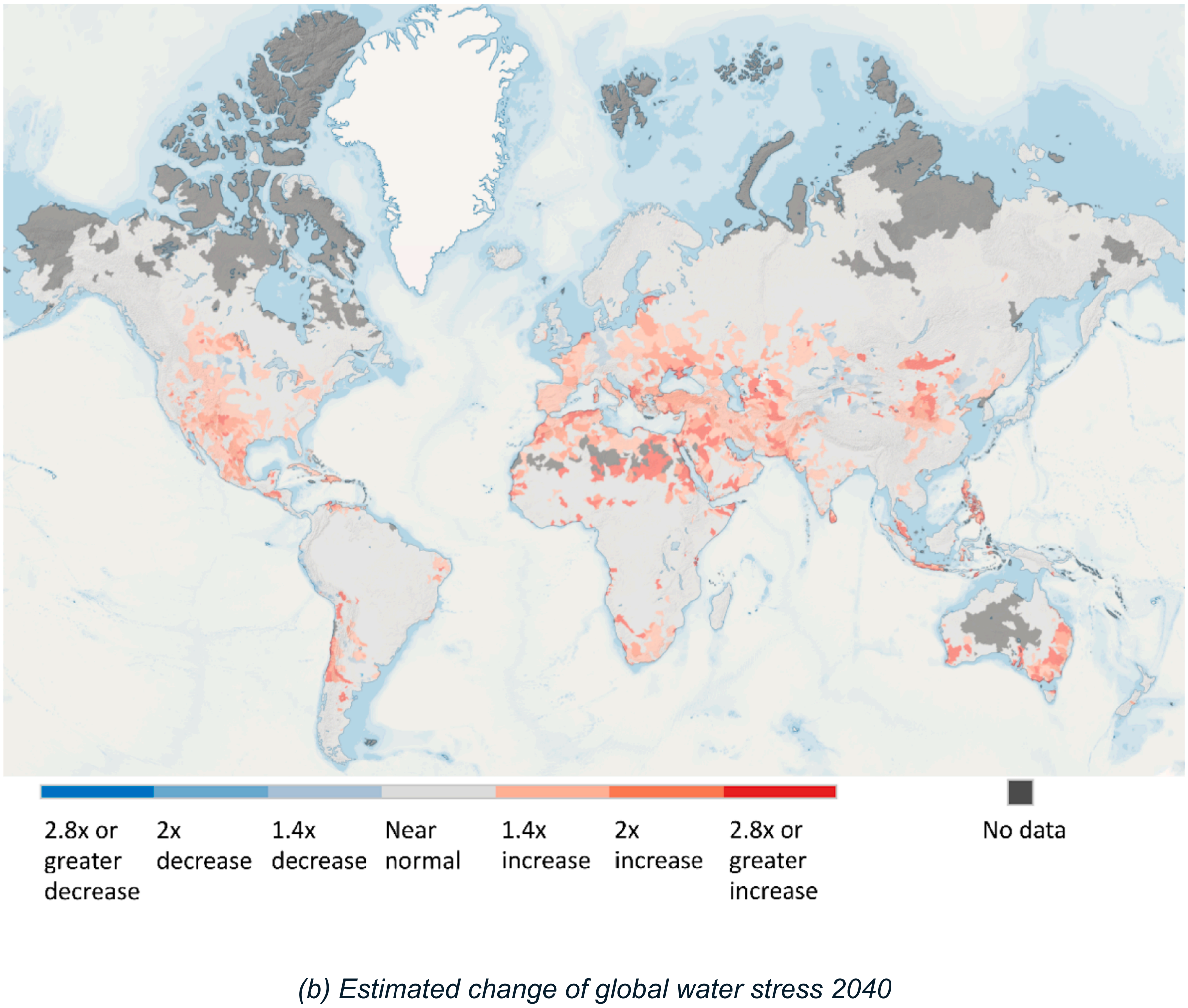

Fig. 6. (*continued*).

Table 8
Overview of the conditions for water and RES at the selected airports and energy and water demand for H_2 in 2050.

Airport (IATA airport code)	Water stress at the airport [26]	Distance to seawater	Local water demand for onsite H_2 production in kt[1]	ETI score [84]	Local energy demand for onsite H_2 production in TWh/yr[1]
Chengdu/China (CTU)	Low (<10%)	1069 km	3.86	57	20.90
Delhi/India (DEL)	Extremely High (>80%)	930 km	4.47	53	24.21
Denver/USA (DEN)	Extremely High (>80%)	1232 km	6.48	67	35.06
London/UK (LHR)	High (40–80%)	62 km	4.42	72	23.93
Los Angeles/USA (LAX)	Extremely High (>80%)	3 km	10.02	67	54.26
Madrid/Spain (MAD)	Extremely High (>80%)	300 km	4.01	68	21.69
Santiago/Chile (SCL)	Extremely High (>80%)	75 km	2.01	65	10.86
Tokyo/Japan (HND)	Medium - High (20–40%)	0.25 km	2.27	64	12.27

[1] Calculated with high H_2 demands based on Hoelzen et al.[36].

so even if seawater is used and desalinated, the water would have to be transported to the H_2 production site.

In addition, the conditions for RES in the airports countries are investigated.

Since there is no detailed and comparable data available to evaluate the renewable energy potential at the airport's surrounding regions, the countries Energy Transition Index (ETI) score based on Singh et al. [83,84] is used. The ETI score rates countries based on their energy systems performance and readiness for transition to a secure, sustainable, affordable and reliable energy future.

The ETI score ranges from 0 to 100 with Sweden scoring highest with 79 and Zimbabwe scoring lowest with 39. The global average ETI score is 59, so most of the selected airports shown in Table 8 are in countries scoring higher than average. The table also shows the calculated energy and water demand based on the estimated H_2 demand of the airports in 2050.

Fig. 7 shows a clustering of the selected airports based on their water availability and ETI score from Table 8. As shown in the figure, none of the selected airports has ideal conditions (i.e. high water availability and good conditions for RES – upper right area of the graph) for local H_2

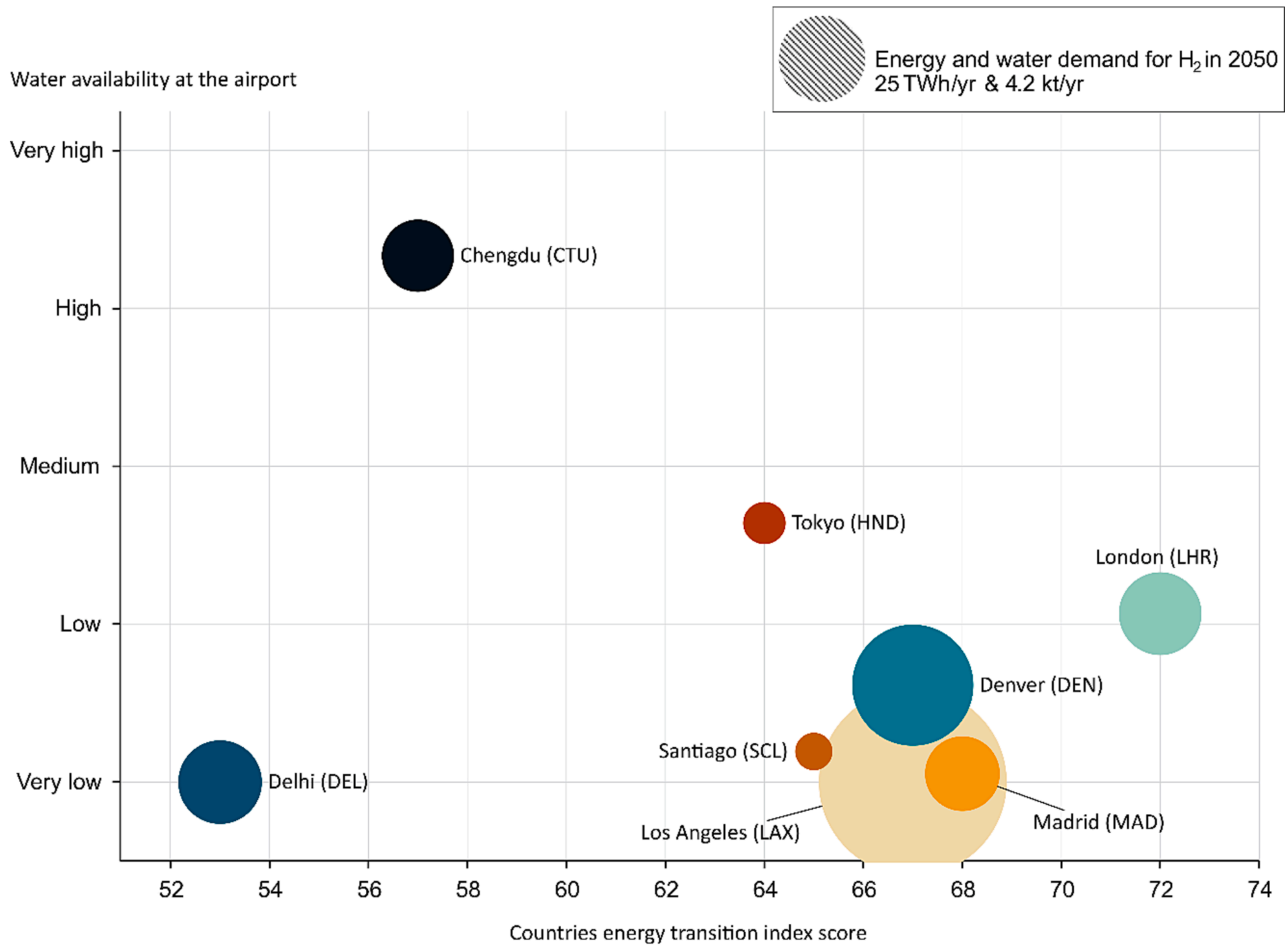

Fig. 7. Clustering of selected airports based on water availability at the airport and countries ETI score.

production at the airport. Airports with low water availability and high ETI score which are located close to the sea like LAX and SCL could use desalinated seawater for local H_2 productions. For airports located in regions with detrimental conditions for RES like CTU and DEL, the import of H_2 from more suitable regions is a viable alternative.

This matrix only provides a general overview of the situation at the investigated airports and no statements can be made about the feasibility of local green H_2 production for the individual airports. Even if the country's renewable energy availability is rated low, it could be entirely possible to produce the required H_2 with RES at the airport. The matrix should help as a methodology for the assessment of industrial policy strategies.

The synfuel production will most likely not be located directly at the airport as high production volumes and economies of scale are required to be economically. In addition, the existing international fuel supply chain could be used for transport [85]. Therefore, production is expected to take place at locations with very good conditions for RES, which are also discussed in the following section.

Regions where a high H_2 import reliance is likely

Based on previous considerations, regions with a high import reliance for H_2 aviation are identified and compared to the country's conditions for RES.

Fig. 8 shows a world map with the suitability for aviation-dedicated H_2 production in each country. Unlike in the previous section, the potential for RES is not shown with the ETI, but with the natural conditions based on the global horizontal irradiation (GHI) and mean wind power density [28,29]. This sets focus on the country's potential for H_2 production without considering circumstances like the county's political agenda or GDP. Since the map only shows the natural conditions and does not include the land availability and other factors that influence the potential for RES, it displays only a general overview of the country's suitability for green H_2 production for aviation. Countries with more than 900.000 annual commercial flights correspond to the label "high H_2 demand in aviation".

The countries are categorized qualitatively into four groups. The first group (marked orange in Fig. 8 represents countries with standard conditions for RES and a high amount of flights corresponding to a potentially high H_2 demand for aviation. These countries are likely to import H_2 from regions with better conditions for RES. The second group (beige) of countries has standard conditions for RES and also a low H_2 demand for aviation. These countries could be self-sufficient or could also import the required H_2. The third group (turquoise) has good conditions for RES and is therefore suitable for producing H_2. This group has also a low H_2 demand for aviation, so an export of H_2 to other demanding countries might be possible. The last group (blue) has in addition to good conditions for RES a high H_2 demand in aviation so the countries could be self-sufficient or even export H_2, too. All evaluated countries are shown in Fig. 8 under consideration of countries affected by high water stress marked accordingly.

As it can be seen, from all countries where the main aviation market takes place, only the USA and Spain are labelled as possible self-sufficient with Spain affected by high water stress. These results are only a first indication, which of course has to be evaluated in detail for each country or even location. In large countries like Canada for

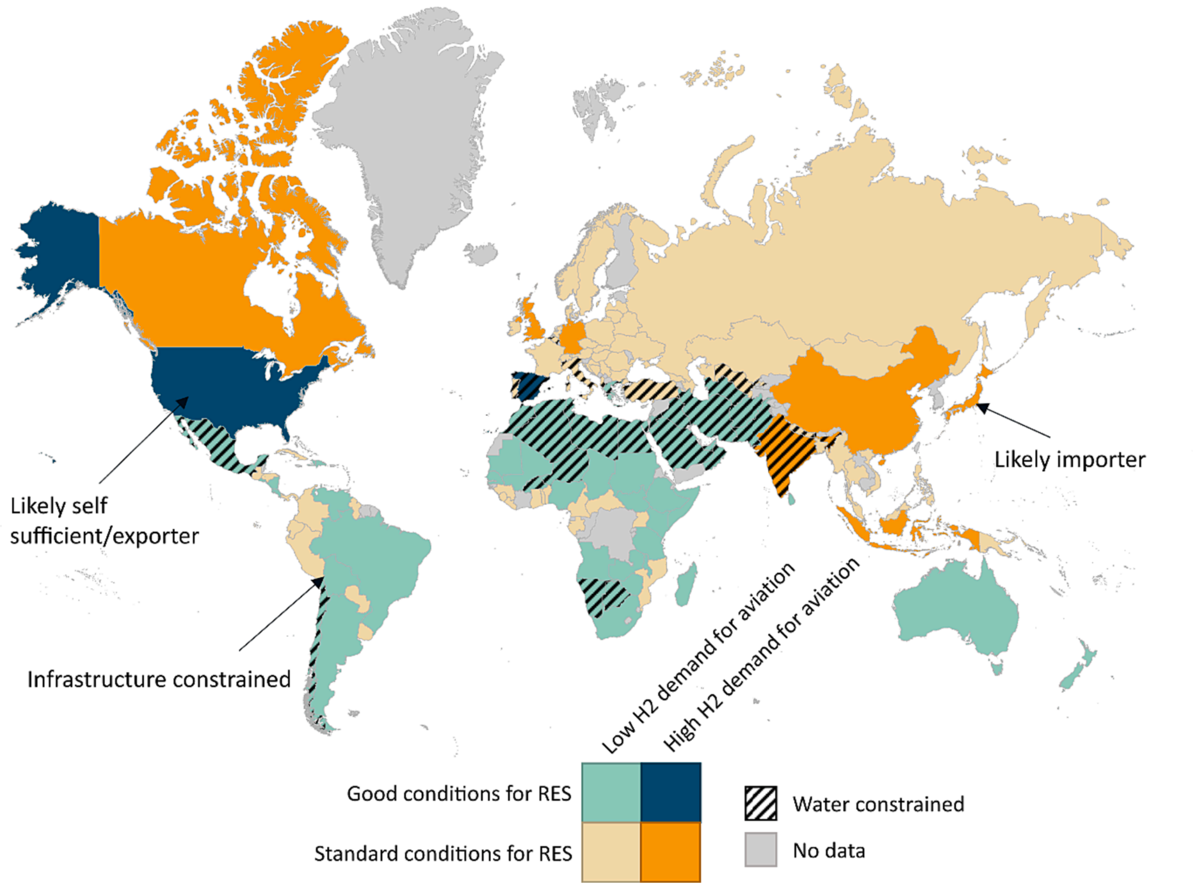

Fig. 8. Global natural conditions for RES, H2 demand for aviation and highlighted water-stressed countries.

example, the conditions for RES vary highly throughout the country leading to standard conditions in this study, while in reality there might be enough potential to even export H_2. The map also highlights the importance of strategies for low water availability, as many countries with good natural conditions are exposed to high or extremely high water stress. In India, for instance, the International Renewable Energy Agency (IRENA) estimates that in 2050 less than 5% of the H_2 demand could be produced domestically when including water availability [34]. In addition, some of the possible export countries like Bolivia for instance could be constrained by the status of its existing infrastructure [33].

As stated before, for synfuel transport, the existing fuel supply infrastructure could be used [85]. For synfuel, it is most likely that the production will take place in regions where it is most cost efficient, which are regions with a high potential for RES shown in Fig. 8.

It has to be noted that this study does not include an economic evaluation of H_2 production. Therefore, even if the potential for renewable energies in some regions like the USA or Spain would allow domestic H_2 production, it might be more economical to import from other regions.

Dealing with the limitations

In this section, strategies for regions with low potential for RES and high water stress are discussed.

In the case of green H_2 production by means of water electrolysis, there is no sustainable and CO_2-neutral substitution for RES to power the electrolysis. For regions with low available RES, either the transmission of renewable energy via a grid or the import of H_2 are a possibility to meet the H_2 demand for aviation and other sectors. As power transmission makes up for a large amount of investment costs, it is only an option for limited distances [86]. Wang et al. [87] compared the cost of electricity transmission infrastructure to that of H_2 pipeline infrastructure over various distances. According to their analysis, the transport of H_2 with a pipeline is the most cost-effective for the investigated distances up to 2,500 km, regardless of the type of electric transmission or pipeline used. Because of this, for regions with detrimental natural conditions and large distances to regions with high renewable energy potential, the import of H_2 might be the most viable option to supply H_2-powered aviation. For the international or intercontinental import of H_2, transport by ship is more economic than pipelines for distances over 4,000 km [87]. Even though the shipping conditions of H_2 when converted into NH_3 might be more advantageous and less costly compared to L H_2, when H_2 is required to be in a liquid state for the end-use, LH_2 shipping is a more economic choice [35,86,87]. According to the Hydrogen Council [88], imported LH_2 from Latin American countries could be less costly than domestic production in the United States. The main reason for the lower costs is the achievable load factor for the electrolyzers [88]. The full load hours for the electrolysis and related RES determine the load factor. For example, Chile has the highest load factors for solar PV in the world and high load factors for wind, which could decrease H2 production costs significantly [89].

Oceania, Africa, the Middle East and Latin America are likely to be the main H_2 export regions, where already 28 export projects have been announced [66]. The Fraunhofer Institute for Energy Economics and Energy System Technology (Fraunhofer IEE) has calculated the potential for producing and exporting H_2 in different countries outside of Europe [31]. In the analysis, besides the natural conditions, also land availability, water stress, political conditions and other factors have been included. In South America, especially Chile and Argentina have a high potential to be major H_2 export countries. According to the Fraunhofer IEE analysis, the two countries could produce more than 460 million tons of LH_2 per year, which is almost 70% of the Hydrogen Council's forecasted global H_2 demand in 2050 [37] and could supply the high H_2 demand for aviation assumed in this study's model. Also in Oceania, Australia and New Zealand have a high export potential, which is especially relevant for countries in Asia like Japan because of the expected high H_2 import demand [33].

In contrast to RES, for the water supply, there are several strategies for regions with low availability. In the following, four strategies for substituting conventional freshwater supply are discussed. First and as also implemented in the model, seawater desalination represents a good option for water supply in water stressed regions close to the sea. The seawater reverse osmosis (SWRO) requires less than 0.1% of the energy demand for H_2 production with water electrolysis. Also, the cost makes up for about 0.6% of the levelized H_2 costs [42]. With the water demand for electrolysis assumed in the model, the SWRO makes up for about 0.008 USD/kg H_2.

Second, another method of using seawater is the direct electrolysis of low-grade and saline water [38]. In contrast to the SWRO, direct seawater electrolysis is at an early stage of development [90]. A major challenge in the development is the design of selective catalysts for the oxygen evolution reaction to reach stable and industrial relevant current densities. Furthermore, bacteria, microbes and small particles limit the long-term stability of the catalysts and membranes. Due to these challenges, direct seawater electrolysis is still far away from commercialization. [42].

Third and for regions with low availability of freshwater supply and large distances to the sea, water could be transported from regions with low water stress or desalinated from the coast. There is only little information about the transport costs of water available in the literature. The costs are highly dependent on the elevation that has to be overcome and also on the way of transport, as transportation by pipeline would almost triple the water costs [91]. Also, the specific transportation costs rise with lower demands of water to be transported. Zhou et al. [91] found the cost of transporting 100 million m^3 of water per year to New Delhi, whose airport was investigated earlier in this section, would cost 0.9 USD/m^3. That would account for a cost increase of 0.01 USD per produced kg of LH_2, which is 1.5 times the cost of desalination. For the airport in New Delhi in the modelled ambitious scenario, 5 million m^3 of water would be necessary every year for H_2 production. That would increase the cost if the water would be only transported for H_2 production and no synergies with other high water demanding sectors are used to increase the total amount of transported water. As the water demand for most single airports is comparatively low, the costs for water transport could make up for a significant share of the overall H_2 costs – hence, might not be a preferable option.

Forth, another option for the water supply in regions with limited access to freshwater could be water from direct air capture (DAC). With a low-temperature DAC based on alkaline solid sorbents, about 1 kg of water is extracted per kg of CO_2 captured [38]. As water is collected as a by-product low additional costs result from the utilization of the collected water. Since the DAC process is associated with high costs, it is not expected to be deployed for water supply but the water from installed DAC plants for other uses like the discussed use of synfuel or even high-quality compensation could be utilized for H_2 production. It is also possible to win water directly out of the air with a hygroscopic electrolyte although the technology is not yet mature [92].

Conclusion and outlook

Focus of the present study was the analysis of resource limitations for the implementation of H_2-powered aviation on a global scale.

For this purpose, the resource requirements for H_2 and synfuel production were calculated based on selected demand scenarios and compared to the resource availabilities from a global and regional perspective.

Our analysis of the deployment phase identifies iridium used as catalyst for PEMWE to be possibly a critical raw material for a global H_2 supply of all sectors if a high PEMWE share is assumed and the specific raw material loading is not reduced. For iridium, both the annual production and the current reserves might be exceeded.

Based on the estimated demand for other future technologies also the annual lanthanum and nickel demand for H_2 production could be critical if the annual raw material production cannot be increased. Aviation's share in this global H_2 supply picture is about a maximum of 20% in a high-demand scenario and even higher for the equivalent synfuel production, which could enhance the raw material limitations.

The development of PGM-free catalysts could solve the resource conflicts for the PEMWE, although it is not expected to reach industrial relevance soon. To meet future demands, efficient recycling infrastructure and increased iridium production are essential. If significantly lower raw material loadings for the electrolyzers are achieved and the annual raw material production can be increased, besides a possible supply dependency no further limitations are identified for installing the required electrolysis capacity from the raw material perspective.

For the renewable energy required in the operational phase, no conflicts have been found on a global level. Aviation's share of the estimated technical renewable energy potential by the German Environment Agency in 2050 is about 0.24% at a high H_2 demand scenario. For water demand, also no conflicts have been found from a global perspective, as H_2-powered aviation in 2050 could be accountable for 0.04% of the current global freshwater used.

Additionally, the evaluation of regional cases provides a general overview of H2 supply at airports. It was found that conditions for RES and freshwater supply vary significantly. High H2 demand at certain airports could conflict with other sectors due to limited RES and freshwater availability. Of over 600 large airports, 31.4% face high water stress, making conventional freshwater supply unsuitable. In such cases, importing H2 becomes the most sensible option (e.g., Indira Gandhi International Airport in Delhi). Alternatively, H2 production in the airport's region is possible when water is available from alternative sources (e.g., Madrid airport). Desalination is a viable alternative for regions with water scarcity near the sea.

The resource requirements for synfuel production are even higher compared to H_2-powered aviation due to high H_2 and energy demands. As the existing fuel transport infrastructure could be used, the regional varying resource limitations are not as crucial as for the H_2-powered aviation, but nonetheless high amounts of RES, water and raw materials are required. An import of synfuel from a few large production sites could also entail a high supply dependency.

Besides the findings of this study, also the limitations of the work are reflected and future research opportunities are discussed. As there is no reliable data available for the forecasted annual production of raw materials, the modelled demands are compared to the current mining capacities and reserves. However, future raw material productions are uncertain and potential conflicts between countries, or new extraction methods could significantly alter production levels. A more detailed evaluation of future production and reserves needs to be provided to better anticipate possible conflicts regarding the raw material demands. Additionally, considering the technical potential for RES depends on various factors, requiring more data for an in-depth evaluation of available potential at airports.

A unified evaluation method for the airport regions needs to be developed, to investigate the local H_2 production potential or the need to implement a supply chain for H_2 import. Besides the resource requirements, also the levelized costs of H_2 need to be evaluated to identify economical H_2 production locations with sufficient availability of RES and water. For the installation of water electrolysis plants, regulations should be implemented to ensure that H_2 production does not exacerbate local water stress.

Overall, potential resource conflicts have been determined and the importance of an individual analysis for every airport has been highlighted. For the decarbonization of the aviation sector, airports need to be evaluated for the suitability of local H_2 production, so that possible conflicts can be identified and H_2 transport routes can be developed. The ambitious scenarios and strategies need to be translated into concrete measures to enable the introduction of H_2-powered aviation. Green H_2 production needs to be scaled up and transport routes have to be implemented to lower the cost of H_2 and enable competitiveness with conventional jet fuels. Although synfuel has many benefits when handling, for a carbon neutral aviation, H_2-powered and synfuel-powered aviation could be complementary to make efficient use out of the limited resources. While realising the supply of carbon neutral fuels, the sustainable use of raw materials, renewable energy and water must not be neglected, so aviation in the future will not only be carbon neutral but also truly sustainable.

CRediT authorship contribution statement

F. Schenke: Methodology, Visualization, Writing – original draft. **J. Hoelzen:** Conceptualization, Writing – review & editing. **C. Minke:** Conceptualization, Writing – review & editing. **A. Bensmann:** Writing – review & editing. **R. Hanke-Rauschenbach:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors gratefully acknowledge the financial support by the Federal Ministry of Education and Research of Germany in the framework of HyNEAT under grant no 03SF0670A.

Appendix

A. Model

The energy demand for the electrolysis $E_{\text{electrolysis}}$ is calculated with the total amount of H_2 to be produced m_{H2} and the specific energy demand $E^s_{\text{technology},i}$ for the electrolysis technology i with

$$E_{\text{electrolysis}} = m_{\text{H2}} \cdot \sum \left(E^s_{\text{technology},i} \cdot n_{\text{technologyshare},i}\right) \tag{A.1}$$

The $n_{\text{technologyshare}}$ in Eq. (4) is the share of the individual technology assumed for the H_2 production. The total amount of H_2, which needs to be produced with the water electrolysis, is calculated with the H_2 demands m_{H2demand} discussed in Section 2.1 and the H_2 losses along the supply chain to

$$m_{\text{H2}} = m_{\text{H2demand}} + m_{\text{H2demand}} \cdot \left(m^s_{\text{H2loss,fueling}} + m^s_{\text{H2loss,boiloff}} + m^s_{\text{H2loss,liquefaction}}\right). \tag{A.2}$$

The specific losses during fueling $m^s_{\text{H2loss,fueling}}$, the boil-off losses $m^s_{\text{H2loss,boiloff}}$ and the losses during liquefaction $m^s_{\text{H2loss,liquefaction}}$ are stated in percent. To calculate the total raw material demands, the necessary electrolyser capacity $P_{\text{electrolysis}}$ has to be calculated with the required energy and the full load hours $t_{\text{fullloadhours}}$ to

$$P_{\text{electrolysis}} = \frac{E_{\text{electrolysis}}}{t_{\text{fullloadhours}}}. \tag{A.3}$$

The energy demand of the other components is calculated analogous to Eq. (A.1) with their specific energy demand and the total H_2 demand.

The energy demand for the electrolysis for synfuel production is calculated with Eq. (A.1). The amount of required CO_2 m_{CO2} and the resulting energy demand for its production are calculated with

$$m_{\text{CO2}} = m_{\text{syncrude}} \cdot m^s_{\text{CO2/syncrude}} \tag{A.4}$$

$$E_{\text{DAC}} = m_{\text{CO2}} \cdot E^s_{\text{DAC}} . \tag{A.5}$$

$m^s_{\text{CO2/syncrude}}$ is the specific CO_2 demand for syncrude production and E^s_{DAC} is the specific energy demand for the DAC. The energy demand for the Fischer-Tropsch process is calculated with the specific energy demand $E^s_{\text{FT+RWGS}}$ to

$$E_{\text{FT+RWGS}} = m_{\text{syncrude}} \cdot E^s_{\text{FT+RWGS}} \tag{A.6}$$

The water demand for synfuel production $m_{\text{H2O, synfuel}}$ is calculated with

$$m_{\text{H2O,synfuel}} = m_{\text{H2O}} + m^s_{\text{H2O,FT}} \cdot m_{\text{syncrude}} \tag{A.7}$$

with the water demand for H_2 production m_{H2O}, the specific water demand of the Fischer Tropsch process $m^s_{\text{H2O,FT}}$ and the total syncrude demand. With this and the specific energy demand for the desalination process, the energy demand for seawater desalination is calculated with

$$E_{\text{desalination}} = m_{\text{H2O,synfuel}} \cdot E^s_{\text{desalination}}. \tag{A.8}$$

At last, the energy demand for the transport is calculated with the distance to be covered d, the specific energy demand of the transport medium $E^s_{\text{transport}}$ and the amount to be transported m_{fuel} to

$$E_{\text{transport}} = m_{\text{fuel}} \cdot d \cdot E^s_{\text{transport}}. \tag{A.9}$$

B. Input Parameter for the Model

Table B.1
Input parameter assumed for the model.

Parameter	Unit	Value	Source
H2-losses along the supply chain			
Boil-off-rates trucks	%/d	0.96	[93,94]
Boil-off-rates ships/airport	%/d	0.06	[52,53,95]
Total H_2 transfer losses	%	0.5	[96,97]
Liquefaction losses	%	1.65	[11,36]
H_2 compression losses	%	0.5	[96,97]
Energy demands			
PEMWE	kWh/kg H_2	54.6 (45.04)[1]	[98,99]
AWE	kWh/kg H_2	47.6 (41.66)[1]	[14,99]
SOE	kWh/kg H_2	36.14	[98,99]
Liquefaction	kWh/kg H_2	6	[48,50]
Seawater reverse osmosis	kWh/kg H_2O	0.003	[42,100]
LHV of H_2	kWh/kg H_2	33.33	[45]
Truck transport	kWh/tkm	0.5	[94,101]
Ship transport	kWh/tkm	0.0189	[101]
Pipeline transport	kWh/tkm	1.619	[94]
Full load hours electrolysis	h	5000	
Water demand			
PEMWE	l/kg H_2	10.7	[38,102]
AWE	l/kg H_2	10	[38,45]
SOE	l/kg H_2	9.1	[38,103]
Fischer-Tropsch process	l/kg synfuel	0.03	[104]
Transport			
Capacity LH_2 ship	t	20,000	[95,105]
Average distance shipping	km	5,000	
Average ship speed	km/h	30	[105,106]
Total loading and discharge time	h	96	[106]
Ship operating time	h/a	7,920	[106]
Capacity LH_2 truck	t	4,300	[93,96,97]
Average truck distance	km	300	
Average tuck driving speed	km/h	50	[49,97]
Total loading and discharge time	h	3	[96,97]
Trucks operating time	h/a	2,000	[49,97]
Synfuel			
LHV of synfuel	kWh/kg synfuel	12.22	[104,107]
Specific H_2 demand	kg H_2/kg syncrude	0.48	[104,107]
Specific CO_2 demand	kg CO_2/kg syncrude	3.06	[104,107]
Specific syncrude demand	kg syncrude/kg synfuel	1.28	[57]
Energy demand DAC	kWh/kg CO_2	1.28 (1.09)[1]	[108–110]
Energy demand Fischer-Tropsch + RWGS	kWh/kg syncrude	0.37	[107]

[1] Reduced energy demand due to higher efficiency.

References

[1] Clean Sky 2 JU, Fuel Cells and Hydrogen 2 JU, Hydrogen-powered aviation A fact-based study of hydrogen technology, economics, and climate impact by 2050, 2020. https://cleansky.paddlecms.net/sites/default/files/2021-10/20200507_Hydrogen-Powered-Aviation-report.pdf.

[2] Lee DS, Fahey DW, Skowron A, Allen MR, Burkhardt U, Chen Q, et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmos Environ 2021;244:117834. https://doi.org/10.1016/j.atmosenv.2020.117834.

[3] Pavlenko N, Searle S, Fueling flight: Assessing the sustainability implications of alternative aviation fuels, 2021; 17.

[4] BDLI, DLR, Zero Emission Aviation German Aviation Research White Paper, 2020. https://www.dlr.de/en/media/publications/brochures/2020/white-paper-dlr-bdli-zero-2020-en.

[5] Silberhorn D, Dahlmann K, Görtz A, Linke F, Zanger J, Rauch B, et al. Climate Impact Reduction Potentials of Synthetic Kerosene and Green Hydrogen Powered Mid-Range Aircraft Concepts. Appl Sci 2022;12:5950. https://doi.org/10.3390/app12125950.

[6] Airbus, ZEROe Towards the world's first zero-emission commercial aircraft, (2022). https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe (accessed March 17, 2022).

[7] ZeroAvia, ZeroAvia Completes World First Hydrogen-Electric Passenger Plane Flight, (2020). https://www.zeroavia.com/press-release-25-09-2020 (accessed March 17, 2022).

[8] ATAG, Waypoint 2050, 2021. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf.

[9] Air New Zealand, Zero Emission Aircraft, 2021.

[10] Bruce S, Temminghoff M, Hayward J, Palfreyman D, Munnings C, Burke N, et al. Opportunities for hydrogen in commercial aviation 2020. https://www.csiro.au/-/media/Do-Business/Files/Futures/Boeing-Opportunities-for-hydrogen-in-commercial-aviation.pdf.

[11] Reuß M, Grube T, Robinius M, Stolten D. A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany. Appl Energy 2019;247:438–53. https://doi.org/10.1016/j.apenergy.2019.04.064.
[12] Shibata Y, Sichao K, Yoshida M, Nakamura H, Sakamoto T, Study on the economics of the hydrogen international supply chain, 2020. https://eneken.ieej.or.jp/data/9883.pdf.
[13] Hydrogen Council, Hydrogen decarbonation pathways - A life-cycle assessment, 2021. https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment.pdf.
[14] Wulf C, Reuß M, Grube T, Zapp P, Robinius M, Hake J-F, et al. Life Cycle Assessment of hydrogen transport and distribution options. J Clean Prod 2018;199:431–43. https://doi.org/10.1016/j.jclepro.2018.07.180.
[15] Hoelzen J, Silberhorn D, Zill T, Bensmann B, Hanke-Rauschenbach R. Hydrogen-powered aviation and its reliance on green hydrogen infrastructure – Review and research gaps. Int J Hydrogen Energy 2022;47:3108–30. https://doi.org/10.1016/j.ijhydene.2021.10.239.
[16] Minke C, Suermann M, Bensmann B, Hanke-Rauschenbach R. Is iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis? Int J Hydrogen Energy 2021;46:23581–90. https://doi.org/10.1016/j.ijhydene.2021.04.174.
[17] DERA, Mineralische Rohstoffe für die Wasserelektrolyse, (2022). https://www.bgr.bund.de/DERA/DE/Downloads/DERA%20Themenheft-01-22.pdf?_blob=publicationFile&v=3#:~:text=Nach%20unterschiedlichen%20Quellen%20werden%20derzeit,wenigen%20verarbeitenden%20Unternehmen%20deutlich%20konzentriert.
[18] Reiter G, Zauner A, Energieinstitut an der JKU Linz-Analyse Kritischer Rohstoffe von Elektrolyseuren, 2017.
[19] Stropnik R, Lotrič A, Bernad Montenegro A, Sekavčnik M, Mori M. Critical materials in PEMFC systems and a LCA analysis for the potential reduction of environmental impacts with EoL strategies. Energy Sci Eng 2019;7:2519–39. https://doi.org/10.1002/ese3.441.
[20] Lim A, Kim J, Lee HJ, Kim H-J, Yoo SJ, Jang JH, et al. Low-loading IrO2 supported on Pt for catalysis of PEM water electrolysis and regenerative fuel cells. Appl Catal B 2020;272:118955. https://doi.org/10.1016/j.apcatb.2020.118955.
[21] Yang X, Zhang G, Du L, Zhang J, Chiang F-K, Wen Y, et al. PGM-free Fe/N/C and ultralow loading Pt/C hybrid cathode catalysts with enhanced stability and activity in PEM FUEL CELLs. ACS Appl Mater Interfaces 2020;12:13739–49. https://doi.org/10.1021/acsami.9b18085.
[22] Hegge F, Lombeck F, Cruz Ortiz E, Bohn L, von Holst M, Kroschel M, et al. Efficient and stable low iridium loaded anodes for PEM water electrolysis made possible by nanofiber interlayers. ACS Appl Energy Mater 2020;3:8276–84. https://doi.org/10.1021/acsaem.0c00735.
[23] Umweltbundesamt, Climate Change 18/2009: Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply, (2009) 344.
[24] Moriarty P, Honnery D. What is the global potential for renewable energy? Renew Sustain Energy Rev 2012;16:244–52. https://doi.org/10.1016/j.rser.2011.07.151.
[25] Kakoulaki G, Kougias I, Taylor N, Dolci F, Moya J, Jäger-Waldau A. Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables. Energ Conver Manage 2021;228:113649. https://doi.org/10.1016/j.enconman.2020.113649.
[26] Aqueduct, Water Risk Atlas, (2022). https://www.wri.org/applications/aqueduct/water-risk-atlas/ (accessed February 25, 2022).
[27] Alcamo J, Flörke M, Märker M. Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrol Sci J 2007;52:247–75. https://doi.org/10.1623/hysj.52.2.247.
[28] The World Bank, Global Solar Atlas, (2021). https://globalsolaratlas.info/ (accessed February 4, 2022).
[29] Technical University of Denmark, Global Wind Atlas, (2021). https://globalsolaratlas.info/ (accessed February 4, 2022).
[30] ESMAP, REZoning THE RENEWABLE ENERGY ZONING TOOL, (2021). https://rezoning.energydata.info/ (accessed January 21, 2022).
[31] Fraunhofer IEE, PtX-Atlas, (2021). https://maps.iee.fraunhofer.de/ptx-atlas/ (accessed February 26, 2022).
[32] Irena. Geopolitics of the Energy Transformation. The Hydrogen Factor 2022. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf.
[33] Pflugmann F, Blasio ND, Geopolitical and Market Implications of Renewable Hydrogen, (2020) 63.
[34] IRENA, Global hydrogen trade to meet the 1.5°C climate goal: Part III – Green hydrogen cost and potential, (2022) 45.
[35] Sens L, Neuling U, Wilbrand K, Kaltschmitt M, Conditioned hydrogen for a green hydrogen supply for heavy duty-vehicles in 2030 and 2050 – A techno-economic well-to-tank assessment of various supply chains, Int J Hydrogen Energy. 2022; S0360319922031275. 10.1016/j.ijhydene.2022.07.113.
[36] Hoelzen J, Flohr M, Silberhorn D, Mangold J, Bensmann A, Hanke-Rauschenbach R. H2-powered aviation at airports – Design and economics of LH2 refueling systems. Energy Convers Manage: X 2022;14:100206. https://doi.org/10.1016/j.ecmx.2022.100206.
[37] Hydrogen Council, Hydrogen for Net Zero Full-Report, 2021. https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf.
[38] Global Alliance Powerfuels. Water Consumption of Powerfuels 2021:14.
[39] Peñate B, García-Rodríguez L. Current trends and future prospects in the design of seawater reverse osmosis desalination technology. Desalination 2012;284:1–8. https://doi.org/10.1016/j.desal.2011.09.010.
[40] Kim J, Park K, Yang DR, Hong S. A comprehensive review of energy consumption of seawater reverse osmosis desalination plants. Appl Energy 2019;254:113652. https://doi.org/10.1016/j.apenergy.2019.113652.
[41] Jones E, Qadir M, van Vliet MTH, Smakhtin V, Kang S. The state of desalination and brine production: A global outlook. Sci Total Environ 2019;657:1343–56. https://doi.org/10.1016/j.scitotenv.2018.12.076.
[42] Khan MA, Al-Attas T, Roy S, Rahman MM, Ghaffour N, Thangadurai V, et al. Seawater electrolysis for hydrogen production: a solution looking for a problem? Energy Environ Sci 2021;14:4831–9. https://doi.org/10.1039/D1EE00870F.
[43] Marscheider-Weidemann F, Langkau S, Eberling E, Erdmann L, Haendel M, Krail M, et al, Rohstoffe für Zukunftstechnologien 2021: "Auftragsstudie," Datenstand: Mai 2021, Aktualisierung im August 2021, Deutsche Rohstoffagentur (DERA) in der Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Berlin, 2021. https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-50.pdf?_blob=publicationFile&v=4.
[44] Smolinka T, Wiebe N, Sterchele P, Palzer A, Lehner F, Jansen M, et al., Studie: IndWEDe Industrialisierung der Wasser-elektrolyse in -Deutschland: -Chancen und -Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und -Wärme, 2018; 201.
[45] Töpler J, Lehmann J, editors. Wasserstoff Und Brennstoffzelle: Technologien Und Marktperspektiven. Berlin Heidelberg, Berlin, Heidelberg: Springer; 2017. https://doi.org/10.1007/978-3-662-53360-4.
[46] Smolinka T, Günther M, Garche J, Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien, 2011. https://www.now-gmbh.de/wp-content/uploads/2020/09/now-studie-wasserelektrolyse-2011.pdf.
[47] Sdanghi G, Maranzana G, Celzard A, Fierro V. Review of the current technologies and performances of hydrogen compression for stationary and automotive applications. Renew Sustain Energy Rev 2019;102:150–70. https://doi.org/10.1016/j.rser.2018.11.028.
[48] Aasadnia M, Mehrpooya M. Large-scale liquid hydrogen production methods and approaches: A review. Appl Energy 2018;212:57–83. https://doi.org/10.1016/j.apenergy.2017.12.033.
[49] Reuß M, Dimos P, Léon A, Grube T, Robinius M, Stolten D. Hydrogen road transport analysis in the energy system: A case study for Germany through 2050. Energies 2021;14:3166. https://doi.org/10.3390/en14113166.
[50] Peschel A. Industrial perspective on hydrogen purification, compression, storage, and distribution. Fuel Cells 2020;20:385–93. https://doi.org/10.1002/fuce.201900235.
[51] Mangold J, Silberhorn D, Moebs N, Dzikus N, Hoelzen J, Zill T, et al. Refueling of LH2 aircraft—assessment of turnaround procedures and aircraft design implication. Energies 2022;15:2475. https://doi.org/10.3390/en15072475.
[52] Fesmire J, Swanger A, Jacobson J, Notardonato W. Energy efficient large-scale storage of liquid hydrogen. IOP Conf Ser: Mater Sci Eng 2022;1240:012088. https://doi.org/10.1088/1757-899X/1240/1/012088.
[53] Gautam M, Rao KVS, Saxena BK. Reduction in liquid hydrogen by weight due to storage in different sizes of containers for varying period of time. In: 2017 international conference on technological advancements in power and energy (TAP Energy). Kollam: IEEE; 2017. p. 1–6. https://doi.org/10.1109/TAPENERGY.2017.8397347.
[54] USDRIVE, Hydrogen Delivery Roadmap, (2013) 54.
[55] Wuppertal Institut, DIW Econ, Bewertung der Vor- und Nachteile von Wasserstoffimporten im Vergleich zur heimischen Erzeugung, (2020) 131.
[56] European Commission, Study on the EU's list of Critical Raw Materials, 2020. https://ec.europa.eu/docsroom/documents/42883/attachments/1/translations/en/renditions/native.
[57] HaldorTopsoe, Sasol, Expect more... by turning green energy into fuels G2L™ eFuels – a business ready solution, 2021. https://info.topsoe.com/en/g2l-expect-more-with-a-busines-ready-solution (accessed November 8, 2022).
[58] Kiemel S, Smolinka T, Lehner F, Full J, Sauer A, Miehe R. Critical materials for water electrolysers at the example of the energy transition in Germany. Int J Energy Res 2021;45:9914–35. https://doi.org/10.1002/er.6487.
[59] International Energy Agency, The Role of Critical Minerals in Clean Energy Transitions, 2021; 287.
[60] Reichl C, Schatz M. World Mining Data 2021;2021:268.
[61] Hughes AE, Haque N, Northey SA, Giddey S. Platinum Group Metals: A Review of Resources, Production and Usage with a Focus on Catalysts. Resources 2021;10:93. https://doi.org/10.3390/resources10090093.
[62] USGS, RARE EARTHS, 2022. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-rare-earths.pdf.
[63] USGS, NICKEL, 2022. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-nickel.pdf.
[64] USGS, TITANIUM, 2022. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-titanium-minerals.pdf.
[65] USGS, YTTRIUM, 2021. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-yttrium.pdf.
[66] DERA, Rohstoffinformationen Rohstoffrisikobewertung –Platingruppenmetalle, 2014.
[67] Graedel TE, Allwood J, Birat J-P, Buchert M, Hagelken C, Reck BK, et al., United Nations Environment Programme, Working Group on the Global Metal Flows, Recycling rates of metals: a status report, 2011. http://www.unep.org/resourcepanel/Portals/24102/PDFs/Metals_Recycling_Rates_110412-1.pdf (accessed April 5, 2022).

[68] Patrick Friedrichs, Development of a Rare Earth Element Resource Database Management System, 2017. https://publications.rwth-aachen.de/record/688117/files/688117.pdf?subformat=pdfa.
[69] Rasmussen KD, Wenzel H, Bangs C, Petavratzi E, Liu G. Platinum demand and potential bottlenecks in the global green transition: A dynamic material flow analysis. Environ Sci Technol 2019;53:11541–51. https://doi.org/10.1021/acs.est.9b01912.
[70] Moschkowitsch W, Lori O, Elbaz L. Recent progress and viability of PGM-free catalysts for hydrogen evolution reaction and hydrogen oxidation reaction. ACS Catal 2022;12:1082–9. https://doi.org/10.1021/acscatal.1c04948.
[71] Salonen LM, Petrovykh DY, Yu V, Kolen'ko,. Sustainable catalysts for water electrolysis: Selected strategies for reduction and replacement of platinum-group metals. Materials Today Sustainability 2021;11–12:100060. https://doi.org/10.1016/j.mtsust.2021.100060.
[72] REN21, RENEWABLES 2021 GLOBAL STATUS REPORT, 2021. https://www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf.
[73] Teske S, ed., Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C, Springer International Publishing, Cham, 2019. 10.1007/978-3-030-05843-2.
[74] McKinsey & Company, The net-zero transition: What it would cost, what it could bring, (2022) 224.
[75] IRENA, World Energy Transitions Outlook: 1.5°C Pathway, (2021) 312.
[76] World Bank Group, Global Photovoltaic Power Potential by Country, 2020. https://documents1.worldbank.org/curated/en/466331592817725242/pdf/Global-Photovoltaic-Power-Potential-by-Country.pdf.
[77] BP, Statistical Review of World Energy 2021, 2021. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf.
[78] BP, Statistical Review of World Energy 2022, 2022. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf.
[79] International Energy Agency, World Energy Outlook 2022, 2022. www.iea.org/weo.
[80] Hofste RW, Reig P, Schleifer L, 17 Countries, Home to One-Quarter of the World's Population, Face Extremely High Water Stress, World Resource Institute. (2019). https://www.wri.org/insights/17-countries-home-one-quarter-worlds-population-face-extremely-high-water-stress (accessed February 25, 2022).
[81] UN-Water, Progress on Level of Water Stress, Sustainable Development Goal 6 on Water and Sanitation (SDG 6). (2022). https://sdg6data.org/indicator/6.4.2 (accessed August 17, 2022).
[82] UN-Water, Summary Progress Update 2021: SDG 6 — water and sanitation for all, 2021. https://www.unwater.org/sites/default/files/app/uploads/2021/07/SDG-6-Summary-Progress-Update-2021_Version-July-2021.pdf.
[83] Singh HV, Bocca R, Gomez P, Dahlke S, Bazilian M, The energy transitions index_ An analytic framework for understanding the evolving global energy system, (2019). 10.1016/j.esr.2019.100382.
[84] World Economic Forum, Fostering Effective Energy Transition 2021 edition, 2021. https://www3.weforum.org/docs/WEF_Fostering_Effective_Energy_Transition_2021.pdf (accessed August 16, 2022).
[85] Schemme S, Breuer JL, Köller M, Meschede S, Walman F, Samsun RC, et al. H2-based synthetic fuels: A techno-economic comparison of alcohol, ether and hydrocarbon production. Int J Hydrogen Energy 2020;45:5395–414. https://doi.org/10.1016/j.ijhydene.2019.05.028.
[86] Teichmann D, Arlt W, Wasserscheid P. Liquid Organic Hydrogen Carriers as an efficient vector for the transport and storage of renewable energy. Int J Hydrogen Energy 2012;37:18118–32. https://doi.org/10.1016/j.ijhydene.2012.08.066.
[87] Wang A, Jens J, Mavins D, Moultak M, Schimmel M, Kees van der Leun, Daan Peters, Maud Buseman, Analysing future demand, supply, and transport of hydrogen, 2021. https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021.pdf.
[88] Hydrogen Council, Path to Hydrogen Competitiveness, 2020. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf.
[89] Bloomberg NEF, Chile Power System Outlook, 2019. https://data.bloomberglp.com/professional/sites/24/Flexibility-Solutions-for-High-Renewable-Energy-Systems-Chile-Outlook.pdf.
[90] Tong W, Forster M, Dionigi F, Dresp S, Sadeghi Erami R, Strasser P, et al. Electrolysis of low-grade and saline surface water, Nat. Energy 2020;5:367–77. https://doi.org/10.1038/s41560-020-0550-8.
[91] Zhou Y, Tol RSJ. Evaluating the costs of desalination and water transport: costs of desalination and water transport. Water Resour Res 2005;41. https://doi.org/10.1029/2004WR003749.
[92] Guo J, Zhang Y, Zavabeti A, Chen K, Guo Y, Hu G, et al. Hydrogen production from the air. Nat Commun 2022;13:5046. https://doi.org/10.1038/s41467-022-32652-y.
[93] Decker L. Liquid hydrogen distribution technology. Linde 2020:27.
[94] Zemo Partnership, Element Energy, Low Carbon Hydrogen Well-to-Tank Pathways Study - Full Report, 2021. https://www.element-energy.co.uk/wordpress/wp-content/uploads/2021/08/Zemo-Low-Carbon-Hydrogen-WTT-Pathways-full-report.pdf.
[95] Alkhaledi AN, Sampath S, Pilidis P. A hydrogen fuelled LH2 tanker ship design. Ships and Offshore Structures 2021:1–10. https://doi.org/10.1080/17445302.2021.1935626.
[96] Nexant, Inc., Air Liquide, Argonne National Laboratory, Chevron Technology Venture, Gas Technology Institute, National Renewable Energy Laboratory, Pacific Northwest National Laboratory, TIAX LLC, H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results, 2008. https://www.energy.gov/eere/fuelcells/articles/h2a-hydrogen-delivery-infrastructure-analysis-models-and-conventional.
[97] Reuß M, Grube T, Robinius M, Preuster P, Wasserscheid P, Stolten D. Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. Appl Energy 2017;200:290–302. https://doi.org/10.1016/j.apenergy.2017.05.050.
[98] Mehmeti A, Angelis-Dimakis A, Arampatzis G, McPhail S, Ulgiati S. Life cycle assessment and water footprint of hydrogen production methods: from conventional to emerging technologies. Environments 2018;5:24. https://doi.org/10.3390/environments5020024.
[99] Grigoriev SA, Fateev VN, Bessarabov DG, Millet P. Current status, research trends, and challenges in water electrolysis science and technology. Int J Hydrogen Energy 2020;45:26036–58. https://doi.org/10.1016/j.ijhydene.2020.03.109.
[100] Global Alliance Powerfuels, Powerfuels in a Renewable Energy World, 2020. https://www.powerfuels.org/test/user_upload/Global_Alliance_Powerfuels_Study_Powerfuels_in_a_Renewable_Energy_World_final.pdf.
[101] Umweltbundesamt, Carbon Footprint – Teilgutachten "Monitoring für den CO2-Ausstoß in der Logistikkette", 2011;81.
[102] Bareiß K, de la Rua C, Möckl M, Hamacher T. Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. Appl Energy 2019;237:862–72. https://doi.org/10.1016/j.apenergy.2019.01.001.
[103] Motazedi K, Salkuyeh YK, Laurenzi IJ, MacLean HL, Bergerson JA. Economic and environmental competitiveness of high temperature electrolysis for hydrogen production. Int J Hydrogen Energy 2021;46:21274–88. https://doi.org/10.1016/j.ijhydene.2021.03.226.
[104] Albrecht FG, Nguyen T-V. Prospects of electrofuels to defossilize transportation in Denmark – A techno-economic and ecological analysis. Energy 2020;192:116511. https://doi.org/10.1016/j.energy.2019.116511.
[105] Alkhaledi ANFNR, Sampath S, Pilidis P. Propulsion of a hydrogen-fuelled LH2 tanker ship. Int J Hydrogen Energy 2022. https://doi.org/10.1016/j.ijhydene.2022.03.224.
[106] Ishimoto Y, Voldsund M, Nekså P, Roussanaly S, Berstad D, Gardarsdottir SO. Large-scale production and transport of hydrogen from Norway to Europe and Japan: Value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers. Int J Hydrogen Energy 2020;45:32865–83. https://doi.org/10.1016/j.ijhydene.2020.09.017.
[107] König DH, Techno-ökonomische Prozessbewertung der Herstellung synthetischen Flugturbinentreibstoffes aus CO2 und H2, 2016. https://doi.org/10.18419/opus-9043.
[108] Cames M, Chaudry S, Göckeler K, Kasten P, Kurth S, E-fuels versus DACCS, 2021. https://www.transportenvironment.org/wp-content/uploads/2021/08/2021_08_TE_study_efuels_DACCS.pdf.
[109] Fasihi M, Efimova O, Breyer C. Techno-economic assessment of CO2 direct air capture plants. J Clean Prod 2019;224:957–80. https://doi.org/10.1016/j.jclepro.2019.03.086.
[110] Heß D, Klumpp M, Dittmeyer R, Nutzung von CO2 aus Luft als Rohstoff für synthetische Kraftstoffe und Chemikalien, (2020). https://vm.baden-wuerttemberg.de/fileadmin/redaktion/m-mvi/intern/Dateien/PDF/29-01-2021-DAC-Studie.pdf.