CHEMICAL ENGINEERING TRANSACTIONS
VOL. 106, 2023
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Peck Loo Kiew, Hon Huin Chin

ISBN 979-12-81206-05-2; **ISSN** 2283-9216
DOI: 10.3303/CET23106137

Systematic Approach in Designing a Novel Hydrogen-based Integrated Hybrid Renewable Energy System with a Small-scale Combined Cycle Plant

Tuck Kong Lok, Jeng Shiun Lim*

Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia.
jslim@utm.my

The energy transition stage is experiencing significant growth in renewables, waste-to-energy, and hydrogen-based systems for electricity generation. Energy storage is being recognized as a crucial solution to enable these penetrations especially with recent advancement in water electrolysis. The rise of hydrogen-fueled power generation and future mobility further support the development of a hydrogen economy. To address off-grid installations research gap, a hydrogen-based integrated hybrid renewable energy system (HIHRES) with a small-scale combined cycle plant is proposed. This system aims to replace aging conventional energy systems dominated by fossil fuels, which suffer from power outages and environmental issues. The paper focuses on developing a design framework for the HIHRES with a small-scale combined cycle plant for an off-grid industrial load integrated waste management facility (IWMF). The proposed configuration includes a hydrogen-based system, solar PV, combined cycle, incinerator, diesel generator, and hybrid battery-hydrogen storage. The model shows that the integrated system can provide reliable, sustainable electricity without interruption, making low-CO_2 hydrogen a promising alternative. The results indicate that the hydrogen-based integrated system, coupled with primary renewables and small-scale combined cycle, addresses challenges faced by off-grid installations, such as lack of planning, difficult grid extension, technology gap and operational challenges.

1. Introduction

In recent years, the global energy sector has faced the challenge of balancing energy security, affordability, and sustainability across various sectors, both onshore and offshore. To address this, countries and industries are exploring the integration of sustainable renewables into the global energy system during the energy transition.
Currently, the worldwide share of renewables is 11 %, and it is expected to increase by 60 % by 2070 (Ajadi et al., 2019). In this transition, hydrogen-based technologies have emerged as key sustainable energy sources, playing a crucial role in ensuring secure and reliable decarbonized energy systems. Renewable energy technologies and emerging energy sources are being extensively studied to achieve these goals.
The ultimate goal of utilizing hydrogen or establishing a hydrogen economy is to decarbonize the energy transition. In some regions, green hydrogen has recently become more cost-effective than grey hydrogen. There’s growing initiatives for carbon-neutral versions of fuel oil and it is anticipated that green hydrogen will not only become economically viable in various sectors, but also providing significant decarbonization benefits.
For the hydrogen economy to be realized, the adoption and demonstration of integrated technologies are crucial. Current efforts to generate hydrogen, especially through economical methods like water electrolysis, hold promise for hydrogen production from abundant biomass, as well as clean and renewable sources (Rashmi et al., 2013). By coupling different energy sources and waste heat recovery, alongside with hybrid storage systems, an efficient approach to producing high-quality energy is achieved (Obara et al., 2013). The integration of a biomass fermentation with the hybrid renewable energy system (HRES), which consists of a solar PV module, a wind turbine, an electrolyzer, and a fuel cell, was the subject of an economic analysis by Chang et al. (2013). For residential off-grid household use, a number of studies and several hybrid off-grid applications-based wind turbine and solar PV generating combinations have been put out in the literature (Kumar et al., 2020). There

Paper Received: 20 August 2023; Revised: 18 September 2023; Accepted: 10 October 2023
Please cite this article as: Lok T.K., Lim J.S., 2023, Systematic Approach in Designing a Novel Hydrogen-based Integrated Hybrid Renewable Energy System with a Small-scale Combined Cycle Plant, Chemical Engineering Transactions, 106, 817-822 DOI:10.3303/CET23106137

has been limited attention given to combining renewables with a combined cycle plant (utilizing gas turbine and heat recovery steam generator (Nag,2002)), incinerator and hybrid energy storage for industrial power loads. Existing literature primarily discusses solar PV, wind turbines, waste/biomass as renewable energy sources, along with potential energy storage technologies (Sawle et al., 2013). These systems typically rely on a single type of energy storage technology coupled with hydrogen system as well as thermal energy system (Wan Abdullah et al., 2022). One drawback of these renewable energy system architectures is their vulnerability to seasonal and daily climatic variations (solar radiation, wind speed, temperature) and geographical conditions, as well as power demand profiles. Previously, numerical and analytical techniques are utilized to analyze the performance of hybrid system, considering various load demands, key variables impact and fixed parameters of the integrated components. Additionally, existing research often analyzes data either using single numerical tool or one strategy (e.g., cyclic charging (CC) or load following (LF)) approach, with limited exploration of other approaches. This work aims to address the research gaps by proposing a hydrogen-based hybrid renewable energy system (HIHRES) integrated with a small-scale combined cycle plant. The objective of this research work is developing a framework to evaluate technical feasibility and parameters of the proposed system.

2. The Conceptual Design of the Proposed Off-Grid Technology

The design elements of combined cycle plants using hydrogen as a low-carbon fuel have not been thoroughly investigated, neglecting the potential for hydrogen as both an energy storage medium and a power generation source. Therefore, developing a HIHRES that harnesses clean and waste-heat energies could be a compelling low-carbon emission technology. It should be an expandable hybrid off-grid system, incorporating energy storage through batteries and hydrogen, offers the advantage of self-sustainability while overcoming limitations in single type energy storage. Such systems provide energy savings since all generated energy is consumed, and they can be installed in remote area where grid access is challenging and having operational constraints.

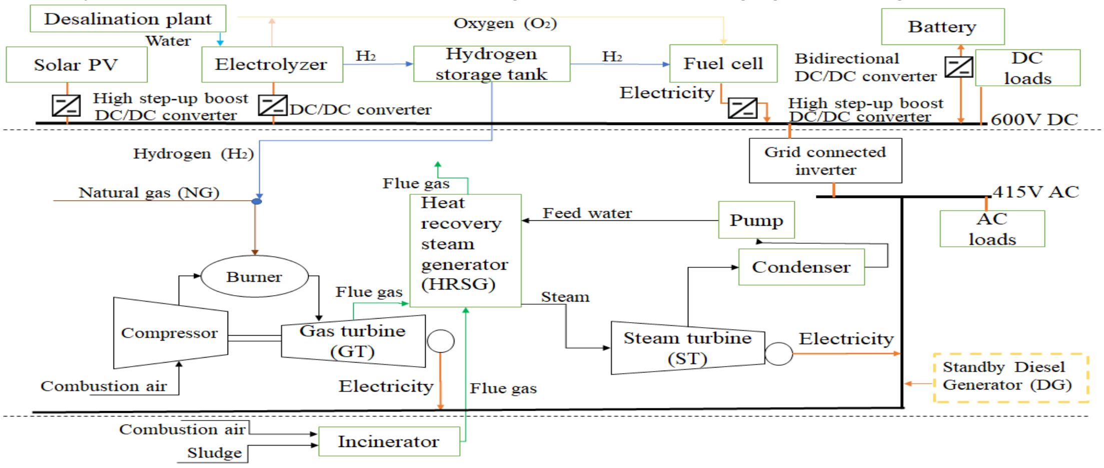

Figure 1: An Overview Architecture of the HIHRES with a Combined Cycle Plant

With the increasing prevalence of DC loads in residential, electric vehicle, industrial, and commercial settings, future power systems may become DC-dominated. To address this, the paper proposes a hybrid coupled AC/DC configuration, connected through a bidirectional converter, to reduce loss, and improve system efficiency. The proposed off-grid topology offers easier access to both DC and AC grids, minimizing the need for AC/DC and DC/DC converters for supplying DC loads. The proposed pre-design framework also considers other several factors, such as linking the AC load bus to AC generators and the DC load bus to the renewable energy (RE) sources and battery (BB) storage system through a power converter. Hence, the HIHRES with a combined cycle plant (as illustrated in Figure 1) includes a solar photovoltaic (PV) array, hydrogen (H_2) system (including electrolyzer (electro), hydrogen storage tank (HST), and fuel cell (FC), gas turbine (GT), heat recovery steam generator (HRSG), and battery bank been developed and proposed for the facility to address the research gaps. The system's primary renewable energy source, solar PV, is connected to a common DC grid, and maximum power point tracking (MPPT) is employed for consistent power generation. The DC-powered electrolyzer converts desalinated water into hydrogen through electrolysis. The hydrogen is stored either as metal hydride, which allows for low-pressure storage (10-20 barg) or compressed (which requires more energy to store H_2) and stored in a pressure vessel. The reversible metal hydride can be used as a standby generator or secondary energy storage system and can fuel various applications such as gas turbines, fuel cells, combined cycle combustion, and future transportation fuel stations. Excess power is stored primarily in a battery bank connected to the DC grid through a bidirectional boost converter. This setup ensures year-round power production to meet operational loads demand while considering the power consumption fluctuations and the climate variations. Compared to conventional HRES, HIHRES is more robust and versatile in electrification, capable of handling dynamic loads thanks to its high power and energy storage capabilities. The proposed system encompasses low carbon technologies, electrification enhancements, and energy efficiency opportunities, enabling renewable energy generation while efficiently utilizing hybrid storage charging/ discharging and recycling the waste heat.

3. Methodology

Figure 2 presents the proposed framework in planning, system's requirements consideration and integration to design for the HIHRES system. The key components' modelling equations are discussed in Section 3.1.

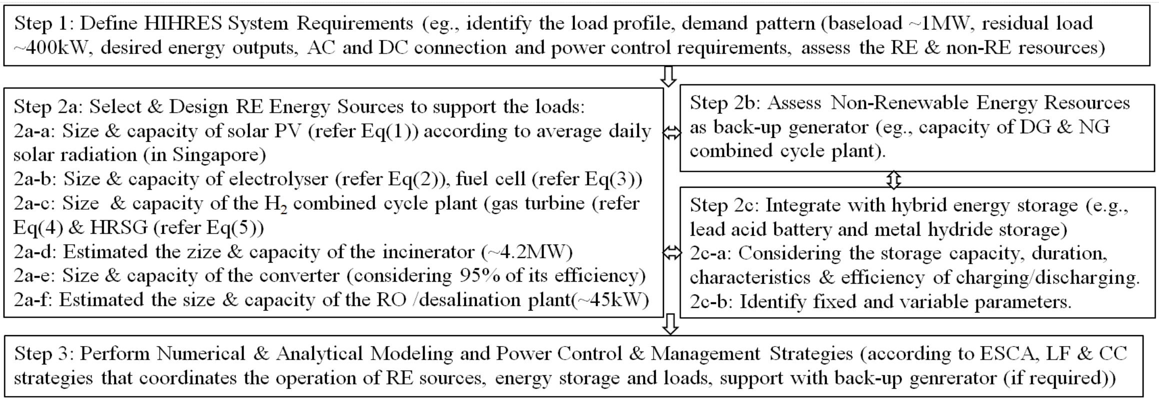

Figure 2: Methodology Framework of HIHRES with a Combined Cycle Plant

Upon performing the step 1 and step 2, going through cascade analysis upon construction cascade table (shown in Table 2) as below-described columns i-xix, followed by LF and CC strategies that coordinates the operation of renewable energy source, energy storage and loads as well as supporting with back-up generator (if required):

- column i: 1 h is selected as the time step, which is sorted in ascending order
- column ii-vi: Hourly demand (inclusive RO load), HRSG's output (whereby ~74 % out of 50 % capacity of incinerator output being supply to HRSG), GT's output, solar output, fuel cell's output
- column vii: Hourly energy generation from all renewables and generators (DC & AC buses connected)
- column viii: Hourly excess/deficit power/energy
- column ix: Percentage of power/energy direct to battery and electrolyzer (base on the unit size's ratio)
- column x-xii: Battery charging and discharging power/energy and nett charge-in and charge-out
- column xiii-xv: Hourly cumulative power/energy and net cumulative power/energy in the battery
- column xvi: Electrolyzer loading from balance power/energy to generate additional hydrogen
- column xvii: Diesel generator (DG) supporting to loads (according to LF strategy to regulate the output voltage amplitude of DC grid, ensuring stable power exchange AC/DC grids and meeting demands)
- column xviii-xix: Hourly cumulative energy and net cumulative energy in the hydrogen

3.1 Modeling and Description of Key Components

Utilize technical analyses and followings equations to evaluate the system's efficiency, the power inputs and output. This involves analyzing the system component's equations and mathematical relationships to gain insights into system performance. It also calculates the flows of energy to-and-fro the components in the Electric System Cascade Analysis (ESCA).
The energy generated by the solar PV panels can be calculated as shown in Eq(1) (Kumar et al., 2020):

$$E_{PV}(t) = N_{PV} \, . \, P_{PV}(t). \Delta t \tag{1}$$

where N_{pv} is the number of solar PV panels and Δt is the time period and it is considered as 1 h.
In a water electrolyzer, water is decomposed into hydrogen and oxygen by using electricity. The electricity/power consumption of the electrolyzer as shown in Eq(2) is identified as a function of rated hydrogen flow rate (Q_{n-H2}) and actual hydrogen flow rate (Q_{H2}) (Nallapaneni et al., 2020).

$$P_{elec} = A_E \, . \, Q_{n-H2} + B_E . Q_{H2} \tag{2}$$

where A_E=20 kWh/kg and B_E=40 kWh/kg are the electricity consumption curve coefficient of the electrolyzer.

According to Naoto et al. (2020), the fuel cell's output power is related to the rate of hydrogen consumption.

$$P_{fc} = N_{fc}.I_{fc}.E_{fc} \tag{3}$$

where N_{fc} is the number of cells and I_{fc} is the current flow of cells in ampere while E_{fc} refers to the electromotive energy of a fuel cell in volt as shown in Eq(3).
A high-temperature power plant, such as a gas turbine, can be integrated with a steam plant to achieve higher energy conversion efficiency when using fuel, whether it's hydrogen or natural gas. This is possible because the combined cycle plant operates at a higher temperature range. The Eq(4) – Eq(5) are derived from Nag (2002).

$$W_1 = \eta_1 Q_1 \tag{4}$$

$$W_2 = \eta_2 Q_2 \tag{5}$$

where W_1, η_1 and Q_1 represent the gas turbine output, efficiency and input.
where W_2, η_2 and Q_2 represent the output, efficiency and input of the HRSG.

4. Results and Discussion

The case study pertains to an offshore Integrated Waste Management Facility in Singapore, focused on managing slop oil and toxic industrial waste, which faces growing energy demand, rising fuel costs, and the need to ensure a continuous fuel supply. It handles approximately 20 t/d of sludge while with the estimated yearly average solar energy is 10.2 kWh/m^2/d. Its geographical location, the environment surrounded by seawater, the availability and scarcity of environmental resources, the ease of access to energy sources, and the availability of water sources are all being evaluated. In the baseline, the off-grid installation is entirely dependent on fossil fuels which produces significant amount of air emissions from its DGs and incineration process without wasteful heat recovery from flue gas. Table 1 shown the resulting design input parameters and capacity of the respective components into cascading table calculations by referring to the sizing equations.

Table 1: The analysis of input parameters and capacity of components

Input	Operating Capacity
0.56 MW gas turbine	35.0 %
1.59 MW HRSG	57.2 %
4.20 MW incinerator	50.0 %
2.80 MW_{peak} solar PV (irradiance 400-1000 W/m^2)	20.0 %
1.00 MW electrolyzer	98.0 %
1.00 MW fuel cell	60.0 %
1.00 MW hydrogen storage tank	77.0 %
2107.28 Ah battery storage (12 V DC, 200 in series)	90.0 %
2.71 kWh/m^3 RO desalination plant	57.3 %
1.50 MW bi-converter	95.0 %
720 kW diesel generator (standby)	50.0 %

The results of hybrid cascading table as shown in Table 2 following the implementation of adopted methodologies as discussed in Section 3. The integration of power control & management strategies (ESCA and LF) shown that battery and hydrogen complement each other in cyclic charging pattern under different demands, variables (e.g., irradiation, sludge mass), and environmental conditions. ESCA outcome showed not only ensure power/energy balance for both DC and AC grid power production and loads, it can be used to re-confirm the battery storage and solar PV ratings. Following the extension of cascading analysis, the LF and CC strategies determine the running modes of the different energy generation sources. It calculates the percentage of loading for each source (inclusive the DG to support the deficit loading), indicating how much power each source should contribute to the system. This determination takes into account factors such as the availability of renewable energy sources, the priority of using renewables & hydrogen generation sources and the system's operational constraints (DC-voltage, State-of-Charge’s level, system’s energy balance). The DG which taps the measurements of DC-voltage to adjust the loading percentages to maintain energy balance and maximize the utilization of RE resources while considering the HIHRES system's stability and reliability. It is noticeable that the power production in the configurations with hybrid storage are sufficient to meet the load demand with additional 15 % power supply and support from the standby diesel generators. Table 3 shown the selected technical parameters of the proposed system in comparison against the baseline system upon technical analyses to assess its feasibility, technical functionality, and to determine the performance and its efficiency.

Table 2: Hybrid Cascading Table

i	ii	iii	iv	v	vi	vii	viii	ix	x	xi	xii	xiii	xv	xvi	xvii	xviii	xix
Time	Demand (kW)	HRS G/Inci (kW)	H_2GT (kW)	Solar (kW)	Fuel cell (kW)	Power output (kW)	Excess / deficit (kW)	Direct to BB/electrolyzer (ratio)	BB Charge-in (kW)	BB Charge-out (kW)	Nett Charge in/out	BB cont. (infeasible Casc.)	BB content (kW)	Electrolyzer (kW)	DG support (kW)	Add. H_2 Gen. (kg/h)	H_2 content (kW)
Size	(kW)	1592	558	2800	1000				1100	1100				1000	720		1000
Cap.	%	49.5	35.0	20.0	60.0				90.0	90.0		0.0	216.2	98.0	50.0		77.0
0000	1,000	910.0	195.0	0.0	0.0	1,105	105.3	0.52/0.48	49.66	0	49.7	49.7	265.9	392.1	360.0	9.71	630.5
0100	1,000	910.0	195.0	0.0	0.0	1,105	105.3	0.52/0.48	49.66	0	49.7	99.3	315.5	392.1	360.0	9.71	488.9
0200	1,000	910.0	195.0	0.0	0.0	1,105	105.3	0.52/0.48	49.66	0	49.7	149.0	365.2	392.1	360.0	9.71	347.3
0300	1,000	910.0	915.0	0.0	0.0	1,105	105.3	0.52/0.48	49.66	0	49.7	198.6	414.9	392.1	360.0	9.71	205.7
0400	1,000	910.0	0.0	0.0	0.0	910	-90.0	0.52/0.48	0.00	-100.0	-100.0	98.6	314.9	342.0	360.0	8.47	424.7
0500	1,000	910.0	0.0	0.0	0.0	910	-90.0	0.52/0.48	0.00	-100.0	-100.0	-1.4	214.9	342.0	360.0	8.47	643.7
0600	1,200	910.0	195.0	0.0	0.0	1,105	-94.7	0.52/0.48	0.00	-105.2	-105.2	-106.6	109.6	68.4	72.0	1.69	294.8
0700	1,200	910.0	0.0	223.8	0.0	1,134	-66.2	0.52/0.48	0.00	-73.6	-73.8	-180.2	36.0	68.4	72.0	1.69	338.6
0800	1,200	910.0	0.0	335.8	0.0	1,246	45.6	0.52/0.48	21.52	0.0	21.5	-158.7	57.6	55.9	36.0	1.38	374.4
0900	1,200	910.0	0.0	335.8	0.0	1,246	45.6	0.52/0.48	21.52	0.0	21.5	137.1	79.1	55.9	36.0	1.38	410.2
1000	1,200	910.0	0.0	335.8	0.0	1,246	45.6	0.52/0.48	21.52	0.0	21.5	-115.6	100.6	55.9	36.0	1.38	446.0
1100	1,200	910.0	0.0	335.8	0.0	1,246	45.6	0.52/0.48	21.52	0.0	21.5	-94.1	122.1	55.9	36.0	1.38	481.8
1200	1,100	910.0	0.0	559.4	0.0	1,469	369.4	0.52/0.48	174.21	0.0	174.2	80.1	296.3	381.0	216.0	9.43	725.9
1300	1,100	910.0	195.0	559.4	0.0	1,665	564.7	0.52/0.48	266.31	0.0	266.3	346.5	562.7	576.6	324.0	14.27	702.4
1400	1,360	910.0	195.0	559.4	0.0	1,665	304.7	0.52/0.48	143.70	0.0	143.7	490.1	706.3	487.0	360.0	12.06	621.5
1500	1,405	910.0	0.0	559.4	600.0	2,069	664.4	0.52/0.48	313.33	0.0	313.3	803.4	1020	658.3	360.0	16.29	37.1
1600	1,405	910.0	0.0	559.4	0.0	1,469	64.4	0.52/0.48	30.37	0.0	30.4	833.8	1050	235.9	216.0	5.84	188.1
1700	1,405	910.0	0.0	447.5	0.0	1,358	-47.5	0.52/0.48	0.00	-52.8	-52.8	781.1	997.3	102.6	108.0	2.54	253.8
1800	1,145	910.0	0.0	335.8	0.0	1,246	100.6	0.52/0.48	47.46	0.0	47.5	828.5	1045	150.5	108.0	3.73	350.2
1900	1,100	910.0	0.0	223.8	0.0	1,134	33.8	0.52/0.48	15.92	0.0	15.9	844.4	1060	16.1	0.0	0.40	360.5
2000	1,100	910.0	0.0	0.0	0.0	910	-190.0	0.52/0.48	0.0	-211.1	-211.1	633.3	849.6	102.6	108.0	2.54	426.2
2100	1,100	910.0	0.0	0.0	0.0	910	-190.0	0.52/0.48	0.0	-211.1	-211.1	422.2	638.4	136.8	144.0	3.39	513.8
2200	1,100	910.0	0.0	0.0	0.0	910	-190.0	0.52/0.48	0.0	-211.1	-211.1	211.1	427.3	136.8	144.0	3.39	601.4
2300	1,100	910.0	0.0	0.0	0.0	910	-190.0	0.52/0.48	0.0	-211.1	-211.1	0.0	216.2	273.6	288.0	6.77	776.7
Total		21,840	1,367	5,370	600	29,177	1,557.0			1,276	-1276				4,824		

Table 3: Comparison of selected technical parameters for proposed configurations against the baseline

Parameters	Capacity (MW)	Energy Production (kWh/d)	Average Energy Consumption (kWh/d)	Excess Energy (kWh/d)	Capacity factor	Reserve Factor	RE Fraction (%)
Baseline	3.31	27,440	27,440	0	0.345	2.435	0
HIHRES	5.95	34,001	27,440	1,557	0.192	4.372	83.5

5. Conclusions

A grid-independent HIHRES was developed to meet the electricity demand continuously of an off-grid installation with renewable fraction of 83.5 % whereby technical analyses were conducted to determine the optimal configuration of the system. Based on load profiles and feasible renewable sources in the location, the HIHRES with a combined cycle plant (H_2 as alternative fuel), comprising of solar PV, incinerator, hydrogen system, and hybrid storage system was found to be feasible.
The primary contribution lies in developing a methodology and modeling for the system's components. The aim to enhance electrification for integrated solutions aligning with Singapore's Green Plan which sets ambitious 10-year targets, strengthening Singapore's commitments under the UN's 2030 Sustainable Development Agenda and Paris Agreement and positioning the nation to achieve a long-term net zero emissions aspiration by 2050. Other main contributions of this study include determining system configurations for continuous power supply to an offshore installation, considering reliance on renewables, hybrid energy storage systems, emerging hydrogen technologies, and power flow management according to ESCA, LF, CC strategies between DC and AC buses with DC-voltage control. Future work can focus on techno-economic study and optimizing the design parameters to determine economic feasibility and achieve the best configurations which involve maximizing certain optimization functions as well as considering integrating other renewables into the system.

Acknowledgments

The authors would like to thank Universiti Teknologi Malaysia (UTM) for providing the research fund for this study (grant number: Q.J130000.2451.08G48).

References

Ajadi T., Boyle R., Strahan D., Kimmel M., Collins B., Cheung A., Becker L., 2019, Global trends in renewable energy investment 2019, Frankfurt School-UNEP Centre/BNEF, Frankfurt, Germany.
Chang P., Hsu C., Hsiung C., Lin C., 2013, Constructing an innovative bio-hydrogen integrated renewable energy system, International Journal Hydrogen Energy, 38, 15660–15669.
Kumar P. P., Saini R. P., 2020, Optimization of an off-grid integrated hybrid renewable energy system with various energy storage technologies using different dispatch strategies, Energy Sources, Part A: Recovery, Utilization, and Environmental, DOI: 10.1080/15567036.2020.1824035.
Nag P.K., 2002, Power Plant Engineering Second Edition, International Edition, Tata McGraw-hill Publishing Company Limited, Singapore.
Nallapaneni M. K., Shauhrat S. C., Aneesh A. C., Elavarasan R. M., Shafiullah G.M., 2020, Hybrid renewable energy microgrid for a residential community: A techno-economic and environmental perspective in the context of the SDG7, Sustainability, 12(10), 3944.
Naoto T., Hooman F., 2020, Techno-economic analysis of a novel hydrogen-based hybrid renewable energy system for both grid-tied and off-grid power supply in Japan: The Case of Fukushima, Applied Science, 10(12), 4061.
Obara S., Morizane Y., Morel J., 2013, Economic efficiency of a renewable energy independent microgrid with energy storage by a sodiume-sulfur battery or organic chemical hydride, International Journal of Hydrogen Energy, 38, 8888-8902.
Rashmi C., Satanand S., Olusola O. J., Sudip M., 2013, A review on development of industrial processes and emerging techniques for production of hydrogen from renewable and sustainable sources, Renewable and Sustainable Energy Reviews, 23, 443-462.
Sawle Y., Gupta S. Bohre A.K., 2017, Optimal sizing of standalone PV/wind/biomass hybrid energy system using GA and PSO optimization technique, Energy Procedia, 117, 690–698.
Wan Abdullah W. A. S., Ismail I., Liew P. Y., Woon K. S., Ho W. S., Klemeš J. J., 2022, Hydrogen-based Energy Storage Targeting for the Integrated Heat and Power System in Urban-Industrial Symbiosis, The Italian Association of Chemical Engineering, Chemical Engineering Transaction, 94,1291-1296.