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Supporting green Urban mobility – The case of a small-scale autonomous hydrogen refuelling station

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ABSTRACT

Nowadays, the development of hydrogen economy in the transportation sector is hindered by the principal barriers arising from the lack of adequate infrastructure and the small fleet of hydrogen-based road vehicles.

This study investigates the potential of small-scale autonomous hydrogen refuelling stations with onsite production via an alkaline electrolysis apparatus powered by a small wind turbine. In this context, an urban area with promising wind resources has been selected. Based on the wind conditions and an indicative hydrogen demand for refuelling light-duty fuel cell electric vehicles such as bicycles, the sizing of the wind turbine and the electrolyser has been theoretically calculated. For supporting the daily hydrogen refuelling demand of the fuel cell electric bicycles, which is estimated at approximately 6 kg, it is calculated that a 50 kW wind turbine should be installed in order to power a 70 kW alkaline electrolyser for producing hydrogen. The capital cost of the hydrogen station is calculated at €248,130, while the retail price of the produced hydrogen is estimated to be more than 50.2 €/kg_{H₂} in order to achieve a positive internal rate of return.

Ultimately, the present paper aims at delivering a feasibility study of a small-scale H₂ refuelling station for fuel cell bicycles in order to provide investors with initiatives to implement such schemes in urban environments where problems of low air quality and high traffic are intense.

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Introduction

Today, although the transition to environmentally friendlier means of transportation faces several challenges, green mobility develops continuously, owing to the introduction of new vehicle concepts and refuelling technologies based on Renewable Energy Sources (RES) [1,2]. One of the most promising options for supporting green transportation is the use of hydrogen as a fuel. A comparative study performed by Bicer

and Dincer in 2017 indicated that hydrogen-based vehicles present more environmental benefits in a life cycle assessment as compared to electric and methanol vehicles. Specifically, the authors concluded that the global warming potential of hydrogen vehicles is approximately three times lower than the other investigated green vehicles [3].

Since Toyota introduced the first commercialised fuel cell electric vehicle (FCEV) in 2015, many other automotive industries followed suit, deploying FCEV models in order to keep

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Nomenclature			
<i>Greek Letters</i>			
α	Activity coefficient	M_{H2bfr}	Maximum H ₂ mass stored in the buffer tank, g
Δ	Technical availability of the wind turbine	M_{H2dem}	Hydrogen daily demand, kg
η_{el}	Electrolyser's efficiency	n	Number of electrons
η_F	Faraday's efficiency	N_{bikes}	Estimated number of daily refuelling processes
Φ	Tax on income	$N_{bikes,hose}$	Daily number of refills per hose
ω	Mean power coefficient	n_c	Number of electrolytic cells
<i>Symbols</i>		N_{days}	Days of the year
A	Electrode's surface area, m ²	N_{FCEB}	Calculated number of daily bike refills
Ad	Depreciation, €	$\dot{n}_{H2}$	Hydrogen production flow rate, mol/s
c	Wind speed scale factor	$N_{HRS,hose}$	Total number of station's hoses
Ct	Electrolyser's thermal capacity, J/°C	N_{inh}	City's inhabitants
CV_{coef}	Conversion factor in present values	p	Pressure, bar
D_{dist}	Average daily distance travelled, km	p_{el}	Electrolyser's output pressure, bar
E_{el}	Electricity demand of the electrolyser, kWh	P_{ex}	Power output of the wind turbine, kW
E_{WT}	Required production from the wind turbine, kWh	P_{in}	Input power to the electrolyser
F	Faraday's constant	P_{max}	Electrolyser's maximum power, kW
f	Faraday's parameter	PO	Labour wage, €
FC	Operating and maintenance costs, €	P_R	Rated power of the wind turbine, kW
f_{cost}	Construction work cost parameter	Q	Heat, W
h_{day}	Hours of the day	R	Universal gas constant
h_{year}	Hours of the year	r	Ohmic parameter
I	Electrolysis current, A	r_c	Weighted average cost of capital
i	Loan rate of interest	R_{bike}	Average range of fuel cell bike, km
IC	Investment cost, €	Rn	Land lease, €
l_{inst}	Payment amount of the loan, €	s	Anode's overvoltage parameter
Il	Interest of loan, €	t	Cathode's overvoltage parameter
In	Insurance cost, €	T_{el}	Electrolyser's operational temperature, K
k	Wind speed shape factor	t_{other}	Additional time during refill, min
LHV_{H2}	Low heating value of hydrogen, kWh/g	Tr	Revenues of H ₂ sales, €
LL	Rest of the loan amount, €	t_{refill}	Time to refill H ₂ , min
$m_{H2,stored}$	Hydrogen mass inside bike's tank, g	U_{rev}	Reversible voltage, V
$m_{H2,electr}$	Daily H ₂ mass production, g	V	Wind speed, m/s
		v	Volume, l
		$v_{bfr,WV}$	Buffer tank's water volume, l

up with the emerging hydrogen market in the transportation sector.

However, this trend moving towards hydrogen mobility seems to be hindered by several factors such as lack of adequate infrastructure and high cost of ownership [4,5]. As for hydrogen infrastructure and specifically hydrogen refuelling stations (HRSs), more than 315 stations are in operation today with at least 2/3 of them representing publicly accessible refuelling spots [6–8]. The region with the most HRSs in operation at the beginning of 2018 was Europe with more than 130 HRSs, while Asia ranked second with approximately 120 HRSs, mostly located in Japan. America came in third with more than 60 stations installed (mostly in USA) [8]. Fig. 1 illustrates how operative HRSs are distributed globally, highlighting the regions where the new hydrogen market emerges. However, the main barriers that limit the rapid deployment of new hydrogen infrastructure stem from the low number of on-road FCEVs and the high capital investment of an HRS.

At this time, the number of FCEVs reaches 6,000, with more than 2500 units sold in 2017. Although Europe, compared to

other regions, has a more developed hydrogen network in terms of HRSs (see Fig. 1), the leader in FCEVs is North America with more than 50% of total vehicles, followed by Asia with 40% and, lastly, Europe with a 10% share of the FCEV fleet [9]. On the other hand, the capital cost of an HRS can still be considered prohibitive for small investors, and depending on the capacity (kg/day of H₂), the type of the station (Onsite Steam Methane Reformer or Electrolysis, Delivered Gaseous H₂ or Liquid H₂) and the country where the HRS is installed, it ranges between \$0.85 million and \$4.5 million [10,11].

Although hydrogen fuel can be produced via several methods, the most appealing in terms of environmental benefits is through water electrolysis powered by RES. One of the most mature renewable technologies comprises wind power, and many researches analyse the coupling of wind power with water electrolysis topologies. Greiner et al. (2007) presented a sizing and optimisation method for a hydrogen system powered by wind energy in a Norwegian island based on the demand of a hypothetical H₂-propelled vessel [12]. A techno-economic analysis of wind power produced hydrogen

Fig. 1 – HRSs in operation, early 2018. Adapted from Ref. [7].

was published by Gökçek (2010). The author concluded that the operation of the system presented high variations of hydrogen production based on the available wind resource, and the levelised cost of hydrogen ranged between 12.5 €/kg_{H₂} and 18.9 €/kg_{H₂} [13]. Likewise, Genç et al. (2012) financially analysed a wind power hydrogen system, presenting results for hydrogen fuel cost between 7.3 €/kg_{H₂} and 26.6 €/kg_{H₂} based on different wind and water electrolysis topologies [14]. On the other hand, Ulleberg et al. (2010) analysed the results of a pilot wind power electrolysis system in Norway, and argued that for having an efficient system it is required to install efficient electrolyzers able to operate dynamically [15]. More recently Kim and Kim (2017) compared wind onshore and offshore installations coupled with a centralised water electrolysis unit and indicated a levelised H₂ cost between 8.93 €/kg_{H₂} and 13.1 €/kg_{H₂}. Hou et al. (2017) on the other hand, presented business cases on wind energy-based hydrogen production where it is demonstrated that a cost of hydrogen for power to gas applications should be above 5 €/kg_{H₂} in order to have an economically viable scenario [16].

Hydrogen as a renewable energy storage medium presents today an appealing technology to many applications. During the last decade, the scientific community studied the utilisation of hydrogen for mobility purposes through the research on FCEVs and H₂ refuelling processes. Ahmadi and Kjeang (2015) examined the prospects of FCEVs in Canada through a life cycle assessment based on different technologies used for the production of hydrogen fuel. Specifically, H₂ production through thermochemical process by using renewable waste heat presented the best life cycle cost compared to other H₂ and gasoline technologies [17]. Reddi et al. (2017) presented a techno-economic evaluation regarding HRSs, pointing out that current dispenser prices of H₂ fuel in USA ranges between 11.4 €/kg_{H₂} and 13.2 €/kg_{H₂} and

are highly dependent on the technologies used and the capacity of the station [18]. A cost analysis of hydrogen fuel based on two scenarios of FCEV deployment in Normandy has been published by Brunet and Ponssard (2017) [19]. The outcomes of the research indicated that moving to higher capacity of HRSs to cover an increased fleet of FCEVs, will result to an H₂ production cost of approximately 5 €/kg_{H₂}. Ezzat and Dincer (2018) presented their research on a hydrogen-ammonia system for FCEVs able to recover hydrogen during the operation of the vehicle through an ammonia electrolyte electrolyser powered from on-board photovoltaics. The results indicated that the system can produce and store approximately 314 g_{H₂} during 1 h of operation of the vehicle under an output power of 98.3 kW [20].

Apart from the commercialisation of medium-scale passenger FCEVs, many studies conducted since 2000 focused in developing light-duty fuel cell vehicles such as scooters and bicycles at a relatively low cost of ownership. In 2002, Cardinali et al. tested a modified electric bicycle charged by a fuel cell and published their results on the system's efficiency and the components' performance [21]. Tso and Chang (2003) revealed the necessity of integrating fuel cell scooters in Taiwan and presented the promotional activities initiated by the local government [22]. A hydrogen bicycle's development and performance in correlation with its efficiency and autonomy have been investigated by Hwang et al. (2004) who concluded that this technology under commercialisation would be profitable [23]. In 2005, Hwang et al. also described the development of a light-duty fuel cell vehicle and reported positive results in terms of performance and efficiency of the vehicle compared to conventional ones [24]. Indicative research on specifications and cost analysis of a hydrogen scooter has been presented by Chao et al. (2009) through the modelling of a Taiwan fuel cell scooter. The authors evaluated

the performance of the scooter based on their simulation results and suggested that the cost of ownership is directly comparable with that of a conventional scooter [25]. Tso et al. (2012) analysed the results of a project where 30 fuel cell scooters were tested under various conditions and across different route patterns and driving profiles. The results showed adequate technical feasibility of the scooters, but also revealed parameters such as driving performance, hydrogen storage and outdoor temperature in correlation to hydrogen storage that need to be considered when developing this kind of vehicle [26]. Tolj et al. (2013) studied the performance of a fuel cell used as a range extender of an electric golf cart. The authors demonstrated a range extension of 63% and up to 110% [27]. Another research conducted by Kheirandish et al. (2014) was based on experimental investigation of a fuel cell bicycle. Their results showed that hydrogen-based vehicles are superior to conventional vehicles operating in urban environments [28].

Taking the above into consideration, it is obvious that a new market of hydrogen-powered light vehicles is emerging. Hence, in order to support the growth of this urban hydrogen mobility, it is imperative to promote feasible solutions concerning the refuelling processes. To this end, this paper analyses the potential of a small HRS for cycling transportation with onsite hydrogen production via electrolysis powered by a small wind turbine (WT) installed near urban areas. The main purpose of this research is to present a low-cost solution for small HRSs providing H_2 to light-duty vehicles such as fuel cell electric bicycles (FCEBs), primarily in countries where this mean of transportation dominates in urban regions.

Methodology

The proposed methodology consists of four main sections, where a detailed analysis of the proposed configuration is described in both technical and financial terms. Fig. 2 presents a schematic outline of the system under study, consisting of a small wind turbine, an alkaline electrolyser, auxiliary systems, a hydrogen buffer tank and a low-pressure output H_2

Fig. 3 – Main steps of the sizing process.

compressor for keeping the refuelling pressure constant. Fig. 3 indicates the steps followed during the review of the technical aspects of this topic, including the sizing of the wind turbine based on the available wind resource and an assumed average number of FCEBs to be daily refuelled, the sizing and optimisation of an alkaline electrolyser able to absorb the highest amount of the produced wind-based electricity. The sizing of the low-pressure H_2 buffer tank and the exact number of FCEBs that can be refuelled on a daily basis have been determined subsequently. Auxiliary components such as the H_2 compressor are assumed to be electrically supplied directly from the grid.

Following the above, the last part of this paper's methodology section presents a financial evaluation of the proposed topology in order to provide future stakeholders and investors with all the necessary data and results on a hydrogen economy in the transportation sector.

Sizing of the wind turbine

As it was previously mentioned, the first step in the investigation of a small HRS near an urban environment consists in

Fig. 2 – Proposed small HRS configuration.

the sizing of the wind turbine on the basis of an estimate of the final energy needed to daily refuel a certain number of FCEBs and the available wind speed data on the specific region to be studied.

The urban environment under investigation is the city of Herning, which is located in central Jutland in Denmark. The city's population in 2017 was 49,229 inhabitants (N_{inh}) based on Statistics Denmark [29], while the percentage of inhabitants using bicycles on a daily basis is 28% and the average daily distance covered (D_{dist}) approximates 1.5 km/cyclist [30].

The region's average annual wind speed at 25 m above ground level is approximately 6 m/s. The area of the wind measurements and the proposed location of the WT and the HRS are indicated in Fig. 4.

The specifications of the FCEB are presented in Table 1. According to the data given, the FCEB has an autonomy of 100 km with a maximum quantity of 30 g H_2 stored in its fuel tank at a pressure of 200 bar. However, based on Boyle's law (see Eq. (1)) and the specific density of hydrogen, one can obtain the quantity of the hydrogen stored in g ($m_{H,stored}$) under lower pressure (i.e. 30 bar) assuming constant temperature [31]. Thus, by assuming a linear relationship between the stored hydrogen quantity and the vehicle's autonomy, the driving range of the bicycle in the case of storing H_2 at 30 bar of pressure can be estimated as follows:

$$p_1 v_1 = p_2 v_2 \quad (1)$$

where p_1 and v_1 are the pressure and the volume of a gas in bar and in l, respectively, at an initial condition, while p_2 and v_2 are the pressure and the volume of the same gas at a different condition.

In this regard, the daily number of refuelled bicycles can be estimated by dividing the number of bicycles used daily (28% of Herning's population) with the average days of each bicycle's autonomy (R_{bike}/D_{dist}) (see Eq. (2)).

$$N_{bikes} = N_{inh} \cdot 0.28 / \left(\frac{R_{bike}}{D_{dist}} \right) \quad (2)$$

Table 1 – Specifications of the FCEB [32].

Parameter	Value	Units
Motor power	250	W
Motor voltage	36	V
Fuel cell rated power	150	W
Water volume of the H_2 tank	2	l
Maximum H_2 storage pressure	200	bar
Quantity of H_2 at maximum pressure	30	g
Riding range at maximum H_2 storage	100	km
Min. time for refill	2	min

where N_{bikes} is the estimated total number of refuelled FCEBs per day, and R_{bike} is the average range of the FCEB refuelled at 30 bar of H_2 pressure.

However, on account of the magnitude of refills that may result from Eq. (2), one refuelling hose may not be able to cover the demand due to the specific time required to refill one FCEB. To this end, based on the time to refill (t_{refill}) a FCEB found in Table 1, and by also taking into account the time used on other procedures in the process (e.g. the purchase procedure) (t_{other}) (assumed 1 min), the maximum number of FCEBs/refuelling hose served daily from one HRS ($N_{bikes, hose}$) can be calculated via Eq. (3), where h_{day} represents the daily hours.

$$N_{bikes, hose} = \frac{h_{day} \cdot 60}{t_{refill} + t_{other}} \quad (3)$$

In addition, the total number of HRS hoses ($N_{HRS, hoses}$) can be estimated through Eq. (4).

$$N_{HRS, hoses} = \frac{N_{bikes}}{N_{bikes, hoses}} \quad (4)$$

Acknowledging the above and the electricity demand of an electrolyser (E_{el}) [33], Eq. (5) calculates the average annual electricity production of the wind turbine (E_{WT}) (kWh) required to cover the hydrogen demand of the FCEBs.

$$E_{WT} = N_{bikes} E_{el} N_{days} = N_{bikes} \left(\frac{m_{H, stored} LHV_{H_2}}{\eta_{el}} \right) N_{days} \quad (5)$$

Fig. 4 – Location of the wind turbine and hydrogen refuelling station.

Fig. 5 – Non-Dimensional power curve of a small WT. Based on [39].

LHV_{H_2} is the low heating value of hydrogen in kWh/g, η_{el} is the electrolyser's efficiency which is assumed to be 60% (LHV-based) [34] and N_{days} represents the days of the year.

The WT's rated power (P_R) can then be calculated by taking into account the capacity factor (CF) of its annual operation (hours of the year, h_{year}) through Eq. (6) [35]. The CF can be designated via Eq. (7), where Δ represents the technical availability of the WT, indicating the ability of a wind turbine to operate with minimal downtime and thus produce higher energy yield. The technical availability of small wind turbines is lower than larger converters and may reach approximately 91% [36]. On the other hand, ω is the mean power coefficient, which is dependent on the wind resource and can be calculated via Eq. (8) [35].

$$E_{WT} = CF P_R h_{year} \quad (6)$$

$$CF = \omega \Delta \quad (7)$$

$$\omega = \int_0^{\infty} \frac{P_{ex}(V)}{P_R} f(V) dV = \int_{V_c}^{V_f} \frac{P_{ex}(V)}{P_R} f(V) dV \quad (8)$$

$f(V)$ represents the probability density curve of the wind speed, V , and can be calculated through the Weibull distribution (see Eq. (9)) [37], $P_{ex}(V)/P_R$ corresponds to the non-dimensional power curve (see Fig. 5) of the wind turbine with $P_{ex}(V)$ being the power output of the wind converter (of P_R -rated power) at different wind speeds, V , at hub height. V_c and V_f are the cut-in and cut-out speed of the wind turbine, respectively [35].

$$f(V) = \frac{k}{c} \left(\frac{V}{c} \right)^{k-1} e^{-\left(\frac{V}{c} \right)^k} \quad (9)$$

k is the dimensionless shape parameter, and c is the scale parameter in units of wind speed. For the calculation of the parameters k and c , the authors used the Moment Method (MOM) proposed in international literature [37,38], where the local annual wind resource of the region has been used as input (see Fig. 6).

In this context, it is possible to select a commercial WT able to provide the necessary energy in order to cover the annual hydrogen demand of the FCEBs.

Sizing of the alkaline electrolyser

Considering the power curve of the selected WT given by the manufacturer, the actual annual generated power of the WT can be calculated by using the available wind speed resource (Fig. 6).

Fig. 6 – 2016 annual wind speed at 25 m height at the proposed location.

Based on an electrolysis sizing and optimisation algorithm developed by the first author in MATLAB code (see Fig. 7) and by using as input, P_{in} , the output power of the wind turbine, the electrolyser's maximum operational power for producing the maximum hydrogen quantity can be calculated [40].

In Fig. 7, the upper right section concerns the power absorbed by the electrolyser for different values of rated power (P_{max}) depending on the electrolyser's operational power range (e.g. 10%–100%) and the respective available input. The upper left part of the block diagram displays the estimation of the current-power equations at different operational temperatures, between 10 °C and 80 °C, for different values of current ranging from 0 A to 720 A. The electrolysis simulation is presented at the lower part of the figure. In this connection, the algorithm estimates in a loop mode the appropriate size of the electrolyser for producing the maximum hydrogen quantity (n_{H_2}), and at the same time, it calculates all the parameters associated with the electrolysis process [40].

The algorithm used to determine the optimum size of the electrolyser, and therefore the electrolysis' additional parameters (e.g. hydrogen production, efficiency), was based on a set of equations (Eq. (10)–(14)) describing the electrolysis process as well as a heat transfer model proposed by Kavadias et al. (2017) and Diéguez et al. (2008) [40,41]. Through these equations, the voltage current curves of each cell are determined (see Fig. 8). The specifications of each cell appear from Table 2.

$$U_{rev} = U_{rev, T, P^0} - \ln\left(\frac{R T_{el}}{n F}\right) \ln\left(\frac{a_{H_2O}}{a_{H_2} a_{O_2}^{1/2}}\right) \quad (10)$$

$$U_{cell} = U_{rev} + \left(\frac{r_1 + r_2 T_{el}}{A}\right) I + (s_1 + s_2 T_{el} + s_3 T_{el}^2) \log\left[\left(\frac{t_1 + \frac{t_2}{T_{el}} + \frac{t_3}{T_{el}^2}}{A}\right) I + 1\right] \quad (11)$$

$$\eta_F = \left(\frac{\left(\frac{1}{A}\right)^2}{f_1 + \left(\frac{1}{A}\right)^2}\right) f_2 \quad (12)$$

$$\dot{n}_{H_2} = \eta_F \left(\frac{n_e I}{n F}\right) \quad (13)$$

$$C_t \frac{dT}{dt} = \dot{Q}_{gen} - \dot{Q}_{loss} - \dot{Q}_{cool} - \dot{Q}_{sens} \quad (14)$$

U_{rev} is the reversible voltage representing the necessary voltage to split water into H_2 and O_2 , $U_{rev, T, P}^0$ is the reversible voltage at standard conditions ($=1.229$ V), R is the universal gas constant in J/(mol K), F is the Faraday constant in C/mol, n is the number of electrons to split each molecule of water, T_{el} is the operational temperature in K and a_{H_2} , a_{O_2} , a_{H_2O} are the activity coefficients of hydrogen, oxygen and water, respectively. These factors are obtained by the ratio of the reactants to the atmospheric pressure.

I is the electrolysis current in A, A is the surface of the electrodes in m^2 , r_1 , r_2 are the ohmic parameters, s_1 , s_2 , s_3 and t_1 , t_2 , t_3 are the overvoltage coefficients of the anode and cathode, respectively.

η_F is the Faraday efficiency, which expresses the ratio between the actual hydrogen production to the theoretical one

Fig. 7 – Sizing and optimisation algorithm of the alkaline electrolyser. Based on [33,40].

Fig. 8 – Voltage-current curves of the electrolytic cell.

and f_1 in $\text{mA}^4\text{cm}^{-4}$, f_2 are the Faraday parameters that depend on temperature.

$\dot{n}_{\text{H}_2}$ is the hydrogen production rate, and it is highly dependent on the ion transfer between the electrodes of a cell, which reflects to the electrical current of the electrolysis, n is the number of electrons to split each molecule of water and n_c is the number of cells of the electrolyser.

C_t is the overall thermal capacity of the electrolyser in $\text{J}/^\circ\text{C}$, Q_{gen} is the generated heat in W and Q_{loss} is the heat loss transfer to the environment in W and depends on the electrolysis and the ambient temperature, which has been assumed to be steady (indoors operation). Q_{cool} is the heat removed from the electrolysis via the cooling system in W. Q_{sens} includes the enthalpy leaving the system with the H_2 - and O_2 -produced streams along with the heat transferred from the device to the incoming deionized water in W [40,42].

Sizing of the low-pressure buffer tank – determination of the daily FCEBs refuelling processes

The sizing of the low-pressure buffer tank was based on the daily demand for hydrogen, $M_{\text{H}_2\text{dem}}$. The maximum storage capacity of the tank ($M_{\text{H}_2\text{bfr}}$) is defined in Eq. (15). However, if the maximum hydrogen production from the electrolyser is higher than the daily H_2 demand, then the buffer storage

should be able to accommodate this maximum produced quantity.

Thereafter, the buffer tank's water volume ($v_{\text{bfr},\text{wv}}$) can be calculated through the maximum value of daily produced hydrogen mass, the specific density of hydrogen and Boyle's law (see Eq. (1)), where p_1 and v_1 are the pressure and volume of hydrogen at STP conditions, while p_2 and v_2 are the pressure and volume of hydrogen at 30 bar v_2 equals the water volume of the buffer tank, representing the actual size of the buffer tank for the respective daily storage of the produced hydrogen under pressure of 30 bar.

$$M_{\text{H}_2\text{bfr}} = N_{\text{bikes}} m_{\text{H}_2\text{stored}} \quad (15)$$

The actual daily number of FCEB (N_{FCEB}) refills from the proposed HRS can be determined from the hydrogen mass in the buffer tank ($m_{\text{H}_2\text{bfr}}$), the H_2 quantity stored in each FCEB tank ($m_{\text{H}_2\text{stored}}$) and the daily H_2 production from the electrolyser ($m_{\text{H}_2\text{electr}}$). Fig. 9 indicates the algorithm used for calculating the daily FCEB refuelling processes. In order to secure fuel availability on a daily basis, it is assumed that whenever the hydrogen quantity inside the buffer tank is lower than the daily H_2 demand, only half of this quantity can be used for refuelling purposes.

Financial evaluation

Review of the financial parameters in relation to the proposed configuration plays a major part in the investment decision and the techno-economic analysis. In this context, the Net Present Value (NPV), the Internal Rate of Return (IRR) and the payback period (PP) of the project have been used to assess different investment scenarios.

For the calculation of the above parameters, a set of equations regarding all the different factors of the small-scale HRS business was used based on [43,44]. The investment cost of the entire project is assumed to be covered by own capital and a bank loan (equity-loan ratio). Eq. (16), which includes the different components of the installation, indicates the formula for the calculation of the capital cost.

$$IC_o = IC_{\text{WT}} + IC_{\text{el}} + IC_{\text{CS}} + IC_d + IC_{\text{bfr}} + IC_{\text{comp}} + IC_{\text{constr}} \quad (16)$$

where IC_o is the project's investment cost in €, IC_{WT} is the total cost of the WT installation, IC_{el} is the total cost of the electrolysis system, IC_{CS} is the cost of the control and safety components, IC_d is the cost of the dispenser, IC_{bfr} is the cost of the H_2 buffer tank and IC_{comp} is the cost of the H_2 compressor.

In addition, the total investment cost includes the construction and contingency (unexpected costs during construction work) costs (IC_{constr}), which can be estimated (see Eq. (17)) as a percentage of the equipment cost ($f_{\text{cost, constr}}$ and $f_{\text{cost, cont}}$, respectively), excluding the wind turbine installation costs that have been taken into account in IC_{WT} [45].

$$IC_{\text{constr}} = (IC_{\text{el}} + IC_{\text{CS}} + IC_d + IC_{\text{bfr}} + IC_{\text{comp}}) * (f_{\text{cost, constr}} + f_{\text{cost, cont}}) \quad (17)$$

The low-pressure compressor for maintaining a pressure of 30 bar during the refuelling processes and a flow rate of approximately $200 \text{ Nm}^3/\text{h}$ is assumed to be a 3 kW compressor ideally used for hydrogen [46].

Table 2 – Specifications of the electrolytic cells.

Parameter	Symbol	Value	Units
Electrode's surface per cell	A	0.25	m^2
Operational pressure	p_{el}	30	bar
Empirical ohmic parameter 1	r_1	7.3×10^{-5}	$\Omega \text{ m}^2$
Empirical ohmic parameter 2	r_2	-1.1×10^{-7}	$\Omega \text{ m}^2/^\circ\text{C}$
Cathode overvoltage parameter 1	t_1	1.6×10^{-2}	m^2/A
Cathode overvoltage parameter 2	t_2	-1.3	$\text{m}^2/^\circ\text{C}/\text{A}$
Cathode overvoltage parameter 3	t_3	412	$\text{m}^2/^\circ\text{C}^2/\text{A}$
Anode overvoltage parameter 1	s_1	1.6×10^{-1}	V
Anode overvoltage parameter 2	s_2	1.38×10^{-3}	$\text{V}/^\circ\text{C}$
Anode overvoltage parameter 3	s_3	-1.6×10^{-5}	$\text{V}/^\circ\text{C}^2$

Based on [42].

Fig. 9 – Algorithm used to determine number of FCEBs to be refuelled daily.

Table 3 presents the data used for the calculation of the investment cost of the proposed scheme.

The assumptions used in the financial evaluation included a project lifetime of 20 years (n), a bank loan with a repayment period of 10 years, an HRS workforce of 2 people and a required footprint of 1000 m². Any form of subsidy in relation to the business plan is disregarded.

For the calculation of the NPV of the project, the following formula (Eq. (18)) has been used [43,44].

$$NPV = \left(\Phi * \left(\sum_{j=1}^{j=n} T_j - \sum_{j=1}^{j=n} PO_j - \sum_{j=1}^{j=n} FC_j - \sum_{j=1}^{j=n} In_j - \sum_{j=1}^{j=n} Rn_j - \sum_{j=1}^{j=n} Ad_j - \sum_{j=1}^{j=n} Il_j \right) + \sum_{j=1}^{j=n} Ad_j - \left(\sum_{j=1}^{j=n} Inst_j - \sum_{j=1}^{j=n} LL_j * i \right) \right) * CV_{coef} - IC_o \quad (18)$$

with

$$CV_{coef} = \frac{1}{(1+r)^j}, j = 1 \text{ to } n \quad (19)$$

where Φ is the income tax coefficient, T the revenues from the H₂ fuel sales, PO the amount of salaries during the operational period and FC the O&M costs as a percentage of the investment cost, including a replacement cost of the main electrolyser parts at the 11th year of operation (FC_{el}) and the O&M costs of the wind installation.

In is the annual insurance cost, Rn is the land lease amount, Ad is the depreciation, Il is the interest of the loan, $Inst$ is the payment amount of the loan assuming a rate of interest i , LL is the remainder of the loan amount and CV_{coef} is the conversion coefficient in current value ratio with r being the weighted average cost of capital.

The factors used for the calculation of the above parameters are presented in Table 4.

Subsequently, the calculation of the final cash flows during the operational lifetime of the project derived through the NPV formula results in an estimation of the IRR and the payback period.

In order to provide the best-case scenarios in relation to the project viability, a sensitivity analysis showing how IRR changes at different H₂ fuel costs and equity-loan ratios has been compiled. Additionally, a comparison between the cost per kilometre for FCEBs and electric bicycles (EBs) has been made for the same region and the same traveling distance.

Results and discussion

Sizing of the HRS's components

As it was mentioned in the previous sections of this paper, the sizing of the WT powering the electrolyser depends on the final hydrogen demand for refilling the FCEBs as well as the wind resource of the investigated region. The results, which are based on Eqs. (1)–(9), are presented in Table 5.

Based on Table 5, the WT's rated power should be more than 48.4 kW in order to satisfy the hydrogen energy demand

Table 3 – Cost values used for the estimation of the HRS's investment cost.

Parameter	Symbol	Value	Units	Source
Cost of the WT installation	IC _{WT}	1477	€/kW	[47]
Cost of the electrolysis system	IC _{el}	1200	€/kW	[48,49]
Cost of control-safety systems	IC _{CS}	255	€/kgH ₂ /day	[50]
Dispenser cost	IC _d	15300	€/hose	[51]
Cost of buffer tank	IC _{bfr}	1350	€/m ³	[52]
H ₂ compressor cost	IC _{comp}	7250	€/kW	[18,53]
Construction work parameter	f _{cost,constr}	0.15	–	[45]
Contingency parameter	f _{cost,constr}	0.08	–	[45]

Table 4 – Parameters used during the estimation of the NPV.

Parameter	Symbol	Value	Units	Source
Income tax coefficient	Φ	22%	–	[54]
Labour wage	PO	3500	€/month/person	[55]
O&M costs	FC	2.0% IC_o	€	[56–58]
Replacement of electrolyser cost	FC_{el}	50% IC_{el}	€	[43]
Insurance cost	In	1.0% IC_o	€	[56]
Land lease	Rn	2	€/m ² /month	[59,60]
Depreciation	Ad_j	10% ($IC_o - Ad_{j-1}$)	€	[61]
Loan rate of interest	i	3.2%	–	[45,62]
Weighted average cost of capital	r	3.0%	–	[63]

of N_{bikes} . To this end, a H17.0–50 kW wind turbine manufactured by Anhui Hummer Dynamo Co., Ltd. has been selected for the proposed configuration. The specifications are shown in Table 6.

Fig. 10 presents the annual power generation of the WT based on the wind speed data shown in Fig. 6, the specifications of the proposed WT and the power curve given by the manufacturer.

The sizing of the electrolyser is based on the algorithm presented in the previous chapter (see Fig. 7). Fig. 11 indicates the number of electrolysers whose rated power was checked during the algorithm application. According to Fig. 11, a 70 kW capacity electrolyser is optimal for utilising the WT's generated energy to produce the largest quantity of hydrogen. 71.8% of the WT's available production is transformed into hydrogen. It is obvious that the capacity of electrolysis is higher than the one of the WT because of the electrolyser's operational power limits ranging between 10% and 100% of its nominal capacity.

The daily hydrogen production (m_{eH_2}) of the 70 kW electrolyser is depicted in Fig. 12. The maximum quantity produced per day reaches 21.2 kg, while the average daily production is calculated at 7.9 kg.

By comparing Figs. 10 and 12, one may observe that although the hydrogen production rate follows a similar pattern with the power output of the WT, there is an obvious

difference when it comes to the maximum points. In many cases, when the WT's output power is maximum, the hydrogen production is lower than the expected 21.2 kg. This is happening because of the relationship between the operational temperature of the electrolysis and the electrolytic cell voltage (see Eqs. (10) and (11)). These equations suggest that even at similar power input values observed during a certain time period, the electrolyser does not produce the same amount of hydrogen when it operates under different temperatures. Fig. 13 illustrates the electrolyser's operational temperature variations on an annual, hourly basis. By comparing Figs. 12 and 13, it becomes apparent that the operational temperature of the electrolyser decreases whenever the power input is low, while when operating under maximum input, the temperature rises to the highest set value. However, this variation does not follow the power changes immediately because of the heat capacity and the thermal resistance of the electrolysis stack. Thus, this phenomenon explains the differences observed between the H_2 production values at the highest values of power input.

Regarding the hydrogen buffer storage tank, it should obviously be able to store the maximum daily H_2 produced by the electrolyser in order to avoid rejection of the produced hydrogen to the atmosphere. In this regard, and by taking into consideration that the maximum daily production of the electrolyser exceeds the daily demand (see Section 2.3, Table 5, and Fig. 12), the maximum H_2 mass that the tank should be able to store amounts to 21.2 kg. Hence, based on Eq. (1), the water volume of the H_2 buffer tank is calculated at 7.8 m³.

By taking into consideration the daily hydrogen production and the buffer tank's water volume, the number of FCEBs that can be refuelled per day is shown in Fig. 14. Fig. 15 indicates the hydrogen mass rate inside the buffer storage tank when factoring in the number of daily refills.

As is obvious, the daily demand for FCEB refills could not be covered entirely due to the intermittency of the wind-generated electricity. Based on the data from Table 1, the

Table 5 – Results of the WT sizing process.

Parameter	Symbol	Value	Units
Mass stored in the FCEB at 30 bar pressure	$m_{H_2,stored}$	5.465	g
Estimated range of the FCEB with $m_{H_2,stored}$ of H_2	R_{bike}	18	km
Number of daily FCEB refills	N_{bikes}	1149	–
Maximum number of daily served FCEBs/hose	$N_{bikes,hose}$	480	–
Number of HRS refuelling hoses	$N_{HRS,hoses}$	3	–
Daily demand for hydrogen	M_{H_2dem}	6.8	kg
Annual energy production of the WT	E_{WT}	127,211	kWh
Scale parameter of wind resource	c	6.495	m/s
Shape parameter of wind resource	k	2.289	–
Mean power coefficient	ω	0.402	–
Capacity factor	CF	0.298	–
The WT's minimum rated power	P_R	48.4	kW

Table 6 – Specifications of the H17.0–50 kW WT [64].

Parameter	Value	Units
Rotor diameter	17	m
Rated power	50	kW
Cut-in speed	3.5	m/s
Cut-out speed	25	m/s
Wind speed at rated power	9.5	m/s

Fig. 10 – Annual power output of the WT.

Fig. 11 – The WT's stored energy percentage at different electrolyser's maximum operational power.

Fig. 13 – Operational temperature of the electrolyser.

Fig. 12 – Daily hydrogen mass production.

Fig. 14 – Number of daily FCEB refills.

Fig. 15 – H₂ annual mass flow rate in the buffer tank.

total annual demand for FCEB refuelling processes equals 420,534 refills. Instead, the proposed HRS would be able to cover the entire daily refuelling demand 322 times on an annual basis, while the total annual FCEB refills would reach 384,498.

Consequently, in order to cover the total daily demand of the investigated region, implementation of at least one more HRS with lower capacity than the one investigated is required.

Table 7 summarises the results concerning the electrolysis process, the hydrogen buffer tank and the number of daily served FCEBs.

Financial results of the HRS

The economic viability of the proposed configuration is highly dependent on the equity-loan ratio and the price of the H₂ fuel. Fig. 16 shows the results of the sensitivity analysis concerning how IRR is affected by the H₂ fuel cost and the percentage of own capital in the initial investment.

The capital cost of the business plan, including the replacement of main electrolyser stack parts after the 10th year of operation, has been calculated at €248,130 from Eqs.

Table 7 – Results of the electrolysis-buffer storage algorithm-FCEB refills.

Parameter	Symbol	Value	Units
Electrolyser's maximum operational power	P_{el}	70	kW
Electrolyser's maximum operational temperature	T_{el}	70	°C
Number of electrolytic cells	n_c	54	–
Electrolyser's maximum H ₂ mass flow rate	m_{H_2}	0.24	g/s
Calculated electrolyser's average overall efficiency	η_{el}	0.59	–
Buffer tank's water volume	$V_{bfr,wv}$	7.8	m ³
Maximum H ₂ buffer tank storage at 30 bar pressure	M_{H_2bfr}	21.2	kg
Average daily H ₂ quantity stored in buffer tank	–	15.3	kg
Average daily refuelling processes	–	1051	–
Number of days of covered H ₂ demand for refuelling in 1 year	–	322	–

Fig. 16 – Changes in IRR under different cost and investment scenarios.

(16) and (17). Based on the results illustrated in Fig. 16, it is apparent that an H₂ fuel price above 50.2 €/kg_{H2} is required in order to have a financially viable project. It can also be seen that even in the case of a lower equity-loan ratio (e.g. 20/80), the minimum price of hydrogen fuel is not lower than the above-mentioned value. Nevertheless, in this scenario, the IRR of the project would increase significantly should the H₂ prices increase only slightly.

Table 8 presents the NPV, IRR and PP for different costs of H₂ fuel under two different equity-bank loan ratio scenarios.

As Table 8 suggests, the NPV values for each ratio scenario are almost the same for the same H₂ fuel price. However, the calculations show that in the case of a self-financing ratio of 20%, IRR is significantly higher and PP is substantially reduced. Although the most profitable scenario for an investor would be to set a fuel price higher than 53 €/kg_{H2}, the price of the fuel should be appealing to customers in order to support the transition to hydrogen-based urban transportation.

In relation to urban cycling, the main alternative to FCEBs is the use of electric bicycles (EBs). The electricity price for household consumers in Denmark is the highest among the EU countries. The cost of electricity in 2017 was 0.3 €/kWh [65]. According to Gebhard et al. (2016) [66], the average indicative trip segment consumption of an EB is 7.9 Wh/km. Hence, the respective cost would be approximately 0.04 €/km for a consumer who uses an EB under the same conditions and driving distance (i.e. 18 km) as the one investigated.

In contrast, for the FCEB, assuming a 54 €/kg_{H2} fuel price, an end-use fuel tax exemption and the 25% valued added tax (VAT) applied in Denmark [67], then – based on Table 5 – the fuel cost per driven kilometre would be €0.02 for a consumer.

By taking the above into account, it becomes clear that even with higher cost of the H₂ fuel, the fuel price that a consumer is to pay when using a FCEB instead of an EB would be approximately half.

However, it is important at this point to note that all the calculations were based on Denmark's economic status and data from its financial system. To this end, it should be stressed that in case of other countries and different regulations, this outcome may vary a lot.

Table 8 – HRS business scenarios at different H₂ fuel costs.

H ₂ fuel cost (€/kg _{H₂})	Equity-bank loan ratio 50/50			Equity-bank loan ratio 20/80		
	NPV (€)	IRR	PP (years)	NPV (€)	IRR	PP (years)
51	25,860	3.19%	12	26,203	6.11%	12
52	61,764	7.00%	10	62,107	14.20%	6
53	97,668	10.41%	8	98,011	22.13%	5
54	133,572	13.57%	7	133,915	29.85%	4
55	169,476	16.58%	6	169,818	37.37%	4

Conclusions

The scope of this study was the assessment of a small-scale autonomous HRS powered by wind energy, able to support a relatively small city's FCEB fleet. The research on this specific topic provides a tool for the estimation of the technical and financial parameters of a small-scale HRS coupled with an onsite wind turbine powering a water electrolysis system. The results indicate that this venture is feasible only by employing proper sizing and optimisation techniques in order to accommodate the daily hydrogen fuel demand, while keeping the cost of the station as low as possible.

In sum, the research results show that a medium-scale urban area with relatively good wind resources, such as the Herning municipality located in Denmark, can accommodate at least one HRS in a scenario where conventional bicycles would be replaced by FCEBs. The proposed three-hose HRS would be able to support the daily demand for hydrogen fuel more than 87% of the annual calendar days, while no refuelling processes would occur in only one day of the year. From a financial point of view, the capital investment required for this type of HRS is not prohibitive for an investor, and the IRR in conjunction with the NPV and the PP presents positive results for an unsubsidised price of the H₂ fuel above 51 €/kg_{H₂}. Although this cost seems relatively high compared to previous researches for hydrogen production coupled to wind power (i.e. price up to 26.6 €/kg_{H₂}), it is normal to observe this price increase due to the other components required for even a very small capacity HRS.

In conclusion, this research consists of a feasibility assessment of the proposed solution in order to identify possible business opportunities for energy investors and contribute positively in the transition to a future hydrogen-based economy.

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