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Techno-Economic Analysis of Alkaline Electrolyzers' Scaling-up Strategies

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ABSTRACT

Water electrolysis systems accelerate the green transition in Danish power, notably via mature alkaline electrolyzers integrated with renewables. The demand for clean and sustainable energy sources has spurred significant interest in electrolysis for hydrogen production. Electrolyzers play a pivotal role in this context, and efforts to scale up their operation are central to meeting the growing hydrogen demand. This study develops MATLAB/Simulink models of various-sized alkaline electrolyzers to design large hydrogen plants, assessing their scalability and economic viability.

Keywords: alkaline electrolyzers, MATLAB/Simulink simulation, net present value, scaling-up, techno-economic analysis

NONMENCLATURE

Abbreviations	
AEL	Alkaline electrolyzer
CAPEX	Capital expenditures
NPV	Net present value
O&M	Operation and maintenance
OPEX	Operating expense
PEM	Polymer electrolyte membrane
RES	Renewable energy sources
SOEC	Solid oxide electrolysis cells
Symbols	
A	Area of the electrodes
c	Hydrogen density at standard temperature and pressure
C_{bst}	Cost of H_2 buffer tank
C_{omel}	O&M electrolysis system
C_{comp}	Cost of H_2 compressor
C_e	Cost of electricity
C_{el}	Cost of electrolysis system
C_{ic}	Total CAPEX
C_{in}	Cost of insurance
C_{lw}	Cost of labor wage
C_{omcomp}	O&M H_2 compressor
d_1, d_2	Fitted parameters related to cell overpotentials
f	Faraday constant
f_1, f_2	Fitted parameters related to the Faraday efficiency
I_{elec}	The electrolyzer's current
N_c	The number of cells in series
r_1, r_2	Fitted parameters related to cell overpotentials
R_{H_2}	Hydrogen sales price
s	Fitted parameters related to cell overpotentials
t_1, t_2, t_3	Fitted parameters related to cell overpotentials
T	Temperature
U_{elec}	Electrolyzer cell voltage
U_{rev}	The reversible voltage of the cell
v_{std}	The volume of an ideal gas at standard conditions
z	The number of electrons transferred in the reaction

1. INTRODUCTION

Hydrogen is the most abundant element, a clean and renewable energy source (RES) that can be used to generate electricity [1]. The enormous Danish offshore wind resources can not only be utilized for Danish energy consumption but can also become a significant contribution to the green transition of European energy supply. In the process of producing green hydrogen, electrolyzer devices are used to split the water into hydrogen and oxygen using electricity from RES. There are several different types of electrolyzers, including alkaline electrolyzers (AEL), polymer electrolyte membrane (PEM) electrolyzers, solid oxide electrolysis cells (SOEC), etc. Each type of electrolyzer has its own

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advantages and disadvantages, and the choice of electrolyzer depends on the specific application and the required production capacity. In recent years, there has been a growing interest in the development of large-scale AEL systems to produce green hydrogen [2]. Except for the decreased cost, scaling up the electrolyzer allows large-scale RES integration, which allows for more efficient use of RES and helps balance intermittent energy generation by converting excess electricity into hydrogen. In [3], Brezak etc. uses MATLAB/Simulink to simulate a PEM electrolyzer operated under various conditions. This paper focuses on AEL. In [4], Martinez, etc., uses the Lambert W function to provide a current-based Simulink model for AEL. The main objective of this paper is to empirically explore strategies for attaining the optimal configuration of a substantial hydrogen production facility, considering various scaling-up configurations of AEL, with a specific focus on their techno-economic implications.

The rest of the paper is organized as follows: In section 2, the AEL's electrical model is built using mathematics and the Lambert W function, and the Simulink models of different sizes are validated with the results in literature references. Several scale-up strategies and the techno-economic assessment criteria are introduced in section 3. In section 4, the technical and economic performance is analyzed, including a sensitivity analysis. Conclusions are drawn in section 5, followed by future research.

2. MODELLING

2.1 AEL electrical model

AEL has two metal electrodes immersed in a water-based liquid and separated by a diaphragm porous to negative charged ions. The overall water electrolysis reaction is shown in Eq.(1).

$$CATHODE: 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (1)$$

$$ANODE: 2OH^- \rightarrow H_2O + 2e^- + \tfrac{1}{2}O_2 \quad (2)$$

$$H_2O \rightarrow H_2 + \tfrac{1}{2}O_2 \quad (3)$$

The electrolyzer's electrochemical process is related to temperature and pressure. In this study, three different capacities of AEL are chosen to evaluate the performance of each size. The basic form of the relationship of the voltage and current used in this study is described in Eq.(4) and Eq.(5).

$$U_{elec} = N_c * \left(U_{rev} + (r_1 + r_2 \cdot T) \cdot \frac{I_{elec}}{A} + s \cdot log\left[\left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}\right) \cdot \frac{I_{elec}}{A} + 1\right]\right) \quad (4)$$

$$U_{elec} = N_c * \left(U_{rev} + [(r_1 + r_2 \cdot T) + (d_1 + d_2 \cdot P)] \cdot \frac{I_{elec}}{A} + s \cdot ln\left[\left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}\right) \cdot \frac{I_{elec}}{A} + 1\right]\right) \quad (5)$$

The reversible voltage, which is the minimum voltage needed for water electrolysis process as the reaction occurs ideally. In this study, the reversible voltage is using an experimental equation to calculate.

$$U_{rev} = 1.5184 - 1.5421 \cdot 10^{-3}T + 9.526 \cdot 10^{-5}Tln(T) + 9.84 \cdot 10^{-8}T^2 \quad (6)$$

In some cases, adjustments are needed to improve accuracy and reduce complexity when using equations like Eq.(4) and Eq.(5). For instance, at very low current levels, these equations can produce complex values due to negative logarithmic results. Additionally, it's essential for the external voltage applied to the electrolyzer to exceed its reversible voltage and initiate the chemical reaction, as these equations assume the presence of both current and voltage. To address this, equation reorganization becomes necessary.

First, putting aside voltage-containing items:

$$\frac{V_{elec}}{N_c} - V_{rev} = (r_1 + r_2T)\frac{I_{elec}}{A} + s \cdot log\left(\left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}\right)\frac{I_{elec}}{A} + 1\right) \quad (7)$$

And then, the equation above can be simplified as:

$$a = bI_{elec} + log(cI_{elec} + 1) \quad (8)$$

where, $a = \frac{1}{s}\left(\frac{V_{elec}}{N_c} - V_{rev}\right)$, $b = \frac{1}{sA}(r_1 + r_2T)$, $c = \frac{1}{A}\left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}\right)$.

Taking power of ten to both sides of Eq.(8):

$$10^{bI_{elec}} = \frac{c}{10^a}I_{elec} + \frac{1}{10^a} \quad (9)$$

Substituting I_{elec} in Eq.(9), using $I_{elec} = \frac{t}{b} - \frac{1}{c}$ and after simplified, the equation can be transformed to:

$$t10^t = \frac{b}{c}10^{a+\frac{b}{c}} \quad (10)$$

where, $t = bI_{elec} + \frac{b}{c}$.

Since the Eq.(10) has both exponential and logarithm form, which makes it difficult to calculate the current. The Lambert W function is used to solve the situation. In [5], the equation $xb^x = a$ can be solved by $x = \frac{W(alnb)}{lnb}$. Thus, the current can be calculated.

The final expression of the current calculation dependent on the temperature is in Eq.(11), and the current calculation dependent on the pressure and temperature is in Eq.(12).

$$I_{elec} = \frac{W\left(10^{\frac{(r_1+r_2T)}{s\left(t_1+\frac{t_2}{T}+\frac{t_3}{T^2}\right)}} ln10 \frac{(r_1+r_2T)}{s\left(t_1+\frac{t_2}{T}+\frac{t_3}{T^2}\right)} 10^{\frac{1}{s}\left(\frac{V_{elec}}{N_c}-V_{rev}\right)}\right)}{\frac{1}{sA}(r_1+r_2T)ln10} - \frac{A}{\left(t_1+\frac{t_2}{T}+\frac{t_3}{T^2}\right)} \tag{11}$$

$$I_{elec} = \frac{W\left(e^{\frac{(r_1+r_2T+d_1+d_2P)}{s\left(t_1+\frac{t_2}{T}+\frac{t_3}{T^2}\right)}} \frac{(r_1+r_2T+d_1+d_2P)}{s\left(t_1+\frac{t_2}{T}+\frac{t_3}{T^2}\right)} e^{\frac{1}{s}\left(\frac{V_{elec}}{N_c}-V_{rev}\right)}\right)}{\frac{1}{sA}(r_1+r_2T+d_1+d_2P)} - \frac{A}{\left(t_1+\frac{t_2}{T}+\frac{t_3}{T^2}\right)} \tag{12}$$

However, since the Lambert W function is a multivalued function, there are some limitations on its use. For each integer *k* there is one branch, denoted by $W_k(z)$, which is a complex-valued function with a complex number of parameters. When dealing with real numbers, for $ye^y = x$, there are two branches sufficient which is W_0 and W_1. The graph of $y = W(x)$ is shown in Fig. 1. The upper blue branch is the W_0 branch, and it can be solved for y only if $x \geq -\frac{1}{e}$; the lower red branch is the W_1 branch. It can be solved for y if $-\frac{1}{e} \leq x < 0$. In the interval where $-\frac{1}{e} \leq x < 0$ is less than 4, y has two values. For this study, the W_0branch satisfies the model [9].

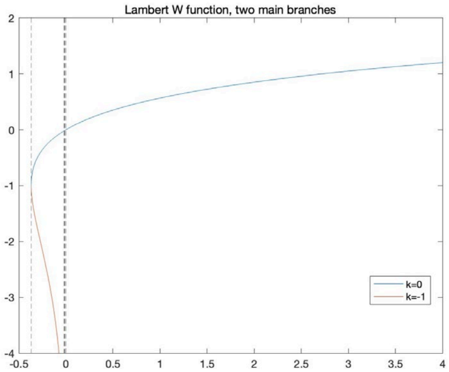

Fig. 1 Two main branches of Lambert W function

Moreover, for efficient water electrolysis, it's crucial that the input voltage exceeds the reversible voltage to initiate current production gradually. Therefore, a voltage limit condition, $V_{elec} \geq N_c V_{rev}$, must be incorporated into the current calculation.

In the AEL, the required heat is provided by the additional heat generated due to the internal resistance created by the current flowing through the stack. This heat demand can be traced directly to the power supply and translates into a cell voltage of 1.48V. The thermoneutral voltage for AEL in this study is 1.48V.

To obtain the UI curve of the electrolyzer, an empirical model is used. In which, a fitted Faraday efficiency expression is in Eq.(13), and this equation is used in further simulation and analysis.

$$\varepsilon_F = \frac{\left(\frac{I_{\{elec\}}}{A}\right)^2}{f_1+\left(\frac{I_{\{elec\}}}{A}\right)^2} f_2 \tag{13}$$

where, f_1 and f_2 are the fitted parameters related to the Faraday efficiency.

Besides, Eq.(14) is used to calculate the amount of hydrogen production, and the unit of the hydrogen production is kWh/Nm^3, which nowadays electrolyzer manufacturers have adopted it as a measure of system efficiency:

$$n_{H_2} = \left(\frac{(I_{elec}/A)^2}{f_1+(I_{elec}/A)^2} f_2\right) N_c \frac{1}{zF} V_{std} * 3600\ (Nm^3/h) \tag{14}$$

Based on the physical formulas and theories above mentioned, a Simulink model is built and shown in Fig. 2. Fig. 2 features four distinct color-coded regions. The gray area signifies the sampling point and voltage input settings. In purple, the model for a 26kW AEL, while the blue area represents a 2.5MW AEL model, and the pink area corresponds to a 250kW AEL model. These AEL models can be adjusted through parameter modification, enabling both series and parallel connections, as groundwork for scaling-up.

Table 1 The alkaline electrolyzer parameters

Size	26kW[6]	250kW[7]	2.5MW[8]
$r_1/\,\Omega\, m^2$	8.05e-5	7.3255e-1	0.8
$r_2/\,\Omega\, m^2\ ^\circ C^{-1}$	-2.5e-7	-4.68e-6	-0.00763
s/V	0.185	9.3603e-2	0.1795
$t_1/A^{-1}m^2$	1.002	16.497	20
$t_2/A^{-1}m^{2\circ}C$	8.424	-1.1318e4	0.1
$t_3/A^{-1}m^{2\circ}C^{-1}$	247.3	1.9538e6	3.5e5
$d_1/\,\Omega\, m^2$	/	-7.3077e-1	/
$d_2/\,\Omega\, m^2 MPa^{-1}$	/	-1.85e-5	/

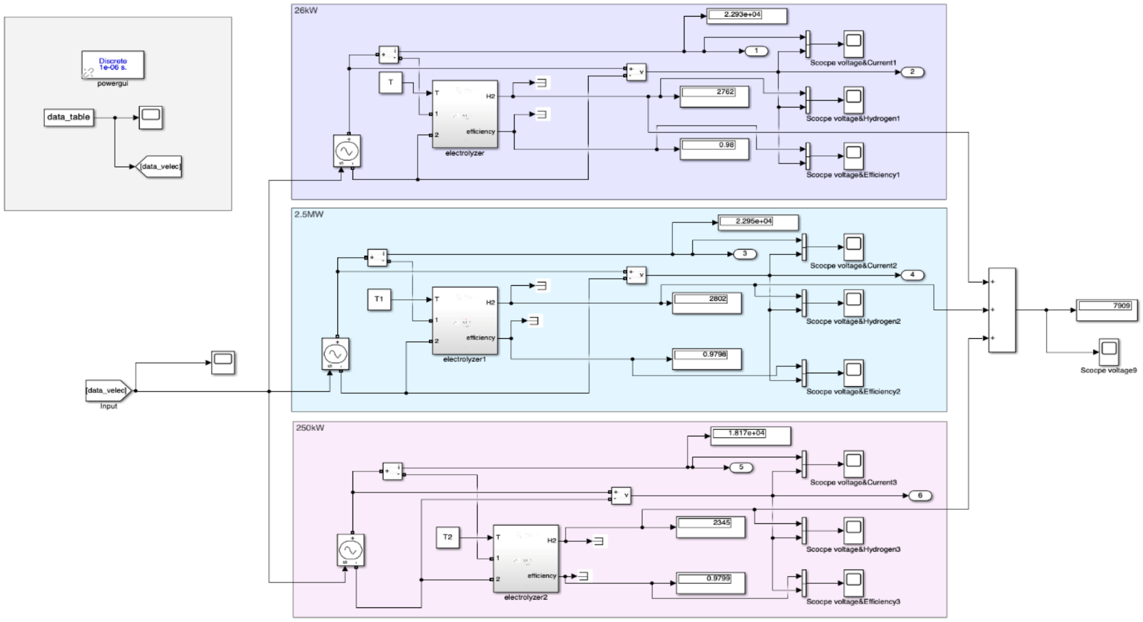

Fig. 2 AEL Simulink models with different sizes

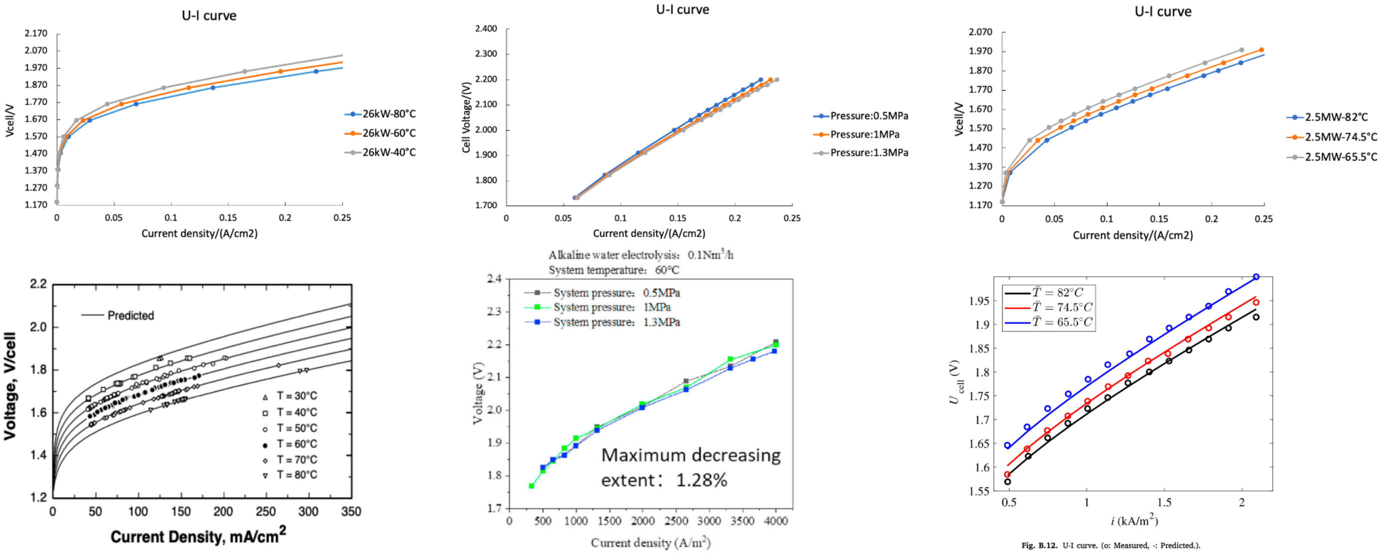

Fig. 3 The models validation for each size of AEL.

2.2 AEL electrical model validation

After building the model, the accuracy of the model can be verified. The detailed parameters for each size of alkaline electrolyzer simulated in this study are shown in Table 1. And the comparison of the models and the references (See Table 1) can be seen in Fig. 3.

From Fig. 3, the results of simulation model and reference case are relatively similar, which indicated the model accuracy. This successful validation further substantiates the precision of the models and establishes a solid foundation for the subsequent stage of scaling-up.

Table 2 Scaling-up configuration cases

No.	Cases	Type
1	Each size 30MW, for 26kW, 1154 in parallel.	Single size scale-up
2	Each size 30MW, for 250kW, 120 in parallel.	
3	Each size 30MW, for 2.5MW, 12 in parallel.	
4	Each size 15MW, for 26kW, 2 in series , 288 in parallel; for 250kW, 60 in parallel.	Two sizes scale-up ***Each size has the same share***
5	Each size 15MW, for 26kW, 14 in series, 41 in parallel; for 2.5MW, 6 in parallel.	
6	Each size 15MW, for 250kW,7 in series, 9 in parallel; for 2.5MW, 6 in parallel.	
7	20MW by 2.5MW, 8 in parallel; 10MW by 26kW, 14 in series, 28 in parallel.	Two sizes scale-up ***Larger size electrolyzer accounts for a larger share***
8	20MW by 2.5MW, 8 in parallel; 10MW by 250kW, 7 in series, 6 in parallel.	
9	20MW by 250kW, 80 in parallel; 10MW by 26kW, 2 in series, 192 in parallel.	
10	20MW by 250kW, 7 in series, 12 in parallel; 10MW by 2.5MW, 4 in parallel.	Two sizes scale-up ***Smaller size electrolyzer accounts for a larger share***
11	20MW by 26kW, 2 in series, 384 in parallel; 10MW by 250kW, 40 in parallel.	
12	20MW by 26kW, 14 in series, 56 in parallel; 10MW by 2.5MW, 4 in parallel.	
13	Each size 10MW, for 26kW, 14 in series , 28 in parallel; for 250kW, 7 in series , 6 in parallel; for 2.5MW, 4 in parallel.	Three sizes scale-up

Different scaling-up configuration cases are listed in Table 2.

2.3 Economic assessment criteria for scaling-up cases

To assess a hydrogen plant's economic feasibility, the related hydrogen storage tank and other ancillary facilities should also be included. In this study, the hydrogen storage tank and compressor are considered. The size of the hydrogen storage tank is used.

3. SCALING-UP STRATEGIES

3.1 Scaling-up cases and technical assessment criteria

In this section, several scale-up cases will be introduced and analyzed the actual energy consumption when operating at rated power. The AEL will be connected in series and in parallel to build a 30MW hydrogen plant. The actual energy consumption is the indicator of Faraday efficiency. At present, the actual electrical energy consumption for producing 1 m^3 of hydrogen by electrolyzer is 4.5-5.5 kWh. The actual energy consumption should be as low as possible, and nowadays, the world's most energy efficient electrolyzer's power consumption is as low as 3.8 kWh/Nm^3 of hydrogen produced [9]. The actual energy consumption can be calculated by Eq.(15).

$$actual\ energy\ consumption = \frac{Power}{H_2}(kWh/Nm^3) \quad (15)$$

Before transportation, the volume can be calculated using Eq.(16), and the pressure is set to 30 bar. The size of compressor can be calculated using the online calculator [10].

$$P_1V_1 = P_2V_2 \quad (16)$$

After sizing the ancillary facilities and the electrolyzer plant, the plant's financial calculation can be calculated. The economic assessment indicator is using the net present value (NPV). The parameters used in calculating NPV are shown in Table 3. 2020's electricity price data are collected for analysis.

Except for the CAPEX and OPEX, for a finical calculation, the inflation and discount rate should also be considered, since in this study, the investment is considered payable, so the interest rate is ignored. The inflation is considered 2%, and the discount rate is considered 8%.

The equation for calculating the NPV is expressed in Eq.(17), where, $C_{ic} = C_{el} + C_{hst} + C_{comp}$ represents the CAPEX, and C_A is the annual income of cashflow, $C_{var,y}$ is the OPEX each year after base year y, Y is the lifetime of the project, and r is the discount rate.

$$NPV = -C_{ic} + \sum_{y=1}^{Y} \frac{C_A - C_{var,y}}{(1+r)^m} \quad (17)$$

The lifetime of the hydrogen plant is set to 20 years, which is related to the minimum expected lifetime of wind turbines.

Table 3 The finical parameters

Parameter	Symbol	Cost	Data source
Cost of electrolysis system	C_{el}	1100€/kW	[11]
Cost of H_2 buffer tank	C_{bst}	1350€/m^3	[12]
Cost of H_2 compressor	C_{comp}	7250€/m^3	[12]
O&M electrolysis system	C_{omel}	2.5%C_{el}	[13]
O&M H_2 compressor	C_{omcomp}	4%C_{comp}	[14]
Cost of electricity	C_e	28.37€/MWh	[15]
Cost of insurance	C_{in}	1%C_{ic}	[16]
Cost of labor wage	C_{lw}	3500€/m/p	[12]
Hydrogen sales price	R_{H_2}	5€/kg	[17]

4. RESULTS

4.1 Technical assessment

The simulation results of the actual energy consumption are shown in Table 4.

Table 4 The actual energy consumption in each case

Case	Unit	85˚C	75˚C	65˚C
1	kWh/Nm^3	4.80	4.84	4.88
2	kWh/Nm^3	4.61	4.83	5.07
3	kWh/Nm^3	4.61	4.70	4.74
4	kWh/Nm^3	4.721	4.832	4.935
5	kWh/Nm^3	4.639	4.775	4.910
6	kWh/Nm^3	4.724	4.780	4.832
7	kWh/Nm^3	4.684	4.826	4.965
8	kWh/Nm^3	4.638	4.752	4.864
9	kWh/Nm^3	4.682	4.7455	4.806
10	kWh/Nm^3	4.748	4.831	4.910
11	kWh/Nm^3	4.626	4.777	4.950
12	kWh/Nm^3	4.741	4.789	4.836
13	kWh/Nm^3	4.687	4.783	4.875

From the results, for the single size AEL scale-up, the large size of AEL scale-up has lower energy consumption, which has the best performance among them. For the two sizes AEL scale-up, among the various cases, the case with 2.5MW always performs better than the case without 2.5MW. And all the results of two sizes of scale-up show that when the temperature is higher than 65˚C, the combination of 2.5MW and 250kW performs better than the combination of 2.5MW and 26kW, and this might cause by the single electrolyzers' performance of 250kW is better than the 26kW. Besides, the case, which the larger capacity accounts for a larger share is better than the case with the same share and smaller capacity accounts for a larger share. Among three main scale-up cases, a comparison of the actual energy consumption shows that the two sizes of AEL with the larger size accounts for a larger share has the lowest actual energy consumption which indicates that this is the optimal case.

4.2 Economic assessment

After calculating all the NPV in each case, the highest NPV is the combination of 250kW electrolyzer and 2.5MW electrolyzer, which the 250kW accounts for a larger share. One interesting thing is that in all cases, the results are similar to the technical assessment. In another word, the case which has a better technical performance also has a better economic performance.

4.3 Sensitivity analysis

Besides, a sensitivity analysis is also included. In this study, the sensitivity analysis is conducted from the highest NPV case, which is the combination of 250kW electrolyzer and 2.5MW electrolyzer, which the 250kW accounts for a larger share. The sensitivity analysis is done for CAPEX, OPEX, electricity prices, hydrogen selling price, inflation rate and discount rate. Moreover, two different scenarios have been considered: "best case" and "worst case", to analyze realistic variations for the input parameters. In this sense, the variations for these parameters are calculated in the low and high scenarios according to the data presented in [18]. For the price of electricity and the inflation rate, the variation has been applied for all values throughout the different years of the lifetime of the project. The considered parameters and their variations are shown in Table 5.

Table 5 Considered parameters and their variations

Parameter	Best	Reference	Worst
CAPEX (*1000€)	50869.1 (-15%)	59846	62838.3 (+15%)
OPEX (*1000€)	6851 (-15%)	8060	8463 (+15%)
Electricity price (€/MWh)	22.672 (-20%)	28.37	34.008 (+20%)
Inflation rate (%)	3% (+50%)	2%	1% (-50%)
Discount rate (%)	4% (-50%)	8%	12% (+50%)
Hydrogen price (€/kg)	6% (+20%)	5%	4% (-20%)

Fig. 4 represents the positive or negative variation of the NPV compared to the reference scenario. It can be noticed that the NPV is highly affected by the variation of the discount rate and the hydrogen price. The variation on the electricity price and inflation rate, also affects significantly the NPV of the project. Furthermore, the NPV is also dependent on the CAPEX and OPEX values. However, the variations to which these values can be subjected are smaller, due to the small range of uncertainty that they entail. In this sense, the variations suffered by the NPV are notable, but smaller than others.

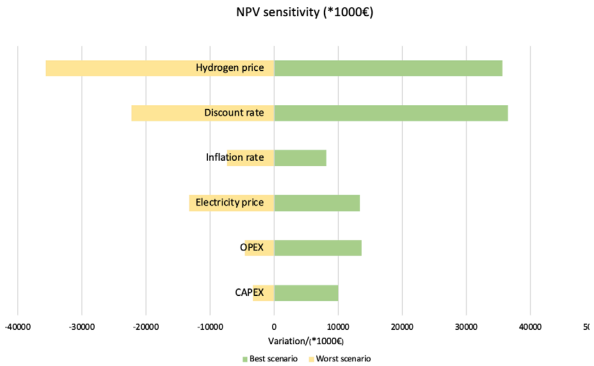

Fig. 4 NPV sensitivity

5. CONCLUSIONS

In this paper, a current source based AEL electrical model is built by using the Lambert W function. The use of MATLAB/Simulink simplified the simulation progress, by adding a timetable function, several inputs can be simulated in single simulation loop. The simulation results show that for a large-scale hydrogen plant, the optimal AEL scaling-up configuration for maximizing profitability is to combine two AEL sizes, with the smaller size accounting for a larger share, which can also yield the highest NPV value.

The simulation can be further used for more complicated, more realistic cases. Besides, we will focus on advanced scaling-up strategies considering ancillary services provision to reduce green hydrogen OPEX.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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