Preprints.org

Article

Not peer-reviewed version

Techno-Economic Analysis of Hybrid Energy Storage System with Renewable Energy Coupling Hydrogen Technology

Hye Young Jung *

Posted Date: 19 July 2023

doi: 10.20944/preprints202307.1281.v1

Keywords: techno-economic analysis; hybrid optimization of multiple energy resources (HOMER); hybrid energy storage system (HESS); hydrogen energy storage system (HydESS),; levelized cost of energy (LCOE); battery energy storage system (BESS),

Preprints.org is a free multidiscipline platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 July 2023 doi:10.20944/preprints202307.1281.v1

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

Techno-economic Analysis of Hydrogen Energy Storage System with Onshore Wind Turbine Coupled Fuel Cell and Electrolyzer

Hye Young Jung

Graduate School of Energy and Environment, KU-KIST Green School, Korea University, Seoul 02481, Republic of Korea

*Corresponding Authors: Tel.: 82-70-8098-6890; fax: 82-504-317-1720; E-mail address: hyj07@korea.ac.kr

Abstract: When intermittent renewable energy sources reach a penetration level of 100%, they can lead to power outages. In order to mitigate the fluctuations in the supply and demand curves of renewable energy, the implementation of an energy storage medium and carrier is necessary. The Hydrogen energy stotrage system (HydESS), which combines a proton exchange membrane (PEM)-based water electrolysis (WE) system and a fuel cell (FC), has the quickest response time, the longest duration, and the greatest storage capacity. In present study, a techno-economic analysis are used to evaluate the HydESS hybrid system. Kyiv, Ukraine, is appealing due to its spatial-temporal wind speed, solar irradiance, and energy security. With an levelized cost of electricity (LCOE) of \$0.245 kWh^{-1} and 9.3% fuel cell power output, the most feasible solution is onshore wind turbine-coupled PEMFC HydESS. As a result 1,000-kW wind power, 250-kW PEMFC, 250-kW PEMWE, and 441-kW BESS are optimized to serve a 3,900 kWh day^{-1} academic residence load. When compared to a diesel generator and a BESS, the hybrid HydESS reduces CO_2 emissions by 5,582 tons over a 25-year period. This study recommends accelerating PEMFC development with fluctuation-endurable design and system configuration.

Keywords: techno-economic analysis; hybrid optimization of multiple energy resources (HOMER); hydrogen energy storage system (HydESS); hybrid energy storage system (HESS); battery energy storage system (BESS); levelized cost of energy (LCOE)

1. Introduction

The utilization of fossil fuels by humanity for the advancement of civilization has led to a swift escalation in the atmospheric concentration of CO_2. The aforementioned circumstances have given rise to climate crises, including global warming and atypical climate patterns. Consequently, the expeditious resolution of these issues has become an urgent imperative in order to safeguard both biodiversity and humanity. Among environmentally friendly alternative fuel candidates, hydrogen has a low carbon footprint, a high energy density, and a long-term storage capacity. Additionally, it has the advantage of energy storage due to its high energy density of 142 MJ kg^{-1} (higher heating value, HHV) [1]. Renewable energy-coupled water electrolysis minimizes CO_2 emission during hydrogen production compared to steam methane reforming and grid-connected water electrolysis. Hybrid system from renewable energy and energy storage system (ESS) provides benefits such as self-sufficiency, expandability with grid connection, and climate adaptability from diverse power sources [2]. Among the ESS, the Hydrogen storage method has three distinct advantages compared to other energy storage systems. The advantages of hydrogen as an energy medium are high-volume storage, mid-long term load shifting, and clean energy in transportation or power generation applications [3].

As regulations and constraints on CO_2 address the global climate crisis, a new global order to safeguard nationalism in energy trade is emerging. After Russia's attack, EU urgently revised the hydrogen and renewable energy roadmap through the 'REPower EU' policy [4]. An outpost of neo cold war, Ukraine need to accelerate the energy self-sufficient transition for decarbonization claiming by International Renewable Energy Agency (IRENA) [5] and US National Renewable Energy Laboratory (NREL) [6]. The target is 68% reduction of total greenhouse gas (GHG) emissions from a thermal plant by 2050, based on the data of renewable energy trends and demand in Ukraine [7] and the sector management plan [8]. Accordingly, Ukraine build more onshore wind farm after war crisis as reported in Washington post in 2023 to commit the EU renewable energy policy [9].

The renewable energy potential of Ukraine is highly feasible due to its beneficial geometrical features. Most of the territory is flat plain suitable for agriculture. Furthermore, *Kudria et al.* [10] proposed the renewable energy potential

© 2023 by the author(s). Distributed under a Creative Commons CC BY license.

from wind–hydrogen system in Ukraine due to the high wind speed compared to the other region. According to the study [10], the wind has 688 GW nominal capacity and 2174 TWh (2.174 PWh) annually on its territory and 43 million tons of green hydrogen (capacity factor: 24.04~54.55%). This wind-hydrogen potential of Ukraine territory is higher than in Japan, the United Kingdom, and Norway. Furthermore, a positive outlook is anticipated for market expansion to require the decarbonized energy demand [10]. Therefore, accurate scale and feasibility of renewable hydrogen in Kyiv should be evaluated by the technoeconomic analysis.

The establishment of renewable energy infrastructure and power utilities necessitates substantial financial resources and is perceived as a formidable undertaking, necessitating public and governmental authorizations prior to conducting technical economic evaluations. These evaluations encompass various stages such as engineering, procurement, and construction (EPC) processes, which are essential for the implementation of these systems. HOMER, a technoeconomic engineering tool known as Hybrid Optimization of Multiple Energy Resources, stands out as a highly accessible program for optimizing renewable energy systems and grids [11]. Its invention by the NREL further enhances its credibility and significance in the field. As climate crisis float on the surface of main objective in this era, the rate of growth in systematic analysis findings has exhibited a notable acceleration over the past triennium (2019-2021). Specifically, within the corpus of recent bibliometric research compilations, approximately 14 instances have been recorded wherein HOMER was employed as a tool for technoeconomic investigation out of a total of 120 papers [12].

Renewable energy shows significant flexibility and volatility, hence the distribution and storage problem restricts its deployment. There are several energy storage system options such as battery, flywheel, and hydrogen energy for distributing electricity spatially and temporarily for any system on and off grid with renewables [13]. Among the systems, the hydrogen energy storage system (HydESS) is possible to 100% decarbonize energy transfer compared to other technologies [12]. As the land scape, the onshore wind and photovoltaic (PV) have some advantages of geometrical proximity in electricity providers for metropolitan regions [14]. Moreover, distributed renewable energy systems could reduce infrastructural investment costs due to hydrogen pipelines or high-voltage cables for electricity transmission [15]. Heat and water utilization of renewable hydrogen system could be more effective to supplying buildings and small industrial facilities near cities [16]. Research facilities need backup power to prepare for research facility shutdowns that may occur due to power outages. In addition to the power supplied from the well-developed power grid in the city center or suburbs, it is a necessary item as an energy independent research facility to be able to store and use power from new and renewable energy.

The present study evaluates the economics of hydrogen, including production, storage, and usage in a stand-alone distributed power system, from two perspectives. First, A cost-effectiveness analysis of the HESS model, which included solid oxide fuel cell (SOFC) for stationary use and PEM water electrolysis (PEMWE) were also conducted. The installation region was identified using HOMER software, actual climatic data were established, and equipment was set up. After the optimized system design was calculated, the LCOE and other indices were obtained, compared, and assessed. Second, capital and operation cost sensitivity analysis of fuel cells, water electrolysis, and commercial loads linked to the system was used to check the distribution range of LCOE as Net present cost (NPC) This work provided a quick overview of the cost-effectiveness and specific directions for future system and component development initiatives.

2. Methodology

2.1. Research framework & Flow

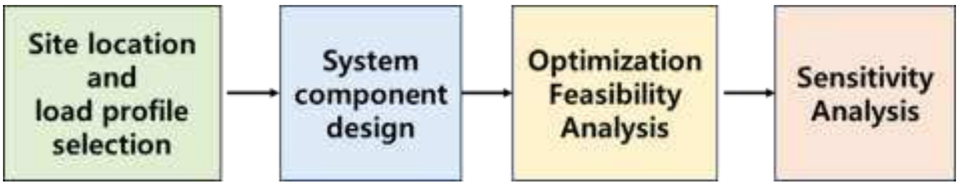

Figure 1. Schematices of Technoeconomic analysis using HOMER platform.

To analyzing the techno-economic research for hydrogen society, many approaches were applicated to quantification for hydrogen technologies. NREL invented the software HOMER for public research. It provides accurate climate data from the satellite in the specific region. The foremost advantage of the tool was the proposal of an optimized energy system via techno-economic analysis. The techno-economic study was carried out using HOMER to examine PEMWE's LCOH for renewable energy-linked operation as well as LCOH change relied on system unit costs.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 July 2023 doi:10.20944/preprints202307.1281.v1

2.2. Literature Review

The carbon emission of thermal plants (Diesel power plant), including systems, exclude the plant in the literature survey. In any case, the benefit is mainly GHGs reduction, which is unsuitable energy storage compared to this work. The location of renewable energy generation site was limited to land and onshore due to the city. Offshore wind or floating PV were possible to transfer electricity, but the additional infrastructure cost could be added. There are many literature reviews including "Homer", "hydrogen", "Fuel cell" "electrolyzer", "PV", and "wind" in previous bibliometric analysis. By Scopus, total19 literatures were listed and then excluded the system containing diesel plant, and the finalized as six papers (17-22) are tabulated in Table 2.

Table 1. Summary of publications conducting the technoeconomic analysis of energy storage systems including hydrogen using HOMER.

Ref	Item	COE	NPC	PV	Wind	BESS	PEMWE	PEMFC	H_2 tank	Region	AC load or Hydrogen demand
	Objective	$ kWh^{-1}	$	kW	kW	kW	kW	kW	kg		kWh day^{-1} kgH$_2$ day^{-1}
[17]	BESS vs. HydESS comparison	1.208	75,428	4	2	0	3	2	1	Saudi Arabia	14 kWh day^{-1}
[18]	BESS vs. HydESS comparison	0.52	7,160,000	469	1500	396	350	100	500	USA	70 kgH$_2$ day^{-1}
[19]	HydESS feasibility	0.8399	1,006,293	120	-	-	60	13	20	Spain	200 kWh day^{-1}
[20]	HydESS case study	1.901	910,415	1	1	-	150	1	100	Oman	12 kWh day^{-1}
[21]	PV vs. Wind comparison	0.374	2,990,000	69	88	581	250	450	700	Canada	125 kgH$_2$ day^{-1}
[22]	PV vs. Wind comparison	0.366	5,276,069	900	700	1088	300-kW	100	300	Korea	2187.6 kWh day^{-1}
This work	BESS vs. HydESS comparison	0.245	4,508,672	0	1,000	441	250	250	700	Ukraine	3,900 kWh day^{-1}

Al-Sharafi et al. [17] evaluated the economic factor, LCOE as 1.208 $ kWh^{-1} in Abha area for the hydrogen production storage system, In the reference, the result of System #6 exhibits the minimum LCOE with 1.208 $ kWh^{-1} and LCOH is 43.3 $ kg^{-1}. The optimum configuration has 4 kW PV array, two wind turbines, 2 kW converter, 2 kW fuel cell, 3 kW electrolyzer and 1 kg hydrogen tank. Another case by *Abdin et al.* [18] calculates the minimum COE as 0.5 $ kWh^{-1} for Golden Colorado equipped with 400 kg H_2 tank. *Peláez-Peláez et al.* [19] simulated the LOCE as 0.8399 $ kWh^{-1} containing 20kg tank with PV coupled electrolyzer and fuel cell. *Okonkwo et al.* [20] conceptualized the system as PV, wind, fuel cell and hydrogen tank with LCOE, 1.901 $ kWh^{-1} in Oman and the hydrogen storage capacity was set to 100 kg tank. *Babaei et al.* [21] acquired LCOE 0.374 $ kWh^{-1} with the hydrogen based microgrid composed with PV, wind, fuel cell, hydrogen tank, and batteries in Saint Pierre Island caseRecently, *Zhang et al.* [22] optimized the off-grid hybrid energy system in Ui island. The system was composed of 990-kW PV panels, 700-kW wind turbines, a 1088-kWh Li-ion battery bank, 534-kW converter, 300-kW PEMWE system, 300-kg hydrogen tank, and 100-kW PEMFC. The total NPC of the system is $5,276,069, and the LCOE is 0.366 $ kWh^{-1}. This case study proved that the self-sufficient energy system in isolated area for community demand without any auxillary power supply, and the hypotheses of the simulation results are limited by the low capacity factor of electrolyser. And the system showed the good feasibility compared to diesel plant, but the fuel cell was adopted as PEM type with 40,000 lifetime span. Moreover, the Battery cost is increased within a few years up to 596 $ kWh [23].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 July 2023 doi:10.20944/preprints202307.1281.v1

2.3. System and site outline

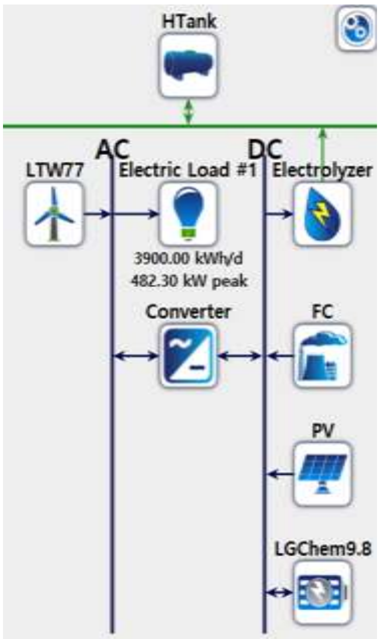

Figure 2. Basic hybrid hydrogen energy storage system (HydESS) and battery energy storage system(BESS) configuration with renewable energy sources, PV, wind turbine.

In this study, the optimum specifications of water electrolysis capacity and other ancillary devices were derived based on the system's actual operation results, including the 1,000 kW-class wind turbine power generation. As simulation results, the NPC and the levelized cost of electricity (LCOE) were calculated. The optimized system result is resulted in Figure. 2 from system (a) to system (c). The difference between system (a) and (b) is photovoltaic panel and the difference between (a, b) and (c) is HydESS usage. The most optimized system is (a), and it will be discussed in result and discussion section.

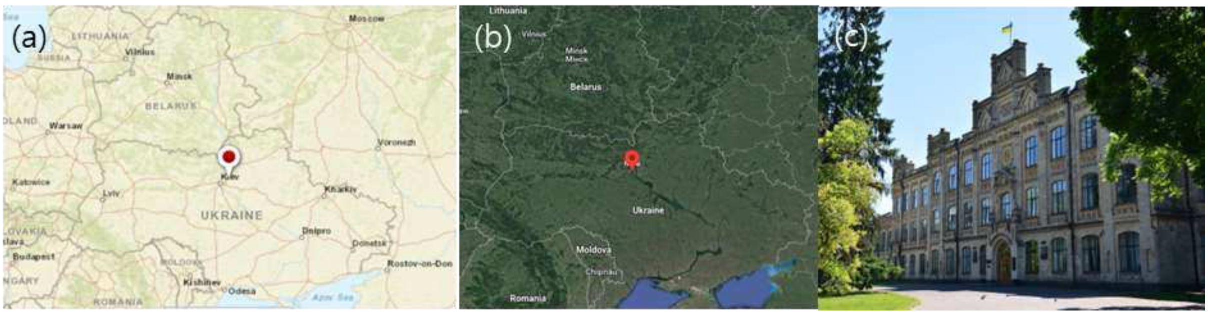

Figure 3. Location of Igor Sikorsky Kyiv polytechnic institute in Kyiv, Ukraine (50°40.0'N, 30°59.5'E), (a) load view, (b) arial view, and (c) Igor Sikorsky Kyiv polytechnic institute building.

The capital city of Ukraine, Kyiv (50°40.0'N, 30°59.5'E) is studied as the subject of the analysis in Figure 4. This study limited on local area point is technoeconomic comparison between HydESS and BESS for renewable energy storage in Kyiv, capital of Ukraine, as center of culture and economy. The NASA satellite data was used to obtain statistics on average solar radiation and wind speed during a one-year period. According to Figure 4a, the yearly average solar radiation on Kyiv is 3.10 kWh $m^{-2}day^{-1}$. Additionally, clearness nearly cloudy independent on the season, from 0.367 in November and 0.496 in Aug. Referring to Figure 4b, the average wind speed was around 6.20 m s^{-1} when the wind turbine was erected at the height of 65 m above sea level. Temperature is coldest in January as −6.14 °C and hottest as 20.83 °C in July as shown in Figure 4c.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 July 2023 doi:10.20944/preprints202307.1281.v1

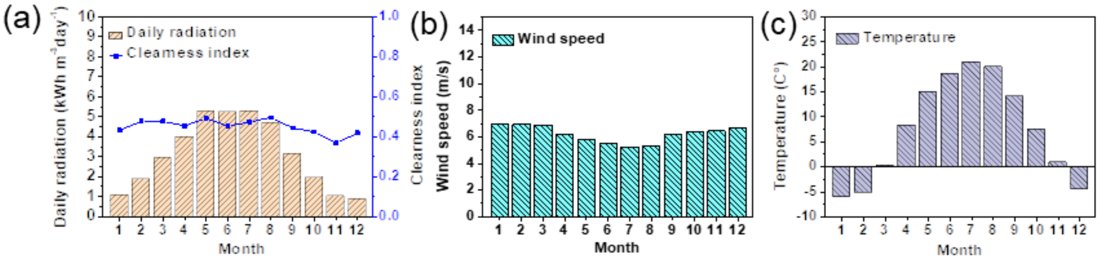

Figure 4. Climate profile of Kyiv, (a) daily solar radiation and clearness index per month, (b) wind speed, and (c) temperature of Kyiv, Igor Sikorsky Kyiv Polytechnic Institute location in Ukraine.

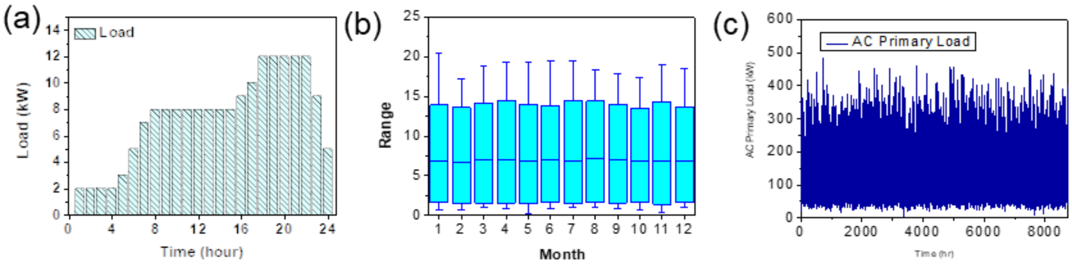

Figure 5. AC Primary load profiles of Kyiv, (a) daily, (b) monthly, and (c) yearly of Kyiv, Igor Sikorsky Kyiv Polytechnic Institute location in Ukraine.

Power demand was set as a residence load provided as a sample case from HOMER to select the AC (alternating current) electric load scale size. As shown in Fig. 4, the total daily load of 3,900 kWh day^{-1}, and the maximum peak load is 482.3 kW and load factor is 0.34. This AC load is calculated from the average electricity consumption per capita data and capacity of dormitory building . Average power (electricity) consumption per capita in Ukraine is 2,844 kWh year^{-1} , 7.8 kWh^{-1} according to world data [24]. Recently opened dormitory in Igor Sikorsky Kyiv Polytechnic Institute about 500 students and staffs are capable to residence in 2021 [25].

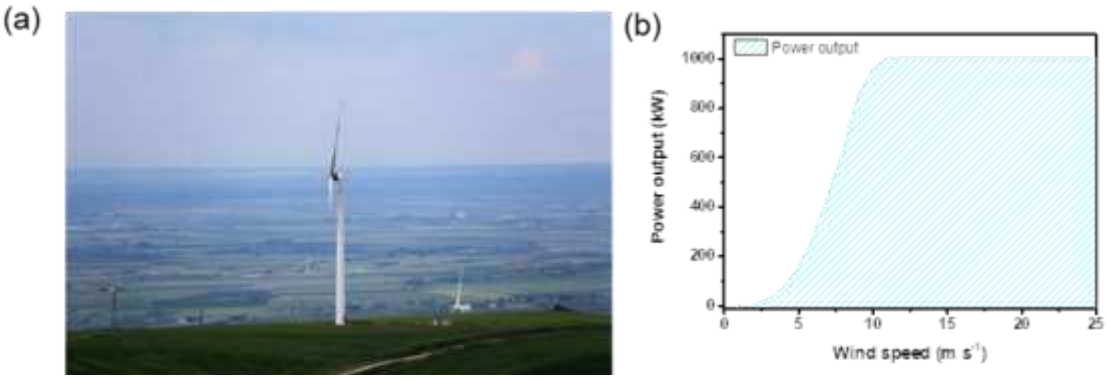

Figure 6. Wind turbine (a) Leitwind AG / Leitwind LTW77 / 1000 kW wind turbine generator / Melfi, Italy (maker's web site), (b) Power curve of wind turbine LWT77 from Leitwind 1,000 kW model.

Table 3. Energy storage system components cost, technical data, and lifetime.

System data		
PV Unit		
Capital expenditure	1252	$ kW^{-1}
Operation and maintenance expenditure	18	$ y^{-1} kW^{-1}

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 July 2023 doi:10.20944/preprints202307.1281.v1

Lifetime	25	years
Derating factor	85	%
Wind turbine system		
Capital expenditure	1500	$ kW^{-1}
Operation and maintenance expenditure	50	$ y^{-1} kW^{-1}
Lifetime	25	years
Batteries (100 kWh Li BESS)		
Nominal voltage	480	V
Nominal catacity	90.7	kWh
Maximum capacity	189	Ah
Captial expenditure	415	$ kWh^{-1}
Replacement expenditure	280	$ kWh^{-1}
Operation and maintenance expenditure	25	$ y^{-1} kWh^{-1}
Lifetime	10	years
Converter		
Capital expenditure	90	$ kW^{-1}
Replacement c expenditure	90	$ kW^{-1}
Operation and maintenance expenditure	0	$ y^{-1}
Lifetime	15	years
Efficiency	95	%
Electrolyzer		
Capital expenditure	1400	$ kW^{-1}
Replacement expenditure	650	$ kW^{-1}
Operation and maintenance expenditure	60	$ y^{-1}
Lifetime	25	years
Storage tank (High pressure)		
Capital expenditure	635	$ kg^{-1}
Operation and maintenance expenditure	3	$ y^{-1}
Lifetime	25	years
Fuel cell		
Capital expenditure	4800	$ kW^{-1}
Replacement expenditure	3800	$ kW^{-1}
Operation and maintenance expenditure		$ y^{-1}
Lifetime	5	years

The cost information of system components is listed in Table. 2. The cost of new PV is estimated as $ 1,252 kW^{-1} and the annual OPEX is estimated as18 $ kW^{-1} from the reference [26]. The panel lifetime is expected to be 25 years and the derating factor is set to 85%. The wind turbine is the Leitwind LTW77 1,000 kW model used in the existing literature, and the cut in speed is around 11~12 m s^{-1} [27]. It can be seen from Figure. 6; the manufacturer provided the wind turbine's power curve and the capital expenditure (CAPEX) is $ 1,500 kW^{-1}. The operation and maintenance expenditure (OPEX) cost is annually $ 50 kW^{-1} and the total lifetime is 25 years.

BESS adopted the Li ion battery such as LG Energy Solution, the 10-kWh class model [23]. The nominal voltage and capacity are 48 V and 9.8 kWh and the maximum capacity is 189 Ah. CAPEX is $ 596 kWh^{-1} [28] and replacement expenditure is $ 280 kWh^{-1}, O&M cost is $ 23.3 kWh^{-1} [29]. The battery lifespan is 10 years [30]. The CAPEX of converter is $ 80 kW^{-1} form NREL's report for grid energy storage technology cost [29]. The efficiency is 95% and the lifetime of converter is expected to 15 years. The converter system and installation cost is estimated as 90 $ kW^{-1} and the replacement cost is identical to CAPEX. Operation and maintenance cost of the converter is 0 in practically according to other research [31].

The water electrolyzer is adopted as PEM type in this study, easily operable compared to other electrolysis, counting on the relatively high capital expenditure as 1,400 $ kW^{-1} [32] and the OPEX is estimated as 2% of CAPEX [33]. Solid oxide fuel cell (SOFC) is chosen for its highest efficiency and adaptability for stationary applications. The specific power

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 July 2023 doi:10.20944/preprints202307.1281.v1

generation is 27.52 kWh $kg^{-1}H_2$, if the voltage efficiency of SOFC is 79.3% from the reference [34]. And the specific fuel consumption is calculated in HOMER following the procedure [35]. The capital cost and maintenance expenditures become more higher c.a. 4,800 \$ kW^{-1} [36, 37] than that of PEM fuel cell, 3,300 \$ kW^{-1} [22]. The capital and maintenance cost of Hydrogen tank is referenced by NREL's previous report [38]. Life time span of SOFC is based on the literature as 40,000 hrs [39, 40] and expected optimum value as 50,000 hrs [41].

2.4 Calculation

Homer software simulate the cost-effective system configuration by calculating the minimum NPC. The NPC is defined as total annual cost during project years normalizing with unit cost recovery factor as presented in Eq. 1. These definitions and calculations of indices for technoeconomic analysis are referenced from Homer manual [32].

$$NPC = \text{total } C_{annual} \,/\, CRF \qquad \text{(Eq. 1)}$$

The capital recovery factor (CRF) was calculated by Eq. 2 suggested by handbook and manual [42, 43] Using an interest rate i, auuity, n , the capital recovery factor is :

$$CRF = i\,(1+i)^n / ((1+i)^n - 1) \qquad \text{(Eq. 2)}$$

Annual cost of plant is reduced as the facility is operated considering the depreciation, where d denotes discount rate,

$$C_{annual}\ (\$\ y^{-1}) = C_{plant} \cdot d \cdot (1+d)^n / ((1+d)^n - 1) \qquad \text{(Eq. 3)}$$

where n is the number of annuities received. This is related to the annuity formula, which gives the present value in terms of the annuity, the interest rate, and the number of annuities. The capital recovery factor is a fraction determined as indicated above where overnight capital cost is expressed as dollars per installed kilowatt (\$ kW^{-1}). O&M expenses are divided into fixed costs per kilowatt-year (\$ kW^{-1}-yr) and variable costs per kilowatt-hour (\$ kW^{-1}). In the denominator 8,760 is the number of hours in a year and capacity factor is a fraction between 0 and 1 representing the portion of a year that the power plant is generating power. Fuel cost is optional since some generating technologies like solar and wind do not have fuel costs. In this work, the fuel cost is only applied in the diesel BESS comparison case, while other HydESS systems use hydrogen as fuel cost, 0.

Levelized Cost of Energy (LCOE, also called Levelized Energy Cost or LEC) is a cost of generating energy (usually electricity) for a particular system. It is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel, cost of capital. A NPC calculation is performed and solved in such a way that for the value of the LCOE chosen, the project's NPC becomes zero. The following formula is used to compute the levelized simple cost of energy. In this case, the LCOE follows the off grid system type without disel generator according to other reference [44].

$$LCOE\ (\$/kWh) = C_{annual} \,/\, E_{served} \qquad \text{(Eq. 4)}$$

The LCOH was calculated by dividing the yearly capital expenditure (CAPEX) and the operating expenditure (OPEX) cost of the system by the amount of hydrogen production, as illustrated in the following equation[45]. LCOH[18] in HOMER was where $C_{ann\ tot}$, is the total annualized cost, v_{elec} is the value of electricity, E_{prim} is the primary electrical load, E_{def} is the deferrable load, E_{grid} sales ,is the total energy sold to the grid and M_{H2} is the total hydrogen production.

$$LCOH\ (\$/kg) = C_{ann,total} - v_{elec}(E_{prim,\,AC} + E_{prim,\,DC} + E_{def} + E_{grid,\,sales}) \,/\, M_{H2} \qquad \text{(Eq. 5)}$$

The efficiency of the water electrolysis system (ε_{WE}) was calculated as follows. As of this time, the HHV (High heating value of hydrogen, 39.4 kWh kg H_2^{-1}) was 1.48 V.

$$M_{H2} = \varepsilon_{WE} \,/\, HHV \cdot H_2 \qquad \text{(Eq. 6)}$$

As shown in Fig. 5, the system configuration was evaluated for a water electrolysis system connected with a renewable energy source. With an assumption, a hydrogen storage tank (1,000 kg capacity) was added for the minimum system requirement, and a lead-acid battery was added to store surplus power and supply it back to the system. The cost of a hydrogen tank is obtained from [46].

The system was designed with size as feasible as renewable energy without compromising the streaming factor for 1 MWh water electrolysis. The power for water electrolysis was supplied to the electrolyzer through an inverter from the DC solar panel in series and a converter of AC wind turbine in parallel. As a result, the minimum operating capacity for water electrolysis was deduced as 10%, and the voltage efficiency of the water electrolysis system was set to 80%. The performance of the water electrolysis system was calculated through voltage efficiency, and the calculation formula was as follows. The 80% system performance means that the stack driving voltage was 1.85 V at the current target density. In this circumstance, the power consumption was 49.3 kWh kgH_2^{-1}.

Voltage efficiency (%)=V_{op}/HHV (Eq. 7)

The economic analysis model combined the renewable energy sources, water electrolysis, and hydrogen refueling stations was entered by referring to the evaluation setting values in the previous literature [18]. Each system unit cost and lifespan were entered into the software, as shown below. As shown in Table 1, the solar panel specifications, wind turbine, battery, and converter to run the system were applied. Based on these fundamental unit values, in the existing system, the result of direct optimization in the system was used as it is without adding a scaled factor or setting the capacity. The inflation rate and discount rate are set to 2% and 8%, respectively, as adopted in other researches [47, 48].

3. Results and Discussion

3.1. Optimized system configuration

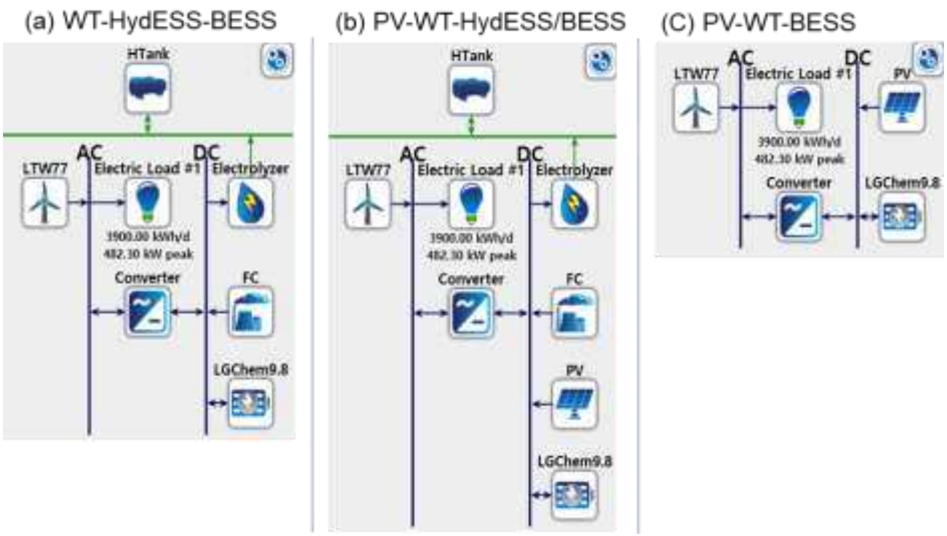

Figure 7. System configurations, target configuration consist of hybrid ESS with BESS and HydESS, (a) optimized system with WT-HydESS-BESS (b) second optimized system with PV-WT-HydESS-BESS, and (c) comparison configuration including BESS.

Table 4. Simulated optimization system with different fuel cell type as proton exchange membrane fuel cell and solid oxide fuel cell and different life time.

Case	FC type	Lifetime	Levelized cost of energy (LCOE)	Total net present cost (NPC)	PV	Wind turbine	FC	Li-ion battery	Converter	PEMWE
Units	-	hrs	$/kWh⁻¹	$	kW	kW	kW	kWh	kW	kW
(a) HydESS-1	PEMFC	40,000	0.249	4,584704	0	1,000	250	499.8	474	250
	PEMFC	50,000	0.245	4,508,672	0	1,000	250	441	464	250
	SOFC	40,000	0.369	6,794770	0	1000	250	2,274	632	250
	SOFC	50,000	0.289	5,316,831	0	1,000	250	911	481	250

(b) HydESS-2	PEMFC	40,000	0.250	4,591,366	1	1000	250	509.6	466	250
	PEMFC	50,000	0.246	4,526,294	2	1,000	250	450.8	524	250
	SOFC	40,000	0.348	6406074	140	1000	250	1,744	500	250
	SOFC	50,000	0.282	5,179,203	10	1,000	250	755	573	250
(c) BESS	none	-	0.516	9,483,948	518	2,000	-	3,959.2	677	-

According to Table 4, the NPC for the optimized system is $4,584,704, and the LCOE is 0.245 $ kWh^{-1} (Figure 7a). Without PV, the full system consists of WT, HydESS, and BESS. Additionally, PEMFC fuel cells with a lifespan of 50,000 hours have been programmed into the system. Due to the low PV power of the system in Figure 7b, the LCOE and NPC are very similar to those in Figure 7a.

On the other hand, the presence or absence of PV has a greater effect on the LCOE difference when using SOFC than when using PEMFC. A system with 140 kW of PV was calculated to be the most cost-effective over a 40,000-hour lifetime at 0.348 $ kWh^{-1} versus a 0.369 $ kWh^{-1} in without PV system.

Only the BESS system without HydESS, as shown in Figure 7c, has the highest LCOE of 0.516 $ kWh1 and NPC of 9,483,948 $. The renewable energy sources, which include PV and WT, have been optimized to the maximum size of 518 kW PV and 2,000 kW WT. Furthermore, the Li ion BESS has the largest capacity of 3,959 kW. Too large a Li ESS usually causes thermal runaway and fire problems, so minimizing risk is critical when installing and operating BESS [49].

3.2. Electricity production

The total electricity produced by system configuration (a), lowest LCOE, 0.245 $ kWh^{-1} is 3,895,029 kWh yr^{-1} with 9.25% of PEMFC and 90.8% WT plant as shown in Figure. 8a. At the point of excess electricity, the excess fraction is 45.0% of total production, as 1,754,632 kWh yr^{-1}. The PEMFC with 50,000 hrs lifetime shows 189 kW mean electrical output. And the hydrogen production is 13,349 kg per year and the 12,751 kg hydrogen is supplied to fuel cell. The electrolyzer exhibits the mean output as 75.1 kW with capacity factor 30.1 % equal to 3,612 hrs operation per year.

Secondly optimized system as shown in Figure 7b, the PV generates 0.04% electricity, and FC takes 9.18% and WT produces 90.8% electricity as total 3,893,588 kWh yr^{-1}. And the excess electricity 1,758,397 kWh yr^{-1} is equal to 45.2% of total electricity production.

In contrast, the BESS system in Figure 7c generates electricity with 8.14% PV power and 91.9% WT power for a total of 7,418,136 kWh yr^{-1} as displayed in Figure 8 c and d. The excess electricity of 5,960,755 kWh yr^{-1} (80.4% of total electricity generation) is roughly 3.4 times that of HydESS, implying that the system's rated power is over-specified.

Figure 8 depicts a monthly profile of production, showing that higher wind speeds in January and March result in greater output compared to June and July. The pattern is identical in all system configurations such as a, b, and c because wind power accounts for 90% of total production.

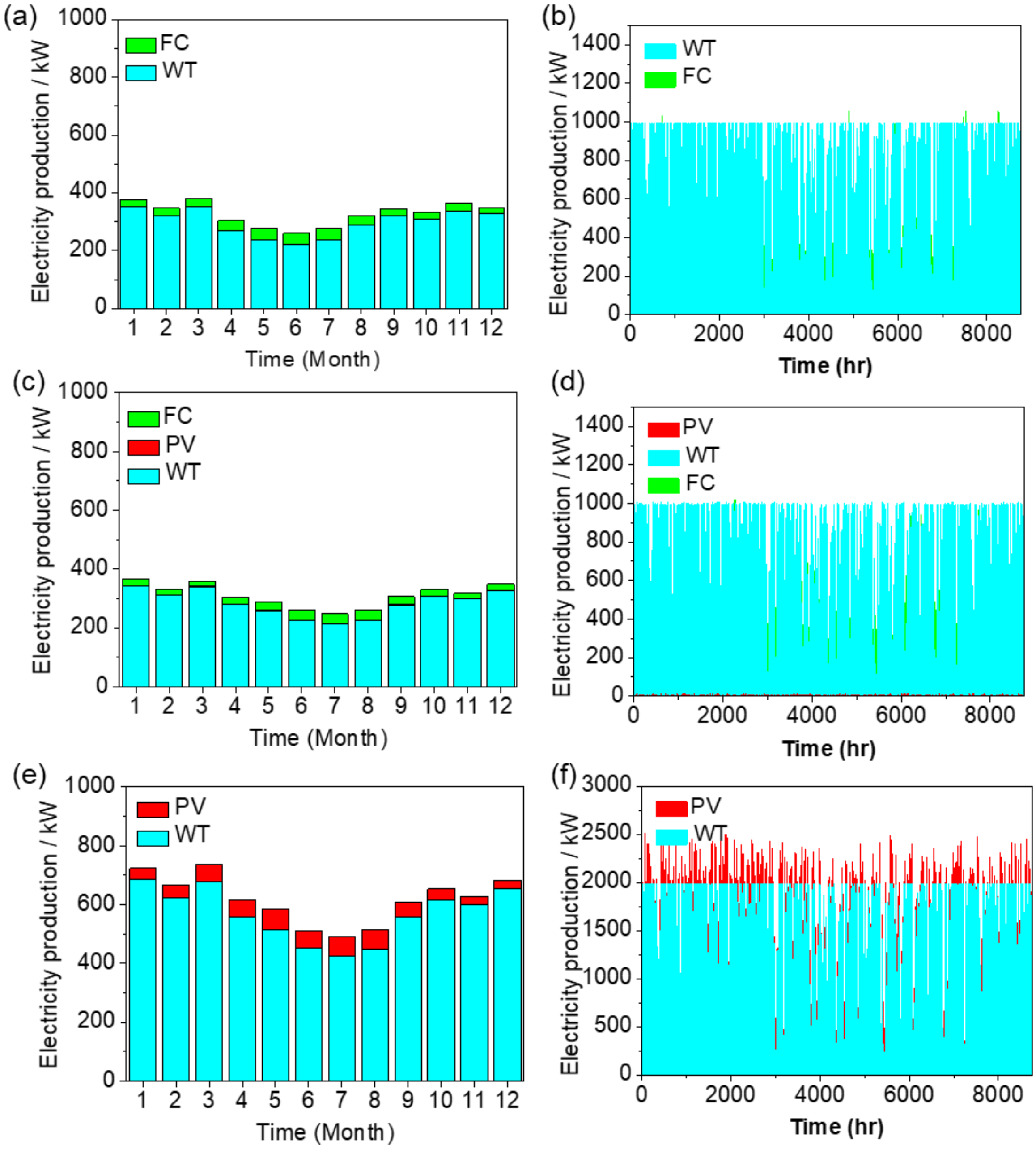

Figure 8. Electricity production from optimized system HydESS-BESS and BESS adopting PEMFC and 50,000 hrs life time, (a) Monthly production profile with WT-HydESS-BESS, (b) hourly production profile with WT-HydESS-BESS, (c) monthly profile with with PV-WT-HydESS-BESS, and (d) hourly production profile with PV-WT-HydESS-BESS, (e) Monthly production profile with BESS, and (f) hourly production profile with PV-WT-BESS.

Table 5. Electrolyzer operation results.

Quantity	Case 1 WT-HydESS-BESS	Case 2 PV-WT-HydESS-BESS	Units
Rated capacity	250	250	kW
Mean input	75.1	74.6	kW
Total input energy	658,185	653,062	kWh yr^{-1}

Capacity Factor	30.1	29.8	%
Hours of operation	3,612	3,657	hr yr^{-1}

3.3. Operation strategy

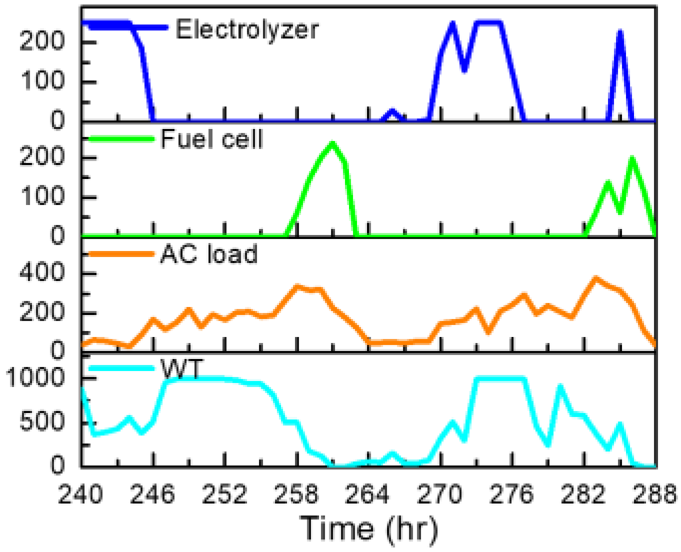

Figure 9. Day operation profiles for the cycle charging dispatch strategy with WT-HydESS-BESS system. .

The most optimized result is adapted the charge cycling (CC) mode rather than load following (LF) mode. The CC mode, power generator is always operated to meet the primary AC load in priority, and then the excess power is dispatched in electrolyzer, battery, and flywheel etc. Therefore, the maximum output power of generator is set to meet the average AC load on demand side.

As shown in Figure 8, the AC load requirement increases during day 1 from 240 hr to 264 hr, but the WT power supply is insufficient. Same operation pattern is observed in 264 hr to 288 hr in day 2. The fuel cell will then begin to produce insufficient electricity for the residence. The electrolyzer, on the other hand, typically operated at night and early morning with excess WT power to produce hydrogen for fuel cell operation. The daily profile of hydrogen production and utilization demonstrates a suitable ESS system for variable wind energy.

3.4. CO_2 Emissions

Table 6. Emission data comparison between Diesel generator (DG)-BESS and HydESS-1.

Material	DG-BESS	HydESS-1	Units
Carbon dioxide	223,297	0	kg yr^{-1}
Carbon monoxide	1,408	2.61	kg yr^{-1}
Unburned hydrocarbons	61.4	0	kg yr^{-1}
Particle matter	8.53	0	kg yr^{-1}
Sulfur dioxide	547	0	kg yr^{-1}
Nitrogen oxides	1,322	0.261	kg yr^{-1}

From an economic perspective, this can be elucidated as a significant cost reduction, taking into account the prevailing European market value of CO_2, which stands at approximately 7 € ton^{-1} [50]. This aspect will exhibit greater significance in the foreseeable future due to the anticipated implementation of CO_2 taxation. 94.66 $ ton^{-1} of CO_{2eq} total carbon tax during the project period will be 528,295 $ as depicted in Table 6.

Oxygen cost is based on the literature 168.55 $ ton^{-1} [51]. The optimized system WT-HydESS-BESS produces 13.349 ton of H_2 annually, so the O_2 produces auxiliary 6.675 ton annually. During the project years, the total O_2 production sales is expected to 28,124 $ with 250-kW PEMFC and PEMWE configuration.

5. Conclusion

The economic feasibility of the hydrogen-based hybrid energy storage system is evaluated through the utilization of the HOMER program. This program adopted actual climate data that is specific to Kyiv, the capital city of Ukraine, which is recognized for its challenging conditions. The unit AC load is set to adequate academic residence building in the city centre for approximately 500 students and staffs commodity. The technoeconomic feasibility of an energy vector as hydrogen is evaluated by comparing it to or without a hydrogen ESS configuration (HydESS). And a cost analysis is performed for various fuel cell types and life times, such as proton exchange membrane and solid oxide, with 40,000 and 50,000 hrs, respectively.

The least LCOE optimal configuration is 0.245 $ kWh^{-1} with PV-WT-HydESS-BESS system using 50,000 hrs endurable PEM FC and WE system as HydESS. The system is consists of 1,000 kW Wind turbine, 250 kW PEMFC, 250 kW PEMWE, 700 kg H_2 tank, 441 kWh Li ion BESS, and 464 kW converter. As shown in system component, the best optimized system is economical to use only wind power.

(1) As a result of economic analysis of the optimal system configuration through HOMER, the LCOE of the standalone PV-WT-HydESS (water electrolysis/fuel cell)-BESS model centered on Kyiv can reach a final 0.245 kWh^{-1} configuration scenario has been derived.

(2) The LCOE in the case of the lowest case was found to be $0.245 , which is a result of almost no economic feasibility of electricity production unit cost at the current system CAPEX and OPEX levels.

(3) PEMFC life time of 50,000 hours is economically recommended during the project period of 25 years with capacity factor 16.4% and 630 starts per year.

(4) When compared to diesel plant-BESS systems, hydrogen-based ESS systems prevent approximately 5,582 tons of CO_2 emission during the project period, accelerating the transition to a carbon-neutral economy.

Acknowledgments: This research was supported by the KU-KIST Graduate School Project. This research was supported by the BK21 FOUR (Fostering Outstanding Universities for Research) funded by the Ministry of Education (MOE, Korea) and National Research Foundation of Korea (NRF).

Reference

[1] Jain, I.; Lal, C.; Jain, A.; Hydrogen storage in Mg: a most promising material, *Int. J. Hydrogen Energy* **2010**, *35 (10)*, 5133-5144, https://doi.org/10.1016/j.ijhydene.2009.08.088

[2] Olatomiwa, L.; Mekhilef, S.; Ismail, M.S.; Moghavvemi, M.; Energy management strategies in hybrid renewable energy systems: A review, *Renew. Sustain. Energy Rev.* **2016**, *62*, 821-835, https://doi.org/10.1016/j.rser.2016.05.040

[3] He, T.; Pachfule, P.; Wu, H.; Xu, Q.; Chen, P.; Hydrogen carriers, *Nat. Rev. Mat.* **2016**, *1 (12)*, 1-17, https://doi.org/10.1038/natrevmats.2016.59

[4] Lambert, L.A.; Tayah, J.; Lee-Schmid, C.; Abdalla, M.; Abdallah, I.; Ali, A.H.; Esmail, S.; Ahmed, W.; The EU's natural gas Cold War and diversification challenges, *Energy Strategy Rev.* **2022**, 43, 100934, https://doi.org/10.3929/ethz-b-000551952

[5] Ścigan, M.; Gonul, G.; Türk, A.; Frieden, D.; Prislan, B.; Gubina, A.; Cost-Competitive Renewable Power Generation: Potential across South East Europe, International Renewable Energy Agency (IRENA), Abu Dhabi., **2017**.

[6] Arent, D.; Sullivan, P.; Heimiller, D.; Lopez, A.; Eurek, K.; Badger, J.; Jorgensen, H.E.; Kelly, M.; Clarke, L.; Luckow, P.; Improved offshore wind resource assessment in global climate stabilization scenarios, National Renewable Energy Lab.(NREL), Golden, CO (United States), **2012**. https://dx.doi.org/10.2172/1055364

[7] Kuzior, A.; Lobanova, A.; Kalashnikova, L.; Green energy in Ukraine: State, public demands, and trends, *Energies* **2021**, *14 (22)*, 7745, https://doi.org/10.3390/en14227745

[8] Sabishchenko, O.; Rębilas, R.; Sczygiol, N.; Urbański, M.; Ukraine energy sector management using hybrid renewable energy systems, *Energies* **2020**, *13 (7)*, 1776, https://doi.org/10.3390/en13071776

[9] In the middle of war, Ukraine is building a wind farm. https://www.washingtonpost.com/climate-solutions/2023/03/09/ukraine-wind-green-power/. (Accessed on 09 March 2023)

[10] Kudria, S.; Ivanchenko, I.; Tuchynskyi, B.; Petrenko, K.; Karmazin, O.; Riepkin, O.; Resource potential for wind-hydrogen power in Ukraine, *Int. J. Hydrogen Energy* **2021**, *46 (1)*,157-168, https://doi.org/10.1016/j.ijhydene.2020.09.211

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 July 2023 doi:10.20944/preprints202307.1281.v1

[11] Lilienthal, P.; HOMER® micropower optimization model, National Renewable Energy Lab.(NREL), Golden, CO (United States), **2005**.

[12] Arsad, A.; Hannan, M.; Al-Shetwi, A.Q.; Mansur, M.; Muttaqi, K.; Dong, Z.; Blaabjerg, F.; Hydrogen energy storage integrated hybrid renewable energy systems: A review analysis for future research directions, *Int, J. Hydrogen Energy* **2022**, *47 (39)*, 17285-17312, https://doi.org/10.1016/j.ijhydene.2022.03.208

[13] Nadeem, T.B.; Siddiqui, M.; Khalid, M.; Asif, M.; Distributed energy systems: A review of classification, technologies, applications, and policies: Current Policy, targets and their achievements in different countries (continued), *Energy Strategy Rev*. **2023**, 48, 101096, https://doi.org/10.1016/j.esr.2023.101096

[14] Singlitico, A.; Østergaard, J.; Chatzivasileiadis, S.; Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs, Renew. Sust. Energ. Rev. **2021**, *1*, 100005, https://doi.org/10.1016/j.rset.2021.100005

[15] Voronova, A., Kim, H.J., Jang, J.H., Park, H.Y., Seo, B., Effect of low voltage limit on degradation mechanism during high-frequency dynamic load in proton exchange membrane water electrolysis, *Int. J. Energy Res.* **2022**, 11867–11878, https://doi.org/10.1002/er.7953

[16] Mottaghizadeh, P.; Jabbari, F.; Brouwer, J.; Integrated solid oxide fuel cell, solar PV, and battery storage system to achieve zero net energy residential nanogrid in California, *Appl. Energy* **2022**, *323*, 119577, https://doi.org/10.1016/j.apenergy.2022.119577

[17] Al-Sharafi A.; Sahin A.Z.; Ayar, T.; Yilbas, B.S.; Techno-economic analysis and optimization of solar and wind energy systems for power generation and hydrogen production in Saudi Arabia, *Renew. Sustain. Energy Rev.* **2017**, 69, 33-49, https://doi.org/10.1016/j.rser.2016.11.157

[18] Abdin Z.; Mérida, W.; Hybrid energy systems for off-grid power supply and hydrogen production based on renewable energy: A techno-economic analysis, *Energy Convers. Manage.* **2019**, 196, 1068-1079, https://doi.org/10.1016/j.enconman.2019.06.068

[19] Peláez-Peláez, S.; Colmenar-Santos, A.; Pérez-Molina, C.; Rosales, A.-E.; Rosales-Asensio, E.; Techno-economic analysis of a heat and power combination system based on hybrid photovoltaic-fuel cell systems using hydrogen as an energy vector, *Energy* **2021**, *224* 120110, https://doi.org/10.1016/j.energy.2021.120110

[20] Okonkwo, P.C.; Barhoumi, E.M.; Mansir, I.B.; Emori W.; Uzoma, P.C.; Techno-economic analysis and optimization of solar and wind energy systems for hydrogen production: a case study, *Energy Sources A: Recovery Util. Environ. Eff.* **2022**, *44 (4)*, 9119-9134, https://doi.org/10.1080/15567036.2022.2129875

[21] Babaei, R.; Ting, D.S.; Carriveau, R.; Optimization of hydrogen-producing sustainable island microgrids, *Int. J. Hydrogen Energy* **2022**, *47 (32)*, 14375-14392, https://doi.org/10.1016/j.ijhydene.2022.02.187

[22] Zhang, X.; Wei, Q.S.; Oh, B.S.; Cost analysis of off-grid renewable hybrid power generation system on Ui Island, South Korea, *Int. J. Hydrogen Energy* **2022**, *47 (27)*, 13199-13212, 13199-13212

[23] Steinbach, A.; Low-Cost, High-Performance Catalyst Coated Membranes for PEM Water Electrolyzers, NREL, **2022**. https://doi.org/10.2172/1863440

[24] Taibi, E.; Miranda, R.; Carmo M.; Blanco, H.; Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 °C Climate Goal; International Renewable Energy Agency (IRENA): Abu Dhabi, United Arab Emirates, **2020**.

[25] Energy consumption in Ukraine World data. https://www.worlddata.info/europe/ukraine/energy-consumption.php. (Accessed on 10 July 2023)

[26] Igor Sikorsky Kyiv Polytechnic Institute Opens a New Dormitory. https://kpi.ua/en/2021-d-5. (Accessed on 10 July 2023)

[27] Zhao, S.; Stocks, A.; Rasimick, B.; More, K.; Xu, H.; Highly active, durable dispersed iridium nanocatalysts for PEM water electrolyzers, *J. Electrochem. Soc.* **2018**, *165 (2)*, F82-F89, https://doi.org/10.1149/2.0981802jes

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 July 2023 doi:10.20944/preprints202307.1281.v1

[28] Park, S.; Shviro, M.; Hartmann, H.; Mayer, J.; Carmo, M.; Stolten, D.; Cation-Exchange Method Enables Uniform Iridium Oxide Nanospheres for Oxygen Evolution Reaction, *ACS Appl. Nano Mater.* **2022**, *5 (3),* 4062-4071, https://doi.org/10.1021/acsanm.2c00031

[29] Europe Solar Store.com. https://www.europe-solarstore.com/lg-chem-resu-10-48v-lithium-ion-storage-battery.html. (Accessed on 07 July 2023)

[30] Viswanathan, V.; Mongird, K.; Franks, R.; Baxter, R.; Grid Energy Storage Technology Cost and Performance Assessment 2022, **2022**, 1-174, Technical Report Publication No. PNNL-33283

[31] LG Energy Solution Product info of grid/C&I/UPS battery, https://www.lgensol.com/en/business-ess-battery, (Accessed on 30 May 2023).

[32] Hoarcă, I. C.; Bizon, N.; Șorlei, I. S.; Thounthong, P.; Sizing design for a hybrid renewable power system using HOMER and iHOGA simulators, *Energies*, **2023**, *16 (4)*, 1926, https://doi.org/10.3390/en16041926

[33] Muñoz Díaz, M. T.; Chávez Oróstica, H.; Guajardo, J; Economic Analysis: Green Hydrogen Production Systems. *Processes*, **2023**, *11(5)*, 1390. https://doi.org/10.3390/pr11051390

[34] Iora, P.; Taher, M.; Chiesa, P.; Brandon, N.; A novel system for the production of pure hydrogen from natural gas based on solid oxide fuel cell–solid oxide electrolyzer, *Int. J. Hydrogen Energy* **2010,** *35 (22*), 12680-12687, https://doi.org/10.1016/j.ijhydene.2010.07.078

[35] Yu, W.; Xie, H.; A review on nanofluids: preparation, stability mechanisms, and applications, *J. Nanomater.* **2012**, 2012, 1-17, https://doi.org/10.1155/2012/435873

[36] Maestre, V.; Ortiz, A.; Ortiz, I.; Challenges and prospects of renewable hydrogen-based strategies for full decarbonization of stationary power applications, *Renew. Sustain. Energy Rev.* **2021**, *152*, 111628, https://doi.org/10.1016/j.rser.2021.111628

[37] Zhao, Y.; Jing, R.; Zhang, Z.; Feasibility of solid oxide fuel cell stationary applications in China's building sector and relevant progress, Design and Operation of Solid Oxide Fuel Cells, Elsevier, **2020**, 359-393.

[38] Parks, G.; Boyd, R.; Cornish, J.; Remick, R.; Hydrogen station compression, storage, and dispensing technical status and costs: Systems integration, National Renewable Energy Lab.(NREL), Golden, CO (United States), **2014**. https://doi.org/10.2172/1130621

[39] Qin, H.; Jiang, J.; Cheng, Z.; Zhang, B.; Zhou, R.; Li, J.; Analysis of the influence of SOFC degradation on system State and performance, *2021 China Automation Congress (CAC),* IEEE, **2021**, 7417-7422. https://doi/org/10.1109/CAC53003.2021.9727958

[40] Chou, Y.-S.; Stevenson, J.W.; Choi, J.-P.; Long-term evaluation of solid oxide fuel cell candidate materials in a 3-cell generic short stack fixture, Part II: sealing glass stability, microstructure and interfacial reactions, *J. Power Sources* **2014**, *250*, 166-173, https://doi.org/10.1016/j.jpowsour.2013.12.067

[41] Yokokawa, H.; Report of five-year NEDO project on durability/reliability of SOFC stacks, *ECS Trans.* **2013**, *57 (1)*, 299, https://doi.org/10.1149/05701.0299ecst

[42] Turton, R.; Bailie, R.C.; Whiting, W.B.; Shaeiwitz, J.A.; Analysis, synthesis and design of chemical processes, Pearson Education **2008**. https://doi.org/10.1002/cite.330711124

[43] Short W.; Packey D.J.; Holt T.; A manual for the economic evaluation of energy efficiency and renewable energy technologies, National Renewable Energy Lab.(NREL), Golden, CO (United States), **1995**. https://doi.org/10.2172/35391

[44] Moon, H.E.; Ha, Y.H.; Kim, K.N.; Comparative Economic Analysis of Solar PV and Reused EV Batteries in the Residential Sector of Three Emerging Countries—The Philippines, Indonesia, and Vietnam, *Energies* **2022**, *16 (1)*, 311, https://doi.org/10.3390/en16010311

[45] Leland Blank, P., Anthony Tarquin, P., Engineering economy, 7 ed., Oxford, New York, 2014.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 July 2023 doi:10.20944/preprints202307.1281.v1

[46] Mayer, T.; Semmel M.; Morales M.A.G.; Schmidt, K.M.; Bauer, A.; Wind, J.; Techno-economic evaluation of hydrogen refueling stations with liquid or gaseous stored hydrogen, *Int. J. Hydrogen Energy* **2019**, *44 (47)*, 25809-25833, https://doi.org/10.1016/j.ijhydene.2019.08.051

[47] Kim J.-H.; Kim G.-E.; Yoo S.-H.; A valuation of the restoration of Hwangnyongsa temple in South Korea, Sustainability **2018**, *10 (2)*, 369, https://doi.org/10.3390/su10020369

[48] NREL, Exploring Renewable Energy Opportunities in Select Southeast Asian Countries 2020. https://www.nrel.gov/docs/fy19osti/71814.pdf. (accessed on 5 January 2022).

[49] Shi Y.; Lu Z.; Guo L.; Yan C.; Fabrication of membrane electrode assemblies by direct spray catalyst on water swollen Nafion membrane for PEM water electrolysis, *Int. J. Hydrogen Energy* **2017**, *42*, 26183-26191, https://doi.org/10.1016/j.ijhydene.2017.08.205

[50] European Emission Allowances Futures (EUA). https://www.eex.com (Accessed on 13 July 2023)

[51] Bellotti D.; Rivarolo M.; Magistri L.; Economic feasibility of methanol synthesis as a method for CO2 reduction and energy storage, *Energy Procedia*, **2019**, *158*, 4721-4728, https://doi.org/10.1016/j.egypro.2019.01.730

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.