Energy Proceedings
Vol 45, 2024
ISSN 2004-2965

Techno-economic evaluation of hydrogen production for airport hubs

Mohammed Taha1*, Nick Lundvall1, Konstantinos Kyprianidis1, Awais Salman1, Stavros Vouros1, Valentina Zaccaria 1
1 School of Business, Society, and Engineering, Mälardalen University
(*mohammed.taha@mdu.se)

ABSTRACT

Hydrogen is considered one of the most promising alternative fuels for aviation, which can be used to power aircraft and airport ground services. Onsite hydrogen production from renewables can be suitable for small-size airports, while the larger size airports can be supplied through transportation either from dedicated green hydrogen production plants or other sources of hydrogen. This paper presents a study of two hydrogen supply scenarios, one taking the small airport of Stockholm Skavsta as a case study for in-house hydrogen production. The second is evaluating offshore green hydrogen supply to the large size airport of Arlanda. The in-house hydrogen production evaluates 18 scenarios covering all possible scenarios for alkaline, PEM, and solid oxide electrolysis as production means and compressed, cryo-compressed, and liquid gas as storage, with power supply from grid and grid plus in-house solar system. The optimum production and storage facility size is determined in association with the levelized cost and carbon emissions for each scenario. For the large-size airport, the study evaluates the hydrogen supply from offshore production facilities transported as compressed, cryo-compressed, or liquid gas via offshore pipeline and onshore pipeline, Offshore pipeline and truck, Ship and onshore pipeline, or Ship and truck. The results showed the levelized cost to be between 2.93 - 2.44 Euro/kg H_2 in the case of in-house production. Compressed hydrogen offshore and onshore pipeline is the least cost for Arlanda airport hydrogen supply. This paper demonstrates a direction for aviation sector decarbonization and establishes a pathway for airports' in-house hydrogen production and outsourced hydrogen supply.

Keywords: Hydrogen, Hydrogen for aviation, Electrolysis systems, Hydrogen inhouse production.

NOMENCLATURE

Abbreviations	
Ker	Kerosene
LHV	*Low heating value*
η	Efficiency
H_2	Hydrogen
St	Storage
Elec	Electricity

1. INTRODUCTION

Transportation sector emissions are expected to increase in the future as estimated by the international energy agency [34], in order to reduce that emissions and for the European aviation sector to reach net-zero emissions from all flights within and departing from the European Union by 2050 alternative fuels must be developed. Hydrogen is among the most promising fuels to be used [35]. Hydrogen can be used as a combustion fuel or electrical power source through fuel cells. Several prototypes were made for both usages starting from the early 20th century [1] and more recently for fuel cell usage [2]. Aircraft design must be changed to match the storage and combustion requirements of hydrogen, As the hydrogen have a 2.6 times higher heating value and 4 times storage volume comparing to the Kerosine's [3].

A color code has been assigned to hydrogen based on the environmental effects of the production mean. The green hydrogen is the most environment friendly type which mainly produced by water electrolysis powered by renewable energy [4]. Water electrolysis technologies are mainly classified by the process temperature and the electrolyte PH. Based on the process temperature low-temperature processes (T < 150°C), medium temperature processes (200°C < T < 600°C), and high-temperature processes (>600°C). Based on the PH the electrolysis technologies divided into alkaline and acidic electrolyte [5]. The alkaline electrolyzers work in low temperature range and handle pressure up to 30 bar. The power consumption of this type, range between 7.5 to 4.3 kW.h/Nm^{3}H$_2$ with efficiency in the range of 52.8% and 82.3% [6]. The second type is the proton exchange membrane (PEM) electrolyzers that use acidic electrolyte and work on the medium temperature range with pressure between 30-80 bar. the power consumption of PEM electrolyzers range between 45-65 kW.h/kg H_2 and efficiency reach up to 64 %, (Grigoriev et al., 2020). The third type is the solid oxide (SO) electrolyzers which still in research phase and only available in laboratory- scale with experimental power consumption result obtained about 3.77 kW.h/Nm^{3}H$_2$ with a waste heat share of 16% and electricity share of 84%.

Hydrogen is characterized by low volumetric density, high flammability, and high burning velocity which

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

present ongoing research challenge for hydrogen storage [36]. The main hydrogen storage technologies can be divided into five main forms, high pressure gas, liquid, cryo-compressed gas, chemical compounds and physical adsorbed [8]. The market available high pressure gas cylinders can store hydrogen up to 80MPa where the volumetric density reach 36 kg/m^3, (Züttel, 2004) and (Langmi et al., 2022). The liquid hydrogen is stored in cryogenic tanks at a temperature the critical temperature, commonly around 21K where the liquid hydrogen density is 70.8 kg/m^3, [10]. Cryo- compressed storage is a combination of the latter mentioned storage types where the hydrogen gas compressed at a cryogenic temperature and stored in a vessel equipped with a set of auxiliary equipment to maintain the cryogenic temperature. The energy consumption and efficiency of the cryo-compression storage depend on the process's pressure and temperature (Ahluwalia et al., 2016).

Hydrogen usage in aviation has been a growing research area. Janic, (2010) studied the environmental effects of hydrogen usage in aviation sector where they concluded that the hydrogen would provide a sustainable solution to reduce emissions except the H_2O emissions. Hoelzen et al., (2022) found out that for large demand airports the optimum liquid hydrogen supply method is pipeline with hydrant system while for airports with less than 125 kT LH_2 annual demand, refueling truck set up is the optimum. Inversely [14] concluded that LH_2 to be transported as a liquid is the most economical solution up to 150 t/day demand and for higher demands gaseous pipeline transportation is the most economical Option. Schenke et al., (2023) proved the availability of resources to move toward hydrogen powered aviation globally, the only critical resource they found was the PEM electrolysis catalyst materials, this proves the important of including the solid oxide electrolysis in this study.

The economy of scale has a high impact on hydrogen production cost as highlighted by several authors. Ball & Weeda, (2016) estimated the hydrogen cost to be between 2-6 €/kg for large-scale systems (3000-4000 kg) capacity size, with an electricity price in the range of 25 to 40 €/MWh. Also Kayfeci et al., (2019) estimated the Levelized cost of hydrogen production via electrolysis using different sources of electricity to be between 5.89-2.17 $/kg. UK Department for business, energy, and industrial strategy, (2021) estimated the hydrogen cost to be between 180-50 £/MW.h of H_2 (HHV), depending on the production scale.

This paper contributes to finding the optimum pathway for small airports in- house hydrogen production and the optimum transportation method to supply offshore produced hydrogen to large size airports.

2. METHODOLOGY

This paper adopts readymade simulation models and develops mathematical models to evaluate two case studies, one for in-house hydrogen production and the second for offshore green hydrogen supply.

2.1 Airport inhouse hydrogen production

This scenario simulates an in-house hydrogen production system for Stockholm Skavsta airport. The airport serves 16 east Europe destinations with distance in range of (1942 km - 500 km). The flights are operated by Wizz Air [37], with a fleet comprising Airbus A320 airplanes (170-140 seats) [38] [39]. The passenger's data have been taken for the year 2019 as it represents pre COVID-19 data, [40]. By assuming the equal distribution of passengers to the destinations and considering the airport daily working hours (16 hours) a flight scheduling plan is made accordingly.

2.1.1 Hydrogen Demand

The hydrogen fuel demand is estimated as per the following equations.

Air traffic estimation:

$$dayily\ Number\ of\ flights\ per\ destination = round\ of\left(\frac{Annual\ passengers}{8760.\ \#of\ destinations.\ passengers\ per\ flights}\right) \quad (1)$$

Conventional fuel (Kerosene) demand:

$$Ker\ demand = fuel\ consmption\ .flight\ distance \quad (2)$$

Hydrogen demand fuel cell scenarios:

$$H_2 Demand_{FC} = \frac{Ker\ Demand\ .\ \ Ker\ LHV.\ \eta_{Aircraft\ engine}}{H_2\ LHV\ .\ \eta_{FC}} \quad (3)$$

Hydrogen demand combustion scenarios:

$$H_2\ demand_C = Ker\ Demand\ .Fuel\ consumption\ factor \quad (4)$$

Then we add 10% as safety fuel to the highest consumption of the two methods to be used in the rest of the study.

2.1.2 Scenarios setup

Scenarios are set to study all combinations of power sources, electrolysis types and storage methods as per Table 1.

2.1.3 Input data

Input data mainly collected from literature and applicable reports, the power consumption data for the electrolyzers and storage processes is shown in Table 2. The system components' cost adjusted to Euros and lifetime data can be seen in Table 3. The Energy and emissions data are shown in Table 4.

2.1.4 Calculations

A mixed-integer linear programming model is built to calculate the optimum size of the electrolyzer, storage and decide the optimum operation scheduling using the inputs in Table 2-4 and the equations (5) & (6).

The optimization is under the main assumptions of constant electrolyzer power consumption at all operation levels, no losses in the storage, no degradation, project lifetime is 20 years, and a one-year hourly cost of electricity is assumed the same for the project lifetime.

Table 1 Inhouse hydrogen production scenarios.

Scenario Number	Power Source	Electrolysis system	Storage System
1	Grid	Alkaline	Compressed
2	Grid	Alkaline	Cryo-compressed
3	Grid	Alkaline	Liquified.
4	Grid	PEM	Compressed
5	Grid	PEM	Cryo-compressed
6	Grid	PEM	Liquified
7	Grid	SO	Compressed
8	Grid	SO	Cryo-compressed
9	Grid	SO	Liquified
10	Solar + Grid	Alkaline	Compressed
11	Solar + Grid	Alkaline	Cryo-compressed
12	Solar + Grid	Alkaline	Liquified
13	Solar + Grid	PEM	Compressed
14	Solar + Grid	PEM	Cryo-compressed
15	Solar + Grid	PEM	Liquified
16	Solar + Grid	SO	Compressed
17	Solar + Grid	SO	Cryo-compressed
18	Solar + Grid	SO	Liquified.

Table 2 power consumption data.

Input	Value (kW.h/kg H_2)	Source	Comments
Alkaline	47.85	[6]	68 kg/h system manufactured by ELT DE and Industrie Hauti CH
PEM	45	[7]	Siemens 100-2000 Kg capacity systems
SO	36.04	[18]	Simulation study
Compression	2.85	[19]	Compression at room temperature to 700 bar including fast charge.
Liquification	6	[20]	Industrial expected real power consumption
Cry-compression	3.475	[21]	Compression to 200 bar and cooling to 80 K adjusted for 80 % efficiency.

For scenarios using grid as a power source.

$$Minimize\ z = ELc_{CAPEX}.ELc_{Size} + St_{CAPEX}.St_{Size} + \sum El.Price.HP.\left(Elc_{Pc} + Stp_{pc}\right) + CO_2\,Price.HP\left(Elc_{Pc} + Stp_{pc}\right) \quad (5)$$

For grid + Solar scenarios.

$$Minimize\ z = ELc_{CAPEX}.ELc_{Size} + St_{CAPEX}.St_{Size} + \sum El.Price.HP_{Eg}\left(Elc_{Pc} + Stp_{pc}\right) + CO_2\,Price.HP_{Eg}\left(Elc_{Pc} + Stp_{pc}\right) + SP.LCOE\ .HP_{Ss}\left(Elc_{Pc} + Stp_{pc}\right) \quad (6)$$

The CO2 price is calculated as follows.

$$CO_2\,Price = Crbon\ intencity.\sum CO_2ELU\ units \quad (7)$$

The solar system output is modeled using System Advisor Model (SAM) software [41].

The levelized cost of hydrogen is calculated as per equation 8-10.

$$levelized\ Cost\ of\ Hydrogen = \frac{Net\ Present\ Value\ of\ the\ Total\ Cost}{NPV\ of\ The\ total\ Hydrogen\ Production} \quad (8)$$

Table 3 System components cost.

Input	Value	Unit	Source	Comments
Alkaline Electrolysis CAPEX	32924	€/kg	[22]	
PEM Electrolysis CAPEX	33015	€/kg	[22]	
Solid oxide Electrolysis CAPEX	31298	€/kg	[22]	
Hydrogen compression storage CAPEX	633	€/kg	[23]	Type IV cylinder storage cost.
Hydrogen liquification storage CAPEX	167	€/kg	[24]	Storage Cost
Hydrogen cry-compression CAPEX	390	€/kg	[24]	
Hydrogen liquification process equip. CAPEX	3800	€/kg	[24]	
Hydrogen compression equipment CAPEX	129,500	€	[25]	Large scale for hydrogen vehicle supply of 700 bar hydrogen.
Hydrogen cry-compression process equip. CAPEX	2600	€/kg		Estimated as an average between compression and liquification
Alkaline electrolysis stack lifetime	80000	h	[22]	
PEM electrolysis stack lifetime	40000	h	[22]	
Solid oxide electrolysis stack lifetime	20000	h	[22]	
Stack replacement cost	50	%	[42].	Percentage of the initial cost of the system

$$Net\ Present\ Value\ of\ the\ Total\ Cost = \sum_n \frac{Total\ CAPEX\ \&\ OPEX_n}{(1 + discount\ rate)^n} \qquad (9)$$

$$Net\ Present\ Value\ of\ the\ Total\ Hydrogen\ Production = \sum_n \frac{Total\ Hydrogen\ Production_n}{(1 + discount\ rate)^n} \qquad (10)$$

Table 4 Energy and emissions data

Input	Value	Unit	Source	Comments
Electricity price	-	€/MW.h	[43]	The year 2021 hourly day-ahead price
Solar power Levelized cost	27.37	€/MW.h	[26]	Minimum LCOE found in the literature
Wind power Levelized cost	33.02	€/MW.h	[44]	Minimum LCOE found in the literature
Carbon intensity in Sweden's grid	-	g/kW.h	[45]	Hourly readings for the year 2021
Carbon cost	0.109134	ELU/kg	[36]	ELU≈1€
Kerosene CO2 emissions	3.053	Kg Co2/Kg fuel	[27]	

The carbon emissions is calculated as follows

$$Total\ carbon\ emissions = \sum Carbon\ intencity.HP_{Eg}\left(Elc_{Pc} + Stp_{pc}\right) \qquad (11)$$

$$Kerosein\ annual\ emissions = Kerosein\ emission\ .Fuel\ consumption\ *.Annual\ flights\ distance \qquad (12)$$

2.2 *Offshore green hydrogen production and supply*

This scenario simulates an offshore wind park dedicated to hydrogen production outside of Norrtälje and transport it to the destined location of Arlanda airport. The study used Modelon Impact to simulate the wind turbine output, hydrogen production and hydrogen storage process, MATLAB is used to perform the economical calculations. The study covers ships and pipelines for offshore transportation and trucks and pipeline for onshore transportation which resulted in four scenarios as shown in Table 5.

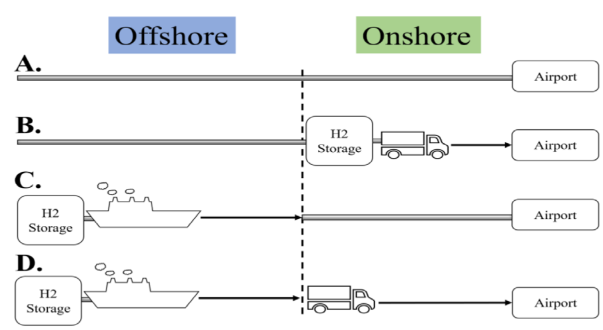

Fig. 1 Offshore hydrogen transpiration scenarios.

The liquified hydrogen and cryo-compressed hydrogen transportation through pipelines pose a high difficulty in maintaining the required temperature and no such application is currently available, the available pathways for our study are as shown in Table 5.

Table 5 Available transportation scenarios

	Liquid H2	Compressed Gas H2	Cryo-compressed H2
Offshore Pipe - Onshore Pipe (A)	✗	✓	✗
Offshore Pipe – Truck (B)	✗	✓	✗
Ship - Onshore Pipe (C)	✗	✓	✗
Ship – Truck (D)	✓	✓	✓

2.2.1 Wind power calculations

Modelon has a ready wind turbine sub model where only the wind speed, temperature and turbine parameters need to be added. Three years average wind speed and temperature data were taken from [47] database, at a station located outside of Norrtälje 20 km from the shore. The data were taken at 14m height then adjusted to 110m height using the equation (13).

$$v_{110} = v_{14}(\frac{H_{110}}{H_{14}})^{\alpha} \tag{13}$$

Where $v110$ is the wind speed at 110 m, $v14$ is the wind speed at 14 m, $H110$ is the turbine height (110 m), $H14$ is the height the data was taken from (14 m) and α is Hellman's exponent, for this case 0.2 is chosen [28].

The wind turbines choice is based on the average wind speed. The models selected are Vestas V164-8.0 MW and 8 MW LEANWIND reference turbine (Leanwind, 2015), with a power coefficient assumed to be 35%.

2.2.2 Electrolysis system Calculations

A sub model for alkaline electrolyzer found in Modelon only the PEM electrolyzer model need to be added. Based on the existing alkaline electrolyzer model the specific PEM electrolyzer equations based on [29], [30], and [31] were adjusted as follow:

$$V_{cell} = V_{Rev} + V_{ohm} + V_{act} + V_{con} \tag{14}$$

Where V_{Cell} is the single cell voltage, V_{Rev} is the reversible voltage, V_{ohm} is the ohmic losses from overvoltage, V_{act} is the activation overvoltage from electrode kinetics, and V_{con} is the concentration overvoltage from mass transport, assumed to be zero.

$$V_{Rev} = V_{Rev0} + \frac{R * T_{el}}{2 * F} * ln\left(\frac{p_{H2} * \sqrt{p_{O2}}}{p_{H2O}}\right) \tag{15}$$

Where V_{Rev0} is the reversible voltage at atmospheric conditions (1.23 V), R is the molar gas constant and T_{el} is the temperature of the electrolyzer in Kelvin. p_{H2}, p_{O2}, and p_{H2O} are the partial pressures exerted from the substances.

$$V_{act} = \frac{R * T_{el}}{\alpha_{an}} * asinh\left(\frac{i_{cell}}{z * i_{o,an}}\right) + \frac{R * T_{el}}{\alpha_{cat}} * asinh\left(\frac{i_{cell}}{z * i_{o,cat}}\right) \tag{16}$$

The above equation is Butler-Volmer Equation where α_{an} is the anode charge transfer coefficient (0.433 p.u. at 60 C), α_{cat} is the cathode charge transfer coefficient, assumed to be 0.5. $i_{o,an}$ and $i_{o,cat}$ are the anode/cathode exchange current densities, assumed to be 1*10-9 and 1*10-3 A/ cm^2 respectively.

$$V_{ohm} = \frac{\delta_m * i_{cell}}{\sigma_m} \tag{17}$$

Where δ_m is the membrane thickness in cm, (usually between 50-250 µm, assumed to be 125 µm) and σ_m is the membrane conductivity (S/cm).

$$\sigma_m = (0.005139 * \lambda - 0.00326) * e^{128*\left(\frac{1}{303} - \frac{1}{T_{el}}\right)} \tag{18}$$

λ is the membrane water content, with the equation for values around 20 being as follows:

$$\lambda = \frac{(-2.89556 + 0.016 * T_{el}) + 1.625}{0.1875} \tag{19}$$

2.2.3 Storage system Calculations

The storage tank capacity is assumed to handle a week production of hydrogen to match the ship transportation scenario and the capacity were calculated as:

$$m_{storage} = \dot{m}_{H2\_max} * t \tag{20}$$

Where $\dot{m}_{H2\_max}$ is the maximum hydrogen output of the electrolyzer per second and t is the number of seconds in a week. The density of the hydrogen differs according to which of the three compression methods are used, and the flow differs depending on electrolyzer type. Thus, there are six different tank size requirements, one for each combination.

A gas compression model exists in Modelon Impact is used to simulate the compressed hydrogen, for liquefied and cryo-compressed hydrogen models are developed.

The liquefication requires 35% of the energy contained in the produced hydrogen ($Liq.FactorH2$) [32]. With this knowledge, and the knowledge of how much hydrogen is produced, the energy required to liquify the hydrogen is calculated thusly.

$$P_{Liquification} = HHV_{H2} * \dot{m}_{H2} * Liq.Factor_{H2} \quad (21)$$

Where HHV_{H2} is the higher heating value of hydrogen, and $\dot{m}_{H2}$ is the mass flow of hydrogen.

The cryo-compression model principally works in the same way as liquefication, the difference being that hydrogen is compressed to 350 bar and cooled to 70 Kelvin. However, according to Yanxing et al. (2019) the energy requirement for both compression and cooling is equal to roughly 25% of the energy stored in the produced hydrogen. This is different from the liquification model, where no compression other than inside the electrolyzer occurred.

Once the model had been fully developed, hydrogen production is simulated over one year, emptying the hydrogen storage tank once a week if transported by ship, or continuously if by pipeline.

2.2.4 Economic Calculations

The economic calculations are performed in MATLAB, extracting values obtained from Modelon Impact and using them for the financial model. To calculate the LCOH the following equation is used [33]:

$$LCOH = \frac{CAPEX_{Project} + \sum_{t=1}^{i} \frac{Total\ yearly\ cost_t}{(1+DR)^t}}{\sum_{t=1}^{i} \frac{Yearly\ Hydrogen\ Production_t}{(1+DR)^t}} \quad (22)$$

The total cost of the project is calculated by adding the investment costs for all system parts Table 6. However, there are several costs that have not been addressed, yet are still needed in the system, such as grid connection, platform costs, reverse osmosis unit, etc., which was accounted for with the BOP factor. This factor was 20% of the total CAPEX of the project.

Table 6 System components cost for the offshore hydrogen production scenario.

Parameter	CAPEX	OPEX
Wind Turbine	15 MSEK/MW	3%
PEM Electrolyzer	7 MSEK/MW	2%
PEM Replacement	3.3 MSEK/MW	
Alkaline Electrolyzer	6.5 MSEK/MW	1.5%
Alkaline Replacement	2.9 MSEK/MW	
CGH2 Storage	4 230 SEK/kg	2%
LH2 Storage	1 450 SEK/kg	5%
CcH2 Storage	3 900 SEK/kg	4%
Onshore Pipeline	5 MSEK/km	
Offshore Pipeline	20 MSEK/km	
Ship	375 SEK/kgH2	4%
Ship Transport	5.5 SEK/tH2, km	
Truck	1.85 MSEK	12%
Truck CGH2 Transport	18 SEK/tH2, km	
Truck LH2 Transport	10 SEK/tH2, km	
Truck CcH2 Transport	12 SEK/tH2, km	
CGH2 Trailer	10 MSEK	2%
LH2 Trailer	6.5 MSEK	2%
CcH2 Trailer	12 MSEK	2%

3. RESULTS AND DISCUSSION

The following sub sections describe and discuss the results obtained from the study, as described in the methodology the study is made as two separate parts so no analytical comparison were made between the inhouse hydrogen production and the offshore hydrogen supply.

3.1 Airport inhouse hydrogen production results

By running the optimization model, the obtained optimum sizes are shown in Fig 2. The optimum capacity of the electrolyzer is found to be (2076 kg/h) for all scenarios. For the storage size, the compressed and cryo-compressed storage share the same optimum value of (12601 kg). In contrast, the liquified hydrogen optimum storage size varies due to the low cost of the storage cylinder and the high-power consumption required by the liquification process. Accordingly, the optimization tool assumed lower operation costs by increasing the hydrogen production and storage during the low-price period.

Fig. 3,4 and 5 show the results of the in-house produced hydrogen levelized cost and its composition, relation to the electrolysis type, and relation to the storage type.

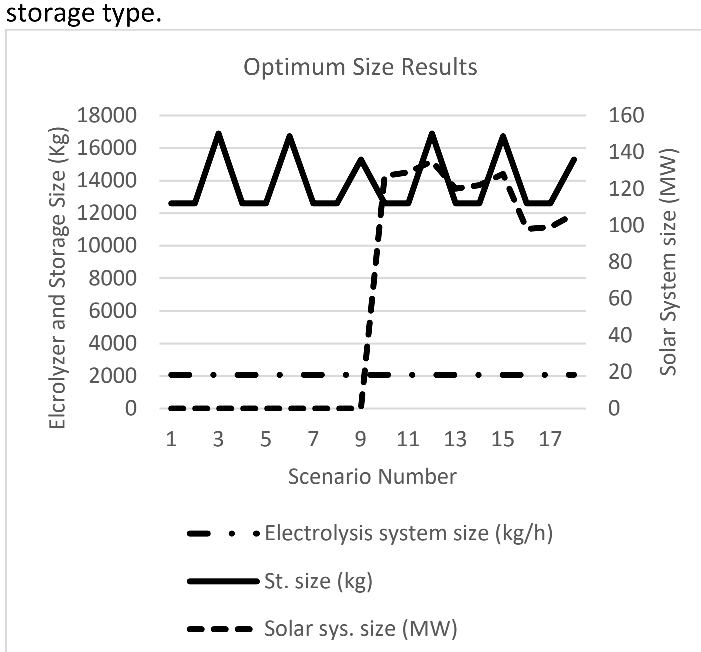

Fig. 2 Optimum size results.

The levelized cost results show a narrow range of values for all scenarios falls in the range of 2.93 - 2.44 Euro/kg H_2, which proves a promising future for hydrogen usage as fuel on a large scale. These results can be attributed to the low cost of electricity as the prices used in the study are the day ahead electricity prices.

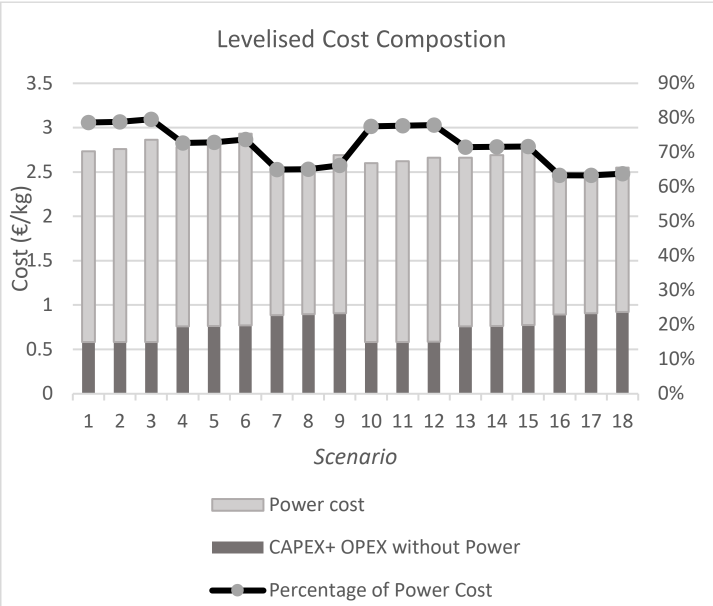

Fig. 3 levelized cost.

The PEM electrolysis showed higher cost compared to the alkaline electrolysis Fig. 4, even though the power consumption (the major levelized cost component) of the PEM is lower than the Alkaline. However, PEM electrolysis system has higher capital cost due to the high-cost metals usage. In contrast, solid oxide electrolysis benefits from its low power consumption and capital cost.

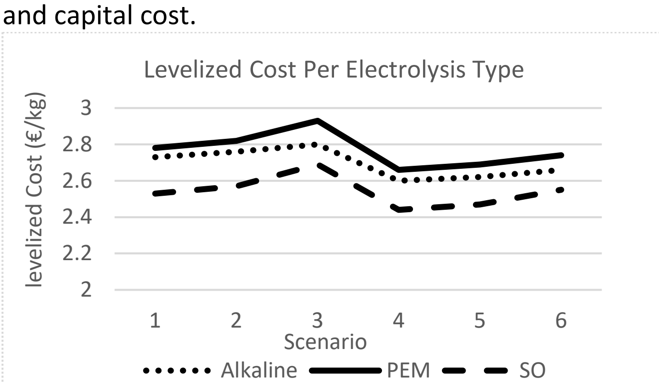

Fig. 4 levelized cost per electrolysis type.

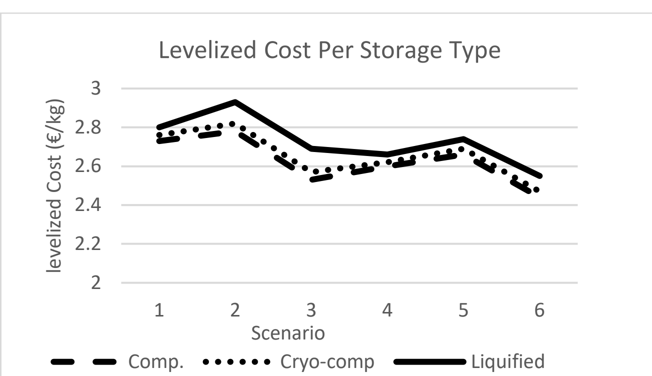

Fig. 5 levelized cost per storage type.

Figures 6.7 and 8 show the calculated carbon emissions resulting from the in-house production and their relation to the electrolysis and storage types. The CO_2 emissions followed the power consumption and varied between 34731 Ton/Year and 20861 Ton/Year, along 72% to 83% emissions reduction compared to the kerosene emissions for the same flights.

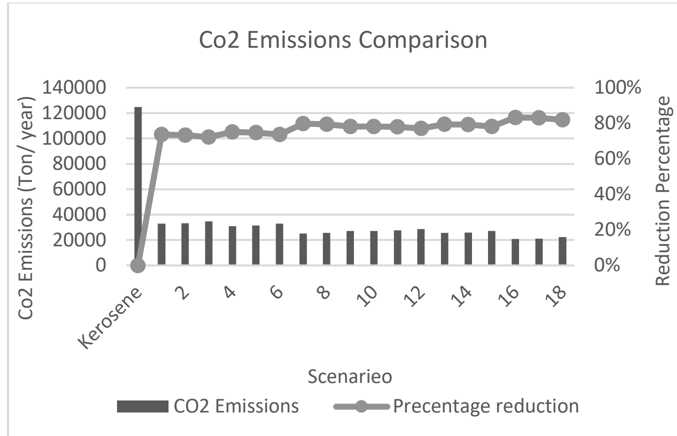

Fig. 6 Co2 emissions.

CO_2 emissions follow the power consumption as it represents the sole emissions source considered in this study, accordingly the Solar + Grid scenarios show lower annual emissions. Similarly, the emissions followed the power consumption in relation to the electrolysis and storage types, the higher the consumption the higher the emissions.

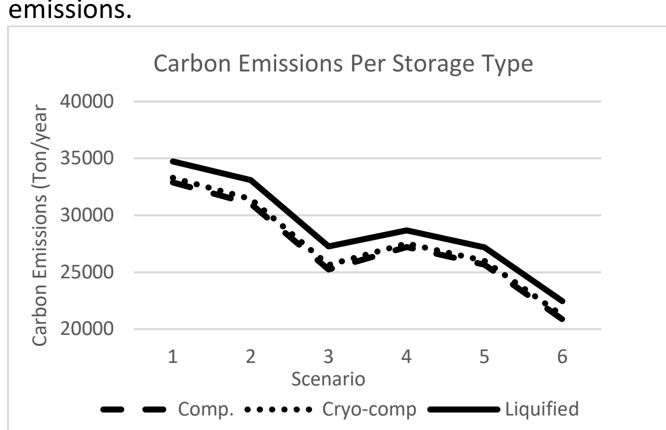

Fig. 7 Emissions per storage type.

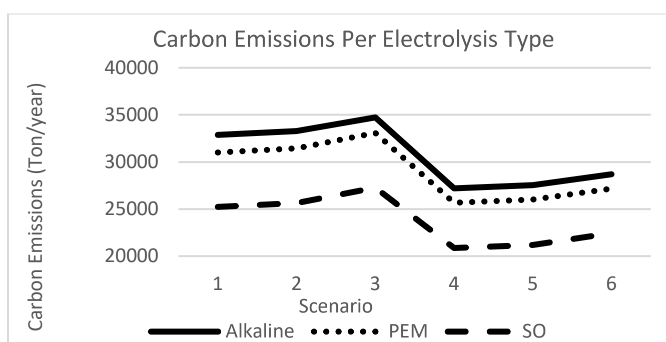

Fig. 8 Emissions per electrolysis type.

3.2 Offshore green hydrogen production and supply results.

The total annual hydrogen production per each type of electrolysis and compression technologies can be seen in Table 7, using a PEM electrolyzer rather than an alkaline electrolyzer produces more hydrogen for all types of compression technologies. Out of these compression methods, gas compression to 700 bars produces the highest amount of hydrogen. The reason for this is the high energy intensity required when cooling hydrogen, something that is present in both liquifying and cryo-compression. Because liquefication cools the hydrogen to temperatures lower than those of cryo-compression, also the boil off rate of 1-2% per day, the annual H2 production of this method is the least of the three.

Table 7 Offshore hydrogen annual production.

	CG	Liq.	Cryo-Comp.
PEM Electrolyzer [kt]	7.9	4.8	5.7
Alkaline Electrolyzer [kt]	7.3	4.5	5.2

The size of storage required to store the hydrogen production of one week is found to be as in Table 8.

Table 8 Offshore hydrogen storage capacity.

	CG	Liq.	Cryo-Comp.
PEM Electrolyzer [kg]	212 800	139 300	161 000
Alkaline Electrolyzer [kg]	196 700	131 600	151 200

The levelized cost of hydrogen is quite similar for all types of hydrogen compression, with cryo-compression being a bit higher than the other two. Gas compression has an LCOH of ~56 SEK/kg H_2, and liquification has roughly 61 SEK/kg H_2, with alkaline electrolysis being slightly more expensive on average as can be seen in Table 9.

Table 9 Offshore hydrogen levelized cost.

	CG	Liq.	Cryo- Comp.
PEM Electrolyzer [SEK/kgH2]	56	61	62
Alkaline Electrolyzer [SEK/kgH2]	56	61	65

As compressed hydrogen is the only type that can be transported by all the scenarios the LCOH come as shown in Table 10.

Table 10 Offshore compressed hydrogen levelized cost per transportation scenario.

	A	B	C	D
PEM Electrolyzer [SEK/kgH_2]	34	56	42	56
Alkaline Electrolyzer [SEK/kgH_2]	35	59	43	56

Even though there is a large difference in annual hydrogen production depending on the type of electrolyzer and compression method used, the LCOH does not differ very much. The smallest was 56 SEK/kg which came from the PEMEL CGH2 scenario, and the highest LCOH was 65 SEK/kg which is for the AEL cryo-compressed hydrogen combination. All four other combinations give results within this interval. PEMEL CGH_2 produced ~8 kt. of hydrogen annually, and the AEL LH_2 produced around 4.5 kt. The difference in LCOH between these two was 5 SEK/kg H_2. This means that even though the compressed gas scenario produced more hydrogen and thus generated more revenue, the components of the liquefication process must cost approximately proportionally less. In the various pathway options for the PEMEL, CGH_2 combination, it can easily be seen that scenario A and C are the best options. The two scenarios are around 20 SEK/kg H_2 cheaper than scenario B and D. This most likely stems from the annual cost of the trucks & trailers being a lot higher than the onshore pipeline which is used in scenario B and D. The trucks are costly for the compressed gas setup since a CGH_2 trailer cannot contain a large amount of hydrogen, only about one seventh as much as a liquid hydrogen trailer. Combine this with the OPEX cost of 12% for trucks and 2% for the trailers, it is a lot costlier to operate than the pipelines, which have a pretty much non-existent operational and maintenance cost.

4. CONCLUSION

Helping to achieve the aim of reducing or eliminating the CO_2 emissions of the aviation sector, this paper showed pathways of hydrogen production to be utilized as aviation fuel. In the case of in-house hydrogen production, CO_2 emissions can be reduced or eliminated by using electricity produced from renewable resources. The wind and solar energy resources in the study case location were not enough to provide an optimum solution utilizing only renewable energy. However, the evolving energy technologies can overcome these obstacles by delivering the renewable energy to the required site. This goal can be achieved by matching the renewable power profile with the hydrogen plant operation and directly linking the control of the plant to the renewable energy source, allowing the hydrogen plant to respond to any fluctuations or disturbance in the renewable output side. On the other hand, the offshore hydrogen production can be a solid solution if more efforts are made to develop and lower the cost of hydrogen transportation.

ACKNOWLEDGEMENT

This work partially made while the first author was sponsored by Swedish Institute Scholarships for Global Professionals.

This work partially made under (E-THRUST Project 52415) financed by Energimyndigheten and (THEMIS Project 202000260) financed by Knowledge Foundation.

REFERENCE

[1] NASA, "LIQUID HYDROGEN AS A PROPULSION FUEL,1945-1959," NASA History.

[2] BBC, "The hydrogen revolution in the skies," *Future Planet*, 2021.

[3] I. Yilmaz, M. Ilbaş, M. Taştan, and C. Tarhan, "Investigation of hydrogen usage in aviation industry," *Energy Convers Manag*, vol. 63, pp. 63–69, Nov. 2012, doi: 10.1016/J.ENCONMAN.2011.12.032.

[4] A. Osman *et al.*, "Hydrogen production, storage, utilisation and environmental impacts: a review," *Environ Chem Lett*, May 2021, doi: 10.1007/s10311-021-01322-8.

[5] P. Millet and S. Grigoriev, "Water Electrolysis Technologies," in *Renewable Hydrogen Technologies: Production, Purification, Storage, Applications and Safety*, Elsevier B.V., 2013, pp. 19–41. doi: 10.1016/B978-0-444-56352-1.00002-7.

[6] A. Ursúa, L. M. Gandía, and P. Sanchis, "Hydrogen production from water electrolysis: Current status and future trends," in *Proceedings of the IEEE*, Institute of Electrical and Electronics Engineers Inc., 2012, pp. 410–426. doi: 10.1109/JPROC.2011.2156750.

[7] S. A. Grigoriev, V. N. Fateev, D. G. Bessarabov, and P. Millet, "Current status, research trends, and challenges in water electrolysis science and technology," *Int J Hydrogen Energy*, vol. 45, no. 49, pp. 26036–26058, Oct. 2020, doi: 10.1016/j.ijhydene.2020.03.109.

[8] S.-Y. ; Lee *et al.*, "Citation: Recent Progress Using Solid-State Materials for Hydrogen Storage: A Short Review," 2022, doi: 10.3390/pr10020304.

[9] A. Züttel, "Hydrogen storage methods," *Naturwissenschaften*, vol. 91, pp. 157–172, 2004, doi: 10.1007/s00114-004-0516-x.

[10] M. Li *et al.*, "Review on the research of hydrogen storage system fast refueling in fuel cell vehicle," *Int J Hydrogen Energy*, vol. 44, no. 21, pp. 10677–10693, Apr. 2019, doi: 10.1016/J.IJHYDENE.2019.02.208.

[11] R. K. Ahluwalia, J.-K. Peng, and T. Q. Hua, "Cryo-compressed hydrogen storage," *Compendium of Hydrogen Energy*, pp. 119–145, 2016, doi: 10.1016/B978-1-78242-362-1.00005-5.

[12] M. Janic, "Is liquid hydrogen a solution for mitigating air pollution by airports?," *Int J Hydrogen Energy*, vol. 35, no. 5, pp. 2190–2202, Mar. 2010, doi: 10.1016/j.ijhydene.2009.12.022.

[13] J. Hoelzen, M. Flohr, D. Silberhorn, J. Mangold, A. Bensmann, and R. Hanke-Rauschenbach, "H2-powered aviation at airports – Design and economics of LH2 refueling systems," *Energy Conversion and Management: X*, vol. 14, May 2022, doi: 10.1016/j.ecmx.2022.100206.

[14] K. Ohmstede, C. Thies, A. Barke, and T. S. Spengler, "Evaluation of Hydrogen Supply Options for Sustainable Aviation," 2023, pp. 27–42. doi: 10.1007/978-3-031-38145-4_2.

[15] F. Schenke, J. Hoelzen, C. Minke, A. Bensmann, and R. Hanke-Rauschenbach, "Resource requirements for the implementation of a global H2-powered aviation," *Energy Conversion and Management: X*, vol. 20, Oct. 2023, doi: 10.1016/j.ecmx.2023.100435.

[16] M. Ball and M. Weeda, "The hydrogen economy—Vision or reality?," *Compendium of Hydrogen Energy*, pp. 237–266, 2016, doi: 10.1016/B978-1-78242-364-5.00011-7.

[17] M. Kayfeci, A. Keçebaş, and M. Bayat, "Hydrogen production," *Solar Hydrogen Production: Processes, Systems and Technologies*, pp. 45–83, Aug. 2019, doi: 10.1016/B978-0-12-814853-2.00003-5.

[18] A. A. Alzahrani and I. Dincer, "Modeling and performance optimization of a solid oxide electrolysis system for hydrogen production," 2018, doi: 10.1016/j.apenergy.2018.04.124.

[19] A. W. Thornton *et al.*, "Materials Genome in Action: Identifying the Performance Limits of Physical Hydrogen Storage," *Chem. Mater*, vol. 29, p. 24, 2017, doi: 10.1021/acs.chemmater.6b04933.

[20] J. Andersson and S. Grönkvist, "Large-scale storage of hydrogen," *International Journal of Hydrogen Energy*, vol. 44, no. 23. Elsevier Ltd, pp. 11901–11919, May 03, 2019. doi: 10.1016/j.ijhydene.2019.03.063.

[21] N. T. Stetson, S. McWhorter, and C. C. Ahn, "1 - Introduction to hydrogen storage," in *Compendium of Hydrogen Energy*, R. B. Gupta, A. Basile, and T. N. Veziroğlu, Eds., in Woodhead Publishing Series in Energy. , Woodhead Publishing, 2016, pp. 3–25. doi: https://doi.org/10.1016/B978-1-78242-362-1.00001-8.

[22] D. Jang, J. Kim, D. Kim, W. B. Han, and S. Kang, "Techno-economic analysis and Monte Carlo simulation of green hydrogen production technology through various water electrolysis technologies," *Energy Convers Manag*, vol. 258, Apr. 2022, doi: 10.1016/j.enconman.2022.115499.

[23] E. Rivard, M. Trudeau, and K. Zaghib, "Hydrogen storage for mobility: A review," *Materials*, vol. 12, no. 12. MDPI AG, Jun. 01, 2019. doi: 10.3390/ma12121973.

[24] G. Petitpas, A. J. Simon, J. Moreno-Blanco, D. Manager, and N. Rustagi, "Liquid Hydrogen Infrastructure Analysis; DOE Hydrogen and Fuel Cells Program FY 2017 Annual Progress Report," 2017. [Online]. Available: https://www.nrel.gov/transportation/

[25] I. A. Richardson *et al.*, "Low-cost, Transportable Hydrogen Fueling Station for Early FCEV Adoption Recommended Citation Low-cost, Transportable Hydrogen Fueling Station for Early FCEV Adoption," 2015. [Online]. Available: https://digitalcommons.unomaha.edu/econrealestatefacpub/15

[26] J. Lindahl, D. Lingfors, Å. Elmqvist, and I. Mignon, "Economic analysis of the early market of centralized photovoltaic parks in Sweden," *Renew Energy*, vol. 185, pp. 1192–1208, Feb. 2022, doi: 10.1016/j.renene.2021.12.081.

[27] A. Barke, T. Bley, C. Thies, C. Weckenborg, and T. S. Spengler, "Are Sustainable Aviation Fuels a Viable Option for Decarbonizing Air Transport in Europe? An Environmental and Economic Sustainability Assessment," *Applied Sciences (Switzerland)*, vol. 12, no. 2, Jan. 2022, doi: 10.3390/app12020597.

[28] A. Mohiuddin, T. Taha, Y. Zweiri, and D. Gan, "UAV payload transportation via RTDP based optimized

velocity profiles," *Energies (Basel)*, vol. 12, no. 16, Aug. 2019, doi: 10.3390/en12163049.

[29] D. S. Falcão and A. M. F. R. Pinto, "A review on PEM electrolyzer modelling: Guidelines for beginners," *Journal of Cleaner Production*, vol. 261. Elsevier Ltd, Jul. 10, 2020. doi: 10.1016/j.jclepro.2020.121184.

[30] R. Moradi and K. M. Groth, "Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis," *International Journal of Hydrogen Energy*, vol. 44, no. 23. Elsevier Ltd, pp. 12254–12269, May 03, 2019. doi: 10.1016/j.ijhydene.2019.03.041.

[31] V. Ruuskanen, J. Koponen, K. Huoman, A. Kosonen, M. Niemelä, and J. Ahola, "PEM water electrolyzer model for a power-hardware-in-loop simulator," *Int J Hydrogen Energy*, vol. 42, Apr. 2017, doi: 10.1016/j.ijhydene.2017.03.046.

[32] Z. Yanxing, G. Maoqiong, Z. Yuan, D. Xueqiang, and S. Jun, "Thermodynamics analysis of hydrogen storage based on compressed gaseous hydrogen, liquid hydrogen and cryo-compressed hydrogen," *Int J Hydrogen Energy*, vol. 44, no. 31, pp. 16833–16840, Jun. 2019, doi: 10.1016/j.ijhydene.2019.04.207.

[33] Y. Yan, H. Zhang, Q. Liao, Y. Liang, and J. Yan, "Roadmap to hybrid offshore system with hydrogen and power co-generation," *Energy Convers Manag*, vol. 247, Nov. 2021, doi: 10.1016/j.enconman.2021.114690.

[34] IEA, "Tracking Transport 2021," IEA, Paris, 2021.

[35] Destination 2050, "INDUSTRY COMMITMENTS," Destination 2050, Amsterdam, 2021.

[36] DOE, "Hydrogen Storage Challenges," 25 3 2022. [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-storage-challenges.

[37] Stockholm Skavsta Airport, "Stockholm Skavsta Airport," 28 3 2022. [Online]. Available: https://www.skavsta.se/en/.

[38] Wizz Air, "Information and Services," 28 3 2022. [Online]. Available: https://wizzair.com/en-gb/information-and-services/about-us/about-wizz.

[39] AIRBUS, "Aircraft A320," 28 3 2022. [Online]. Available: https://aircraft.airbus.com/en/aircraft/a320/a320ceo#:~:text=With%20a%20versatile%20cabin%20that,of%20up%20to%20180%20travellers.).

[40] Stockholm Skavsta Airport, "Passenger statistics 2019," Stockholm Skavsta Airport, Nyköping , 2019.

[41] NREL, "System Advisor Model (SAM)," 29 2 2020. [Online]. Available: https://sam.nrel.gov/.

[42] Department for business, Energy and Industrial Strategy- United Kingdom, "Hydrogen Production Costs-2021," The National Archives, London, 2021.

[43] entsoe, "Day Ahead Price," 1 4 2022. [Online]. Available: https://transparency.entsoe.eu/transmission-domain/r2/dayAheadPrices/show?name=&defaultValue=false&viewType=TABLE&areaType=BZN&atch=false&dateTime.dateTime=31.03.2021+00:00|CET|DAY&biddingZone.values=CTY|10YSE-1--------K!BZN|10Y1001A1001A44P&resolution.va.

[44] F. Dolff, "Swedish wind power-A market analysis for the year 2018," Västra Götalandsregionen, Götaland, 2018.

[45] Electricity map, "Climate Impact by Area," 6 4 2022. [Online]. Available: https://app.electricitymap.org/map.

[46] CPM, " CPM database," 20 4 2022. [Online]. Available: http://cpmdatabase.cpm.chalmers.se/IAM/index.asp?IAM=EPS+default&IAMVer=2000.

[47] SMHI, "Ladda ner meteorologiska observationer," 2022. [Online]. Available: https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer/#param=wind,stations=all.