Part load performance of PEM fuel cell and electrolyser stacks in hybrid energy system for offshore application

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Abstract

Global warming and associated climate change are ongoing processes worldwide, behind which anthropogenic greenhouse gas emissions play the main role. Renewable energy sources integrated in hybrid energy systems (HES) are fundamental solutions to meet energy demands in a sustainable manner. Proton exchange membrane (PEM) electrolysers and fuel cell stacks can be used as integral components of HES in several applications, for instance supplying energy offshore. Due to the integration with irregular renewable energy sources and the variability of energy demands, those stacks will be frequently operated at part-load conditions. The novelty of this work lies in the incorporation of part-load performance in the models of high-capacity fuel cell and electrolysers stacks. A zero-dimensional approach for steady-state behavior was applied to calculate the polarisation and performance curves of the system. The determined curves were implemented in an already developed online tool for analyzing HES. The computational results from the tool show a great ability of the PEM systems for decreasing the carbon intensity of an offshore facility and increase the wind energy integration within the HES.

1. Introduction

Throughout last decades, global warming has been observed and will continue to cause further long-term changes in the climate system [1]. This fact poses a cross-generational challenge for decreasing the greenhouse gas emissions (GHG) worldwide. Therefore, various research frontiers encompasses novel technologies and energy carriers to limit GHG or even completely decarbonize different industrial branches. One of the perspective energy carriers is hydrogen, which is considered as a key instrument for reaching net-zero greenhouse gas emission by 2050 by European continent according to European Union's Green Deal strategy [2]. Hydrogen-based technologies comprise various technologies for heat and power production and energy storage [3]. One of the emerging industrial applications are hydrogen fuel cells (FC) and electrolysers (ELY) stacks incorporated in hybrid energy systems (HES). Many of the proposed hydrogen-based HES systems are reaching commercial maturity [4, 5] while other novel layouts are at earlier stage of commercialization [6]. Whenever energy intensity sectors need to pursue ambitious climate policies, like offshore sector in Norway, the hydrogen-based solutions tied to renewables has the potential to be an effective solution for decarbonizing all related activities and ensure more sustainable production [7].

To address this, a hybrid energy system for stable power and heat supply in offshore oil&gas installation (HES-OFF) was proposed and investigated [8]. HES-OFF integrates offshore wind power, onsite gas turbines (GTs) and an energy storage system based on PEM fuel cell and electrolyser stacks. A previous paper [9] assessed the performance of the concept, considering the power grid stability and optimal design obtained from the optimization framework developed. The analysis proved possible larger integration of wind capacity in the electric grid without violating the 2% grid frequency maximum allowable variation. This enables CO_2 emissions reduction of up to 36% compared to the equivalent standard GT-based system. The optimum capacity of ELY and FC stacks for reference case were defined as 5.7 and 3.0 MW, respectively, providing sense of desired PEM system capacities in future HES systems offshore. Computationally efficient online tool, named HES-OFF app, allows investigation of various designs of the HES-OFF concept [10].

Based on the screening of available technologies for fuel cell and electrolysers, the PEM technology was chosen for HES-OFF, due to the best compactness and operation ability during transients [11]. Since the stack systems are easily scalable and the anticipated capacity falls in the scale of MWs, the question arises about the realistic estimation of the part-load performance of high-capacity PEM systems. Most of the research activities are related to specific small-capacity stacks, which were mathematically modelled and experimentally tested [12, 13]. The case-specific models tuned for representation of the given stack require a detailed knowledge about the cell architecture, which limits the possibility of reusing model in more generic conceptual simulations. On the other hand, some researchers present more universal models, which avoid specification of the cell design. This approach can be accomplished by means of 0-D modelling. Campanari et al. [14] developed a lumped zero-dimensional model of the stacks to represent 2 MW PEM FC system. The model was developed in Aspen Custom Modeler® what allowed to analyse the off-design operation, including variations in the fuel cell stoichiometry, operating temperature as well as the influence of cell performance decay. That facilitated tuning and successful validation of the model. However, part-load performance of the MW-scale PEM FC system has not been reported. Paper [15] presents a method for reproducing the main conversion performance and dynamic features of ELY and FC PEM systems. Both investigated systems had 100 kW of power capacity and were simplified for the integration into an optimisation procedure by means of two approximation methods. PEM fuel cell and electrolysers stack models are also available in commercial simulating software libraries such as MATLAB Simscape [16] and Thermoflow [17]. However, such library models are dedicated for analyses performed within given simulation environment and not all details can be extracted to determine the required part-load performance.

The performed literature review shows various approaches towards modelling of FC and ELY systems at different levels of fidelity. The scope of this paper was to develop suitable approaches to model large-scale FC and ELY systems to be used for the analysis of the HES-OFF concept. The information provided by manufacturers is normally limited to a single operation point, typically full load. Therefore, a well-established, 0 - dimensional approach to calculate the part-load performance of high-capacity PEM systems was developed and embedded in the overall modelling framework in order to accomplish the planned simulation campaign for HES-OFF concept investigation.

The organization of the paper is as follows. A methodology section provides necessary details for introducing the developed models. The results obtained by the implementation of those models in HES-OFF app are then presented. Finally, a short conclusion section outlines the main contributions of this work.

2. Methodology

Modelling of fuel cell and electrolyser systems is a challenging task. Gao et al. [18] outline a general classification of the FC/ELY models based on five sub-categories: spatial dimension, temporal behaviour, the types of equations applied, modelled area and phenomena. Before diving into the selected approach, an introduction to the HES-OFF concept is presented to provide the context for this work. The computational tool [10] developed for the analysis of the HES-OFF concept encompasses an analysis of the HES over its entire lifetime. A 1-hour time discretization is applied in order to include the irregularity of the wind power. With this time interval, the stack systems can be considered as operating in steady-state mode since the dynamics of PEM FC stacks is characterized by order of minutes [15, 19] and PEM ELY by order of seconds [20]. In addition, the purpose-built models of FC/ELY stacks will represent stacks at the component-level, meaning that no physical or spatial approach will be used. Therefore, the incorporated equations do not represent any phenomena in spatial dimension within the stack (such as gas diffusion direction through membrane), but only scalar variables including cell voltage and cell power [11, 21]. According to the previously listed sub-categories, the models of both fuel cell and electrolysers stacks presented in this work, are characterized by means of a zero-dimensional first-principle approach, where analytical and semi-empirical equations for modelling of static behaviour of single cell/stack are used and the electrochemical domain is the phenomenon being investigated. The most significant equations for operational curves calculations are outlined in the following subsections.

2.1. High-capacity PEM system architecture

Commonly available information about high-capacity PEM systems point to their modular designs. The single stack, as a basic component, is installed into modules, then modules are organized into the final system. Exemplary, NEDSTACK 2 MW_e PEM fuel cell system contains 6 modules with 4 stacks and each stack comprises 1046 cells [22]. This approach is common for MW-scale systems [23]. The schematic of the PEM modular system is depicted in Figure 1.

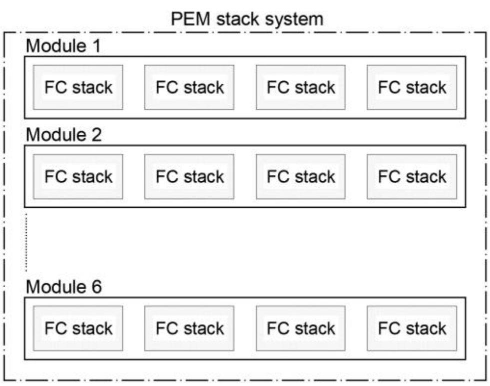

Figure 1: Organisation of fuel cell stacks in modules.

Exact information about the design and configuration of stacks and associated balance of plant (BoP) components are not publicly available, since all manufacturers are cautious about sharing sensitive details, and as for now, not many commercially installed systems are in regular use. Modular design can simplify architecture and reduce cost by sharing common BoP between individual stacks within modules. On the other hand, the control strategy affects the operability of the system and development of an appropriate modelling approach is not a trivial task. In the case of irregular operation, the overarching question is how to load individual stacks defining which ones should be subjected to load changes, hence to more intense cell degradation. At the same time, other stacks can run at relatively steady-state conditions. Another crucial aspect is the weight and footprint of the system. This is the main limitation for designers when it comes to offshore applications. This aspect is thoroughly discussed in [24].

Consideration of complex control strategies and system configuration along with the BoP is out of the scope of this work. The following approach is implemented in analyses accomplished by HES-OFF tool. The total number of required stacks are determined from the desired capacity defined by user. Then for given value of power need determined from the power balance of HES-OFF system, the load is distributed equally to all stacks. In the case of very small amount of power supplied to, or drawn from the system, only one stack is used to provide load as close as possible to the design load conditions of singular stack. To the best authors' knowledge, this approach is a good representation of real systems, especially when the degradation process in not included in the analyses.

2.2. State-of-the-art PEM systems

Currently, the fuel cell manufacturers offer customized scalable systems up to a range of several MW of output power. As mentioned previously, each large-scale PEM system uses a basic singular FC stack, which then is stacked to provide higher power outputs desired by the customer. The performances of some of the commercially available FC stacks are listed in Table 1. The performance is reported in terms of electrical energy output per unit of hydrogen supplied to the FC.

Table 1: PEM fuel cell stacks characteristics.

Stack/ system	**Capacity [kW$_e$]**	**Perf. @full load**	
		[MJ/kg$_{H2}$]	[kWh/ Nm$^3_{H2}$]
PowerCell S3 stack [25]	125	56.24[a]	1.288[a]
Nedstack MT-FCPP-500 system [26]	500 626[b]	61.02 56.34[b]	1.291 1.108[b]
Hydrogenics 1 MW$_e$ system [27]	1 000	58.54	1.461

[a]calculated by the developed model
[b]peak power

Practically, to replicate accurately a specific stack performance is not possible due to lack of information. More uncertainties come from the given nominal power of the stack system by manufacturer. For instance, the total nominal power of 500 kW$_e$ Nedstack stack is accomplished by 60 singular smaller stacks (13.6 kW$_e$ each) [26]. Theoretically, the maximum power is $60 \cdot 13.6$ kW$_e$ = 816 kW$_e$, what is 62.3% more than nominal 500 kW$_e$. This opens possibility to claim that stacks are loaded to values closer to their turndown ratios to get higher overall performance. The peak power of this system is limited to 626 kW$_e$. Thus, the prerequisites behind each specification of particular system, known for manufacturer, adds complexity to tune up and validate the model.

A list of commercial high-capacity PEM electrolyser systems is shown in Table 2. The performance is reported as hydrogen produced per unit of electrical energy supplied.

Table 2: PEM electrolyser stacks characteristics.

Stack/ system	**Capacity [kW$_e$]**	**Perf. @full load**	
		[kg$_{H2}$/MJ]	[Nm$^3_{H2}$/ kWh]
NEL MC 100 unit [20]	500	181.44	4.53
H-TEC system ME 450/1400 [28]	1000	192.26	4.80
Hydrogenics HyLYZER 300-30 [29]	1500	176.24-192.26	4.40-4.80

The performances outlined in Table 2 have been extracted from data sheets and represent rough estimations of expected performances.

For this work, the PowerCell S3 stack for FC system and NEL MC 100 unit for ELY system have been selected. Further literature review has been carried out on those stacks to identify appropriate tuning parameters.

Authors assumed the following simplifications and assumptions for the models development:

- Balance of Plant components are not considered. Thus, there is no limitations for scaling-up the systems' capacities.
- The power consumption for BoP is not considered (power consumption oscillates typically in the range of dozens of kW per 1 MW of the stack capacity).

- The degradation of the stacks is neglected, meaning that the stacks performances at Beginning of Life remain constant until End of Life performance.
- The waste heat produced by stacks is not harvested.

2.3. Fuel cell stack modelling

To compare and assess the performance of the fuel cell stack one needs to know how the operating voltage looks like as a function of current drawn from the fuel cell. To allow comparison of various fuel cells the current density is introduced giving the following correlation:

$$i = I/A_{cell} \tag{1}$$

Where i [A/cm^2] is the current density, I [A] the total electrical current produced by fuel cell, A_{cell} [cm^2] the surface area of the electrode/electrolyte interface where the fuel cell reactions take place.
The current/voltage density curve (i-V) is called polarisation curve and represents the steady-state performance of singular fuel cell or entire stack. The cell i-V characteristics is an inherent part of PEM cell modelling for building a steady state and dynamic models of the FC/ELY stacks [30].
Having the i-V curve one can easily calculate the power curve of the stack, what in turn allow the estimation of the part-load performance of the stack. The common approach for determination of polarisation curve is presented in Spiegel's book [31]. The MATLAB scripts from this book are adopted. For the sake of clarity and simplicity, not all used correlations are outlined, but only those that are were adopted from other literature references and thus are crucial for understanding the applied approach. For more details, the reader should refer to Spiegel's book or to the other literature references such as [32], where all relevant theory is comprehensively presented.
In order to calculate the open circuit voltage and associated voltage losses the following assumptions are considered:

- Ideal and uniformly distributed reactant gases.
- Constant pressure and temperature in the FC/ELY gas flow channels.
- The hydrogen fuel is humidified and the oxidant is humidified air.
- The FC stack is operated at temperature below 100°C and the reaction product is in liquid phase.
- Parameters for individual cells can be lumped together to represent a fuel cell stack.
- The electrolyte is not electrically conductive and impermeable to gases (no fuel crossovers and internal current associated losses).
- A 100% Faradaic efficiency is assumed.

The polarisation curve is determined calculating the operational voltage output of fuel cell and associated voltage losses.
The actual voltage of fuel cell can be calculated using the following equation:

$$V_{out} = E_{Nernst} + V_{act} + V_{ohmic} + V_{conc} \tag{2}$$

E_{Nernst} is given by the Nernst's equation and determines the ideal voltage that a fuel cell can deliver at the given conditions. According to [31], the equation for PEM fuel cell is expressed as:

$$E_{Nernst} = -\frac{G_{f,liq}}{nF} - \frac{RT}{nF} ln\left(\frac{p_{H_2O}}{p_{H_2}p_{O_2}^{1/2}}\right) \tag{3}$$

Where $G_{f,liq} = -228170$ J/mol is the Gibbs energy of water in liquid form in standard state, T= 60°C the operating temperature of fuel cell stack, n the number of electrons transferred per mole of reactant (for hydrogen oxidation n = 2), F = 96485 Coulombs the Faraday's constant, R = 8.31446 J/(mol·K) the ideal gas constant and $p_{H_2O}, p_{H_2}, p_{O_2}$ the partial pressures of water, hydrogen and oxygen, respectively, calculated by the correlations presented in [31].
The voltage losses from Eq. (2) can be determined by the following equations. The activation losses are estimated using the Tafel equation:

$$V_{act} = -\frac{RT}{nF\alpha} log\left(\frac{i}{i_o}\right) \tag{4}$$

Where $\alpha = 0.5$ is the nondimensional charge transfer coefficient and i_o the exchange-current density i.e., the current density at zero overpotential. i_o is assumed to be 6.7·10^{-5} A/cm^2 in accordance with the value for a low temperature PEM fuel cell published in [33]. The assumed i_o value complies with the Tafel's equation assumptions that ($i >> i_o$).
The ohmic losses are estimated using Ohm's law:

$$V_{ohmic} = -ir_{ohmic} \tag{5}$$

Where r_{ohmic} is the area specific ohmic resistance, which is constant for a given fuel cell. In this paper $r_{ohmic} = 0.15\ \mathrm{Ohm \cdot cm^2}$ is assumed, a figure that falls in the range of values seen in the literature [32, 33]. Based upon tuning the adopted value gave the best results.
The concentration losses can be calculated using the following equation [34]:

$$V_{conc} = \frac{RT}{nF} \ln\left(1 - \frac{i}{i_L}\right) \tag{6}$$

Where i_L is the limiting current density, which is assumed to be 0.74 A/cm^2.
The output power of the stack can be determined from the following equation:

$$P_{FCS} = V_{out} \cdot i \cdot A_{FCS} \quad (7)$$

Where A_{FCS} is the total active area of the stack. According to the datasheet [25], the stack comprises 455 cells to provide 125 kW of power output. An assumed value of i_L in Eq. (6) and active area of single cell of 425 cm^2 allowed determining the power curve (Fig. 2) representing the PowerCell S3 stack. The assumed parameters return a power density of the stack of 646 mW/cm^2, which is in line with the range of 500-2500 mW/cm^2 of modern PEM fuel cell systems [32].

2.4. Electrolyser stack modelling

Similarly, as for the fuel cell stack, the model equations representing the electrolyser stack system are programmed in a MATLAB script. The methodology for calculating the polarisation and power curves and performance remain the same as those outlined for the fuel cell stack. The PEM electrolyser works opposite to the fuel cell, relying on the same mechanisms and phenomena. As it is seen in Tribioli et al. [35] the ELY curves can be calculated from Eq. (2), in which the voltage losses are multiplied by reversed coefficient (i.e. -1). This is the simplest approach towards modelling the electrolyser stack and is used for reversible stacks only (i.e. a stack working both in ELY and FC mode, as analysed in [35]). In the case of standalone ELY stack the correlations have to capture the electrochemical phenomenon during electrolyses and for this purpose the following correlation were chosen for the electrolyser modelling.

The actual operating voltage of the ELY system is determined using Eq. (2). The terms of the equation are determined by correlations presented in [36]. The Nernst equation for ELY system is determined by the following formula:

$$E_{Nernst} = 1.229 - 8.5 \cdot 10^{-4}(T - T_a) + +4.3085 \cdot 10^{-5} T ln\left(\frac{p_{H_2} p_{O_2}^{1/2}}{p_{H_2O}}\right) \quad (8)$$

The activation over potential losses is defined by:

$$V_{act} = \left(\frac{\alpha_A + \alpha_C}{\alpha_A \alpha_C}\right)\frac{RT}{nF} log\left(\frac{i}{i_o}\right) \quad (9)$$

Where $\alpha_A = 0.5$ and $\alpha_C = 1.0$ are the charge transfer coefficients of the anode and cathode, respectively. In Eqs. (8)-(9), T stands for operating temperature of the ELY stack and its value is assumed to be 70°C according to [37]. The exchange current density i_o is determined by the following correlation [38]:

$$i_o = 1.08 \cdot 10^{-17} \exp\,(0.086T) \quad (10)$$

The correlation for the ohmic potential is determined by Eq. (5), where $r_{ohmic} = 0.238\ \mathrm{Ohm} \cdot \mathrm{cm}^2$, which is representative of the value seen in the Nafion membranes at moderate thicknesses according to [37].

The last term for determination of the operational voltage of the electrolysers is the concentration over potential losses, which is calculated by the following correlation [39]:

$$V_{conc} = i\left(\beta_1 \frac{i}{i_L}\right)^{\beta_2} \quad (11)$$

Where $\beta_2 = 2$ is a constant according to [40] and β_1 is defined by the following correlation:

$$\beta_1 = \begin{cases} (8.66 \cdot 10^{-5}T - 0.068)P_x - 1.6 \cdot 10^{-4}T + 0.54, & (P_x > 2) \\ (7.16 \cdot 10^{-4}T - 0.622)P_x - 1.45 \cdot 10^{-3}T + 1.68, & (P_x < 2) \end{cases} \quad (12)$$

Where P_x is expressed as:

$$P_x = \frac{P_{O_2}}{0.1173 \cdot 101325} + \frac{P_{sat}}{101325} \quad (13)$$

The limiting current density i_L is assumed to be 20 A/cm^2 [40]. Partial pressure and saturation pressure is calculated in the same manner as for FC and the correlation are available in the literature [31]. The pressure of the produced hydrogen is assumed 30 barg according to the data sheet [20].

In order to calculate the polarisation and power curves, and to determine the part-load performance, a number cells equal to 1695 and an area of single cell equal to 70 cm^2 are selected so to achieve the power output of 500 kW. These values are seen in the state-of-the-art ELY stacks.

Equations (1)-(13) are programmed in the MATLAB script to calculate the polarisation and power curves (Fig. 4). Subsequently, the part load performance of the stack can be estimated.

3. Results and discussion

3.1. Part-load performance – fuel cell stack

Fuel cell and electrolyser manufacturers generally provide scarce information about the performance of their systems. A direct comparison between calculated polarisation and power curves with their counterparts in datasheets become a cumbersome task, partly because of possible lack of compatibility between the operation parameters, partly because of unknown information such as active area or limiting current density. Therefore, the described methodology was used for determination of the operational curves and part-load performance. Some parameters were assumed according to the literature, while some others were tuned to match expected performance. Figure 2 depicts the determined *i-V* curve and the power curve as a function of current density.

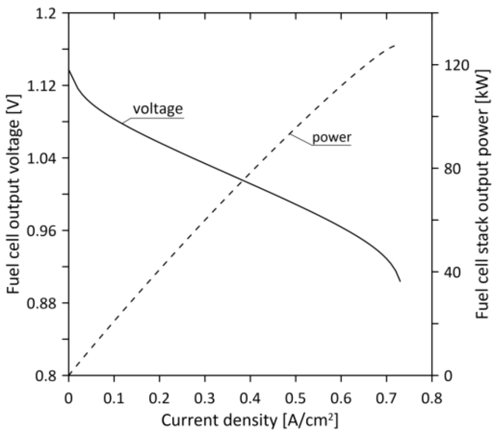

Figure 2: Polarisation curve ('voltage') and power curve of the modelled generic 125 kW fuel cell stack.

The curves appear to be in line with those seen in the literature for similar systems, for instance in [25, 33]. Having power curve as a function of current density i, one can easily determine the actual usage/production of hydrogen by FCS/ELY stack using the Faraday's second law of electrolysis given by Eq. (14).

$$\Delta\dot{N}_{H2,reacted} = \frac{iA}{nF} \tag{14}$$

Where $\dot{N}_{H2,reacted}$ [mol/s] represents the molar flow rate of the hydrogen reacted (consumed or produced by the stack system) and A [cm^2] is the total active area of the stack.

Once the hydrogen consumption is determined, one can calculate the part-load performance of the stack as a function of the output power.

Fig. 3 shows that the performance at full load (125 kW) is 56.24 MJ/kg$_{H2}$, which converts to 1.288 kWh/Nm^3. Such value is in line start-of-the-art stacks, such as those listed in Table 1.

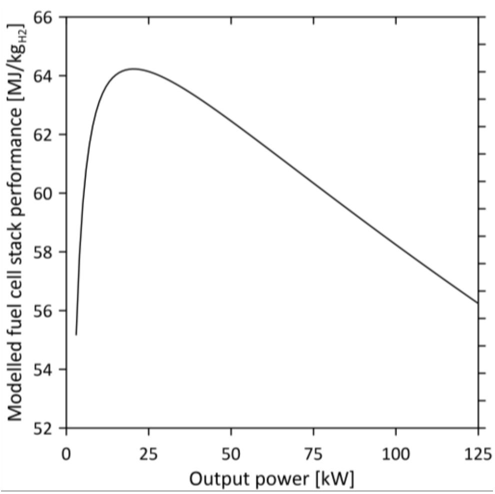

Figure 3: Part-load performance of the modelled 125 kW fuel cell stack.

The performance increases while decreasing the load achieving the maximum at around 20 kW. The fuel cell stack is an electrochemical device so its efficiency is not limited by Carnot cycle, as it is for heat engines. Under those part load conditions the voltage losses are smaller, thus the overall performance is higher. The performance rapidly drops for loads below 20 kW, which is explainable by the activation losses.

3.2. Part-load performance – electrolyser

PEM electrolysers are operated typically at higher current densities. The calculated polarisation and power curves are presented in Fig. 4. The modelled voltage and power curves show a rather linear characteristic. Using the Faraday's law (Eq. (14)), it is possible to calculate the part-load performance of the electrolyser stack. The ELY performance is depicted in Fig. 5.

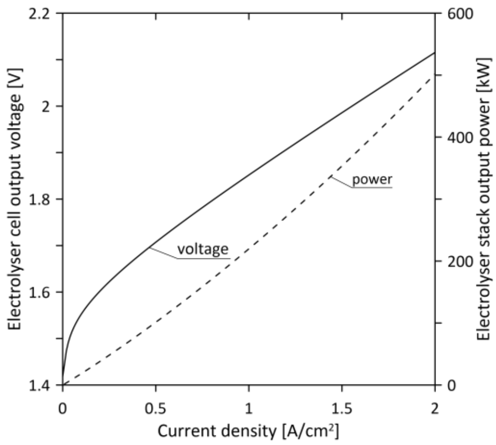

Figure 4: Polarisation curve ('voltage') and power curve of the modelled generic 500 kW electrolyser stack.

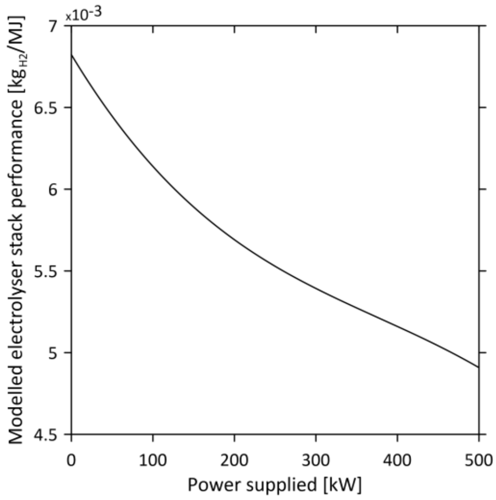

Figure 5: Part-load performance of the modelled 500 kW electrolyser stack.

Similarly, to fuel cells, the electrolyser shows a performance increase as the load drops.

3.3. Results from HES-OFF app

Analysis of the hybrid energy systems requires estimation of performance of their vital components under various loads. Once, the FC and ELY part-load performances are determined and implemented in the HES-OFF app, it is possible to investigate various layouts and configurations of the hybrid system. The default HES-OFF schematic is depicted in Fig. 6.

The offshore installation can be specified by heat and power demand in three distinctive stages of life. The adopted values for this study are specified in Table 4.

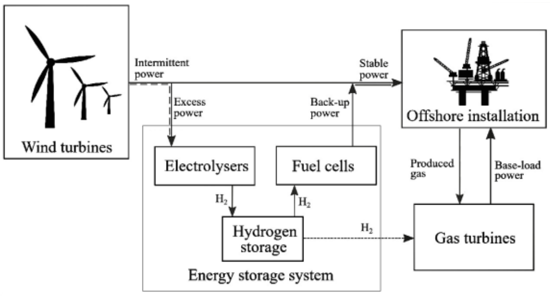

Figure 6: Schematic of the HES-OFF concept.

Table 4: The offshore installation heat and power demands adopted in analyses.

Stage of life	Offshore installation demands	
	Heat [MW]	Power [MW]
Peak years	12.0	35.5
Mid years	10.0	34.2
Tail years	7.0	32.9

The HES-OFF app allows to define own values for parameters and choose predefined components' models used then in the analyses or just assume the predefined default inputs. To demonstrate the HES-OFF performance the following capacities and components have been assumed: single gas turbine (LM2500+G4, rated power 32 MW), NREL wind turbine model, initial level of hydrogen in the storage 80%, wind farm rated power 30 MW, ELY rated power 4 MW, FC rated power 5 MW, hydrogen storage capacity 23 000 kg. The remaining entries were specified according to default values predefined in the app. The calculations were performed for 1 year of time for each stage of life. The results presented in Table 5 outline the environmental gains accomplished by HES-OFF system in comparison to the case where two gas turbines parallel to the same wind farm provide heat and power to the offshore facility.

Table 5: HES-OFF environmental performance with respect to two gas turbines (GT) tied to wind turbines (WT) for a total 30 MW wind farm.

Stage of life	HES-OFF concept vs. GT + WT system	
	CO_2 emission reduction [%]	Extra wind energy integration [%]
Peak	25.7	3.5
Mid	27.0	3.8
Tail	22.8	2.7

As it can be seen from Table 5, the integration of hydrogen ELY and FC system along with hydrogen storage allows reducing the carbon intensity by around 23-27%. A key advantage is the possibility to use a single GT with the HES-OFF system. In addition, the HES-OFF concept allows a better integration of high-capacity wind farm, leading to a higher wind energy usage by 2.7 to 3.8% compared to a similar system without energy storage. Other meaningful results are related to the energy delivered or supplied by the PEM systems. The exact numbers are listed in Table 6.

Table 6: PEM ELY and FC system energy integrated in HES-OFF system.

Stage of life	FC energy [GWh_e]	ELY energy [GWh_e]
Peak	2.66	14.47
Mid	1.17	8.11
Tail	0.24	4.53

Table 6 shows that ELY system transform more electrical energy than FC system. The ELY system absorbs surplus power from the wind farm, allowing not to dissipate it. The surplus power is converted into hydrogen that is stored and later either used in the FC stack or in the GT. FC stack system plays as a backup power supply when the GT power and wind power at given instance cannot meet the platform power demand. The difference between the ELY and FC energy numbers are due to the roundtrip efficiency and to the utilization of part of the hydrogen in the GT. For the sake of clarity not all results obtained from HES-OFF app are outlined in this work. Readers are advised to explore independently the capabilities of the online tool to get more insight into HES-OFF.

4. Summary and conclusion

Conceptual analyses of new innovative hybrid energy systems require sufficiently accurate components' models, which address the simulation requirements and produce reasonable outcomes.

Typically, due to varying heat and power demand of the offshore facility and intermittent nature of wind energy the components are subjected to part-load working conditions. This yields a general need of having insights into part-load performances. Especially, for novel concepts the deep knowledge about the system architecture and exploitation data are not widely available. Therefore, a well-established methodology was incorporated to determine the expected part-load performances of the high capacity PEM fuel cell and electrolyser systems. Thanks to this approach, the knowledge gap for HES-OFF concept has been filled, allowing to accomplish more realistic simulations outcomes.

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