Linkage of a decentralised green energy generation system to the requirements of railway operations

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***Abstract*—The reduction of carbon emissions in the transport sector is one of the main objectives of the railway industry to meet existing and future regulations on decarbonisation. Fuel cells can contribute to this goal, but their usage needs to be further investigated and efficiently integrated into existing systems. A significant technical hurdle is the decoupling of hydrogen generation to the consumption identifying the minimum sufficient storage. To maintain the existing electrical infrastructure for Europe and to keep new investments and operational cost to a minimum, the paper proposes to supply energy to some electric railways using fuel cells. The hydrogen storage tanks needed for the fuel cells are replenished by electrolysers fed by a decentralised power generation. This will not only reduce the peak load demand of the railway but can also allow grid-independent operations in case of grid-outages. By utilizing and extending the existing infrastructure of catenary electrified tracks and operating with a standard mobile electrical application, a low maintenance and efficient stationary energy supply is being proposed by this paper, which has not been assessed as a well to wheel approach considering the consumption and storage as part of the solution. A cost- and energy-efficient, decarbonization of the railway industry with decentral solid oxide fuel cells supplied by green hydrogen, stored and buffered in a tank. A proposal for tank size based on a large-scale hydrogen generation park for a specific geographical location combined with a track-based energy consumption model will be the outcome of this paper.**

Keywords—Railway, decentralised power supply, Renewable sources, decoupling of demand and generation, stationary fuel cells

I. Introduction

Green hydrogen, which is produced by renewable energy sources, is a key energy vector to support large-scale energy storage systems [1], as no CO2 is emitted in the process of generation. Hydrogen is then stored in tanks, which are also transportable in pipelines or trucks. The potential of solar and wind energy to produce green hydrogen depends on the geographical conditions but is given for any location and is therefore the baseline for the proposed concept of railway electrification [2] [3].

The 2022 published report by the International Renewable Energy Agency (IRENA) [4] provides a geographical evaluation of the pros and cons of energy transition to hydrogen from a global perspective. The report shows not only a reduction of waste from fossil fuels but mainly the reduction on the dependency from energy imports from other countries. By being independent from energy imports is positive for the European business case, and a large-scale green hydrogen production can incentivise investments to deliver on a more sustainable energy supply for the railway industry. However, technological developments as well as regulations need further research, which is the main objective of this paper [5]. In particular, this paper provides a methodology to calculate the minimum capacity of the storage and the power generation to satisfy the requirements of a railway line based on a mathematical model of the system, which has been validated with numerical simulations. The results are provided for a case study of a real railway line in the UK considering a historical weather forecast from an available simulation in Morocco to simulate a full year scenario.

II. Grid Connection as a Secondary Energy Supply Option

In the proposed electrification system, the overhead line is supplied by the fuel cell (FC) system and the grid. This is certainly possible for European use cases where a well-established grid infrastructure is available.

Grid-parallel, grid-connected islanding, grid-independent stand-alone and grid-lined architectures are the available operating modes of the combined fuel cell and grid power supply. They have different advantages and disadvantages as investigated by [6]. The grid-parallel power generation requires an AC feed of the fuel cell with the voltage and frequency locked to the grid to operate successfully. This configuration enables the regulation of the power production as well as fail safe control as the grid could always support railway loads. The grid-connected islanding solution would fail if the connection to the grid is not ensured but allows a direct power supply to the load condition [6]. For the grid-independent stand-alone approach a remote solution can be realised, which can be applicable for installation use cases in remote like in the Americas or Afrika, where no well-established grid network would be in vicinity of a railway track segment. For a grid-linked solution a direct power supply from the grid can be realized, which is the preferred solution, as this approach would only consider a utilization of the grid power without feeding the grid from the FC power source.

The selection of the most appropriate operating mode at different times of the day or railway traffic conditions can be optimised to reduce system costs, as the energy supply does not fully rely on the available stored energy.

Each section of the railway line is supplied by such a FC and storage concept to adapt to the specific requirements and the geographical conditions. The power demand for each section is covered by the FC and, in case of a surplus, can be supplied to the grid locally, e.g. for the houses surrounding the railway or the railway station itself to reduce the cost of the costs further. With hydrogen as a transportable storage media the distribution of an energy surplus could also be a profitable option that needs to be considered.

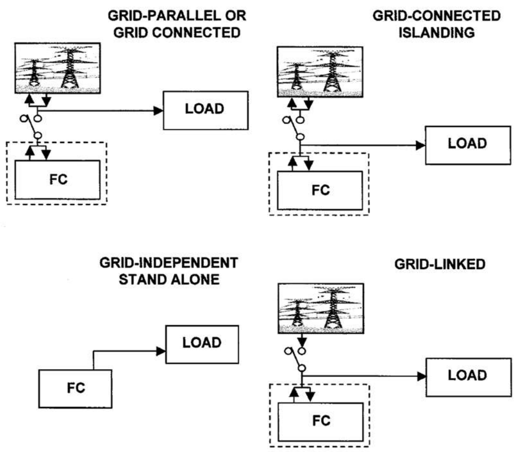

Figure 1: FC grid structures [6]

The grid-linked structure can be used for existing catenary networks to support a decentralised energy generation approach by using a FC instead of the grid infeed. Here the backup approach in case of low energy generation possibilities can be ensured. Areas like in Switzerland with a high electrification network could easily set-up FC feeder stations to build grid-linked systems. For other European setups, a similar situation can be considered, which drives the decision to use this configuration in a wider approach. The simulation of the FC model will consider the grid-linked setup, so the grid is always available to supply the railway in case of a failure or a low generation from renewable power sources due to unforeseen weather conditions.

III. GREEN ENERGY GENERATION TO SUPPORT THE DEMANDS OF THE RAILWAY OPERATIONS

The renewable energy sources used to calculate the input power need to be designed and dimensioned according to the given circumstances. Various studies on large-scale green hydrogen production have presented an in-depth analysis of cases based on water electrolysis [7]. Here the hydrogen production cost as well as the installation cost have been assessed and evaluated to provide a full review on the technical status quo. Especially the energy transformation and storage location are rated as relevant in the decision-making process, which will also drive the configuration for the proposed railway system solution. Large-scale storage facilities are mainly installed at the production or distribution level, to avoid transportation losses, including pipeline terminals and other approaches. Small-scale production and storage facilities are rather used at the end-consumer. For this paper a large-scale storage in vicinity of the consumer and the generator has been considered [8].

Various assessments have been conducted to simulate a complete production of hydrogen based on wind and solar power. For this paper those energy generation methods will be used and combined with a highly efficient electrolyser to store and buffer the hydrogen. The production cost of hydrogen using a hybrid system has a business case, as the production cost of 8.70 EUR/kg is lower than the selling price of 10 EUR/kg [9]. With the further development of solar and wind power generation, an annual output of up to 70 GW of renewable power is expected by 2030, leading to a cost for green hydrogen of 1.50 EUR/kg, with an annual production of 3.6 million tonnes.

Based on real wind and solar profiles and supported by different papers, the following configurations have been defined for the renewable energy sources. An 8.0 MW PV-farm and a 4.5 MW wind farm have been initially selected as a starting point for the minimisation of investment for a specific use case. The wind-farm model simulates a direct relationship from windspeed to power and the PV system according to the efficiency factor.

Table 1: Parameters of the initial PV System

Symbol	Parameter	Value	Unit
D	Area of PV modules	8000	m^2
P	Max power	8	MW
E	Efficiency	10	%
Gi_{ref}	Reference solar irradiance	1000	W/m^2
$TP_{V, ref}$	PV panels reference temperature	25	°C
$TP_{V, nom}$	Nominal operating cell temperature	45	°C

Table 2: Parameters of the wind turbine for the initial wind farm

Symbol	Parameter	Value	Unit
P_{rated}	Rated power	4.5	MW
V_{cut-in}	Cut in wind speed	1.85	m/s
$V_{cut-out}$	Cut out wind speed	30	m/s
V_{rated}	Rated eind speed	9.55	m/s
d	Rotor diameter	9.8	m

A detailed assessment of various solutions for the hydrogen generation has been summarized in [10], showing the potential for alkaline electrolysis. Table 3 shows an example of an electrolyser that is used in this paper.

Table 3 : Parameters of the alkaline electrolyzer used for the initial load

Symbol	Parameter	Value	Unit
N_{cell}	Number of cells	65	-
X	Model units in series	10	-
A_{EZ}	Electrode area	0.25	m^2
T_{EZ}	Operation temperature	80	°C
r_1	Ohmic resistance	8×10^{-5}	Ω
Z	Number of electrons per reaction	2	-
S	Electrode overvoltage	0.185	V
U_{rev}	Electrolyzer reversible voltage	1.229	V
F	Faraday efficiency	$2.5T_{EZ} + 50$	A^2/m^2

Research from Kakoulaki et al. [11] did evaluate the technological readiness of renewable energy resources at the national and regional levels across 27 European countries. The study shows that proton exchange membrane electrolysis at sea offers the highest chances for immediate application. According to estimates by Brändle et al. [12] methane decomposition and wind and solar energy sources should be uses for an effective rate in ninety different countries. The documents contain information on ideal locations for cost-effective solar and wind energy production. Further investigations on the cost for production and transportation of hydrogen have been assessed for truck and pipeline transportation. [13] By comparing the various transportation modes with respect to greenhouse gas emissions, the pipeline transportation is the most favourable option for large-scale terrestrial hydrogen transportation.

IV. Storage and Fuel Cell Setup to supply the electrical energy demand

Within vehicle applications, the majority of FCs are based on low temperature (LT) systems due to the weight and cost perspective as well as their quick start up [14].

For large-scale electricity applications, FCs are based on high temperature (HT) systems to increase power output and efficiency. HT FCs operate with either pure hydrogen or methane, facilitating their adoption. Due to the high temperatures, the FC is more tolerant against carbon oxide, because of the ability in internal reforming. This could potentially allow a supply from pipelines or other sources, in case that the own hydrogen generation would be short due to insufficient wind or solar energy. [6] The following figure shows the target markets for each application with the power output of electrical energy that can be achieved. For the SOFC application the Residential as well as the stationary applications, have been declared as relevant, where the standard applications specifically exclude the Transportation segment [6].

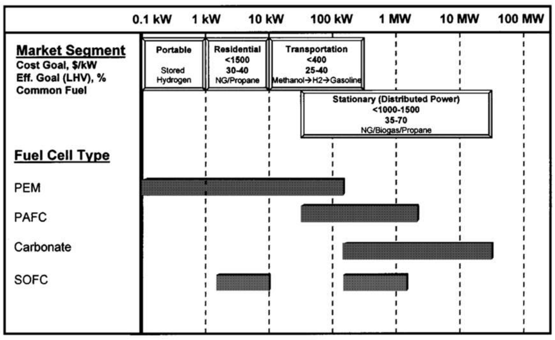

Figure 2: FC target markets: proton exchange membrane (PEM), phosphoric acid fuel cell (PAFC), carbonate fuel cells, solid-oxide fuel cell (SOFC) [6]

Depending on the use case, a primary or secondary energy FC supply needs be controlled and regulated according to the available energy sources like wind or solar power. Buffer solutions based on large-scale or decentralised concepts enable an immediate availability of hydrogen, where a pipeline and or a truck supply can be additionally considered.

Available chemical energy from hydrogen can be used not only to supply the railway, but also as a combined heat source for nearby buildings which would further enhance the system efficiency [15].

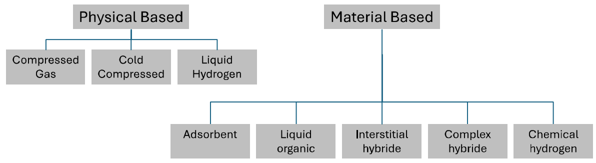

Figure 3: Hydrogen storage and creation possibilities own figure [15]

Hydrogen storage forms as shown in the graph above can vary from physical-based to material-based and have a wide spectrum of use cases depending on the application. To consider a pipeline feed to a nearby fuel cell application like in the case of a railway usage, a physical-based storage would be required.

Authors of the twelfth german local railway transport day (12. Deutscher Nachverkehrstag) have presented a hydrogen supply railway concept, where the train, an Alstom Coradia iLint, was supplied with hydrogen, generated from decentralised renewable sources. For this application, trains still carry on-board the hydrogen tank and the fuel cell, which has the known drawback of mass increase and energy consumption increase, that has been already discussed in the literature [16] [17]. Investment of refuelling stations with their safety requirements and the additional decentralised infrastructure has not been investigated yet and is therefore seen as highly critical with respect to technological and economical aspects.

On the other side, stationary fuel cell applications have multiple advantages, which can be leveraged to increase the overall system efficiency, especially with an intelligent control of renewable power generation and hydrogen storage. Stationary fuel cells with the combined heat output for nearby villages or factories have not been considered in the assessment of the system efficiency and the entire Well-to-Wheel approach. Systems used to power malls, stadiums and hospitals are considered for such an application already and can be used as a baseline for the system approach of CHP with respect to railway transportation. Combining all advantages together, while still be able to operate train applications, does need a sufficient supply of hydrogen. Here a sufficient dimensioning of green energy sources, transformers and storage needs to be ensured, where the following system modelling will deliver on.

V. System modelling to meet the required green Energy demand

A. *Energy demand modelling*

The demand model has been based on [16] [18] [19] [20], where a train simulator model has been modified to simulate a section of a railway line in the UK. For this simulation, the section is electrified and operated with electric trains without regenerative braking.

Using for this paper the same Birmingham route as in [21], the maximum power demand of each train is 550 kW, and the cruising power is 100-150 kW, which can be assumed as the required average power. Considering an allowance of 10%

for power losses due to transmission and transformation, the average power demand is 165kW and the peak power demand is 605 kW. Considering a distance between the feeder stations of 50 km as in [22], 1 train every 10 min, and 1 track fed by the same source, the average and peak power demands of each feeder station are 330 kW and 1,210 kW, respectively.

With these assumptions, the demand of electrical energy would be 6,000 kWh/day for the 100 km railway line and 18 h of operation.

B. Energy generation

Energy generation based on renewable power sources requires various technical systems, that need to be linked accordingly. Depending on the geographical location a large variation of the amount of energy generated can be observed. Solar power parks are highly represented in the south of Europe and deliver energy during daytime on a frequent and predictable occurrence. To forecast day and night is rather simple, but clouds and rain can vary the generation outcome, which needs to be reflected in the modelling of the raw energy source coming from the sun. The following model can be used to predict the power generated by a solar power plant:

$$P_{PV} = N_{PV} \frac{G_i}{G_{i,ref}} \left[P_{PV,max} + \mu_p (T_{PV} - T_{PV,ref})\right] \quad (1)$$

$$T_{PV} = T_a + G_I \left[\frac{NOCT-}{800}\right] \quad (2)$$

Where G_i is the solar irradiance in W/m2, and T_a is the ambient temperature. For ideal conditions like in Alexandria, Egypt the paper from Nasser et all [23] uses the sun profile shown in Fig. 6 as an input.

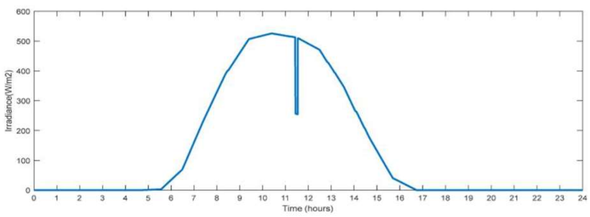

Figure 4: Solar irradiance profile [24]

The solar power plant has been combined with a wind farm to optimize and balance the power generation to produce hydrogen. As Wind farms are generally generating a highe output but do result in higher installation and maintainance cost, the right balance needs to be found for the available profiles considering the cut-in wind speeds. The wind farm is calculated based on the following formula to estimate the electrical energy generated:

$$P_{WT} = P_{rated} \frac{V^3 - V_{cut-i}^3}{V_{rated}^3 - V_{cut-i}^3} \quad (3)$$

Equation (3) describes the wind turbine energy generation, which has also been taken from Nasser et al. and is based on the annual wind profile in Alexandria. From this equation, the average wind profile in Fig. 7 will be used for the model.

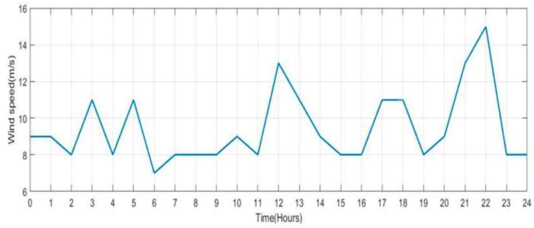

Figure 5: Wind speed profile [24]

C. Energy converter model

The electrical energy from the renewable sources is converted into chemical energy of hydrogen via an electrolyser, fed by a DC bus. A DC/DC converter has been used to connect the solar plant to the DC bus, while an AC/DC rectifier has been used for the wind plant. Additionally, the efficiency of these converters has been assumed constant and equal 95% for simplicity, while the efficiency of the electrical generator of the wind turbine, η_{gen}, has been also assumed equal to 95%:

$$P_{EZ} = \left(P_{PV}\ x\ \eta_{\frac{DC}{DC}}\right) + \left(P_{WT}\ x\ \eta_{gen}\ x\ \eta_{\frac{AC}{DC}}\right) \quad (4)$$

D. Electrolyser model

The electrolyser uses electric energy to decompose pure water into hydrogen and oxygen. The model in this paper is based on [25] and [26], which uses an alkaline electrolyser for a given Temperature:

$$V_{cell} = V_{rev} + v_{act} + v_{ohm} \quad (5)$$

$$V_{act} = log\left(\frac{t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}}{A} I + 1\right) \quad (6)$$

$$V_{Ohm} = \frac{r_1 + r_2 T}{A} I \quad (7)$$

Considering a temperature dependency for ohmic resistance parameter, r and the overpotential coefficient s and t the equation can be solved. The Faraday efficiency is defined as the ratio between the actual and the theoretical maximum amount of hydrogen produced in the electrolyser.

$$\eta_F = \frac{\left(\frac{I}{A}\right)^2}{f_1 + \left(\frac{I}{A}\right)^2} + f_2 \quad (8)$$

$$n_{H2} = \eta_F \frac{n_c I}{zF} \quad (10)$$

Where I and V_{cell} are the electrolyser current and voltage; F is Faraday constant equal to 96,485 C/ mol; η_F is Faraday efficiency; and n is the molar flow rate. The following table shows the parameters of the electrolyser model, where the flowrate of hydrogen is expressed by:

$$Q = \eta_{H2} x\ 3600\ x\ 0.022414 \quad (11)$$

The constants in the equation are the following from Uleberg [25]

Table 4 : Constant Parameters

Constant Parameters	Symbol	Unit	Value
Reversible Voltage	V_{rev}	V	1.229
Area of Electrodes	A	m^2	0.25
Faradays Constant	F	C/mol	96485
Number of Electrons	z		2
Number of cells	n		1
Coeff. For overvoltage on electron	s	V	0.185
Coeff. For overvoltage on electron	t_1	$A^{-1}m^2$	1.002
	t_2	$A^{-1}m^2C$	8.424
	t_3	$A^{-1}m^2C$	247.3
Ohmic resistance parameter	r_1	Ωm^2	8.05 e-7
	r_1	$\Omega m^2\ C^{-1}$	-2.5 e-7

This results in the following, considering a final H_2 storage pressure of 200bar as simulated by [25]. Here an Energy consumption of 10.83 MWh with 162 starts and an average runtime of 9.1h did lead to an overall Hydrogen production of 2,788 m^2 within one day considering input power minus user load.

E. Hydrogen Tank modelling

The hydrogen produced by the electrolyser is compressed and stored in a tank by a compressor, as explained in [10]. Moreover, the storage system can be modelled using either the ideal gas equation, or the van der Waals equation. Within the literature it has been suggested that if the storage pressure does not exceed 200 bar, the ideal gas equation can be used and a molar mass of hydrogen with 2g/mol:

$$P_{tank} = \frac{n_{H_2}RT}{V_{tank}} \tag{12}$$

$$n = \frac{300{,}00g}{\frac{2g}{mol}} = 150{,}000\text{mol} \tag{13}$$

Where V_{tank} is the volume of the tank (m^3) and R is the universal gas constant with the Temperature T of 298K. For the model in the paper, a tank volume of 1837m^3 would be mandatory to store a total weight of 300kg of hydrogen.

VI. System Simulation Based on the Available Parameters to Model the Tank Size

A numerical simulation of a section of electric railway supplied by a SOFC system has been developed and supplied by the tank of a decentralised renewable power system. The objective of the simulation is to design the hydrogen tank to supply the railway all-year round.

With the available solar and wind profile of generated power, Fig. 6 shows the total power generated in one day for a 0.5MW wind plant and a 0.1 MW solar plant.

The cumulated energy over 24 h results in 15 MWh of generated electrical energy, which needs to be transformed into hydrogen. With an efficiency of 75% and a conversion rate of 50 kWh/kg, a total of 300 kg of hydrogen will be generated throughout the day, which needs to be buffered partially, as the consumption of the operation does need to be considered as well.

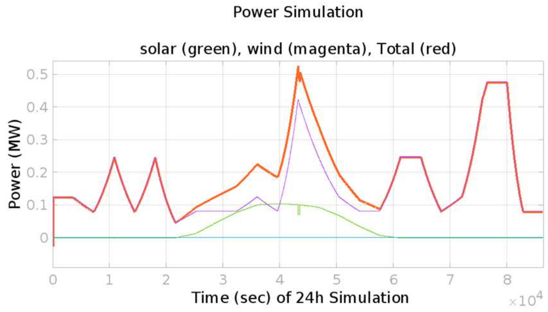

Figure 6: Generated green energy in 24h

Considering an SOFC efficiency of 70% and an energy efficiency of hydrogen of 33.6 kW/kg, the total energy generated by the hydrogen source would be 7,000 kWh. As this energy is higher than the daily requirement of the railway, the chosen powers of the wind and solar plants appear to be sufficient. Considering 3 x 100 kg tanks to buffer 24 h operations or the railway track, a realistic configuration can be proposed also considering the mandatory investments, as such systems are used for other applications already. [27] [21] [28]. With a surplus of 1,000 kWh/day/ tank, a potential downtime or maintenance of a tank can be compensated for 1.5 days, whereas a top-up from the grid would be necessary in case of longer duration of reduced wind and solar power.

VII. Conclusion and Future Work

This paper reports on the development of a hydrogen power supply to support the decarbonisation of railways. A decentralised, demand-oriented and grid independent power supply has been proposed for the supply of electric railways using stationary solid-oxide fuel cells fed by green hydrogen. Green hydrogen is produced in vicinity of feeder stations from wind and solar farms that need to be designed according to the railway requirements. The simulations prove that the predictable energy demand from the trains can be covered by the renewable energy sources when supported by a sufficient size of the hydrogen tank.

The use of hydrogen as energy vector allows an all-year power supply based on renewable sources, where battery and other electrical storage systems cannot deliver for such large-scale applications from a technical and economical point of view.

In this paper four MATLAB Simulink models: 1) energy generation model, 2) energy transformation and storage model, 3) SOFC model, and 4) energy demand model has been used together to design the hydrogen tank and make sure it buffers enough hydrogen to meet the energy demand of the railway.

By designing the fuel cell system and the hydrogen tank according to the requirements of the railway section and considering the expected amount of hydrogen generated by the local renewable energy sources, it has been proven that railway electrification systems can operated mostly independently from the grid.

Future work will look more in depth into the reduction of OPEX and CAPEX for specific railway cases to demonstrate the validity of the proposed supply system with hydrogen fuel cells.

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