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Powering the Future: Scottish Case Study on Optimizing Energy Facilities for Green Hydrogen Production

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Abstract: Green hydrogen is key as a sustainable energy solution amid fossil fuel use, transitioning from harmful finite resources. However, the instability of renewable energy sources and the high cost of the production process constrain the further development of green hydrogen. This study presents an optimization model of a tidal-wind hybrid system for hydrogen production with a focus on maximizing the economic benefits. By modelling an off-grid renewable energy system in the Scottish region, the results of the study show that the hybrid tidal-wind system has the lowest annual total cost of 5,000.19 M$ and the hydrogen cost is 12.347 $/kg, which are both better than other single energy systems. In addition, the CO_2 emissions of the hybrid system are significantly lower than other blue-hydrogen production systems, helping to drive the transition to sustainable energy. Sensitivity analysis shows that the efficiency of electrolyzers and fuel cells has the most significant impact on system costs. Also, the hybrid tidal-wind system stabilizes power output by reducing the need for expensive auxiliary power generation and storage systems. This hybrid approach improves economic viability in remote areas and advances the goal of a sustainable energy transition.

Keywords: Green Hydrogen, Tidal Energy, Wind Energy, Hydrogen Production Optimization, Renewable Energy Integration

1. Introduction

Global reserves of non-renewable energy sources are facing significant depletion and are grappling with increasing difficulties in the extraction process due to various issues [1][2][3]. In response to this, countries and major economies around the globe have stepped up their investments in renewable energy, promoting the transformation of their energy mix so that it will reduce dependence on fossil fuels. As a result, green hydrogen, as a representative of clean energy, is gaining more and more attention. Its unparalleled advantage stems from the fact that the production process eschews the

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generation of greenhouse gases such as carbon dioxide. This renders it inherently carbon neutral at its origin, aligning with the global ambition to mitigate climate change and curtail carbon emissions.

However, the evolution of green hydrogen still confronts formidable obstacles impeding its widespread implementation. Presently, the burden associated with the production of green hydrogen remains exorbitant [4]. Concurrently, the technological apparatus for its generation has not attained a state of maturation, and the development of supporting infrastructure is notably deficient [5]. Consequently, the transition of hydrogen energy from a theoretical concept to utilization necessitates an extended and challenging endeavor.

Combining wind and tidal energy to generate hydrogen is an innovative way to utilize the complementary advantages of these two renewable sources. Wind energy is characterized by abundant resources and a short construction period, but its power generation is greatly affected by climatic conditions and is subject to volatility [6]. Tidal energy is highly predictable and consistent, driven by the gravitational forces of the moon and sun, providing a stable and reliable energy source. Combining tidal power with wind power can help mitigate the variability of wind energy, thereby improving the reliability of the energy supply. Although the technology for producing hydrogen from the synergy of these two renewable sources is under development, it continues to face challenges related to conversion efficiency, storage solutions, and overall system coordination [7].

Scotland, with its distinctive geographical and climatic attributes, stands poised as an optimal locale for an ideal case study of coupled green energy for hydrogen generation, buoyed by its vast wind and hydro resources. In order to optimize the process of hydrogen production from coupled wind and tidal power in the Scottish region, it is essential to develop a thorough optimization model that considers the stability of the energy supply and its economic viability, thereby ensuring efficient and economic hydrogen production from renewable energy sources and promote the sustainable development of the energy structure.

To achieve the objective, this study addresses the economic refinement of a proton exchange membrane (PEM) water electrolysis system designed for hydrogen generation, particularly under a hybrid regime of tidal and wind energy sources. The complexity of this optimization problem arises from the inherent variability and intermittency of wind renewable energy, such as solar and wind, which differs significantly from the more predictable tidal energy sources. Previously, some examples are given for combining different energy types with energy storage systems. Coles et al. [8] quantified the performance of hybrid systems combining tidal stream or wind energy with short-term storage, highlighting the value of cyclic power in such systems. However, the model only assesses short-term benefits and does not provide guidance for a more realistic long-term scenario. To accurately navigate and calibrate this composite energy input, cost optimization necessitates a thorough evaluation of several key aspects, including the capital and operational expenditure of the electrolysis system, the cost of energy from both tidal and wind sources, and the storage and distribution costs of the produced hydrogen. Pearre et al. [9] explored a strategy that integrates solar, wind, and in-stream tidal power with energy storage technologies, aiming to optimize the utilization of intermittent energy.

However, incorporating energy storage introduces not only additional costs but also technical challenges, all of which must be judiciously incorporated into the overarching optimization framework. A formidable obstacle in this context is harmonizing the energy supply with the operational cadence of the electrolysis process. The temporal and quantitative disparities between tidal energy peaks and the electrolysis system’s energy demands necessitate that the optimization model incorporate strategies for load shifting and demand response. This ensures that the system can adeptly navigate these fluctuations without incurring prohibitive costs or undermining the efficiency of hydrogen production.

This paper presents an integrated framework for evaluating the potential for hydrogen production by combining tidal and wind energy based on the above issues. The framework includes a

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methodology for assessing the potential of the integrated system to produce hydrogen and a model for evaluating the potential of the off-grid system in conjunction with the demand for hydrogen. The objective is to achieve economic optimization, i.e. the minimum overall economic capital cost, under conditions that satisfy the hydrogen demand in each region. The applicability and validity of the framework are demonstrated through a case study of Scotland. It will help to coordinate the rational allocation of energy resources, improve the system's overall efficiency, and offer insights for the green energy transition in Scotland and worldwide.

2. Methodology

2.1. System description

This research endeavors to incorporate a more exhaustive range of influential factors, thereby rendering the evaluation model more reflective of the genuine conditions encountered in the Scottish region. Therefore, the system proposed in this study is a closed-loop system that integrates the use of wind and tidal energy, aiming to achieve sustainable production of hydrogen through efficient energy conversion and storage technologies. As shown in Fig.1, the key components of our system include PEM electrolyzers, batteries, PEM fuel cells, and hydrogen storage tanks, while we use black arrows for renewable energy flows, blue arrows for electricity flows and green arrows for hydrogen flows. The core of the system consists of a wind turbine or a wind farm and a tidal energy power station, which convert natural wind and tidal energy into electrical energy, providing clean energy input to the whole system. The generated electrical energy is then used to drive a PEM electrolyzer to generate hydrogen through a water electrolysis reaction. The generated hydrogen is efficiently stored in hydrogen storage tanks for system demand or other uses. To balance the wind and tidal energy intermittency, the system also integrates a battery energy storage system, which ensures stable operation by storing electrical energy during times of excess energy and releasing energy during times of peak demand. In addition, the system includes a fuel cell that converts stored hydrogen back into electrical energy to meet the system's own or external power needs.

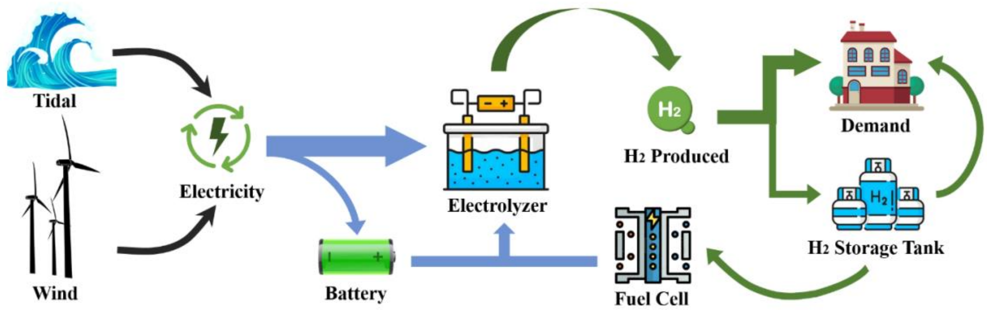

Figure 1: The stages framework for this study.

In this paper, we map the energy system in the Scottish area. We used Renewables.ninja to obtain data of the hourly wind capacity factor for 2019, using the equipment Siemens SWT-2.3-93, shown in Fig.2(a). The location of the sampling point is the Orkney Islands, Scotland (latitude:59.18°N, longitude: 2.77°W). The data of the hourly capacity factor of tidal energy in one year [10], the total potential hydrogen demand in the Scottish region [11], and the hourly electricity consumption in the Scottish region [12] over a one-year period is shown in Fig. 2(b), Fig. 2(c) and Fig. 2(d). The hourly hydrogen demand using the electricity demand in the region is obtained. The economic data of the utilized components in the simulation are listed in Table 1, and the technical data are given in Table

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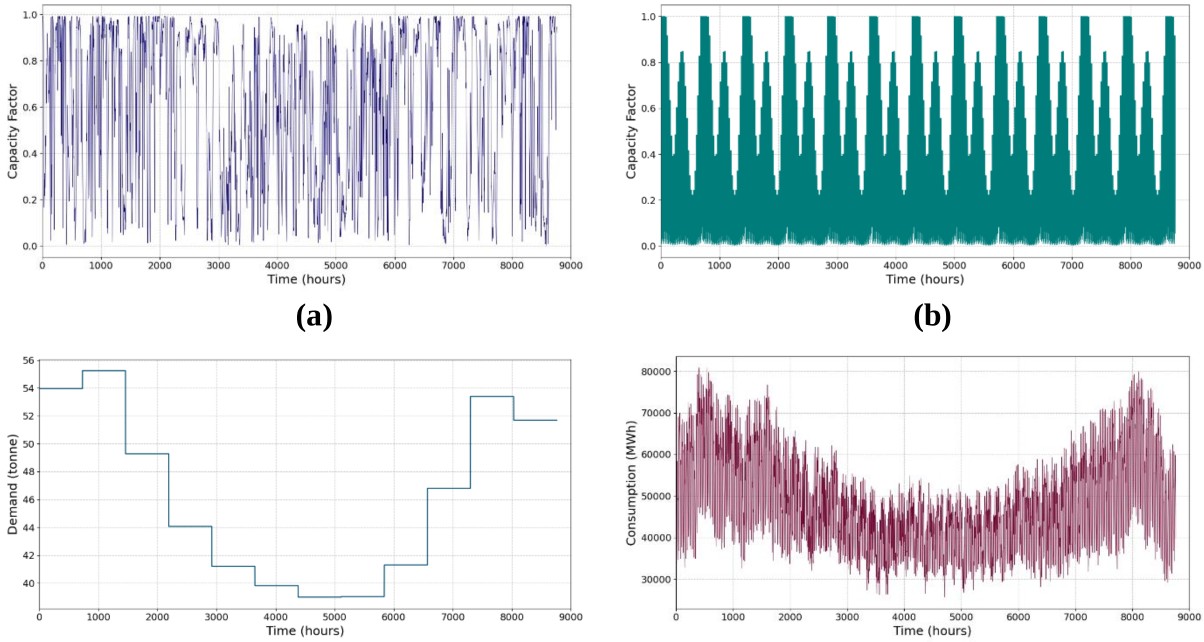
2. Since hydrogen demand is not as volatile as electricity demand, we used the month as the dividing line and averaged the values so that the hourly hydrogen demand was the same within each month.



(c) **(d)**

Figure 2: The overall introduction of (a) the hourly capacity factor data of wind in 2019; (b) the estimation of hourly capacity factor data of tidal in a year; (c) the estimation of hourly hydrogen demand in the Scottish area in 2030 through electricity consumption in England in 2023; (d) the hourly electricity demand in England in 2023.

Table 1: Economic input parameters in the study

Parameters		citation
Project Lifetime	20 years	
Wind Turbine Annual Cost	241,558.44 $\$/MW \cdot year$	[13]
Tidal Power Plant Annual Cost	674,069.26 $\$/MW \cdot year$	[14][15]
Battery Annual Cost	77,922.08 $\$/MWh \cdot year$	[16]
PEM Electrolyzer Annual Cost	244,759.09 $\$/MW \cdot year$	[17][18][19]
Hydrogen Storage Tank Annual Cost	106,906.20 $\$/tonne \cdot year$	[20]
Fuel Cell Annual Cost	286,350.00 $\$/MW \cdot year$	[19]
Water Cost	2.691 $\$/m^3$	[21]

The July 16, 2024 rate was used.
1 USD = 0.77 GBP, 1 USD = 0.92 EUR

Table 2: Technical input parameters in the study

Parameters		citation
PEM Electrolyzer Efficiency	65%	[22]
Fuel Cell Efficiency	60%	[23]
Battery Efficiency	75%	[24]
H_2 LHV	119.9 MJ/kg	[25]
H_2 HHV	141.6 MJ/kg	[25]

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2.2. Objective function

The optimization goal of our evaluation model f is determined to be the minimization of the overall cost, as demonstrated by equation (1), in order to maximize the usage of the power produced from renewable energy sources

$$min\, f = \Sigma_i C_i = C_{WT} + C_{TPP} + C_{BS} + C_{WE} + C_{FC} + C_{HS} + C_{water} \tag{1}$$

where C_i represents the aggregate expenditure of each subsystem within the broader hydrogen production system over the course of a year.

Since the system is based on year-to-year analysis, there should be no change in the H_2 storage level between the beginning and the end of the year, which means there's no H_2 left after one-year production. Therefore, to calculate the hydrogen cost, the following equation is employed:

$$C_{H2} = \frac{f}{\Sigma m_{H_2\, Demand}} \tag{2}$$

where C_{H_2} means the unit cost of H_2. $\Sigma\, m_{H_2\, Demand}$ means the sum of the H_2 demand.

2.3. Constraints

2.3.1. Power supply constraints

In this study, the power supply for each period is calculated from the capacity factor (CF) of the wind turbine (WT) and tidal power plant (TPP) for that period. Therefore, the value of the total power supply is known at each period. The calculations are demonstrated in equations (3) and (4).

$$\begin{aligned} \forall\, t \in n \quad P_{WT}(t) &= W_{cap} \cdot CF_{WT}(t) \\ P_{TPP}(t) &= T_{cap} \cdot CF_{TPP}(t) \end{aligned} \tag{3}$$

$$\forall t \in n \quad P_{tot}(t) = P_{WT}(t) + P_{TPP}(t) \tag{4}$$

All of the energy produced goes into the electrolyzer and the batteries, which means renewable energy produced is either provided to produce hydrogen or stored in the battery. With no extra load, the energy balance equation at each time step t can be written as:

$$\forall\, t \in n \quad P_{tot}(t) = P_{tot\ in\ BS}(t) + P_{tot\ in\ Ely}(t) \tag{5}$$

where $P_{tot\ in\ BS}(t)$ means a portion of the total produced power that goes into the battery, $P_{tot\ in\ Ely}(t)$ means a portion of the total produced power that directly goes into the electrolyzer.

2.3.2. Battery storage constraints

In order for the system to reduce the wastage of electricity, the configuration of the battery system (BS) is one of the methods by which the efficiency of energy utilization can be increased. The power stored within the BS is calculated by modeling the energy being charged and discharged from the battery over a given period. Consequently, the power stored in the BS at a given point in time t is closely linked to the power of the BS at an earlier point in time $(t-1)$.

We assume that the total energy stored in the battery throughout the course of a year is equal to the energy that is used from the battery. Also, the discharge efficiency of the battery $\eta_{BS} = 1$, and the self-discharge rate $\sigma = 0$. The stored energy in the BS system shall be charged and discharged according to the following equation:

$$\forall\, \mathrm{t} \in \mathrm{n} \quad \mathrm{E_{BS}(t) = E_{BS}(t-1) + P_{tot\ in\ BS}(t) - P_{out\ BS}(t)\ /\ \eta_{con}} \tag{6}$$

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where E_{BS} means the energy stored in the battery. $P_{out\ BS}$ means the power output from the battery. η_{con} means the battery efficiency.

At any given time t, the constraint that should be fulfilled is given as:

$$\forall t \in n \quad E_{cap\ Min} \leq E_{BS}(t) \leq E_{cap\ Max} \tag{7}$$

2.3.3. Constraint of H_2 production from electrolyzer

In this system, we use a PEM water electrolyzer (WE) for H_2 production. Throughout the process, the WE is continuously operational, and thus the power input to the WE is expected to be the same as the energy of hydrogen production needed.

$$\forall t \in n \quad m_{H_2}(t) = P_{Ely}(t) \cdot \frac{\eta_{Ely}}{LHV \cdot 1000} \tag{8}$$

For the WE, we set an operating interval for real power to ensure stable hydrogen production.

$$\forall t \in n \quad 0.8 \cdot WE_{cap} \leq P_{Ely}(t) \leq WE_{cap} \tag{9}$$

During this process, we can get the total mass of H_2 production and the total H_2O consumed without losses.

$$m_{H_2} = \sum_{t=1}^{n} m_{H_2}(t) \tag{10}$$

$$m_{H_2O} = \sum_{t=1}^{n} \frac{M_{H_2O}}{M_{H_2}} \cdot m_{H_2}(t) \tag{11}$$

where n means total time periods in one year, M means the molar weight of the water and hydrogen.

2.3.4. Fuel cell constraints

Given the imperative to optimize economic performance of different facilities, it is necessary to curtail the volume of the flow battery and hydrogen storage tanks within the system. Therefore, a PEM fuel cell (FC) is introduced into the system, which harnesses the H_2 in the power generation cycle.

$$\forall t \in n \quad P_{FC}(t) = m_{H_2\ in\ FC}(t) \cdot HHV \cdot \eta_{FC} \cdot 1000 \tag{12}$$

$$0 \leq P_{FC}(t) \leq FC_{cap} \tag{13}$$

2.3.5. H2 Storage constraints

We assume that the net hydrogen stored in the tank within one year is greater than zero, which means the total H_2 production should be equal to the total H_2 consumption. The hydrogen produced by the WE will supply the demand for hydrogen in the Scottish area and the demand of the FC.

$$\forall t \in n \quad m_{H_2}(t) = m_{H_2\ in\ tank}(t) + m_{H_2\ in\ Demand}(t) \tag{14}$$

$$m_{H_2} \geq \sum m_{H_2\ in\ FC} + \sum m_{H_2\ in\ Demand} \tag{15}$$

The hydrogen in the tank should meet the constraints of hydrogen storage (HS) tanks:

$$HS_{cap\ Min} \leq \sum m_{H_2\ in\ tank}(t) - \sum m_{H_2\ out\ tank}(t) \leq HS_{cap\ Max} \quad \forall t \in n \tag{16}$$

In any given period, we must ensure that there is enough hydrogen to meet the demand at all times.

$$\forall t \in n \quad m_{H_2\ Demand}(t) = m_{H_2\ out\ tank}(t) + m_{H_2\ in\ Demand}(t) - m_{H_2\ in\ FC}(t) \tag{17}$$

2.4. Sensitivity analysis

In our research, we use elasticity for our sensitivity analysis, and here's the equation.

$$E_i = \frac{\%\Delta Y}{\%\Delta X_i} \tag{18}$$

where $\%\Delta Y$ is the change rate of the hydrogen cost. $\%\Delta X_i$ is the change rate of each impact factor.

3. Results and analysis

The objective of this research was to explore the potential for combining tidal and wind energy to produce hydrogen through water electrolysis. The developed mathematical model in MATLAB was used to simulate and optimize the off-grid renewable energy system based on hourly data. The hourly data of 8,760 hours for one year was set to a period for 6 hourly data. Separate simulations for the wind-only, tidal-only, and wind-tidal hybrid systems were conducted to explore the minimize annual cost in each system. This section presents the optimized results and the environmental benefit analysis of three different systems.

3.1. Economic benefit results

The detailed optimized result of three different systems, that is the comparison of different annual total costs and hydrogen costs across three systems is shown in table 3 and Fig. 3. The tidal-wind hybrid system has the lowest annual total cost of 5,000.19 M$, followed by the wind-only system for 5,009.00 M$ and the tidal-only system for 9,127.24 M$. The hydrogen cost exhibits a parallel trend with the annual total cost. The hydrogen costs are 12.347 $/kg·H_2$ for the tidal-wind hybrid system, 12.368 $/kg·H_2$ for the wind-only system, and 22.537 $/kg·H_2$ for the tidal-only system. This indicates that the tidal-wind hybrid system is the most cost-effective method among these systems for hydrogen production in off-grid settings. Also, the hydrogen cost for hybrid system and wind-only system is just slightly above the current cost of hydrogen production from renewable energy sources, which is between 4.50$ and 10.50$ in the EU [26].

Table 3: The final result of the tidal-wind hybrid model, compared to the wind-only model and tidal-only model.

	Tidal-wind	Wind-only	Tidal-only
Total Cost / $M\$$	5,000.19	5,009.00	9,127.24
WT Capacity / MW	9,285.14	9,493.19	
TPP Capacity / MW	192.70		9,761.46
Ely Capacity / MW	3,406.10	3,446.66	3,467.47
BS Capacity / MWh	0.00	0.00	0.00
HS Capacity / $tonne$	9,722.56	10,131.44	11,609.12
FC Capacity / MW	2,591.23	2,712.26	1,555.06
H2 in FC / $tonne$	103,670.03	109,639.14	101,364.56
Water Consumption / $kilo\ tonne$	4,577.90	4,631.62	4,557.15
Final Unit Cost / $\$\ per\ kg\ H_2$	12.347	12.368	22.537

It is worth noting that compared to the hybrid system and wind-only system, though the gap between the hydrogen cost of both is small, the hybrid system achieved lower optimization results in the other sub-systems except the power generation system. When we doubled the cost of every auxiliary power generation system and storage system, we found that the hydrogen cost of the hybrid

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system and wind-only system rose to 17.851$ and 18.629$. The rise in hydrogen cost confirms the view above. This demonstrates that the inclusion of tidal energy is beneficial in stabilizing the system's power output while having a positive effect in reducing expensive auxiliary power generation and storage systems.

During the calculation, we found that power generation system inputs only accounted for 53.23%, 53.32%, and 29.85% of the total electricity generated in the hybrid, wind-only, and tidal-only systems respectively. If wasted electricity can be properly utilized, the cost of hydrogen will be further reduced. This implies a strong market viability and competitive advantage for hybrid systems.

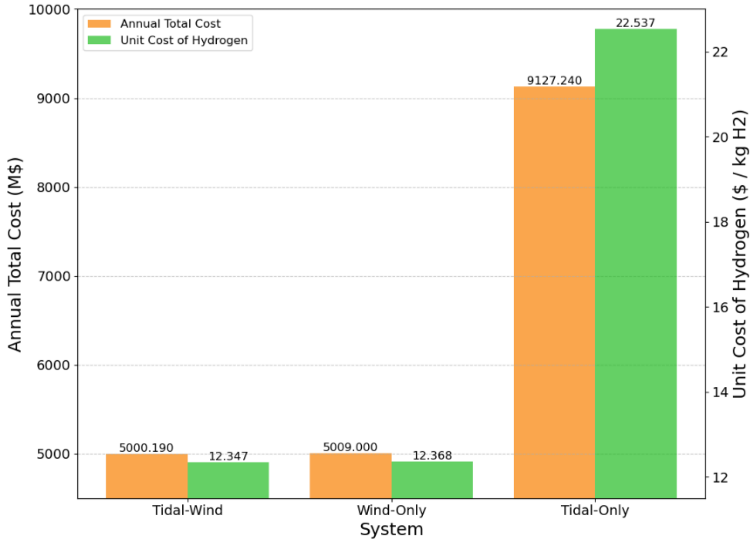

Figure 3: The annual total cost and the unit generating cost of hydrogen for each system.

The cost of each part of the system as a proportion of total expenditure is compared and shown in Fig. 4(a), 4(b), and 4(c). Since TPPs generate less electricity than wind farms in the one-year period in our study, this results in a much higher installed capacity for TPPs than wind farms for the same amount of electricity generation. The optimized result yields an installed capacity of 84.88% of the projected installed capacity in the UK in 2050 [10]. At the same time, the financial cost required for the unit construction of TPPs is much higher than that of wind farms, which significantly increases the unit cost of manufacturing hydrogen in the tidal-only system. As shown in Fig. 5, despite the wind-only system having higher overall annual power generation, the system has a higher instability during the power generation process. From the optimization results in Fig. 6, it can be seen that in order to meet the working demand of the electrolyzer, the wind-only system needs a larger storage system and auxiliary power generation system to fill the power generation gap from the wind farm. In comparison to the other two systems, the tidal-wind hybrid system combines the advantages of both the tidal-only and wind-only systems. These advantages bring more stable energy output, reduce overall installed capacity, and diminish the necessity for large-scale subsystems

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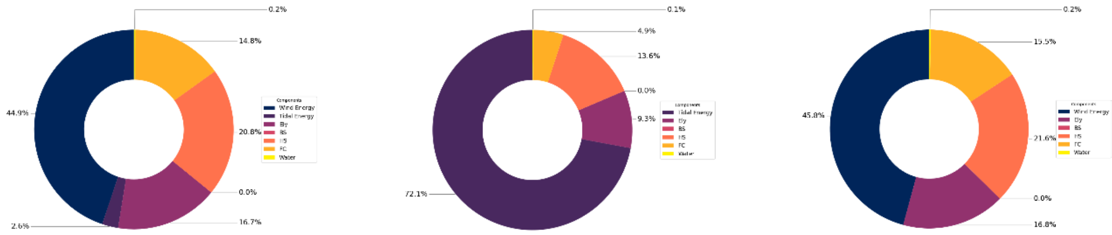


(a) (b) (c)

Figure 4: The cost of each part in (a) tidal-wind hybrid system. (b) tidal-only system. (c) wind-only system.

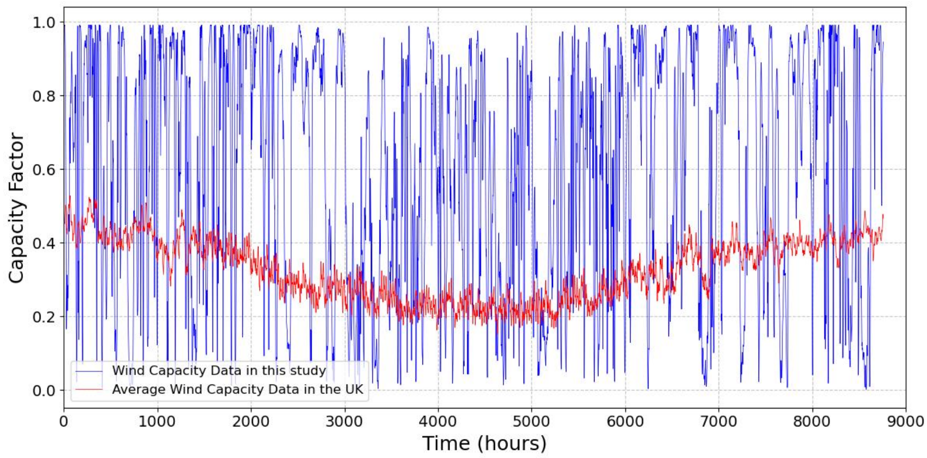


Figure 5: Different wind capacity factors between the data used in this study and the average data of 1980-2019 in the UK

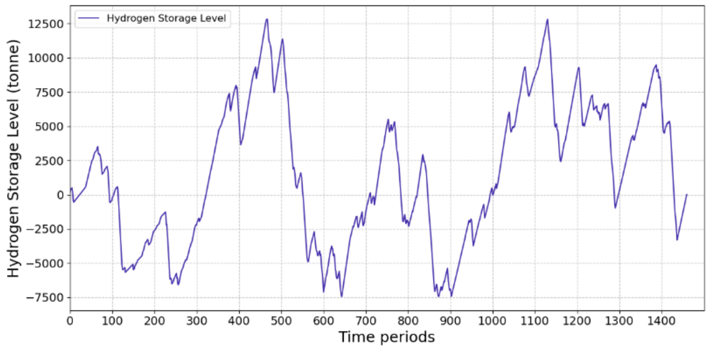


Figure 6: The hydrogen storage data of wind-only system in a year in a 6-hour period.

3.2. Sensitivity analysis

The sensitivity analysis demonstrates the impact of each factor in the model on the total cost and hydrogen cost. This study discusses the impact of the unit cost of each subsystem and the efficiency of the Ely, battery, and FC on the results of the optimized system. Since the cost of water has little impact on the total cost, we omit it from this calculation.

3.2.1. Result of sensitivity analysis

We assumed that the cost and efficiency of each subsystem fluctuate between ±20% and took the eight points of ±20%, ±15%, ±10% and and ±5% for the calculation, and the results of the calculation are shown in Fig. 7. The diagram elucidates the sensitivity of hydrogen cost relative to the variations in unit wind energy cost, tidal energy cost, HS cost, Ely cost, FC cost, and battery cost. It similarly reflects the influence of changes in Ely efficiency, battery efficiency, and FC efficiency on overall cost dynamics. It can be seen that the trend exists for the hydrogen cost for the tidal-wind hybrid system meets our expectations: when the cost goes down or efficiency goes up, the hydrogen cost decreases. In this case, the impact of changes in working efficiency on hydrogen cost is generally greater than the impact of changes in the unit cost of subsystems. In the figure, it is evident that the BS system doesn't have a great impact on either cost change or efficiency change.

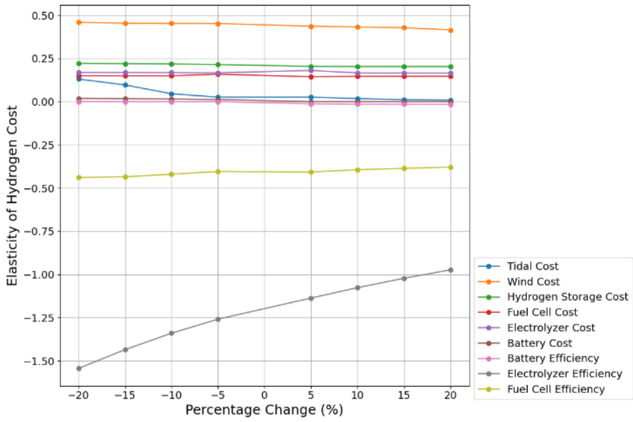
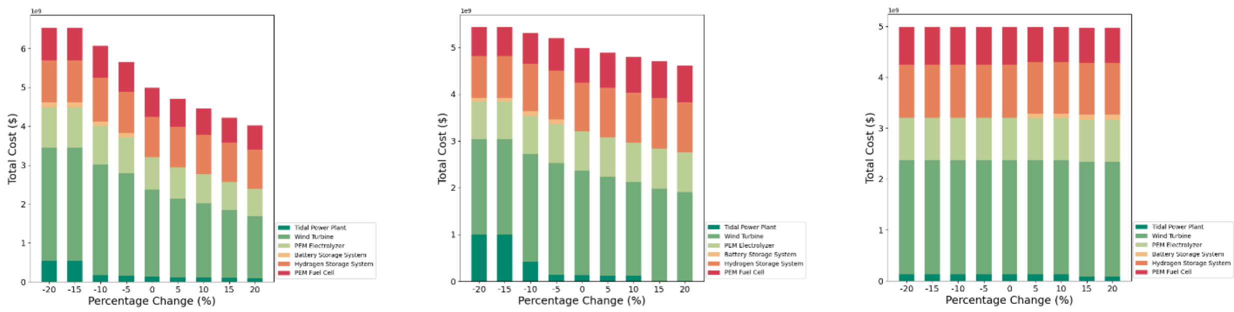


Figure 7: Sensitivity analysis for unit cost of subsystem and efficiency of subsystem through elasticity of hydrogen cost.

3.2.2. Effect of subsystem working efficiency

As mentioned above, changes in the efficiency of a single subsystem's work have a greater impact on hydrogen costs, which have the same trends as total cost, than changes in the unit costs of a single subsystem. It is analyzed in more detail and the results are shown in the Fig. 8(a), 8(b), and 8(c).



(a) **(b)** **(c)**

Figure 8: The total cost trend when the subsystem working efficiency changes. (a)electrolyzer efficiency; (b)fuel cell efficiency; (c) battery efficiency.

We can see that the total cost is gradually decreasing after the efficiency of the Ely and the FC is increased, while the cost of each subsystem is also on a decreasing trend. This may be because the increased efficiency of the subsystems has led to an increase in overall energy utilization. It may also reduce the need for auxiliary systems.

As mentioned above, the BS system doesn't have a great impact on hydrogen cost or in total cost from Fig. 8(c). Though the capacity of the battery increases when the efficiency increases, its impact is still limited.

3.2.3. Effect of subsystem unit cost

From the figure, we can find when changing the unit cost of the different subsystems, the impact on the total cost is low, fluctuating between about (0%, 45%). As observed from Fig. 9, the cost of wind energy has the largest impact on the hydrogen cost. Meanwhile, the remaining subsystems, except the tidal energy cost, have relatively stable impacts on hydrogen cost.

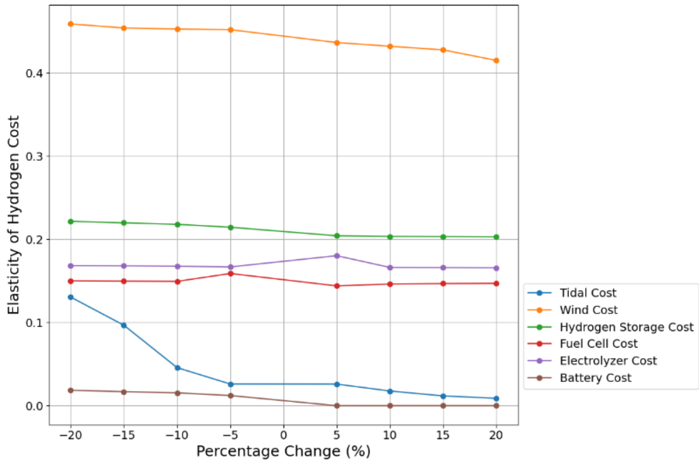
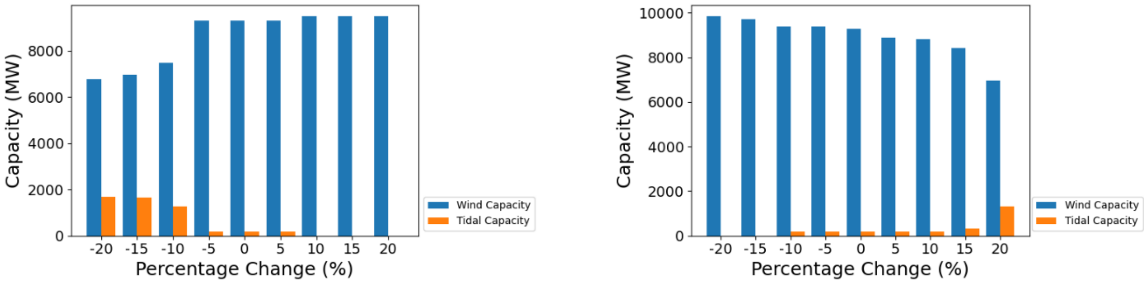


Figure 9: Sensitivity analysis for unit cost of subsystem through elasticity of hydrogen cost.

From Fig. 9, it is evident that the change in the unit cost of wind energy has a more stabilizing effect on the hydrogen cost compared to the change in the unit cost of tidal energy. As observed from Fig. 10(a) and 10(b), when the cost of tidal energy starts to rise, the increase in cost brings little change as the share of tidal energy in the raw data is relatively low, with wind farms being the main generator of electricity for the system. When the cost starts to fall, the cost of tidal energy is relatively more competitive and therefore accounts for a larger share, increasing the impact on the total cost. When the cost of tidal energy becomes more competitive, i.e. its cost decreases or the cost of wind energy increases, we can see a downward trend in total installed capacity. This suggests that the cyclical nature of tidal energy is beneficial in filling the shortcomings of highly volatile wind energy, and also reflects the fact that tidal energy is more stable in the system, compared to wind energy.

At the same time, hydrogen storage costs have a significantly higher impact on system operating costs and hydrogen costs than other auxiliary subsystems. This shows that the future development of hydrogen storage technology has a very high potential and also brings great economic benefits for renewable energy hydrogen production systems.



(a) **(b)**

Figure 10: The capacity change in tidal energy and wind energy. (a) Tidal cost change. (b) Wind cost change.

3.3. Comparison of batteries and fuel cells

From the results above, it can be seen that the BS doesn't play a major role in the energy storage system. FC, as an auxiliary power generation system, has a much larger capacity. The comparison between the result of no-BS system and no-FC system is shown in table 4. It's evident from the comparison that the BS capacity in the non-FC system is considerably larger than the FC capacity in no-BS system. The calculated difference in total power generation between the no-BS and no-FC systems is very small, about 4.6%. The large amount of tidal generation in the no-BS system means that it is difficult for the BS to compensate for the volatility of the wind power generation and relatively stable tidal energy is required for additional power compensation. As a result, in a long-term high volatility power generation scenario, BS is hard to satisfy the need for continuous operation of the system.

In the no-BS system, the continuous operation need of the WE can produce excess H_2 and store it. Compared to the electricity stored in the BS system and its high cost, the excess H_2 can be stored in a relatively inexpensive HS system, considering that the H_2 has a higher energy density. At the same time, the high flexibility of fuel cell power generation can make good use of excess hydrogen for power compensation. It demonstrates the high flexibility and large-scale potential of hydrogen storage for volatile renewable energy power generation.

Table 4: The comparison between the optimized result of no-BS system and no-FC

	No-FC	**No-BS**
Total Cost/ $M\$$	8,537.56	5,000.19
WT Capacity / MW	6,924.90	9,285.14
TPP Capacity / MW	4,568.38	192.70
Ely Capacity / MW	2,666.04	3,406.10
BS Capacity / MWh	30,360.33	0.00
HS Capacity / $tonne$	7,083.84	9,722.56
FC Capacity / MW	0.00	2,591.23
H_2 in FC / $tonne$	0.00	103,670.03
Water Consumption / $kilo\ tonne$	3,644.87	4,577.90
Final Unit Cost / $\$\ per\ kg\ H_2$	21.081	12.347

3.4. Environmental benefit analysis

As observed from Table 3, we obtained similar hydrogen costs on the tidal-wind hybrid system and the wind-only system. In order to highlight the advantages of one over another, we evaluated the environmental benefits of the three systems and used CO_2 emissions as a measure. In our study, we ignored the CO_2 emissions from the delivery of electricity, which means that all the electricity used for hydrogen production is carbon neutral.

Table 5 shows the CO_2 equivalent emission during the working process in the lifespan for each subsystem. Table 6 shows the result of the calculation. The CO_2 equivalent emission is 1.53 kg/kg·H_2 for the tidal-wind hybrid system, 1.55 kg/kg·H_2 for the wind-only system, and 1.28 kg/kg·H_2 for the tidal-only system. We can find that the tidal-wind hybrid system has the lowest unit cost while emitting less CO_2 than the wind-only system. Tidal-only systems have the lowest CO_2 emissions, which suggests that a higher percentage of tidal energy in a hybrid system would be more beneficial to the system's CO_2 emissions. Compared to other hydrogen manufacturing processes like steam methane reforming and coal gasification, which has a large amount of CO_2 emission for 2.85 kg/kg ·H_2 and 4.45 kg/kg ·H_2 with carbon capture and storage (CCS) process [27], the low emissions of the tidal-wind hybrid system are conducive to further reducing the cost of hydrogen and contributing to the process of carbon neutrality.

Table 5: The CO_2 emission equiv. for each subsystem in one year period.

Subsystem	**CO_2 emission equiv. (kg)**	**citation**
Tidal Power Plant	5.0 / MWh	[28]
Wind Turbine	12.0 / MWh	[29]
PEM Electrolyzer	250.0 / $t \cdot H_2$	[30][31]
Battery Storage System	9,200.0 / MWh	[32]
Hydrogen Storage System	665.9 / $t \cdot H_2$	[33][34]
PEM Fuel Cell	2,646.3 / MW	[35]

Table 6: Total CO_2 equivalent emission from all subsystems for three different systems in one-year H_2 production process

	tidal-wind	**wind-only**	**tidal-only**
CO_2 equiv. Emission / $kg/kg \cdot H_2$	1.53	1.55	1.28

4. Conclusion

In the context of an incrementally burgeoning hydrogen energy market, the pursuit of a more economical hydrogen production methodology is an enduring challenge, both present and future. This paper contends that relying solely on a singular renewable energy source for hydrogen production is not only cost-prohibitive but also fraught with volatility. To counter this, a comprehensive framework is proposed, leveraging a hybrid tidal-wind energy system evaluated through a meticulous assessment methodology. This proposed framework meticulously constructs a model to appraise tidal energy, wind energy, and their synergistic hybrid system for hydrogen production, with a specific focus on addressing Scotland's impending hydrogen demands. The primary objective is to achieve the lowest possible annual total cost, concurrently minimizing the hydrogen cost. Anchored in empirical data from Scotland, the case study underscores the immense potential of hybrid energy systems to forge a more stable and economically viable route to hydrogen production compared to mono-energy systems. The discourse on benefits demonstrates that the hybrid approach yielded the lowest total annual cost and unit hydrogen production cost, thereby underlining the economic feasibility of hybrid systems, particularly in off-grid scenarios. Meanwhile, an environmental analysis corroborates the superiority of the hybrid system, underlining the sustainability and environmentally friendly advantages of the system. This study delves into the techno-economic feasibility of green hydrogen production, aiming to catalyze the transition towards sustainable energy solutions in the foreseeable future.

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Nomenclature

Symbols

W_{cap} wind capacity (MW)
T_{cap} tidal capacity (MW)
WE_{cap} electrolyzer capacity (MW)
FC_{cap} fuel cell capacity (MW)
HS_{cap} hydrogen storage capacity($tonne$)
C cost ($M\$$)
E energy (MJ)
m mass($tonne$)
P power (MW)

Greek letters

η efficiency
σ battery self discharge rate

Subscripts

Ely electrolyzer
Max maximum
Min minimum
tot total

Abbreviations

Bs battery storage
$CAPEX$ capital expenditure
CF capacity factor
FC fuel cell
HHV high heating value
HS hydrogen storage
LHV low heating value
$OPEX$ operating expenditure
PEM proton exchange membrane
TPP tidal power plant
WE water electrolyzer
WT wind turbin