

Life Cycle Emissions of Hydrogen Production Technologies in the Nordics

Jenni Iso-Oja* and Olli Himanen

ABSTRACT

Europe has ambitious goals for future hydrogen production. The increasing production of green hydrogen demands for research on the different environmental effects of hydrogen production methods. This study compiles comprehensive and comparable values of the life cycle emissions of three electrolyzer technologies: alkaline water electrolyzers, proton exchange membrane water electrolyzers and solid oxide electrolysis cells. A comparison of hydrogen production via wind and solar electricity is listed. Additionally, the changes in land usage required for the hydrogen production process are considered. The emission comparison reveals that hydrogen produced using wind energy is environmentally more sustainable than using solar energy, regardless of the electrolyzer technology.

Keywords: Electrolysis, greenhouse gas emissions, land use, life cycle analysis.

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1. INTRODUCTION

The risks of climate change have led to increased attention being paid to greenhouse gas (GHG) emissions. Hydrogen is a possible solution for reducing GHG emissions. Hydrogen use is already established in the chemical industry and refining sectors, but is predicted to increase in sectors such as power and transport [1]. Currently, however, hydrogen production is emission intensive [1].

According to the International Energy Agency (IEA), hydrogen use was 95 Mt globally in 2022 [1]. 62% of this hydrogen was produced using natural gas, 21% coal, and 16% as a byproduct. Only 0.7% of the hydrogen production had low emissions. However, its production is continually increasing [1].

The IEA has created a scenario to reach net-zero emissions by 2050 [2]. In this scenario, hydrogen use is over 200 Mt by 2030 and continues to increase. By 2050, hydrogen production is predicted to reach 500 Mt, and nearly all of this would be produced with low carbon emissions. Based on current projects, these numbers are too high [1]; however, clean hydrogen production is rapidly increasing.

Production technologies for clean hydrogen are still developing, and their impact on the planet must be analyzed. Life cycle assessments (LCA) have been carried out for many technologies and specific case studies [3]–[5]. They have not been compared with each other considering criteria such as land use. This study analyzes the differences between electrolysis technologies and their life

cycle emissions in the context of Nordic hydrogen production, as Nordic countries aim to be forerunners in the hydrogen transition. The research was conducted using LCAs found in the literature and data acquired from datasheets from technology manufacturers. The aim is to compare the GHG emissions of three different electrolysis system technologies from cradle-to-gate. Therefore, only the global warming potential (GWP) category of LCA's has been studied. Wind and solar power were compared as the electricity source for hydrogen production. The end use of hydrogen is not within the scope of this study.

The aim of this study is to obtain a comparable emission value for green hydrogen produced in the Nordics. For comparison, the emissions are divided into three categories: system emissions, that is, the manufacturing of the electrolyzer stack and the balance of plant (BoP); the operation and its required electricity production; and necessary changes in land use. Emissions related to manufacturing were acquired from LCAs in the literature. The operation phase emissions consist of the life cycle emissions of the electricity used for hydrogen production. Land use emissions are based on the size of the land area, which requires changes for hydrogen production. The manufacture stage emissions are discussed in Section 3, the operation phase emissions in Section 4, and land use related emissions in Section 5.



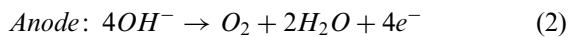
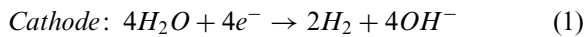
2. WATER ELECTROLYSIS TECHNOLOGIES

Water electrolysis uses electricity to split water molecules into hydrogen and oxygen molecules. This paper covers the three most common water electrolysis technologies: alkaline water electrolysis (AWE), proton exchange membrane water electrolysis (PEMWE), and solid oxide electrolyzer cells (SOEC) [6].

AWE has been used and developed for over 100 years [6], and has reached a technology readiness level (TRL) of 9 [7]. Similarly, PEMWE is also an established technology with a TRL of 9 [7]. Compared with AWE, PEMWE has a slightly higher efficiency and can achieve a higher hydrogen purity [8], [9] with a shorter response time [10]. However, it is more expensive than AWE [7]. SOEC is slightly less developed, with a TRL of 8 [7]. It has a shorter lifetime and significantly higher capital cost than the other two technologies [8]. SOEC operates at higher temperatures, which reduces the demand for electrical energy [8].

2.1. Alkaline Water Electrolysis (AWE)

An alkaline electrolyzer cell has an anode and a cathode, usually made of nickel and a catalytic coating. The electrodes are separated by a diaphragm, as shown in Fig. 1. The diaphragm is usually a material called Zirfon Perl, which is composed of zirconium dioxide and polysulfone [5]. An aqueous electrolyte solution of potassium or sodium hydroxide flows to both electrodes [11]. The electrode reactions are presented in (1) and (2) [3], [11]. The charge carrier in AWE is OH^- as seen from the reactions [3]:



An AWE is typically operated in the temperature range of 60°C – 90°C [5] and it can produce hydrogen with a purity over 99.9% [11]. The efficiency of an AWE system is 50%–70% [9]. The lifetime of an AWE system is approximately 20 years, and the electrodes can withstand 5000–10000 start/stop cycles [11]. According to the literature, AWE systems have CAPEX ranging from 1000 €/kW to 1200 €/kW [9].

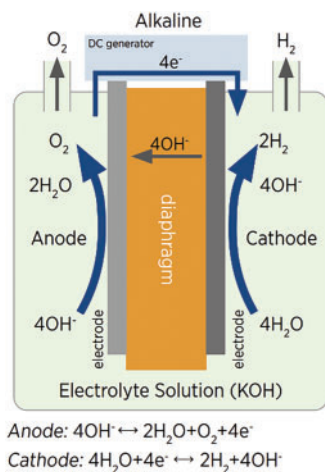
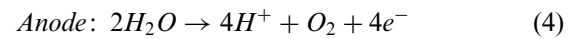
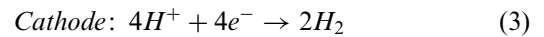


Fig. 1. Structure of an alkaline electrolyzer cell [12].

2.2. Proton Exchange Membrane Water Electrolysis (PEMWE)

PEMWE is the second of the more established electrolysis technologies [13]. PEMWE was first developed in the 1960s [3], [6] and is now an established technology with a TRL of 9 [7]. Similar to an AWE cell, a proton exchange membrane (PEM) cell consists of electrodes and an electrolyte. Instead of a liquid electrolyte, PEM cells have a solid membrane that separates the cathode and the anode [14]. A PEM cell is illustrated in Fig. 2. The membrane is usually a polymer, which goes by the brand name Nafion [14]. The cathode is platinum-based, and the anode is iridium-based [14]. In PEMWE, the charge carrier is H^+ which moves from the anode to the cathode through the membrane. The electrode reactions are presented in (3) and (4) [3]:



The operating temperature of PEMWE usually ranges from 50°C to 80°C [3], and the system produces hydrogen with a purity of 99.99%. PEM cells have an efficiency of 62%–82%, and system efficiencies are approximately 50%–70%, at lower heating value (LHV) [14]. A PEMWE system lifetime is rated at approximately 20 years, and the stack lifetime is approximately seven years [14]. According to the literature, PEMWE can have a CAPEX of approximately 1860 €/kW–2320 €/kW [9]. Both lifetime and cost are system and application specific.

2.3. Solid Oxide Electrolyzer Cell (SOEC)

SOEC differs from AWE and PEMWE in terms of the operating temperature. While AWE and PEMWE systems operate at lower temperatures, an SOEC operates at approximately 600°C – 900°C [5]. SOEC is slightly less developed than the other two water electrolysis technologies, and its TRL is 8 [7]. Owing to the higher operating temperature, the hydrogen production efficiency of an SOEC is higher than that of low-temperature electrolyzers.

An SOEC has a solid membrane through which ions move from the cathode to the anode [3]. In SOEC, O^{2-} acts

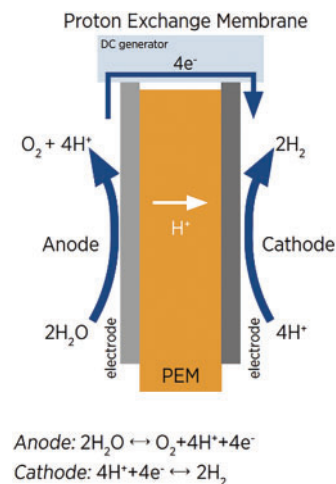
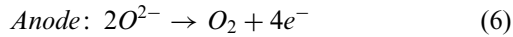
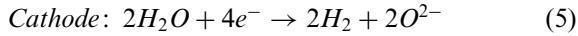


Fig. 2. Structure of a PEM electrolyzer cell [12].

as the charge carrier. The electrode reactions are presented in (5) and (6) [3]. A diagram of an SOEC is shown in Fig. 3.



The operating pressure of SOEC is below 25 bar [3], usually at atmospheric pressure [12], and the hydrogen produced reaches a purity of 99.9%. The electrical efficiency of SOEC is 75%–85% [12]. Current challenges related to SOEC are related to the stability of the system as well as material degradation due to high temperatures [3]. Owing to its high temperature, SOEC is more suitable for constant hydrogen production, whereas low-temperature electrolyzers can be developed for dynamic hydrogen production.

3. SYSTEM LIFE CYCLE EMISSIONS OF ELECTROLYZER TECHNOLOGIES

3.1. Life Cycle Emissions of AWE

Krishnan *et al.* [4] studied the current and potential future emissions of alkaline electrolyzers through a prospective life cycle analysis with a cradle-to-gate system boundary. In the study, emissions were divided into categories of stack manufacture, balance of plant and power electronics, and electricity use. In our study, the stack manufacture and balance of plant and power electronics were considered within the system emissions. This study uses the “baseline scenario” based on data from 2020 [4]. The GHG emissions of an AWE plant, calculated for a 1 GW plant, are 0.21 kgCO₂eq/kgH₂ [4]. Current systems are not yet as large, but they are assumed to develop continually. The electrolyzer plant emissions are divided so that 0.18 kgCO₂eq/kgH₂ come from the stack and 0.032 kgCO₂eq/kgH₂ from the BoP [4]. Gerloff [3] analyzed the environmental impacts of electrolytic hydrogen production using three different technologies and various energy scenarios. He reports total life cycle emissions of 2.90 kgCO₂eq/kgH₂, when using renewable energy. Most of the emissions are caused by solar power generation. 0.14 kgCO₂eq/kgH₂ of the emissions are from the electrolyzer system, as per Krishnan *et al.* [4].

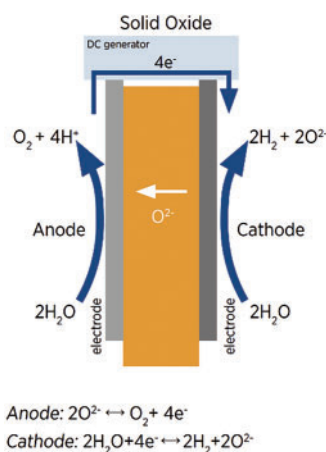


Fig. 3. Structure of a solid oxide electrolyzer cell [12].

Bhandari *et al.* [15] reviewed hydrogen production LCAs, and based on the review, AWE systems have life-cycle system emissions of 0.21 kgCO₂eq/kgH₂. Here, the system also includes compression and storage infrastructure. Ghandehariun and Kumar [16] conducted an LCA of wind-powered hydrogen production through electrolysis in Western Canada. They report total life cycle GHG emissions of 0.68 kgCO₂eq/kgH₂ ± 0.05 kgCO₂eq/kgH₂, of which 0.20 kgCO₂eq/kgH₂ come from the electrolyzer manufacturing and hydrogen compression. The remaining emissions are caused by wind power generation and hydrogen transportation. Khan *et al.* [17] conducted an LCA of green hydrogen production with a cradle-to-grave system boundary. They focused on the electrolyzer value chain, including the stages of manufacturing, transport, operation, and end-of-life. The manufacturing stage of an AWE system was calculated to cause emissions of 0.1 kgCO₂eq/kgH₂–0.2 kgCO₂eq/kgH₂.

Zhao *et al.* [5] conducted an LCA of three electrolysis technologies. The emissions accounted for are related to material acquisition and electricity usage in manufacturing processes. In the study, stacks were manufactured using the Danish electricity mix. The stack and BoP of an AWE system cause a total of 0.016 kgCO₂eq/kgH₂ in emissions. According to Vilbergsson *et al.* [18], AWE stack manufacturing using renewable energy causes emissions of 0.047 kgCO₂eq/kgH₂–0.064 kgCO₂eq/kgH₂. These numbers are based on three scenarios in 2020: wind electricity use in Belgium, grid electricity use in Iceland, and Hellisheidi geothermal power in Iceland. In the case of geothermal power, carbon capture and storage (CCS) is used to mitigate emissions.

Zhang *et al.* [19] compared onshore and offshore wind power coupled with three electrolysis technologies. According to this study, onshore wind electrolysis using an AWE system has total emissions of 0.094 kgCO₂eq/kgH₂. The construction of the hydrogen production plant accounted for 22% of the emissions, causing system emissions of 0.021 kgCO₂eq/kgH₂. Wei *et al.* [20] find the electrolyzer system of an AWE to have a climate change impact of 0.00549 kgCO₂eq/MJH₂–0.00592 kgCO₂eq/MJH₂ (0.66–0.71 kgCO₂eq/kgH₂, LHV basis). Iyer *et al.* [21] found that the manufacturing of AWE stacks and BoP equipment causes emissions of 0.093 kgCO₂eq/kgH₂–0.232 kgCO₂eq/kgH₂. The result depends on the capacity factor and the source of energy used in the manufacturing processes.

Based on these values in literature, the median life cycle emissions of AWE manufacturing are calculated to be 0.17 kgCO₂eq/kgH₂, while the range is 0.016 kgCO₂eq/kgH₂–0.71 kgCO₂eq/kgH₂. This broad range is mainly due to assumptions related to the electricity sources used during manufacturing.

3.2. Life Cycle Emissions of PEMWE

According to Krishnan *et al.* [4], PEMWE has system emissions of 0.17 kgCO₂eq/kgH₂, with the stack manufacture causing 0.13 and the BoP causing 0.04 kgCO₂eq/kgH₂. The calculation was conducted assuming that the system had a capacity of 1 GW. Current PEMWE plants are in the MW scale; therefore,

the emissions per hydrogen produced can be assumed to be higher. However, constant development furthers the decrease in emissions. According to Gerloff [3], the total life cycle GHG emissions of a PEMWE system utilizing renewable energy are 2.94 kgCO₂eq/kgH₂. Of these, those caused by the system manufacturing are 0.07 kgCO₂eq/kgH₂, as per Krishnan *et al.* [4].

Bareiß *et al.* [14] calculated the emissions of a PEMWE system in various scenarios. The most favorable scenario, utilizing only renewable electricity and operating for 3000 h, causes emissions of 3.3 kgCO₂eq/kgH₂. The study estimated 96% of total emissions to come from electricity, approximately 4% from BoP, and less than 1% from the stack. Based on this, the system emissions are less than 0.17 kgCO₂eq/kgH₂, where the BoP causes around 0.13 kgCO₂eq/kgH₂ and the stack less than 0.04 kgCO₂eq/kgH₂. Although the system emissions are similar to those in Krishnan *et al.* [4], the distribution of emissions between the stack and BoP is the opposite. A reason for this might be that Bareiß *et al.* [14] estimated an improved stack, whereas Krishnan *et al.* [4] used the state-of-the-art stack of 2020. A second difference is that Krishnan *et al.* [4] considered the use of three stacks over the lifetime of the entire electrolyzer system. Bareiß *et al.* [14] did not specify how they accounted for the difference in the lifetimes of the stack and the BoP. Khan *et al.* [17] calculate the system emissions of a PEMWE system to be 0.1 kgCO₂eq/kgH₂–0.2 kgCO₂eq/kgH₂. Here about 60% of the emissions were produced by BoP and 40% by the stack. They used the stack lifetime as a reference for the lifetime of the entire system. This means that the BoP does not reach its full lifetime, which increases its emissions.

Vilbergsson *et al.* [18] conducted a case study to analyze hydrogen production in Europe. They compared three electrolysis technologies in three different countries. The PEMWE stack production and electrolysis system reached emissions of 0.074 kgCO₂eq/kgH₂–0.6 kgCO₂eq/kgH₂. This broad range is due to different electricity and full-load hour scenarios. All scenarios used renewable electricity. Patel *et al.* [22] compared different hydrogen production methods and their environmental impact. The results indicated emissions of 0.6 kgCO₂eq/kgH₂–2.5 kgCO₂eq/kgH₂ for hydrogen production using a PEMWE system coupled with wind or PV power. In these scenarios, approximately 0.1 kgCO₂eq/kgH₂ is caused by the electrolysis system, and the rest is from electricity production.

Zhang *et al.* [19] reported emissions of 0.114 kgCO₂eq/kgH₂ when producing hydrogen using a PEMWE system coupled with onshore wind electricity. Of these total emissions, 27% were caused by the construction of the hydrogen plant, equaling to 0.031 kgCO₂eq/kgH₂. In their comparative LCA of hydrogen production technologies, Wei *et al.* [20] calculated PEMWE system equipment emissions of 0.00144–0.00172 kgCO₂eq/MJH₂ (0.17–0.21 kgCO₂eq/kgH₂, LHV basis). Iyer *et al.* [21] reported PEMWE system emissions of 0.033–0.132 kgCO₂eq/kgH₂. Emissions depend on the capacity factor and source of energy used in manufacturing processes. In their LCA of electrolysis technologies, Zhao *et al.* [5] calculated the emissions for the stack and BoP of a PEMWE system. These system emissions reached 0.050 kgCO₂eq/kgH₂.

Based on these values in the literature, the median life cycle emissions of PEMWE system manufacturing are 0.12 kgCO₂eq/kgH₂, and these emissions range from 0.031 to 0.6 kgCO₂eq/kgH₂.

3.3. Life Cycle Emissions of SOEC

According to Mehmeti *et al.* [23], manufacturing an SOEC stack causes emissions of 0.369 kgCO₂eq/kgH₂. The manufacturing of the BoP causes emissions of 0.0427 kgCO₂eq/kgH₂. This gives the total system emissions of 0.412 kgCO₂eq/kgH₂. Mehmeti *et al.* [23] also specified emission categories for maintenance, heat, and water. Maintenance causes emissions of 0.0778 kgCO₂/kgH₂, water causes 0.0088 kgCO₂/kgH₂, and heat causes 1.29 kgCO₂/kgH₂ when the heat is produced using natural gas. In a scenario utilizing wind as the electricity source, the emissions from electricity were calculated to be 0.467 kgCO₂/kgH₂ [23]. This indicates that heat generates more than two times greater emissions than electricity. The total emissions of this wind scenario were 2.26 kgCO₂eq/kgH₂, meaning that heat was responsible for over half of the emissions.

The source of heat is an important factor for environmental sustainability. In our study, renewable electricity was the heat source for SOEC. This was considered in the electricity demand of the system and the level of emissions caused by the total electricity used. In cases where heat is readily available as waste heat from another process, zero heat emissions could be assumed. The source of the heat introduces more complexity into the emissions and requires more exact calculations based on case specifics. For an accurate emission estimate, a share of heat production emissions should be allocated for the electrolysis process if the heat becomes a valuable input instead of waste.

According to Häfele *et al.* [24], the emissions caused by stack manufacturing for an SOEC are approximately 108 kgCO₂eq/kW. With a 20000h lifetime [24], this results in emissions of 0.24 kgCO₂eq/kgH₂. This was calculated using an average electricity demand of 44 kWh/kgH₂. According to Zhao *et al.* [5], SOEC system emissions sum up to 0.016 kgCO₂eq/kgH₂ when accounting for the material use and electricity needed for manufacturing. Vilbergsson *et al.* [18] compared electrolytic hydrogen production in Europe. In the comparison, the SOEC stack production and electrolysis system reached emissions of 0.04–0.33 kgCO₂eq/kgH₂. These values represent different electricity and full-load hour scenarios. All scenarios used renewable electricity.

Zhang *et al.* [19] found that an SOEC electrolyzer causes emissions of 0.211 kgCO₂eq/kgH₂, when producing hydrogen coupled with onshore wind. Of these emissions, the hydrogen production system is responsible for 12%, that is, 0.025 kgCO₂eq/kgH₂. Wei *et al.* [20] conducted a comparative LCA of hydrogen production technologies and found the SOEC system equipment causes emissions of 0.00162 kgCO₂eq/MJH₂ (0.19 kgCO₂eq/kgH₂, LHV basis). The LCA conducted by Iyer *et al.* [21] reached system emissions of 0.045 kgCO₂eq/kgH₂ produced by an SOEC.

TABLE I: ELECTROLYZER SYSTEM EMISSIONS OVER LIFETIME ACCORDING TO LITERATURE (kgCO₂eq/kgH₂)

Reference	AWE	PEMWE	SOEC
Krishnan <i>et al.</i> [4]	0.21	0.17	–
Gerloff [3]	0.14	0.07	–
Bhandari <i>et al.</i> [15]	0.21	–	–
Ghandehariun & Kumar [16]	0.20	–	–
Khan <i>et al.</i> [17]	0.1–0.2	0.1–0.2	–
Zhao <i>et al.</i> [5]	0.016	0.05	0.016
Vilbergsson <i>et al.</i> [18]	0.047–0.064	0.074–0.6	0.04–0.33
Zhang <i>et al.</i> [19]	0.094	0.031	0.025
Wei <i>et al.</i> [20]	0.66–0.71	0.17–0.21	0.19
Iyer <i>et al.</i> [21]	0.093–0.232	0.033–0.132	0.045
Bareiß <i>et al.</i> [14]	–	0.17	–
Patel <i>et al.</i> [22]	–	0.1	–
Mehmeti <i>et al.</i> [23]	–	–	0.42
Häfele <i>et al.</i> [24]	–	–	0.24
Median	0.17	0.12	0.12

The median life cycle emissions of manufacturing an SOEC system are calculated to be 0.12 kgCO₂eq/kgH₂, based on the literature. The emission range is 0.016–0.41 kgCO₂eq/kgH₂.

3.4. System Emission Comparison

Table I presents the system emissions of the three electrolyzer technologies, according to the literature, as discussed in the previous sections. The median of the emissions found in the literature has also been reported. The system emissions shown in Table I include emissions from manufacturing the stack and BoP. Emissions related to operation were not accounted for in these values. The ranges of the emissions of different electrolysis technologies vary slightly, with low-temperature electrolyzers having larger ranges than SOEC. The median emissions of all three electrolyzers are similar.

4. RENEWABLE ELECTRICITY PRODUCTION FOR ELECTROLYSIS

Because electricity is the main emission source in electrolytic hydrogen production [3], [4], achieving low life cycle emissions requires the use of low-emission electricity. Future energy mix scenarios might be able to reach emissions similar to conventional hydrogen production technologies, but these values are far from the EU standards for green hydrogen [3]. The EU has set an emission standard of 3.38 kgCO₂eq/kgH₂ for green hydrogen production [25]. To reach this emission limit, it is important to assess the differences between emissions related to different electricity sources. The electricity scenarios considered for hydrogen production in this study are 100% onshore wind electricity and 100% solar electricity.

As an example of Nordic energy, the Finnish electricity mix is illustrated in Fig. 4. Much of Finnish electricity is produced using renewables, and the average direct emissions are approximately 38 gCO₂/kWh (in 2023) [26]. Additionally, life cycle emissions are higher than direct

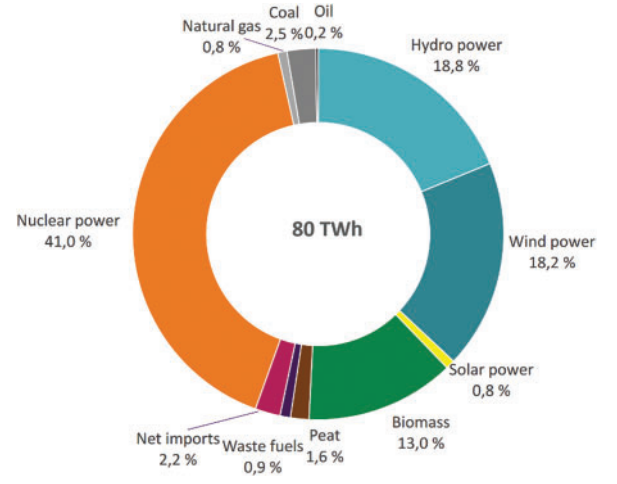


Fig. 4. Finnish energy mix in 2023 [27].

emissions, reportedly 49 gCO₂eq/kWh in 2023 [26]. Renewable electricity, such as wind and solar power, has lower life cycle emissions than the Finnish electricity mix.

4.1. Wind Power

Wind power is an electricity production technology with low emissions. Bhandari *et al.* [28] assessed the life-cycle greenhouse gas emissions from wind farms and analyzed the effect of turbine size on emissions. They found that the emissions from onshore wind farms follow a logarithmic correlation with the annual energy yield of the farm. Data were collected from multiple LCA studies. Most studies were conducted in the years 2000–2015. Four studies were conducted between 2018 and 2019. Of the newer studies, three discussed onshore wind farms, and one discussed offshore wind farms. The emissions of onshore wind farms were 11.8 [29], 8.65 [30] and 52.7 gCO₂eq/kWh, which reduced to 18 gCO₂eq/kWh when end-of-life recycling was accounted for [31].

A study specifically on Finnish wind power found the average life cycle emissions of a “typical Finnish wind farm” to be 7.18 gCO₂eq/kWh [32]. This amount accounts for emissions from manufacturing, transportation, installation, and end-of-life. The emissions of the operational phase of wind power are negligible [32]. An average Finnish wind farm is considered to consist of ten modern horizontal-axis wind turbines operating onshore, located on forest land [32]. The farm has a lifetime of 20 years. The farm in the calculation included a transformer station and service roads. The average Finnish wind farm has a nominal capacity of 48.6 MW, and turbines, buildings, and roads require land changes of approximately 20 hectares [32]. The capacity factor of wind power in Finland is typically 33% [33].

Dolan and Heath [34] conducted a literature review and harmonization of life cycle assessments performed on utility-scale wind power plants before 2012. The review contained 72 studies that fulfilled the criteria for the LCA method, transparency and completeness of reporting, and the relevance of the technology. The life cycle emissions of these assessments ranged from 1.7 gCO₂eq/kWh–81 gCO₂eq/kWh, the median being 12 gCO₂eq/kWh. After harmonization, the median decreased to 11 gCO₂eq/kWh.

Vestas conducted an LCA of a 100 MW onshore wind plant in Germany consisting of its V136–4.2 MW turbines [35]. They calculated emissions of 5.6 gCO₂eq/kWh. The capacity factor of the plant is approximately 43%. In the Nordics, the average capacity factor is lower, approximately 30% [33], so the emissions would be slightly higher. Bošnjaković *et al.* [36] discussed the environmental impact of wind farms. They calculated emissions of 11 gCO₂eq/kWh for onshore wind farms and 14 gCO₂eq/kWh for offshore wind farms.

Dammeier *et al.* [37] quantified the GHG footprints of thousands of wind farms around the world to cover 79% of the global wind capacity installed in 2019. They reached greenhouse gas emissions of 4–56 gCO₂eq/kWh (2.5–97.5 percentile), with a median of 10 gCO₂eq/kWh. Wind farms offshore and along the coast had lower footprints than those further inland. The emission ranges varied from continent to continent, but the median emissions remained similar. One disadvantage of this analysis is that it does not include grid connections in its scope. In addition, the end-of-life stage was not accounted for. Both would slightly affect the emissions. This emission factor has also been used by the EU. The Joint Research Centre (JRC) published a technical report on emission factors in 2017 [38]. They report wind power to have an emission factor of 10 gCO₂eq/kWh, referencing the ELCD v3.2 database. Newer technology might result in lower emissions, but including grid connections would increase emissions. However, the length of the grid connection installations varies case by case and is difficult to account for. Due to the absence of more reliable data, a global median of 10 gCO₂eq/kWh was used as the wind power emissions in this study. This number is of the same order of magnitude as the results of the other studies.

4.2. Solar Power

According to Bošnjaković *et al.* [39], the range of GHG emissions from PV systems is 12.5 gCO₂eq/kWh–126 gCO₂eq/kWh in Europe. The wide range is caused by varying technologies, location differences, and different energy mixes used in manufacturing. In the study, the mean emissions of small systems of 1–4 MW were approximately 40 gCO₂eq/kWh, and systems larger than 4 MW had emissions of 30 gCO₂eq/kWh. Gan *et al.* [40] found that the life cycle emissions caused by solar PV in the United States fall in the range of 26 gCO₂eq/kWh–53 gCO₂eq/kWh, with an average of 37 gCO₂eq/kWh.

Mehedi *et al.* [41] performed a life cycle analysis of utility-scale solar energy systems entailing solar PVs connected to a grid as well as batteries used to balance power. The entire system has life cycle emissions of 98.3 gCO₂eq/kWh–149.3 gCO₂eq/kWh. The emissions related to solar PV production and its mounting and integration into the grid resulted in approximately 40 gCO₂eq/kWh. Ferrara *et al.* [42] conducted a life-cycle assessment of photovoltaic power production in Italy using a scenario for 2022 and a future scenario estimated for 2030. The GHG emissions in the 2022 scenario were calculated to be 37 gCO₂eq/kWh.

Daniela-Abigail *et al.* [43] conducted an LCA of 1 kW crystalline silicon solar panels located in Mexico over a 25-year lifetime. They compared the environmental effects of end-of-life landfilling to those of recycling. In the case of landfilling, the solar panels produced GHG emissions of 798 kgCO₂eq/kW and in the case with recycling the emissions were 593 kgCO₂eq/kW. With energy production according to Nordic insolation conditions (approximately 1000 kWh/kW_p annually [44]), the emissions are 32 and 24 gCO₂eq/kWh, respectively.

The Intergovernmental Panel on Climate Change (IPCC) suggested cost, performance, and emission factors for different technologies [45]. They report median emissions of 48 gCO₂eq/kWh for utility-scale solar PV and 11 gCO₂eq/kWh for onshore wind. However, this estimate was made in 2014. In the technical report by The Joint Research Centre (JRC) [38], it is suggested to use the harmonized life cycle emissions calculated by Amponsah *et al.* [46] for solar PV electricity production. They report average emissions of 30 gCO₂eq/kWh. This was the emission factor used in the calculations in this study.

4.3. Electricity Demand of Electrolysis Technologies

To create an equal comparison between the electricity demands of the three electrolysis technologies, the hydrogen produced is standardized. The aim is 99.99% pure hydrogen at 30 bar pressure. In the literature, the electricity demand of AWE ranges from 49 kWh/kgH₂ to 55 kWh/kgH₂. Krishnan *et al.* [4] use a value of 49 kWh/kgH₂ in their calculations. Gerloff [3] use a value of 51.8 kWh/kgH₂, while Aghakhani *et al.* [47] use 54.7 kWh/kgH₂.

The electricity demand of the electrolyzers was also acquired from manufacturer datasheets. Sunfire GmbH has a 10 MW alkaline module, which produces hydrogen at a pressure of 30 bar with a 99.8% purity before cleaning [48]. This system has a stack-level specific energy consumption of 4.14 kWh/Nm³H₂–4.51 kWh/Nm³H₂, which is approximately 46–51 kWh/kgH₂. An alkaline electrolyzer by Nel run at atmospheric pressure has a stack electricity demand of 50 kWh/kgH₂ (±1.1%) [49]. Hydrogen compression from 0 to 30 bar requires approximately 2 kWh/kgH₂ electricity [50]. As a result, the electricity demand increases to approximately 52 kWh/kgH₂.

Based on the literature and datasheets, the alkaline electrolyzer electricity demand ranges from 46 to 55 kWh/kgH₂, with a mean value of 51.6 kWh/kgH₂. The range found in datasheets from electrolyzer manufacturers is 46–52 kWh/kgH₂. This range and a mean of 50 kWh/kgH₂ are used in the calculations in this study.

The electricity consumption of PEMWE is rated in a similar range. In the literature, it ranges from 53 kWh/kgH₂ to 58 kWh/kgH₂. According to Krishnan *et al.* [4], the electricity demand of PEM systems is approximately 58 kWh/kgH₂. Bareiß *et al.* [14] use a value of 55 kWh/kgH₂, Gerloff [3] uses a value of 54 kWh/kgH₂, and Aghakhani *et al.* [47] report a value of 53 kWh/kgH₂.

The M-series PEM electrolyzers by Nel produce hydrogen at a 30-bar pressure achieving a 99.9995% purity. The electrolyzers have an average power consumption of

4.5 kWh/Nm³H₂ at the stack [51]. This value is approximately 50 kWh/kgH₂. Nel has two turnkey PEM solutions that produce hydrogen with a purity of 99.95% at 30-bar pressure. They have a stack electricity consumptions of 53.2 kWh/kgH₂ [49]. Quest One has a PEM electrolyzer with an output pressure of 20–30 bar and an energy demand of 53 kWh/kgH₂ [52]. The reported energy demand was calculated for an output pressure of 30 bar. The company also produces a 10 MW PEM modular system and reports it to have an energy consumption of 51 kWh/kgH₂ [53].

In the literature and datasheets, PEM electrolyzers are reported to have an electricity demand of 50 kWh/kgH₂–58 kWh/kgH₂, with a mean of 53.8 kWh/kgH₂. The range of demand found in the datasheets is 50 kWh/kgH₂–53 kWh/kgH₂, with a mean of 51.8 kWh/kgH₂. This range and mean were used in the calculations in this study.

An SOEC is a high-temperature electrolyzer. This enables part of the process energy to be supplied as heat, which lowers the electricity demand of hydrogen production. In the literature, the electricity demand of SOEC is rated as 28 kWh/kgH₂–43 kWh/kgH₂. According to El-Shafie [9], an SOEC system uses 2.5 kWh/Nm³H₂–3.5 kWh/Nm³H₂, which is 28 kWh/kgH₂–39.2 kWh/kgH₂. Gerloff [3] uses the value 42.3 kWh/kgH₂ and Mehmeti *et al.* [54] use 36.1 kWh/kgH₂.

FuelCell Energy has an SOEC electrolyzer with a 1.1 MW power rating. It produces hydrogen at atmospheric pressure with 99% purity [55]. Electricity consumption is considered in two cases. First, if heat is available, the electricity demand is 39.4 kWh/kgH₂. Second, if the electrolyzer is heated using electricity, its consumption is 43.8 kWh/kgH₂ [55]. FuelCell Energy states that optional compression is available, which will add 2–4 kWh/kgH₂ power consumption, depending on the target pressure. The total energy consumption of this SOEC electrolyzer is 41.4 kWh/kgH₂ when compression was applied to reach a pressure of 30 bar. With heating using electricity, the consumption is 45.8 kWh/kgH₂. Based on FuelCell Energy's data, heating is assumed to require 4.4 kWh/kgH₂ on average.

Sunfire GmbH manufactures a 10 MW SOEC electrolyzer module. It produces hydrogen with a 99.9% purity but at 0.1 bar [56]. The module has a specific power consumption of 37.8 kWh/kgH₂. With the additional compression to 30 bar and electrical heating, the power consumption increases to 44.2 kWh/kgH₂. According to Topsoe a 100 MW SOEC system has a stack-level power consumption of 3.1 kWh/Nm³H₂, which is 35 kWh/kgH₂ [57]. This is for a system with 99.999% purity after gas cleaning and 2 bar pressure. Additional pressurizing and electrical heating increase electricity consumption to 41.4 kWh/kgH₂. Convion has an SOEC system with a power consumption of 38.8 kWh/kgH₂ [58]. This is assumed to be at 0 bar with integrated heating. With added heating and compression, the power consumption increases to 45.2 kWh/kgH₂. Bloom energy has a 1.2 MW electrolyzer module with a power consumption of 37.5 kWh/kgH₂ [59]. This only includes the consumption of the electrolyzer system. Therefore, with additional

compression and heating, the consumption is 43.5 kWh/kgH₂.

The range of electricity demand for an SOEC is 28–46 kWh/kgH₂, based on literature and datasheets. Based only on datasheets, the range is 41 kWh/kgH₂–46 kWh/kgH₂, when including compression and heat production. The mean of these values is 44 kWh/kgH₂. Overall, the electricity demand of AWE and PEMWE are in similar ranges, and SOEC has a lower electricity demand even when electric heating is included.

5. LAND USE EMISSIONS

Land use changes cause emissions that are often not accounted for in emission calculations. Excavating forested areas for power plants, such as PV installations or wind turbines, causes emissions and removes carbon sinks. If power plants are built on empty industrial lots or old, excavated peatlands, land use emissions are lower than if the power plant requires clear-cutting of forestland.

Different electrolysis technologies require different amounts of land. An alkaline electrolyzer system requires an area of 10 ha/GW and a PEM system requires approximately 5 ha/GW [60]. Wind power plants have an average infrastructure area requirement of 0.5 ha/MW [61]. Fixed-tilt solar PV plants require 1.1 ha/MW [62]. The area requirements of electrolyzers are negligible compared with the land requirements of renewable electricity production plants. Therefore, only the power plant land requirements were accounted for in the emission calculations in this study. The total land requirements of power plants are affected by the need for new transmission lines and maintenance roads. The length of these varies significantly case by case, depending on the plant location and existing infrastructure; therefore, they are not accounted for in the calculations in this study. These need to be accounted for in case specific calculations.

Land use related emissions vary depending on location and land type. There has not yet been wide research on GHG emissions from land use changes due to power plant construction. Existing literature shows varying results depending on the country. Albanito *et al.* [63] calculated the opportunity carbon costs of onshore wind farms in Scotland. They have calculated emissions for windfarms so that those built on peatland cause emissions of 151.7 gCO₂eq/kWh–1759.6 gCO₂eq/kWh, those built on forest land cause emissions of 16.0 gCO₂/kWh–128.3 gCO₂eq/kWh, those on cropland cause emissions of around 44.9 gCO₂eq/kWh and those on other land types, such as grasslands, undefined mixed woodland and pasture land, cause 18.6 gCO₂/kWh–39.9 gCO₂eq/kWh. The lost carbon sequestration potential of the area during a 25-year lifetime of the wind power plant was accounted for in these values.

The Natural Resources Institute Finland (LUKE) published a report on the climate and land impacts of solar PV in Finland [64]. They conducted LCAs on two solar PV plants in Eastern Finland. In the LCA, they included the manufacturing and use of PV plants, as well as GHG emissions caused by land use changes. They calculated the amount of GHG emissions released from the carbon

sequestered in the trees and soil in the area. Additionally, they assumed that the area was previously used as a commercial forest, and the production has now moved elsewhere. Therefore, the calculation included the emissions from the new logging area. GHG emissions released from trees were 5.5 gCO₂eq/kWh and 8.4 gCO₂eq/kWh and emissions from soil were 9.3 and 10.9 gCO₂eq/kWh. Moving wood production to another location caused 14.92 gCO₂eq/kWh and 9.2 gCO₂eq/kWh of emissions in the two locations. The total land change related emissions of the two locations were 29.7 gCO₂/kWh and 28.5 gCO₂eq/kWh. Van de Ven *et al.* [65] computed land use changes related to solar PV installations in the EU, India, Japan, and South Korea. The calculations resulted in emissions of 13 gCO₂/kWh–53 gCO₂/kWh for PV power installed in Europe.

Tikkasalo *et al.* [66] studied the GHG emissions of drained peatland forests after clearcutting. They accounted for CO₂, CH₄ and N₂O emissions and found that during the first full year after clearcutting, emissions were 28.4 tCO₂eq/ha/yr. Korkiakoski *et al.* [67] studied the cutting of boreal peatland forests in Finland. They found initial emissions of 31 tCO₂eq/ha/yr, which decreased to 8.2 tCO₂eq/ha/yr six years after clearcutting. Mäkiranta *et al.* [68] measured the CO₂ flux of a Finnish peatland forest and found emissions of 16 tCO₂eq/ha/yr–22 tCO₂eq/ha/yr during the first three years after clear-cutting. Per Tikkasalo *et al.* Ahmed [69] reported emissions of 20 tCO₂eq/ha/yr after clear-cutting spruce on mineral soil. Kolari *et al.* [70] studied Scots pine stands of different ages in Finnish boreal forests. They found emissions of 14 tCO₂eq/ha/yr four years after clearcutting pine on mineral soil per Tikkasalo *et al.* [66]. These studies measured the direct emissions of clearcutting forests.

Similarly, the carbon balance of clearcut forests has been studied in Sweden. Grelle *et al.* [71] conducted eddy-covariance measurements in young clearcut forests. They found that the forest returned to a carbon sink ten years after clearcutting. The total carbon emissions were 25 MgC/ha. According to Tikkasalo *et al.* [66] the emissions were 16–18 tCO₂eq/ha/yr in the first three years. Vestin *et al.* [72] studied a boreal forest in central Sweden. The GHG emissions were 11 and 17 tCO₂eq/ha/yr during the second year after clearcutting in two different plots on the test site.

Based on the values found in the literature, the emissions of a clearcut forest area are highest after cutting and decrease over time. This decrease is due to increased vegetation growth. If it is assumed that most of the area is left bare, the emissions will not decrease as significantly as they would if the forest grows back. Based on the above literature, that is the direct emissions, a land use emission range of 8.2 tCO₂eq/ha/yr–31 tCO₂eq/ha/yr is assumed in the calculations for Nordic boreal forest land. With this emission assumption the land use emissions are 1.4 gCO₂eq/kWh–5.4 gCO₂eq/kWh for wind power and 9.0 gCO₂eq/kWh–34 gCO₂eq/kWh for solar PV power. The calculated emissions of wind power are low compared to those in [63]. However, indirect emissions of lost carbon sequestration potential were not included. The calculated

TABLE II: OPERATION PHASE EMISSIONS RELATED TO ELECTRICITY

	Electricity consumption (kWh/kgH ₂)	Emissions using wind power (kgCO ₂ eq/kgH ₂)	Emissions using solar PV power (kgCO ₂ eq/kgH ₂)
AWE	46–52	0.46–0.52	1.4–1.6
PEMWE	50–53	0.50–0.53	1.5–1.6
SOEC	41–46	0.41–0.46	1.2–1.4

TABLE III: ASSUMPTIONS USED IN LAND USE EMISSION CALCULATIONS

	Onshore wind	Solar PV
Land use emissions (tCO ₂ /ha/year)	8.2–31	
Space requirement (ha/MW)	0.5	1.1
Capacity factor (%)	33	11.4

TABLE IV: LAND USE EMISSIONS (kgCO₂eq/kgH₂)

Technology	Wind	Solar PV
AWE	0.07–0.28	0.41–1.8
PEMWE	0.07–0.29	0.45–1.8
SOEC	0.06–0.25	0.37–1.6

emissions of solar PV are near the range of [65] and match the calculations of the two Finnish PV plants in [64].

6. COMPARISON OF EMISSIONS

The electrolyzer electricity consumption and emissions related to it are listed in Table II. For all three technologies, the use of wind power is more favorable than that of solar power based on emissions. AWE and PEMWE have very similar electricity demands, with AWE requiring slightly less power than PEMWE. SOEC has the lowest electricity demand because some of the process energy demand is covered by heat. This is optimal when heat is readily available. In this study, the power demand of SOEC was calculated so that heat was produced using electricity. The operation phase emissions were calculated based on electricity consumption. This does not, therefore, provide an idea on whether an electrolyzer should be coupled directly with a power plant and how the power plant should be sized.

The calculation assumptions and emissions related to land use are presented in Tables III and IV, respectively. All technologies have lower land use emissions using wind power than solar power. This is due to the higher land requirement and lower capacity factor of solar power. The emissions were calculated with the assumption of clearcutting forest in the location of the power plant. Regarding wind power, this is often the case, but solar panels could be placed on empty industrial lots, old peat excavation sites, or other land that does not require major changes. This would significantly decrease the land use emissions of solar-powered electrolysis. If no land use changes are required, land use related emissions can be assumed to be zero. This would avoid 0.4 kgCO₂eq/kgH₂–1.8 kgCO₂eq/kgH₂ of emissions.

Table V presents the calculated emissions for each electrolyzer type, both using 100% onshore wind electricity and 100% solar PV electricity. The system emissions are related to stack and BoP manufacturing. The operation

TABLE V: CALCULATED MEAN EMISSIONS AND TOTAL RANGE (kgCO₂eq/kgH₂)

	System	Operation	Land use	Total mean emissions	Total emissions range*
AWE-Wind	0.17	0.50	0.17	0.84	0.54–1.5
AWE-PV	0.17	1.5	1.1	2.7	1.8–4.0
PEMWE-Wind	0.12	0.52	0.18	0.81	0.60–1.4
PEMWE-PV	0.12	1.6	1.1	2.8	2.0–4.0
SOEC-Wind	0.12	0.44	0.15	0.71	0.49–1.1
SOEC-PV	0.12	1.3	0.95	2.4	1.6–3.3

Note: *The minimum of the emission range is calculated using the minimum system emissions found in literature, lowest electricity demand found in datasheets, and smallest land emissions based on literature. Similarly, the maximum of the emission range is calculated using the maximum system emissions found in literature, the highest electricity demand found in datasheets, and highest land emissions based on literature.

phase consists of emissions related to the electricity used to produce hydrogen. This means the lifetime emissions of wind or solar electricity divided according to the amount of hydrogen produced. Land use emissions contain the emissions created by the installation of wind or solar PV power plants in average Nordic forest land.

Fig. 5 displays the mean emissions of each electrolyzer technology coupled with wind and solar electricity. The emission effects of the three different categories are shown, and the error bars represent the total error, illustrating the minimum and maximum total emissions of each technology.

The EU has set an emission standard of 3.38 kgCO₂eq/kgH₂ for green hydrogen production [25]. The emissions are determined by including emissions from inputs, processing, and transport and distribution. In this study, transport and distribution are not considered because they are highly application specific. Additionally, emissions caused by land use changes are included in this comparison, even though they are not calculated in the method by the EU. The results show that land use changes for hydrogen production are an important source of emissions and must be considered. Additionally, it is a useful metric when electrolysis technologies are compared to novel solutions, such as photocatalytic or photoelectrochemical water splitting, which require larger areas of land compared to electrolysis plants.

All electrolysis technologies in this study achieved lower mean emissions than the standard set by the EU. The total emissions found are in line with total emission results reported in the literature. Cho *et al.* [73] review multiple cases and find the GWP of hydrogen production to be 0.03 kgCO₂eq/kgH₂–5.10 kgCO₂eq/kgH₂ for wind-powered electrolysis and 0.37 kgCO₂eq/kgH₂–7.50 kgCO₂eq/kgH₂ for solar PV-powered electrolysis, with the average of 1.29 kgCO₂eq/kgH₂ and 3.38 kgCO₂eq/kgH₂ for wind and solar PV, respectively. The results of all the scenarios in this study fall within these ranges.

The results show that the emissions of all three electrolyzers are similar. System- and site-specific variations determine the best electrolyzer at a certain location. Based on these results, it is impossible to definitively say that one electrolyzer technology is more sustainable than another from an environmental viewpoint. However, on average, wind-powered electrolysis has lower life cycle emissions than solar-powered electrolysis. This is true even if solar PV is located at a site that does not require land use

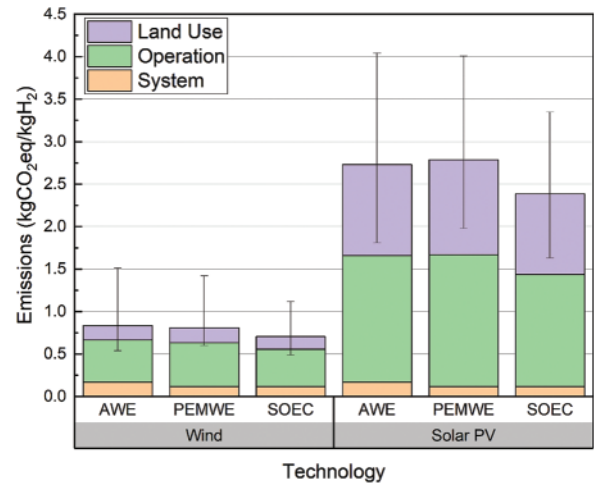


Fig. 5. Total emissions of the electrolyzers by category. Note that the error bars in the figure refer to the total error, not only the error of the “Land Use” category.

changes and land use emissions are omitted. In this case, however, the difference between wind and solar power is less significant, and the emission ranges overlap. A case-specific analysis, also considering technological operation limitations, will reveal which technology is the best option for a certain application.

In all cases, the operation phase causes the largest emissions. In the cases with wind electricity, the electrolyzer system itself causes approximately 14%–21% of the emissions on average, and with solar PV cases, it is responsible for approximately 4%–6% of the emissions on average. The operation phase causes 59%–64% of the emissions in cases with wind and 55%–56% in cases with solar PV. The land use related emissions are responsible for 20%–22% of the emissions in cases with wind and around 39%–40% of the emissions in cases with solar PV. Land use changes cause a significant portion of the total emissions and are therefore important to include in emission analyses.

Of the three electrolyzers, SOEC can reach the lowest emissions, especially when comparing the scenarios utilizing solar PV. If waste heat is readily available at the site, the electrolyzer operation emissions could decrease. In this case the solar powered SOEC would have emissions around 1.4 kgCO₂eq/kgH₂–3.1 kgCO₂eq/kgH₂. However, the difference in emissions is small and the emission ranges overlap; therefore, case specific variations determine which technology is optimal. In-depth calculations of the emissions for a specific case are required. It is important to

include the heat requirement of SOEC and consider the energy and time required for cold startup.

7. CONCLUSION

As hydrogen is an emerging carbon free fuel, it is important to study its lifetime emissions. To achieve climate goals, hydrogen must be sustainably produced with low emissions. This study compares three different electrolysis technologies coupled with onshore wind electricity or solar PV electricity to produce hydrogen in Nordic conditions.

Emissions are mainly caused by the operation phase of the electrolyzer. The source of electricity has the most significant effect on emissions. This study compared using onshore wind power and solar PV electricity. Using solar electricity causes approximately three times more emissions in the operation phase than using wind power. Land use changes required for power plants are another important source of emissions. Especially for solar PV, the emissions caused by clearcutting forests can be close to half of the life cycle emissions of the power plant itself.

The three electrolysis methods compared in this study, AWE, PEMWE, and SOEC, do not significantly differ from each other in terms of emissions. The largest difference between the electrolyzers is seen in the PV scenario, where SOEC has approximately 0.3 kgCO₂eq/kgH₂ lower emissions than the low-temperature electrolyzers on average.

All three electrolysis technologies studied can achieve the EU emission standard when wind or solar electricity is utilized. Regardless of which of the two electricity production methods is chosen, the average emissions remain below the limit of 3.38 kgCO₂eq/kgH₂. Therefore, the hydrogen is considered renewable in the EU. In the case of utilizing solar PV electricity coupled with AWE or PEMWE, the high end of the emission range is above the EU standard.

The effects of land use changes on power plant life cycle emissions have not been widely studied. To ensure sustainable power production, these effects require further research. Especially in the Nordics, forests are an important carbon sink and play a role in mitigating climate change. The emission effect of land use changes is also important when comparing existing technologies with novel ones, which require large areas of land.

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AUTHORSHIP CONTRIBUTION STATEMENT

J. Iso-Oja: Writing–review and editing, Writing–original draft, Investigation. O. Himanen: Writing–review and editing, Conceptualization, Supervision.

CONFLICT OF INTEREST

The authors declare that they do not have any conflict of interest.

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