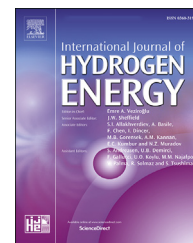


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On the economics of a hydrogen bus fleet powered by a wind park – A case study for Austria



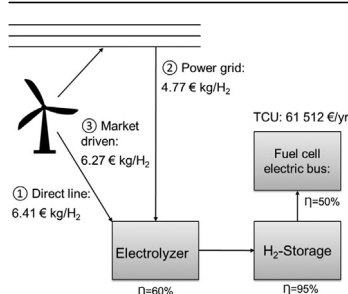
M. Sayer*, A. Ajanovic, R. Haas

Vienna University of Technology (TU WIEN), Vienna, Austria

HIGHLIGHTS

- Economic analysis of fuel cell buses and green hydrogen production.
- Identification of the most suitable electrolyzer operation model.
- Investment costs are still the largest cost component.
- Technological learning and policy funding schemes may decrease the costs.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper investigates the economics of a fuel cell bus fleet powered by hydrogen produced from electricity generated by a wind park in Austria. The main research question is to simultaneously identify the most economical hydrogen generation business model for the electric utility owning wind power plants and to evaluate the economics of operating a fuel cell bus fleet, with the core objective to minimize the total costs of the overall fuel supply (hydrogen production) and use (bus and operation) system. For that, three possible operation modes of the electrolyzer have been identified and the resulting hydrogen production costs calculated. Furthermore, an in-depth economic analysis of the fuel cell buses as well as the electrolyzer technology has been conducted. Results show that investment costs are the largest cost factor for both technologies. Thus, continuous hydrogen production with the smallest possible electrolyzer is the economically most favorable option. In such an operation mode (power grid), the costs of production per kg/H₂ were the lowest. However, this means that the electrolyzer cannot be solely operated with electricity from the wind park, but is also dependent on the electricity mix from the grid. For fuel cell buses, the future cost development will depend very much on the respective policies and funding programs for the market uptake, as to date, the total cost of use for the fuel cell bus is more than two times higher than the diesel bus. The major final conclusion of this paper is that to make fuel cell electric busses competitive in the next years today severe policy

Abbreviations: CO₂, Carbon dioxide; BEB, Battery electric bus; DB, Diesel bus; FCEB, Fuel cell electric bus; FCV, Fuel cell vehicle; H₂, Hydrogen; LHV, Lower heating value; LR, Learning rate; OM, Operation model; O&M, Operation and maintenance; PEM, Polymer electrolyte membrane; TCO, Total cost of ownership; TCU, Total cost of use.

* Corresponding author.

E-mail address: sayer@eeg.tuwien.ac.at (M. Sayer).

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interferences, such as subsidies for these busses as well as electrolyzers and bans for fossil energy, along with investments in the setup of a hydrogen infrastructure, are necessary.

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Introduction

The European Green Deal lays the foundation for Europe to become the first climate-neutral continent by 2050 and sets the stage for Europe's transition to a sustainable economy with economic growth decoupled from resource use. In addition, it explicitly identifies clean hydrogen and fuel cells as priority areas [1]. In 2019, the amendment to the “Directive on the promotion of clean and energy-efficient road transport vehicles” was adopted for public procurement and became national law in 2021 [2]. This implies that 22.5% of newly purchased buses until the end of 2025 have to be zero-emission vehicles and from 2026 onwards, this share increases to 32.5% [3]. Fuel cell electric buses (FCEB) could be a promising technology, especially for long driving distances, where battery electric or trolleybuses are not an option. Unlike the combustion of diesel in an internal combustion engine, no CO₂ is released when hydrogen is used in fuel cell vehicles. Nitrogen oxides are only produced when fuels are burned at extremely high temperatures, which is not the case for polymer electrolyte membrane (PEM) fuel cells. Particulate emissions, which are typically produced during the combustion of diesel, are also eliminated here. Particulate emissions from tire and brake wear, while not avoidable, are significantly lower than for diesel buses because recuperation reduces the need to use the brakes. In addition, the use of FCEB reduce local noise pollution. Increased noise pollution only occurs at refueling stations in connection with the coolers (for compressors) and compressors used.

Fuel cell buses have different advantages, but their full environmental benefits only come into effect when green hydrogen from renewable electricity is used. In view of that, within this paper, a potential combination of benefits of hydrogen production from electricity from wind energy in a bus fleet is being investigated for a province in Austria, which is characterized by two essential aspects. On the one hand, Burgenland is the province in Austria with the largest specific wind power potential. It covers 100% of its electricity demand from renewable energy sources and even exports electricity to other regions. In the meantime, many wind power plants have already dropped out of subsidies, which is why alternatives are being sought for these wind power volumes, as at times of analysis, the electricity prices were rather stable. On the other hand, Burgenland has the least beneficial public transport infrastructure within Austria in terms of environmental aspects. These two aspects motivate to investigate a possible business model where hydrogen is produced from electricity generated by wind power plants and used in public fuel cell buses. However, the economic viability of such a model has not yet been conclusively demonstrated.

The core objective of this paper is to investigate the economics of an FCEB fleet fueled by green hydrogen produced with electricity from a large wind park in Austria. A major derived goal is to identify the most economical operation mode for the electric utility owning wind power plants using the actual hourly operation data of the respective wind park, minimizing the total costs of the overall fuel supply (hydrogen production) and use (bus and operation costs) system.

The first research question relates to the overall cost analysis of the FCEB compared to a diesel bus. This is investigated by means of a total cost of use analysis and a resulting sensitivity analysis regarding hydrogen price, CO₂ price, driving distance and investment cost. The second research question identifies the most economical operation mode of the electrolyzer and the third question focuses on the future cost development of the mentioned technologies up to 2050.

To the authors' knowledge, the analysis conducted in this paper is the first one of the overall supply chain of FCEB powered by wind energy, including a definition of possible business models of the electric utility owning wind power plants. We analyze the electrolyzer setup considering the electricity market system and calculate the costs of different models such as stand-alone or grid integrated systems.

The first research on combining the benefits of a FCEB with hydrogen generation from wind electricity was conducted by Geer et al. [4] on the island Martha's Vineyard in Massachusetts in the United States (US). A relatively small system was analyzed with the operation of one or three buses at a time. Prior to that work, small demonstration projects combining an electrolyzer with wind energy have already been in operation in Sweden, Italy, Canada, Norway and the US, all in the range of a 2–50 kW of electrolyzer capacity, as mentioned in Ref. [4]. Different end-use applications of hydrogen from wind power, among others, the use in methane-hydrogen buses, were subject to economic analysis [5] within the HyFrance 3 project. The study has shown that constant hydrogen production without intermediate storage is the cheapest production method. Within a country analysis, Gunawan et al. [6] model the techno-economic aspects of hydrogen (H₂) fuel supply chains, including FCEB. For hydrogen production, they assume the electrolyzers to be operating at each currently existing wind farm supplemented by storage and photovoltaic (PV) panels. With those arrangements in place, they find that the hydrogen costs lie between 5 and 10 €/kg H₂, making the fuel costs equal to those of diesel buses. An early review without the specific focus on FCEB but on hydrogen-fueled fuel cell vehicles has been conducted by Veziroglu and Macario [7], concluding that in any way, a change to FCVs will reduce overall emissions compared to the actual transport sector with the further benefit of no local emissions in now highly polluted cities. Oldenbroek et al. [8] improve the idea of

emission reductions in cities by applying a smart city concept where FCVs, together with hydrogen as an energy carrier produced through solar and wind, can provide all required energy (power, heat and transport). Applying different future scenarios, using European statistics, they conclude that this approach is feasible for smart city areas [8]. An overall life cycle assessment of hydrogen production has been conducted by Burkhardt et al. [9], who conclude that fuel consumption bears the biggest potential for emission reduction (86–89% fewer emissions compared to ICEs). Further, they highlight the problem of fewer emissions for construction of the electrolyzer with more full-load hours but an additional electricity source needed when only using renewables or excess capacities [9]. That substantial emission reduction can only be achieved when green hydrogen is being used for the operation of FCVs is also being confirmed by Miotti et al. [10]. Granovskii et al. [11] analyze different hydrogen production methods for use in fuel cell vehicles and confirm that wind energy combined with electrolysis has the most advantages to lower greenhouse gas emissions. In a later study Valente et al. [12] also conclude that renewable electricity, in their research scenario from wind, is important for overall emission reduction. Life cycle assessments for FCVs with a focus on specific regions have been conducted by Ahmadi and Kjeang [13] for Canadian provinces and by Watabe and Leaver [14] for Japan. On the newest developments, a vertical wind turbine in a fuel cell passenger car for hydrogen production is being proposed by Oruc and Dincer [15].

Other works focus either on different aspects of FCEB or on the specifics of hydrogen production with electricity from wind power. Sarrias-Mena et al. [16] analyzed the technical configuration of different polymer electrolyte membrane (PEM) electrolyzer models combined with wind electricity and found that all models were suitable for operation. Including not only the electrolyzer in the system but an optimized hydrogen energy storage system Mirzaei et al. [17] show that combining it with a price-based demand response proves to substantially lower the necessary curtailment of wind power plants and the daily running costs. Further important technical aspects, especially regarding the optimal operation of a wind farm combined with a hydrogen energy storage system, were presented in Abdelghany et al. [18] through a model predictive controller. Various feasibility studies on the combination of wind and electrolyzer have been conducted, e.g., by Aiche-Hamane et al. [19] for the region of Ghardaia in Algeria, Nagasawa et al. [20] for Texas in the US, Berg et al. [21] for Denmark and Almutairi et al. [22] for the Yazd province in Iran. A life cycle analysis of Ghandehariun and Kumar [23], which includes the emissions of all production steps from the wind farm to the electrolyzer, comes to the conclusion that the greenhouse gas emissions of wind-based hydrogen systems are 94% lower than those of hydrogen production by steam reforming (grey hydrogen) (Ghandehariun and Kumar, 2016). When further carbon capture, utilization and storage are being applied to the steam methane reforming process (blue hydrogen), the overall emissions can be reduced. Nevertheless, the operation of the capture technologies also requires further energy inputs and the fugitive methane emissions that occur upstream of the gas extraction sites play a fundamental role in grey and blue hydrogen [24]. For wind-

hydrogen plants, the manufacturing and installation of the plants have significant environmental impacts. However, hydrogen produced from wind energy can significantly reduce the greenhouse gas footprint of the energy industry [23]. Earlier, an integrated wind-fuel cell system for remote communities has been analyzed by Khan et al. [25], with the conclusion that despite emissions that occur at the production of the wind turbine and fuel cell, the overall greenhouse gas emissions are well below the comparison of a diesel system. In Vandenborre and Sierens [26] a diesel bus was modified to use hydrogen as fuel and was tested successfully in 1996. This historical development has been well documented by Hua et al. [27], who give a comprehensive analysis of the overall aspects of FCEB. Already in 2007, broad acceptability of FCEB was detected in four major cities: Berlin, London, Luxembourg and Perth, even when associated with higher expenses for the public [28]. These findings have been supported by Bigerna and Polinori [29] for Perugia. Also, focusing on Italy Santarelli et al. [30] provide a comprehensive economic, environmental and social analysis. They conclude that proper policies have to be in place to include the benefits such as lower emissions of FCEB in monetary terms and subsequently would lead to more equal costs of FCEB and diesel buses. This is supported by Ajanovic et al. [31], stressing a policy framework including all environmental impacts for each bus mode. Additionally, they highlight the importance of renewable hydrogen usage, which is solely the case when renewable electricity is being used for hydrogen production. In that case, 93% of CO₂ emissions could be saved in comparison to a diesel bus. Correa et al. [32] also point to the use of renewable hydrogen to reduce the environmental impacts. Overall the literature confirms the environmental benefits and emission reductions of FCEB, e.g. Refs. [33–35]. In two further case studies, one for Oujda city in Morocco [36] and one for the city of Rosario in Argentina [37], the same conclusions were derived. Further case studies on the applications of FCEB in different cities, regions or countries were conducted by Langford and Cherry [38] in Knoxville in the US, Chang et al. [39] for public buses in Taiwan Coleman et al. [40] for the Rhine-Main area in Germany and Zhang et al. [41] for Zhangjiakou in China. Stempien and Chan [42] compare the main available bus technologies (conventional and alternative) and conclude that for FCEB as well as battery electric buses (BEB), a reduction in the total cost of ownership (TCO) is expected with the advantages of the FCEB of higher travel range and shorter charging time compared to BEB. As an outlook to 2030, still, 15.4% higher TCO for the FCEB compared to diesel buses are expected including a scaling effect of electrolyzers and they could even become cheaper in 2030 [43].

In this paper, in the section [Method of approach](#), the method of approach is outlined. The economic viability of the FCEB and electrolyzer technology is being investigated in the section [Analysis of the economics of fuel cell electric buses \(FCEB\) and of hydrogen production](#). In the section [Analysis of strategies for hydrogen production](#), the three possible hydrogen generation modes are documented and the overall costs are calculated. The future investment costs based on the technological learning approach are analyzed in the section [Future prospects](#). Finally, [Conclusions and outlook](#) section provides major conclusions of this work.

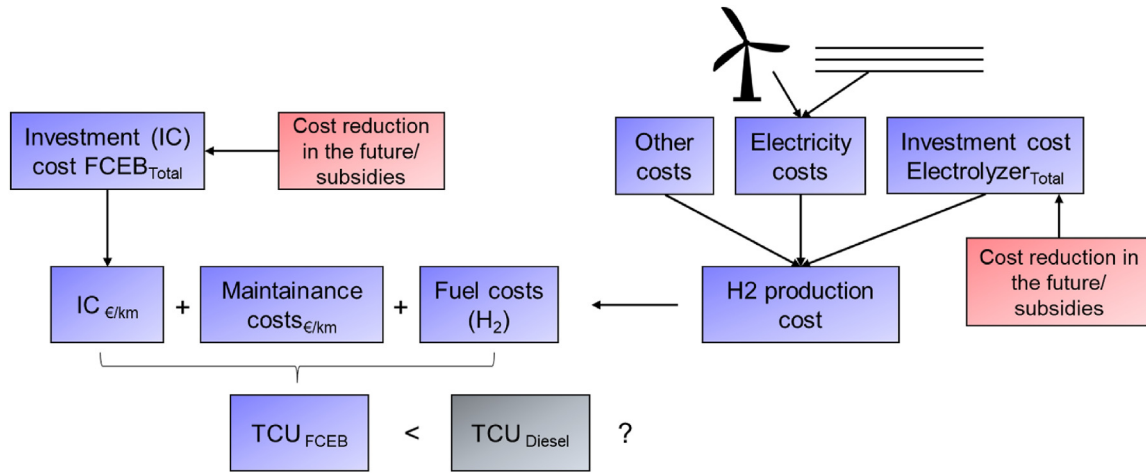


Fig. 1 – Overview on the method of approach and the aim of the analysis.

Method of approach

The methods used in this paper are threefold.

First, we analyzed different cost aspects of the FCEB, as the market penetration has not yet been achieved. In addition to the lack of hydrogen infrastructure, the initial investment costs, which are not yet competitive, represent barriers. In order to better understand how these market barriers can be removed in the long term, the cost structure of the buses was analyzed in detail by comparing the total cost of use (TCU) of FCEB and diesel buses. The TCU include not only the investment costs but also consider the cost structure of the buses over their entire lifetime. For a better understanding of the calculation results, a sensitivity analysis regarding the major input parameters such as the H₂ price, the CO₂ price, the distance driven per year and the investment costs of the FCEB was conducted. The ultimate goal is to identify measures to minimize the total cost of hydrogen production and to lower the TCU of the fuel cell bus, as illustrated in Fig. 1.

The TCU per year are calculated using the investment cost (IC_{0t} , in €), the capital recovery factor (α), the yearly operating, maintenance and repair costs ($C_{O\&M_t}$, in €/yr)¹ and the annual fuel costs (C_{fuel_i} , in €/yr):

$$TCU = IC_{0t} \cdot \alpha + C_{O\&M_t} + C_{fuel_i} \quad (\text{€/yr}) \quad (1)$$

and the calculation of α with discount rate (r) and service life (n)

$$\alpha = \frac{(1+r)^n \cdot r}{(1+r)^n - 1} \quad (2)$$

The annual fuel costs are calculated from the average fuel consumption (f_{c_i} , in kg H₂ per 100 km or l per 100 km), the fuel price (p_{fuel_i} , in €/kg H₂ or €/l) and the annual distance traveled (d , in km). The index i refers to diesel or FCEB, depending on the technology of the bus for which the TCU analysis is performed:

$$C_{fuel_i} = f_{c_i} \cdot p_{fuel_i} \cdot d \quad (\text{€/yr}) \quad (3)$$

Second, we conduct a sensitivity analysis on important influencing factors of the electrolyzer, namely the size of the electrolyzer, to indicate potential economies of scale and the influence of the operating hours (FLH) on the electrolyzer plant. For this, we use the direct investment (IC_{Ely} , in €/kW) and other project costs (e.g., compressor, installation, analysis and infrastructure) (IC_{Other} , in €/kW) of the electrolyzer, the capital recovery factor (α) with the discount rate (r) and depreciation period (n), the operation and maintenance costs ($C_{o\&m}$, in €/kW), the electricity costs (C_{Ele} , in €/kWh) and the efficiency of the electrolyzer (η). The hydrogen production costs (C_{H2}) by an electrolyzer are calculated as:

$$C_{H2} = \frac{(IC_{Ely} + IC_{Other}) \cdot \alpha + C_{o\&m} + \frac{C_{Ele}}{\eta}}{FLH/\eta} \quad (\text{€/kWh}) \quad (4)$$

In addition, in a third step, we define three operation models to identify the most economical production method for the power-to-gas system. In order to calculate the required power (P_{Ele}) of the electrolyzer, we must first calculate the amount of hydrogen (Q_{H2}) needed to run the 15 FCEBs (Q_{FCEB}):

$$Q_{H2} = Q_{FCEB} \cdot f_{c_i} \cdot d \quad (\text{kgH}_2/\text{yr}) \quad (5)$$

$$P_{Ele} = \frac{Q_{H2}}{FLH/\eta} \quad (\text{kW}) \quad (6)$$

The required power of the electrolyzer depends on the operation model since wind energy is not available to the same extent every day. If the wind energy alone is to be used to operate the electrolyzer without additional grid electricity backup, the electrolyzer must be dimensioned larger.

For each model, the hydrogen production costs were calculated using eq. (4) and the respective input factors depending on the scenario. Since, in some cases, the wind energy is supplied directly by the wind farm, the electricity does not have to be purchased on the market. However, we take into account the lost profit since the electricity could otherwise have been sold on the market. This is factored into the hydrogen price. The calculations do not include refueling

¹ We do not include labor costs for bus drivers as they are the same for both bus types.

stations, possible grid expansion, and long-term storage options. The model assumes that the hydrogen can be stored 24 h after production. This means that the required amount of hydrogen must be produced each day.

To identify the possible future investment cost reductions of the FCEB and the electrolyzer, the technological learning approach is being applied:

$$IC(x_t) = IC(x_{t_0}) \cdot \left(\frac{x_t}{x_{t_0}}\right)^{-b} \quad (\text{€ / kW; € / bus}) \quad (7)$$

Within this approach, the investment costs $IC(x_t)$ decrease as output x_t increases. For the case of the FCEB under output, the number of operation buses and for the electrolyzer, the overall installed capacity has been used. This can be described in a diffusion curve with the exponent $-b$ describing the “learning effect” hence the cost reduction over time. For each doubling of the cumulative output, the investment costs decrease by a certain percentage, classified as the learning rate (LR):

$$LR = 1 - 2^{-b} \quad (8)$$

Analysis of the economics of fuel cell electric buses (FCEB) and of hydrogen production

In this section, the TCU of FCEB and hydrogen production via electrolysis, without taking the specific hydrogen production with wind power into account, are analyzed. This served to identify major barriers and challenges in terms of cost development.

Comparison of total costs of use of FCEB and diesel buses

The input data used for the TCU calculations are displayed in Table 1. The investment costs, the values for the maintenance and repair costs, as well as the required travel distance of each bus are based on the experience of bus operator Postbus [44]. The diesel price used corresponds to the official average price in 2019 in Austria [45]. As a comparison, the average diesel price in 2018 amounted to 1.25 €/l, 1.05 €/l in 2020 and 1.24 €/l in 2021. Hence, we can say the data for calculation is well in that price range. The average fuel consumption values of the diesel bus, as well as the FCEB, come from literature, as do the acquisition costs of the diesel bus [42,46–48]. Further specifics on the FCEB are that the overall efficiency lies between 51 and –58%, with a maximum output of 100 kW and a storage tank

Table 1 – Input data of the TCU calculation of the FCEB and the diesel bus.

Type	FCEB	Diesel bus
Investment costs (complete bus)	625 000 €	234 000 €
Maintenance and repair costs	0.20 €/km	0.27 €/km
Fuel costs	9.50 €/kg H ₂	1,21 €/l Diesel
Fuel consumption	9 kg H ₂ /100 km	35 L Diesel/100 km
Discount rate	5%	5%
Analyzed period	10 years	10 years
Distance traveled	45 000 km	45 000 km

of 45 kg with hydrogen at 350 bar [49]. The H₂ purchase price applies to Germany but is assumed to be representative of all of Europe [50].

The major result of the economic analysis is that the investment costs of the fuel cell electric hydrogen buses have a very large influence on the total cost of use due to its share of 63% of the overall total cost of use. The results of the TCU analysis are presented in Fig. 2. It is apparent that the FCEB is not yet competitive with the diesel bus. Table 2 shows the TCU results with the cost shares. Today – in 2022 – the total cost of use for the FCEB is more than twice more expensive with 128 415 €/yr, considerably higher than the diesel bus with 61 512 €/yr.

In a further investigation, a sensitivity analysis has been carried out with the variation of different input parameters for the profitability calculation, which are summarized in Fig. 3 in order to analyze their influence. As a first step, the hydrogen price has been varied. It can be seen that the H₂ price has a very large impact on the O&M costs (operating, maintenance and repair costs). When the H₂ price decreases, the fuel costs of the FCEB decrease drastically. When comparing the overall O&M costs with an H₂ price of 5 €/kg H₂, the costs of the FCEB are slightly lower than those of the diesel bus due to its lower maintenance cost share. The next analysis varies the CO₂ prices, displayed for a very high CO₂ price of 1000 € per t CO₂. We assume CO₂ emissions of 2.63 kg CO₂/l diesel. For the FCEB bus, it is assumed that the electricity for hydrogen production is generated purely from renewable sources. Therefore, the effect can be seen on the fuel cost share of the diesel bus. Only from the assumed high CO₂ price, a noticeable difference is to be recognized. Due to the relatively high hydrogen fuel cost, when varying the driven distance per year, the difference between the diesel bus and FCEB increases. Finally, the investment costs are varied. Fig. 3 shows the results for investment costs of 300 000 € of the FCEB, where the investment cost-share comes quite close to the one of the diesel bus.

Overall, it is evident from the results of the sensitivity analysis that the high H₂ price and the high investment cost of the FCEB in combination are the major barriers to market penetration. If both the acquisition costs could be reduced to around €300,000 in the long term and if the H₂ price were to fall to €5/kg H₂, the FCEB would become economical.

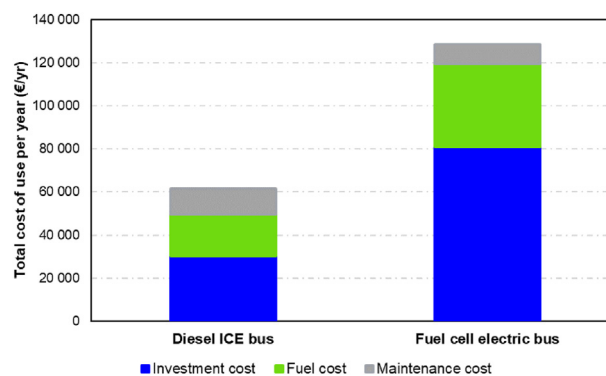


Fig. 2 – TCU of a diesel bus and an FCEB in comparison.

Table 2 – Results of the TCU calculation of the FCEB and the diesel bus.

	Costs of diesel bus	Costs of FCEB
TCU per year	61 512 €/yr	128 415 €/yr
TCU: investment cost share	49%	63%
TCU: fuel cost share	31%	30%
TCU: maintenance cost share	20%	7%

Hydrogen production

Another important factor for FCEB to become competitive is hydrogen production. There are different hydrogen production ways, and currently the most widely used is steam methane reforming of natural gas. To date, only 0.03% of the overall hydrogen is produced with an electrolyzer [51]. However, a shift to more sustainable production methods is inevitable. Hence, our focus in this analysis lies on hydrogen production via alkaline water electrolysis and polymer electrolyte membrane (PEM) electrolysis, as the most mature electrolysis technologies.

In an economic analysis of the electrolyzer costs, there are two main aspects to be considered [52], namely the scale of the plants as well as the overall operation hours. In this analysis, we first want to consider potential economies of scale that result from the installation of a larger electrolyzer plant. In Fig. 4, the investment costs of alkaline and PEM electrolyzers depending on the module size with data from a thorough literature research are displayed. It is important to note that there are hardly any recent and reliable figures for investment costs in the literature. This results from two problems, namely that there is often no precise information

on the plant size in general, and if this is indicated whether it refers to kW_{ele} or kW_{H_2} , as well as the year of the data and the parts of the overall system included. Secondly, the cost of electrolysis depends on the manufacturer and is therefore subject to company secrets in order not to gain a competitive disadvantage. The mentioned points make a direct comparison difficult. However, we have attempted to do so in Fig. 4. The main message of this graphic is that economies of scale are very much evident. These can be seen especially from an electrolyzer size of 2 MW. According to IRENA [53], these cost reductions are mainly due to the “balance of plant” cost component. This includes power supply, deionized water circulation, hydrogen processing and cooling. Compared to the stack, where no significant cost reductions can be achieved due to leakage, manufacturing limitations, mechanical instability issues for large-scale components, the maximum area of the cell, and others, large economies of scale can be achieved by installing a larger compressor, for example. This finding is taken into account in the further analysis for the selection of a suitable electrolyzer.

Due to the high investment costs of the electrolysis plants, the production costs of renewable hydrogen depend significantly on the full load hours and the resulting annual operating time [56]. Fig. 5a shows the total costs of electrolysis as a function of full load hours for a large (5 MW) and a small (500 kW) system indicating, that the costs are lowest, starting from about 4500 full-load hours per year. In this analysis we assumed a different depreciation time of the electrolyzer depending on the number of full-load hours, starting with 30 years for 500 full-load hours and constantly decreasing until 10 years for 8000 full-load hours. Fig. 5b depicts the costs of the large electrolyzer in a more detailed way considering capital-, operation and maintenance as well as energy costs. Again, it can clearly be seen that higher full-load hours lead to an

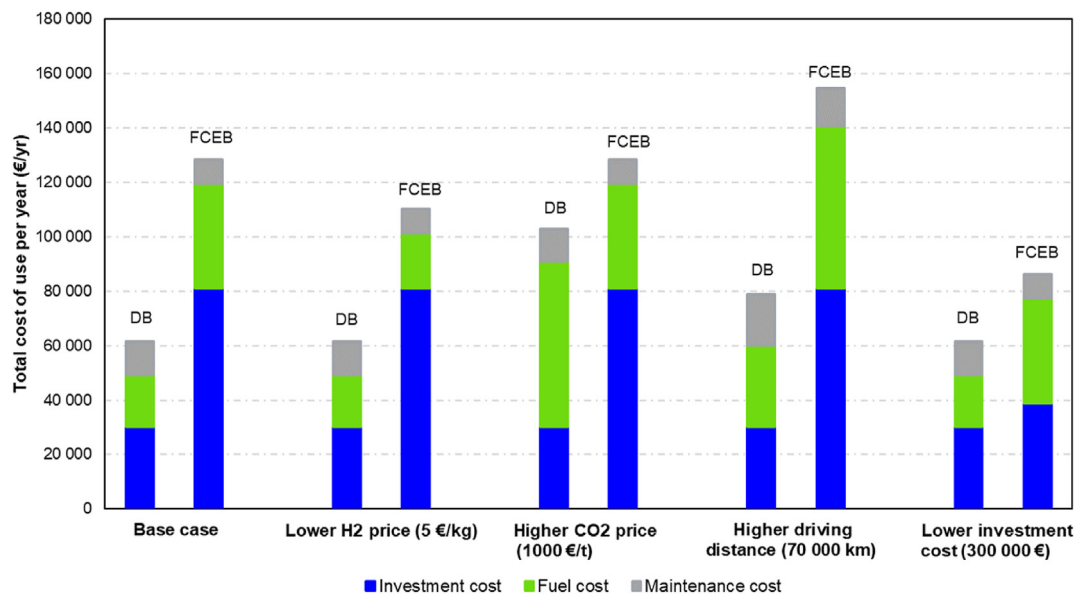


Fig. 3 – Sensitivity analysis of a lower hydrogen price (5 €/kg), a higher CO₂ price (1000 €/t), a higher driving distance (70 000 km) and lower investment cost of the FCEB (300 000 €).

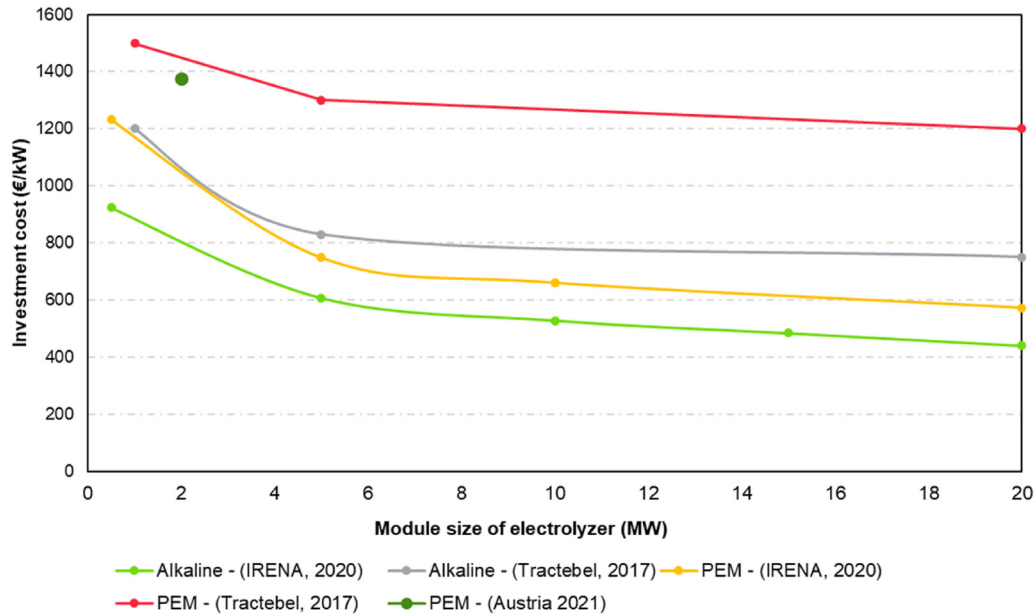


Fig. 4 – Investment cost of the electrolyzer depending on the module size, 0.5–20 MW [53–55].

overall cost reduction. This is also taken into account in further analysis.

A PEM electrolyzer is used for this analysis. The advantage of this technology is the good partial load behavior of the electrolyzer, which is particularly beneficial in the case of fluctuating feed-in, e.g., from wind turbines. To better illustrate the different costs depending on the capacity of the electrolyzer, a sensitivity analysis is performed. In each case, the total costs of an electrolyzer with 500 kW, 2 MW and 5 MW are shown in Fig. 6. Besides the capital costs of the electrolyzer, costs of a 500 m³ storage and other costs were included. Other costs include all additional relevant costs like compressor, installation, analysis and infrastructure.

Analysis of strategies for hydrogen production

In this section, three possible strategies for hydrogen production were analyzed:

Direct line

In this operation mode, the wind farm is connected to the electrolyzer via a “direct line” and not connected to the high-voltage grid. In Fig. 7, the power consumed by the electrolyzer over time is shown in blue and the wind power generated is shown in green. It can be seen that all power for which the electrolyzer is designed is fed directly from the wind farm to

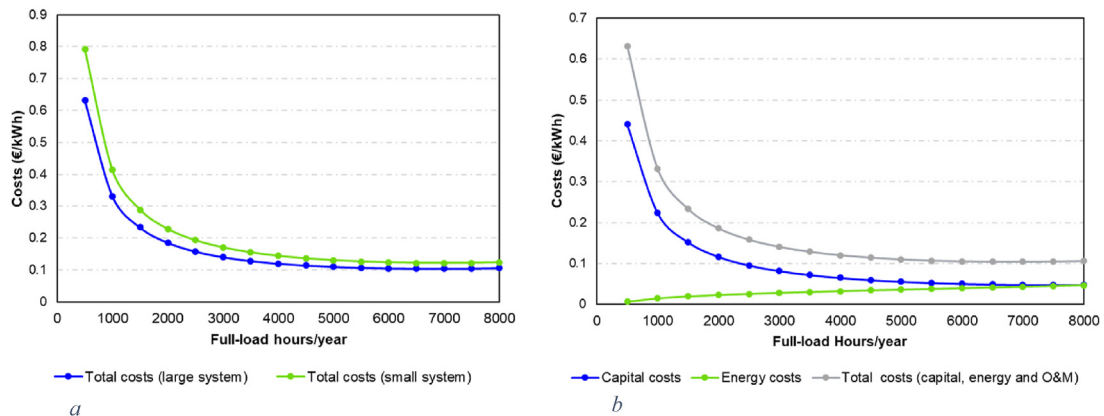


Fig. 5 – a: Total hydrogen production costs of a small (500 kW) and a large (5 MW) size electrolysis plants in relation to full-load hours with a decreasing depreciation time (15–30 years); b: cost structure of hydrogen production of a large 5 MW electrolyzer, including capital-, operation and maintenance-, and energy costs with a decreasing depreciation time (15–30 years) (Energy costs are based on the prices of the Austrian wholesale market over the year 2020).

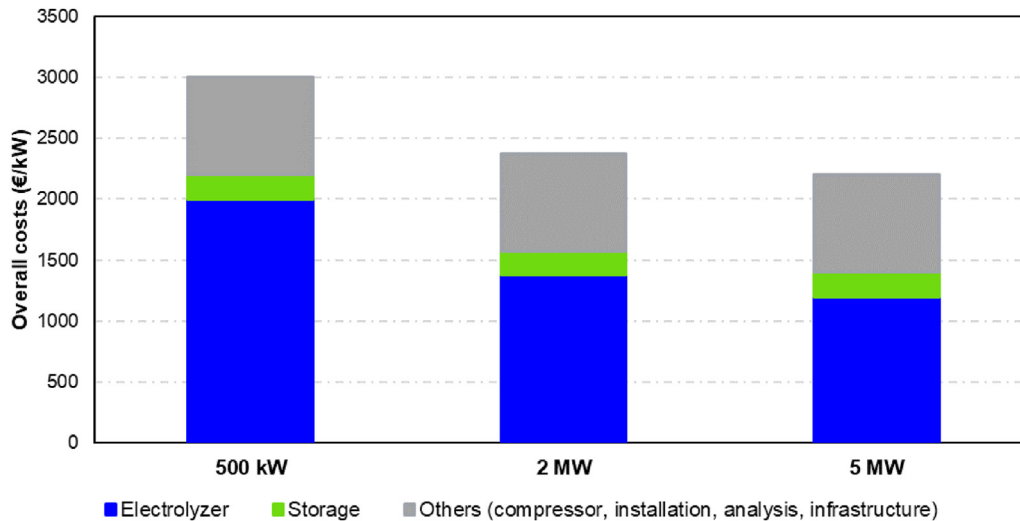


Fig. 6 – Overall investment cost with different capacities of the electrolyzer.

the electrolyzer. If the wind power generated is less than the maximum power of the electrolyzer, the electrolyzer is ramped down (and correspondingly, less hydrogen is generated). Compared to the other variants, this results in a higher capacity of electrolyzer needed.

Direct purchase from the power grid

For the second operation mode, the electrolyzer draws a constant power directly from the high voltage grid, independent of the generation capacity of the wind farm. Thus, the electrolyzer is operated at a continuous load, see Fig. 7. The

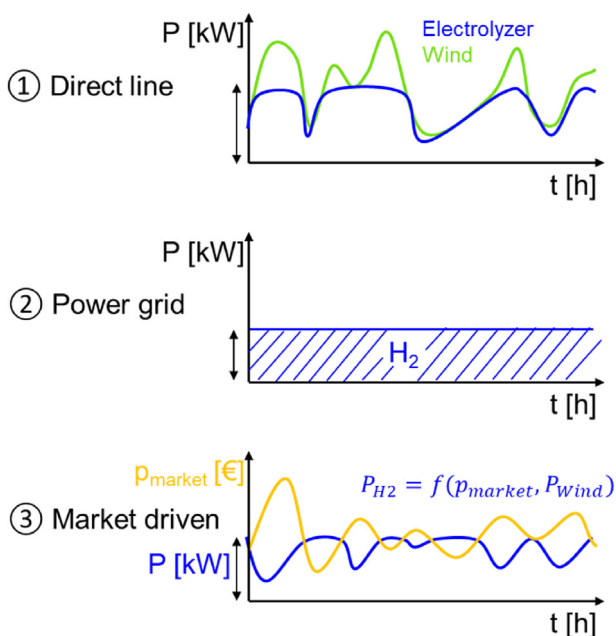


Fig. 7 – Three operation models of the power-to-gas system.

dimensioning of the electrolyzer is “smaller” here but it is in addition dependent on the market price.

Market-driven

In the third market-driven operation mode, the power consumed by the electrolyzer over time is shown in blue and the electricity price on the electricity exchange (in €) is shown in yellow in Fig. 7. The system works similarly to a pumped hydro storage power plant. The spot market price determines whether the generated wind power is fed into the high-voltage grid or consumed by the electrolyzer. At low spot market prices, the electrolyzer is ramped up and produces hydrogen from the generated wind power. In contrast, when spot market prices are high, all electricity is sold on the spot market.

The operation model analysis has been conducted based on wind data of a large wind park in Austria. Generation data from 102 wind turbine generators for the period from the beginning of September 2016 to the end of August 2019 were available for analysis. Fig. 8 plots the sum of wind energy generation output of all relevant wind turbines over the 2018/2019 period. As is usual for fluctuating renewable energy sources, the generation capacities fluctuate strongly over the year and over the day.

These generation outputs can be ordered by magnitude to obtain an ordered wind power duration curve to see the overall wind availability for the whole year, as shown in Fig. 9 for three different years.

To calculate the required amount of hydrogen, a hydrogen consumption of 9 kg H₂ per 100 km was taken in accordance with the range in the literature of 8.5–10.5 kg H₂ per 100 km [57]. A driven distance of 45 000 km/year is assumed, which corresponds to the specific use case of the bus operator as already indicated earlier (Postbus 2019).

For all further calculations, we assume a minimum production quantity of hydrogen of 60 750 kg H₂/year for the operation of 15 buses. It is pointed out in the literature to use at least a maximum value for further calculations since the

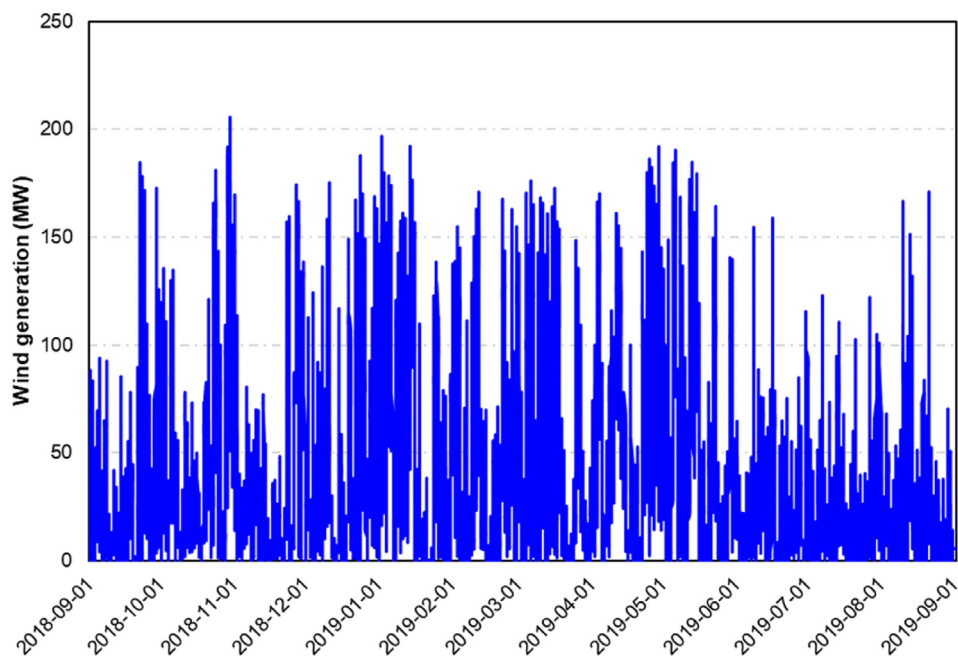


Fig. 8 – Total wind power generation capacity for the year 2018/2019 of the relevant wind power generation plants.

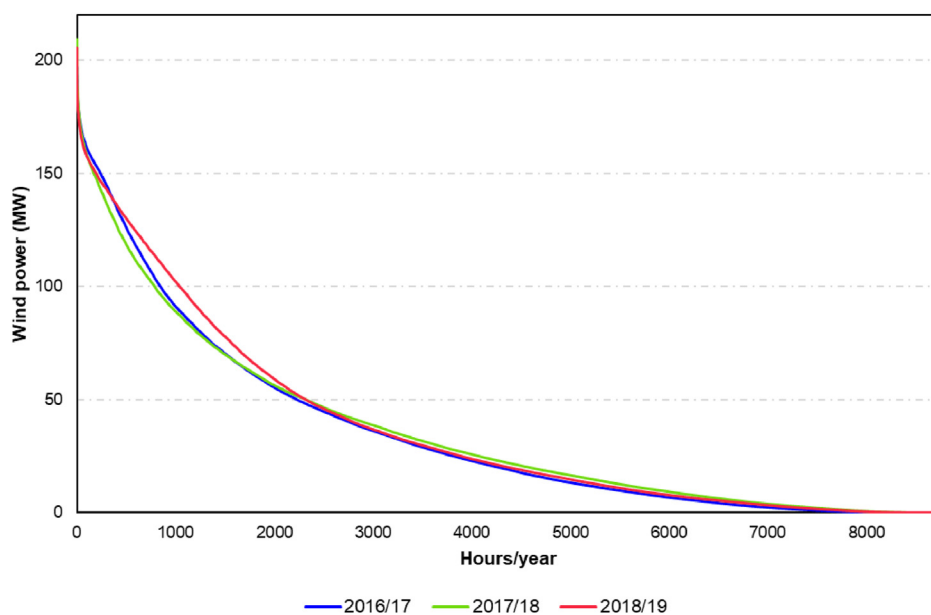


Fig. 9 – Classified wind power curve for Burgenland for three different years.

consumption can vary depending on the season and driving behavior. The quantity is therefore increased by 10%–66 825 kg H₂/year. The required daily quantity is thus 183 kg H₂ on average.

The following data Table 3 are used for the calculation:

Wind generation data from the 2018/19 billing period and electricity price data from EPEX Spot Austria for the same period were used.

With the exception of two days per year, based on the data of the 2018/19 billing period, the required amount of hydrogen for the 15 FCEB buses could be provided by the wind park

alone. However, the cost of hydrogen production in the “direct line” scenario, is higher than in the other scenarios, as the size of the electrolyzer must be matched to the wind production in order to be able to produce sufficient amounts of hydrogen during hours with high wind speed. The required electrolyzer size is 1 MW and the calculated cost per kg of hydrogen is 6.41 €/kg H₂. For this calculation, we used eq. (4) described in the section Method of approach, which takes into account the total investment, operation, maintenance, and energy costs. Since all the electricity required in this case is supplied directly by the wind farm, the losses incurred by hydrogen

Table 3 – Calculation data.

Data for PEM electrolyzer	
Efficiency (LHV)	0.65
Investment costs	500 kW: 2000 €/kW _{Ele} 1 MW: 1600 €/kW _{Ele}
Storage costs	200 €/kW _{Ele}
Other costs	801 €/kW _{Ele}
Operation and maintenance costs	60 €/kW _{Ele} /yr
Interest rate	5%
Depreciation period	15 years

Table 4 – Comparison of hydrogen production costs of each operation model (OM).

	Direct line (Wind- Electrolysis), OM1	Power grid- Electrolysis, OM2	Wind-market driven- Electrolysis, OM3
Size of electrolyzer	1 MW	500 KW	1 MW
Hydrogen cost	6.41 € kg/H ₂	4.77 € kg/H ₂	6.27 € kg/H ₂

production instead of electricity sales are included in the hydrogen production costs for better comparability. In the model, hydrogen is assumed to be produced daily starting at hour one, according to the capacity of the electrolyzer. If the required amount of hydrogen is already produced before hour 24, in the case of high wind energy availability on that day, the electrolyzer is switched off until the next day. Besides the costs, when considering this operation model, an increase in hydrogen production in the future should be considered, resulting in an even higher electrolyzer capacity and further days where an additional backup is needed. Another aspect that has not been investigated in this analysis is a possible

grid overload when high amounts of electricity have to be transported to the electrolyzer and possible additional costs due to the construction of a power cable from the wind park to the electrolyzer.

In the second operation mode, through the constant power availability and operation of the electrolyzer, its capacity could be dimensioned with 500 kW, resulting in the lowest investment cost share of all three analyzed models. However, this makes electricity costs a relatively large part of the total production costs, and it is not possible to adjust production in this model. Nevertheless, the total production costs were calculated to be 4.77 € kg/H₂, which is the lowest of all three models. It can therefore be seen very clearly that the investment costs of the electrolyzer, as well as the operating hours, have a very strong influence. In the future, should the electricity prices remain at the current high level, an optimization of the production times adapted to the electricity price will certainly become more important, and the investment costs of the electrolyzer will be reduced in the future due to technological learning.

The third operation mode envisages a market-driven approach. Similar to pumped storage, hydrogen is produced when prices on the electricity exchanges are low or negative in order to be able to produce more cost-effectively. In this use case, this means that the electric utility owning wind power sells the wind in times of high prices on the market and produces hydrogen himself when these are low. This is certainly a very helpful approach in the long run, also from an electricity market point of view, because if it works optimally, prices are low when there is enough surplus electricity available. In this model, optimization takes place on a daily basis, i.e., the daily required quantity is produced in each case. In order to be able to achieve this, the electrolyzer must be dimensioned larger. A compromise between optimization of the electricity price and too high investment costs with a 1 MW electrolyzer was chosen. The resulting hydrogen production costs are 6.27 € kg/H₂, which is a little lower than in

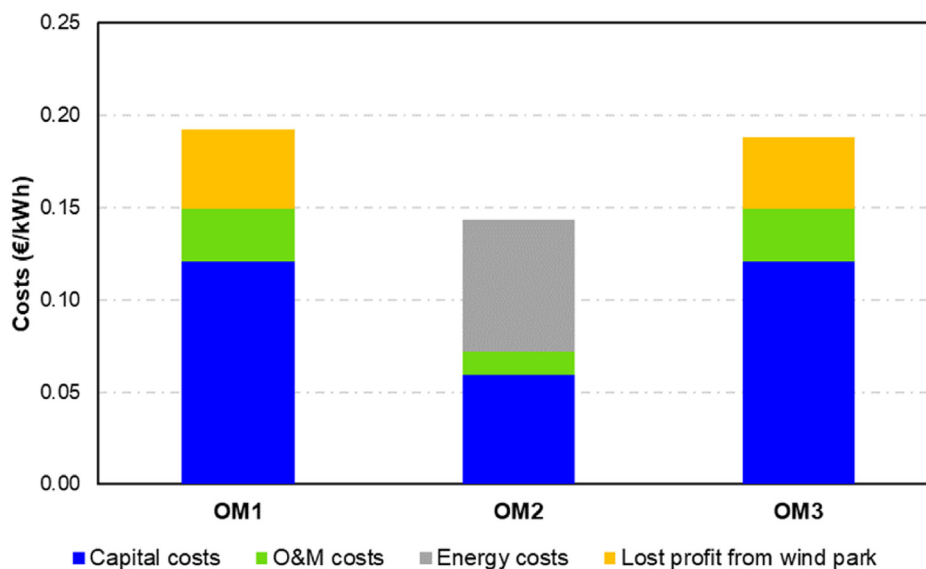


Fig. 10 – Overall hydrogen production costs for each operation model (OM), including capital-, operation and maintenance- and energy costs and the cost of wind energy that was used for electrolysis instead of market sale (lost profit) for better comparison.

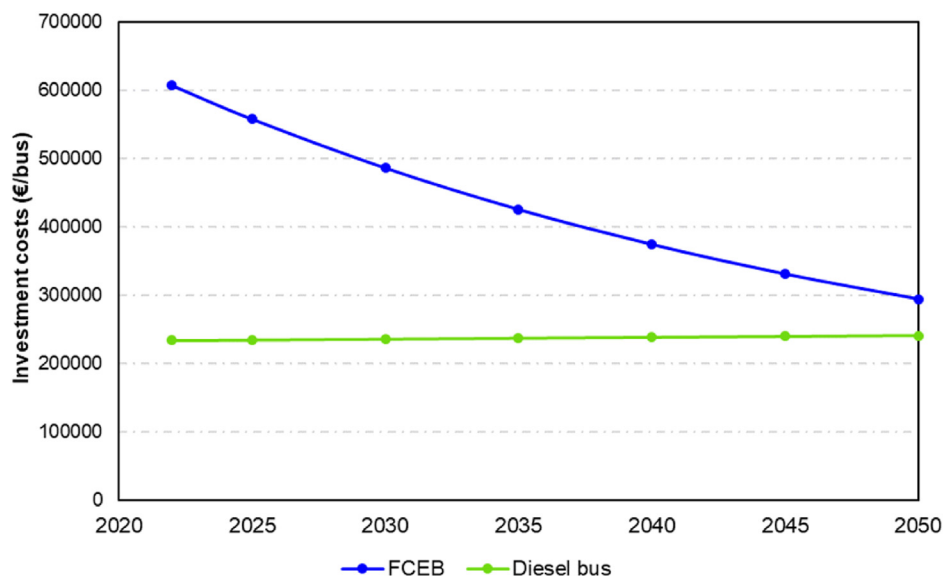


Fig. 11 – FCEB and diesel bus investment costs development until 2050 (own calculations with data from [58,59]).

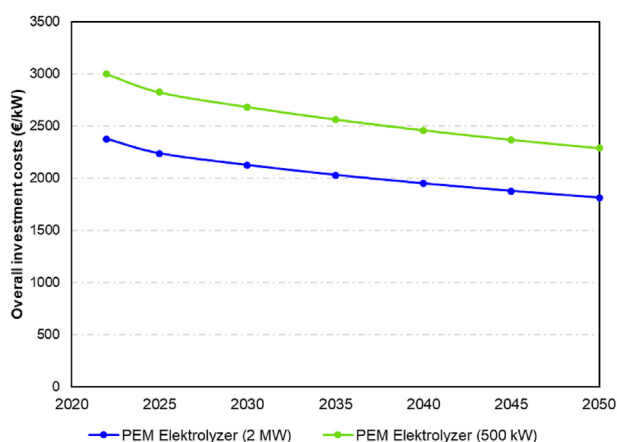


Fig. 12 – Development of overall investment costs (including storage and others) of PEM electrolysis technologies of 500 kW and 2 MW until 2050 (own calculations with data from [60–63]).

the first model. Again, it is expected that higher arbitrage opportunities will be available in the electricity market in the future and thus there will be a greater opportunity for optimization.

All results can be found in Table 4 and Fig. 10.

Future prospects

Finally, the future prospects of the overall system are analyzed. The development of investment costs of FCEB compared to the diesel bus was modeled until 2050 based on the technological learning approach (Eq. (7)). Learning rates of 15% were assumed for the FCEB. No further learning is expected for the diesel bus, as it is already a mature technology. Significant learning effects can be expected for FCEB, see

Fig. 11. In 2040, the cost of an FCB will already be very close to that of a diesel bus.

In order to be able to specifically address the future investment cost development of electrolysis, the learning effects were modeled for a 2 MW and a 500 kW PEM electrolyzer in Fig. 12. A learning rate of 18% is assumed in each case [60]. In summary, it can be said that there is definitely a high learning potential for electrolyzers.

Conclusions and outlook

The conclusion of the economic analysis is that the investment costs of the fuel cell electric hydrogen buses, with the share of 63%, have a very large influence on the total cost of use. Currently, the total cost of use for the FCEB is more than two times higher than that of diesel buses.

With regard to hydrogen production costs, the analysis shows that high utilization of the electrolyzer and low electricity costs are the most important cost factors. Constant utilization of the electrolyzer, shown under the analyzed operation model “power grid,” is the most favorable option. In this specific case, due to the high investment costs of the electrolyzer, the resulting costs of hydrogen are 4.77 € per kg/H₂, compared to 6.27 € per kg/H₂ in the operation model “market-driven” and 6.41 € per kg/H₂ in the “direct line” case.

In addition, the costs of electricity used in the electrolyzer are as well important for the economics of the FCEB. It can be concluded that the higher the electricity prices on the market are, the more unfavorable conditions are for the economics of hydrogen from electrolyzers. An optimization with regard to electricity costs was carried out in the analyzed market-driven model. In this case, hydrogen is only produced when the market price for the sale of wind power is very low or even negative because otherwise, higher revenues can be achieved by selling wind power on the wholesale market than by producing hydrogen.

It is important to note that only the costs associated with hydrogen production, excluding CO₂ costs, were considered in the analysis. Environmental restrictions (e.g., a requirement of a certain amount of green fuel to be used or restrictions on only green hydrogen use) were neglected. As soon as it would be decided to only produce green hydrogen, the market-driven model would be the one to be preferred, as in that case, hydrogen is being produced at times with low or even negative electricity prices. But if we assume constant operation of the electrolyzer, purely green hydrogen production will not be possible as grey electricity from the power grid will be used.

In the future, cost reductions due to learning effects are expected to take place for the FCEB as well as for the electrolyzer. This means that investment costs are expected to decrease gradually for both technologies with increasing numbers of FCEB and installed electrolyzer capacity over the next decades. However, the corresponding conclusion is that it will take some time until these cost reductions are reached. In the short term, investment subsidies could further reduce investment costs and accelerate the number of both, busses and electrolyzers deployed. One example of such rebates is the 45% investment cost reduction of a newly installed electrolyzer as introduced in the Renewable Energy Expansion Act (EAG) in Austria.

In addition, in the future, the introduction of a higher CO₂ price will make hydrogen as a fuel more competitive with diesel. Yet, the electricity price, given the current electricity market design, is likely to also increase. This is due to the fact that marginal costs of fossil generation will remain the price-setting power plant during periods of peak residual load. However, higher electricity market prices make it more attractive for the electric utility owning wind power to sell the wind electricity on the wholesale market rather than use it for hydrogen production.

With regard to the market uptake of FCEBs, in addition to a decrease in investment costs due to technological learning and investment subsidies and a higher CO₂ price for fossil fuel, higher environmental and emission standards and additional policies for emission reductions such as emission-free zones or diesel bans are very important.

In future research, it should be analyzed how hydrogen storage could impact the economic performance of FCEB. In this work, it was assumed that the amount of hydrogen produced per day is constant for all modes analyzed since the buses need to be refueled regularly and small storage capacity is only used for a short time period, one to two days. In the future, it should be analyzed whether the hydrogen production could be optimized on a weekly basis by use of storage in order to be able to react better to longer periods of low electricity prices.

The major final conclusion of this paper is, however, that today severe policy interferences, such as subsidies for FCEB as well as electrolyzers and restrictions on fossil energy, are necessary to make FCEBs competitive with conventional buses in the next years.

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.

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