CHEMICAL ENGINEERING TRANSACTIONS
VOL. 88, 2021
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš

**ISBN** 978-88-95608-86-0; **ISSN** 2283-9216
DOI: 10.3303/CET2188033

# Optimisation of Renewable-Based Multi-Energy System with Hydrogen Energy for Urban-Industrial Symbiosis

Kang Ying Pang[a], Peng Yen Liew[a,*], Wai Shin Ho[b], Kok Sin Woon[c], Sharifah Rafidah Wan Alwi[b], Jiří Jaromír Klemeš[d]

[a] Department of Chemical and Environmental Engineering, Malaysia – Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia
[b] School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM, Johor Bahru, Johor, Malaysia
[c] School of Energy and Chemical Engineering, Xiamen University Malaysia, Jalan Sunsuria, Bandar Sunsuria, 43900, Sepang, Selangor, Malaysia
[d] Sustainable Process Integration Laboratory—SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT BRNO, Technická 2896/2, 616 69, Brno, Czech Republic
pyliew@utm.my

Hydrogen energy technologies have attracted substantial attention due to carbon-free and environmental friendly. However, not much attention is paid to the application of hydrogen in tri- and polygeneration system. Hence, a renewable-based multi-energy system (RMES) is proposed to combine four separate systems: cooling, heating, hydrogen, and power. Renewable solar energy is supplied to the system utilising a photovoltaic solar panel for the electrical supply and a solar thermal collector for the heating supply. Thermal and electrical energy storage is utilised to mitigate the fluctuations in the energy consumption and peak shaving characteristics of the multi-energy system. The hydrogen sub-system consists of solid oxide fuel cell, solid oxide electrolyser cell and hydrogen energy storage. A comparative analysis is performed to study the effect of different energy storage on each objective function. A multi-objective optimisation approach was proposed to evaluate trade-offs between two different objective functions: economic and environment. A well-known decision-making approach Ɛ-constraint method has been applied to identify the final desired Pareto optimal solution for the model to be more suitable in reality. This result will contribute to the global goal on energy (SDG 7) to strive towards affordable and clean energy to significantly increase the share of renewable energy in the global energy mix.

## 1. Introduction

As a result of rising living standards and rapid urbanisation, energy demand is growing worldwide rapidly. The global warming and carbon emissions issue is becoming more crucial nowadays due to the rising energy demand. Optimal cooling, heating, and power energy systems play a crucial role in the regional multi-energy planning for ultimately reducing energy consumption to fulfil the regional energy demand. For instance, Javan et al. (2016) performed a feasibility study on introducing waste heat of Internal Combustion Engine (ICE) to combined cooling, heating and power system (CCHP) for residential buildings. The article had done multi-objective optimisation on the working fluid selection for low-grade waste heat recovery. Abbasi et al. (2018) used ICE and Gas Turbine (GT) as the dual prime mover in the CCHP system and evaluated energy, exergy, and economic aspects. Yong et al. (2020) proposed a CCHP integration methodology to optimise the heating, cooling and power energy system of an industrial park and urban area.
The shift towards renewable energy technologies and the production of energy-efficient infrastructure are also two main factors in ensuring a stable and sustainable energy sector and mitigating global warming. At the same time, renewable energy sources such as solar, biomass, wind, and geothermal energy, famous for inexhaustibility and cleanliness, are increasingly required for future energy consumption. Mohammadkhani et al. (2018) presented solar-based CCHPs for the energy scheduling of the microgrid with energy storage. The integrated energy system for biomass-based polygeneration that providing electricity, heating, cooling and

Paper Received: 8 May 2021; Revised: 29 September 2021; Accepted: 1 October 2021
Please cite this article as: Pang K.Y., Liew P.Y., Ho W.S., Woon K.S., Wan Alwi S.R., Klemeš J.J., 2021, Optimisation of Renewable-Based Multi-Energy System with Hydrogen Energy for Urban-Industrial Symbiosis, Chemical Engineering Transactions, 88, 199-204 DOI:10.3303/CET2188033

chemical supply has been proposed and evaluated by Wu et al. (2020). Guo et al. (2020) established a comprehensive wind power accommodation trading model, including a CCHP-based microgrid.
Hydrogen is an environmentally safe and reliable fuel since its final combustion product is water and therefore does not create any emissions and has a high energy yield. The advantage of using hydrogen as a fuel is the inspiration of many researchers to develop various methodologies to utilise hydrogen properly. Chen et al. (2020) introduced an RMES based on proton exchange membrane fuel cell (PEMFC) and solar energy. Nojavan et al. (2020) integrated hydrogen energy storage (HES) with the power-to-hydrogen and hydrogen-to-power modes in a trigeneration system. An optimal planning model for a solar-assisted solid oxide fuel cell (SOFC) distributed energy system (DES) was designed by Jing et al. (2018) in their study. This work introduced an interactive framework for planning a DES addressing multi-objective optimisation and multi-criteria assessment considerations simultaneously.
This research aims to optimise an RMES integrated with hydrogen energy in low carbon community and industrial parks for minimising environmental impact and maximising economic impact. Therefore, mathematical modelling is proposed by formulates a comprehensive MINLP modelling framework to optimise the technologies (renewable energy and hydrogen), design capacity, and hourly operation strategy of the multi-energy system. A comparative analysis is performed to study the effect of different energy storage on the system.

## 2. Methodology

### 2.1 Superstructure

A multi-objective mixed-integer nonlinear programming (MINLP) model was developed, based on the superstructure, as shown in Figure 1, in this study.

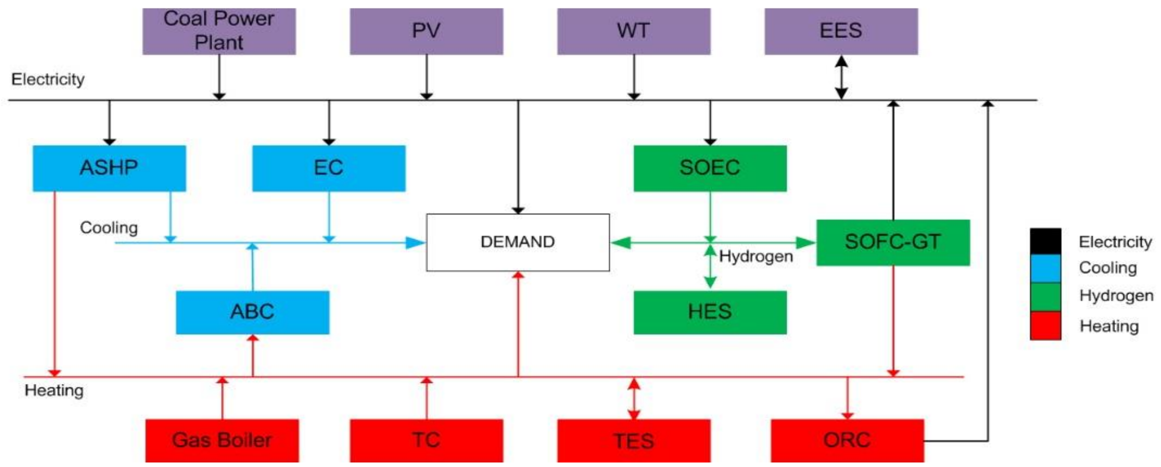


*Figure 1: General superstructure of the mathematical model*

The RMES is assumed to have its hydrogen, heating and cooling network and a local micro-electrical network that can interact with the coal power plant. The devices include PV panel, thermal collector (TC), wind turbine (WT), SOFC, solid oxide electrolyser cell (SOEC), GT, electrical energy storage (EES), thermal energy storage (TES), HES, electric chiller (EC), air source heat pump (ASHP), absorption chiller (ABC), gas boiler and organic Rankine cycle (ORC). Renewable energy is supplied to the system using PV solar panel and WT for the electrical supply and a solar TC for the heating supply. TES and EES are utilised to mitigate the fluctuations in the energy consumption and peak shaving characteristics of the MES.
SOFC is implemented as the representative fuel cell compared to other fuel cells, particularly high-temperature polymer electrolyte fuel cell. SOFC has the best available waste heat recovery that makes it better for the RMES. The waste heat generated from SOFC is recovery at GT to produce electric and heating load. The SOEC unit used electrical power to separate the water molecules into $H_2$ and $O_2$, and then the hydrogen produced is supplied to the hydrogen demand or placed in the HES. The function of HES is to supply hydrogen to hydrogen demand and SOFC as a backup supply. Since the demand for electricity, heating, and cooling cannot be met simultaneously only by the prime movers, the natural gas boiler is installed to meet the insufficient demand for heating. At the same time, the EC and ABC fulfil the cooling demand shortage. When there is a shortage, an ASHP is activated to deliver either hot or cold supply to the system. An MINLP model has been designed to solve the optimal design and dispatch problem. Several specific constraints are being introduced and clarified as follows to enable the model more practical.

**2.1 MINLP Model Development**

The utilisation of renewable energy sources varies at different times of the day, so proper energy storage systems are needed to mitigate the fluctuations in energy consumption. In this study, three different energy storage systems are used which consists of TES, HES and EES

$$0 \le \mathrm{P}_{j,\mathrm{ch,t}} \le \mathrm{P}_{j,\mathrm{ch,t}}^{\mathrm{max}} / \eta_{j,\mathrm{ch}} \times \mathrm{I}_{j,\mathrm{ch,t}} \tag{1}$$

$$0 \le P_{j,dch,t} \le P_{j,dch,t}^{max} \times \eta_{j,dch} \times I_{j,dch,t} \tag{2}$$

$$I_{j,ch,t} + I_{j,dch,t} \le 1 \tag{3}$$

$$Q_j^{min} \le Q_{j,t} \le Q_j^{max} \tag{4}$$

$$Q_{j,t} = Q_{j,t-1} + \left(P_{j,ch,t} \times \eta_{j,ch}\right) - P_{j,dch,t}/\eta_{j,dch} \ , \forall t \ge 1 \tag{5}$$

$$\eta_{j,ch} \sum_{t=1}^{24} P_{j,ch,t} = \sum_{t=1}^{24} P_{j,dch,t}/\eta_{j,dch} \tag{6}$$

where j is the type of energy storage; $\mathrm{P}_{j,\mathrm{ch,t}}$ and $P_{j,dch,t}$ are the charging and discharging of storage in each interval t; $Q_{j,t}$ is the storage energy contents at time t; $\eta_{j,\mathrm{ch}}$ and $\eta_{j,dch}$ are the efficiency of charging and discharging to/from the energy storage; $I_{j,ch,t}$ and $I_{j,dch,t}$ state the binary variables for energy input and output states of the storage system.

All three energy storage are structured according to the following constraints. Eqs(1-2) ensure the charging/discharging energy to/from the energy storage in each time interval t does not exceed a minimum/maximum value. Eq(3) using binary variables to prevents charging/discharging energy simultaneously. The maximum and minimum limitations of storage energy contents are formulated as Eq(4). The stored energy at time slot t $\geqslant$ 1 is given by Eq(5). Eq(6) ensures equal charging/discharging of energy in the scheduling horizon.

In this study, two objectives of minimising annual total cost (ATC) and annual carbon emissions (ACE) have been considered from economic and environmental perspectives. Meanwhile, the trade-off between them has been analysed by multi-objective optimisations.

The ATC is defined as the economic objective, Eq.(7), which consists of five parts: (1) the capital cost of each installed equipment, $C_{CC}$, (2) the maintenance cost of each equipment, $C_{OM}$, (3) the cost to purchase electricity from the power plant, $C_{ELE}$, (4) the fuel cost from a gas boiler, $C_{NG}$, (5) the carbon tax implement on emission, $C_{CT}$.

$$\mathrm{Min}\ (ATC) = C_{CC} + C_{OM} + C_{NG} + C_{ELE} + C_{CT} \tag{7}$$

$$C_{CC} = CRF \times \sum_i \sum_t CAP_{i,t} \times c_i^{CAP} \tag{8}$$

$$C_{OM} = \sum_i \sum_t N_{i,t} \times c_i^{MAINT} \tag{9}$$

$$C_{ELE} = \sum_t E_{ele,t} \times c_{ele} \tag{10}$$

$$C_{NG} = \sum_t Q_{NG,t} \times c_{NG} \tag{11}$$

$$C_{CT} = ACE \times c_{CT} \tag{12}$$

$$CRF = r \times (1+r)^n/(1+r)^n - 1 \tag{13}$$

where *CRF* is the capital recovery factor (Bracco et al. 2013), *r* is the interest rate, *n* is the project life (y), *i* is the number of components, t is time in hours, $CAP_{i,t}$ is the maximum capacity that the components used in 1 h/d, $c_i^{CAP}$ is capital cost of each component *i*, $N_{i,t}$ is the total usage of each supply technologies, $c_i^{MAINT}$ is the maintenance cost of each component *i* , $E_{ele,t}$ is the electricity usage generate from coal power plant, $c_{ele}$ is the electricity cost that purchase from coal power plant , $Q_{NG,t}$ is the natural gas usage for the gas boiler, $c_{NG}$ is the natural gas cost, $c_{CT}$ is carbon tax.

The annual carbon emissions (ACE), Eq.(14), which measures the emissions from fuel consumed and the electricity purchased from a coal power plant, are selected as the environmental objective.

$$\text{Min (ACE)} = \sum_t E_{ele,t} \times \varepsilon_{ele} + \sum_t Q_{NG,t} \times \varepsilon_{NG} \quad (14)$$

Where $\varepsilon_{NG}$ and $\varepsilon_{ele}$ represent the CO2 emissions per unit consumption of natural gas and the electricity import from coal power plant.

## 3. Results and Discussions

### 3.1 Scenario Analysis

The scenario analysis explored the optimal solution with both individual objective functions for all the scenario listed. Four scenarios are analysed for comparison, as listed below:

(1) Baseline scenario, wherein all technologies are allowed to be invested.
(2) Scenario with TES as the only energy storage system
(3) Scenario with EES as the only energy storage system
(4) Scenario with HES as the only energy storage system

Table 1 shows the best results when the total cost and emission objectives are optimised individually. As seen, Scenario 1 offers the lowest cost and pollution due to it provides the flexibility for the system to utilised different energy storage at the appropriate time. It can be concluded that Scenario 2 operational strategy imposes higher emissions than case 1 due to the higher purchasing of electric power with the primary grid. On the other hand, the Scenario 3 operational strategy results in the most significant emission levels due to high rates of heat energy supplied by the gas boiler. Scenario 2 and 3 had a higher annual total cost by implementing a carbon tax to the system than Scenario 1. However, Scenario 4 uses a different strategy than Scenario 2 and 3, which reduces the dependency of the electric power on the primary grid and increases SOEC & SOFC. Hence, in comparison with Scenario 1, Scenario 4 had slightly higher hydrogen production and consumption but lower hydrogen energy stored in HES. The high usage of SOEC and SOFC will increase the system's capital cost and cause higher ATC than Scenario 1.

*Table 1: Single-objective optimisation results of minimising ATC and ACE for all scenarios*

| | Scenario 1 (EES+TES+HES) | Scenario 2 (EES) | Scenario 3 (TES) | Scenario 4 (HES) |
|---|---|---|---|---|
| ATC ($/y) | 1,167,742 | 1,309,384 | 1,311,824 | 1,187,020 |
| ACE (kgCO$_2$-eq/y) | 144.67 | 521.26 | 645.88 | 177.64 |

For a closer look, the amount of stored energy of EES, TES and HES in each hour for scenarios 2, 3 and 4 with minimising ATC is depicted in Figure 2. In scenario 2, EES are charged at off-peak hours (when energy is cheaper) and discharged during periods of supply shortage. The EES is charged during off-peak hours between 0:00 and 4:00 and discharged between 4:00 and 8:00 when the system has a high hydrogen demand but no solar irradiation to operate the PV panel. Hydrogen demand may affect the electrical network since water electrolysis is only a hydrogen production method. In scenario 3, TES charged between 14:00 and 15:00 when solar thermal collector supplies and discharged at 18:00 to 20:00 with the absence of solar irradiation. For HES in scenario 4, it charged at hours 11:00 to 16:00 as the SOEC mainly utilised the electricity production from the PV panel and discharged at high hydrogen demand hours, which are 17:00 to 20:00.

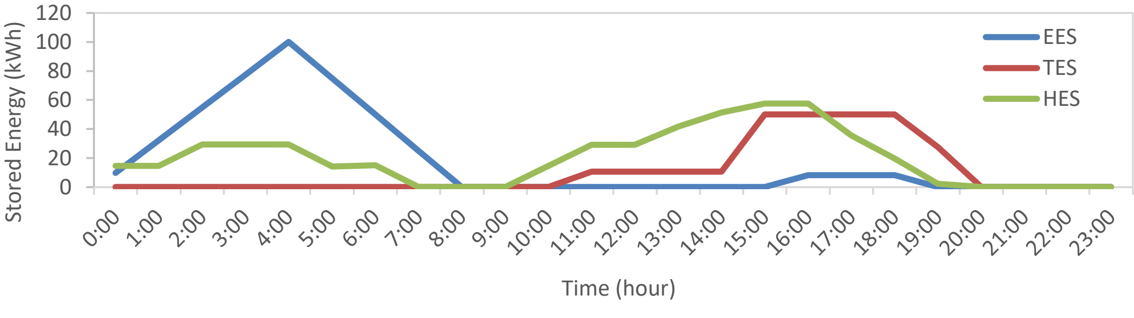


*Figure 2: Stored energy of EES, TES and HES in each hour for scenarios 2, 3 and 4 with minimising ATC.*

### 3.2 Multi-objective optimisation

The multi-objective optimisation problem is solved to minimise both the ATC and ACE simultaneously. Scenario 1 with three different energy storage systems was used for this multi-objective optimisation. Figure 3 illustrates a summary of the set of Pareto optimal front that obtained after 500 generations. The ε-constraint method used in this paper provides the optimal Pareto front and trades-off the two independent optimisation objectives. A total of 11 non-dominated Pareto optimal solutions were selected. The solutions represent the equally good alternatives with different trade-offs spreading from minimum ATC to the minimum ACE. All the Pareto optimal solutions satisfy the constraints and targets, as indicated in Eqs(7-14).

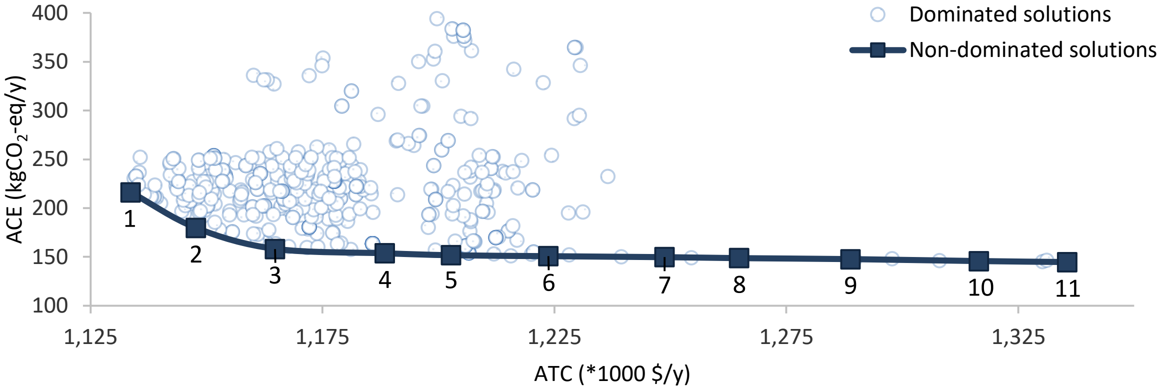


*Figure 3: Pareto optimal set with multi-objective optimisation with EES, TES and HES.*

It is also interesting to note that the Pareto optimality changes are not consistent across the Pareto frontier. The cost gap of each Pareto optimal solution significantly increases when the Pareto optimal solutions transit from the least cost solution ($1^{st}$ Pareto optimal solution) to the least carbon emissions solution ($11^{st}$ Pareto optimal solution). Therefore, the result demonstrates little change for the ACE when shifting from the $4^{th}$ Pareto optimal solution to the $11^{th}$ Pareto optimal solution with only a reduction of 6.23 % of carbon emissions. However, there is an 11.01 % increment of the total cost.

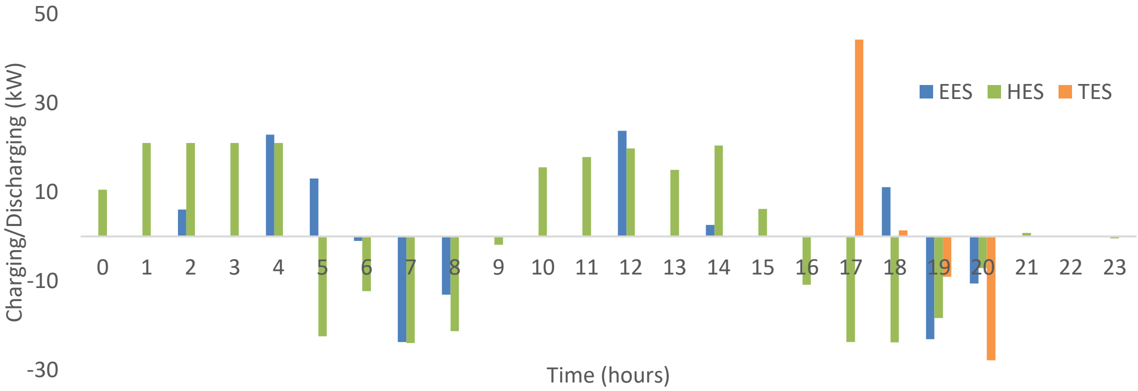


*Figure 4: Charging rate for all energy storage systems at point 1 of the Pareto optimal front (least cost solution)*

Point 1 with the least cost solution was taken as an example to find out the activities of each energy storage in the RMES. Figure 4 shows the charging and discharging activities for each energy storage system at the Pareto optimal point 1. HES has the most frequent charging and discharging activity as it discharges when the hydrogen demands reach their peak level and charge in off-peak hours. As seen, the activities of EES and TES are not as frequent as HES due to the energy generation units can fulfil the demand most of the time except during night time (19:00 and 20:00). This is due to the solar devices unable to generate enough supply to the system.

## 4. Conclusions

In the present paper, we successfully developed a mathematical modelling model using MINLP to size the components of an RMES. The multi-objective optimisation method is used to define the operation strategy, which aims to minimise the total cost and carbon emission through an MINLP algorithm. The multi-objective problem is formulated as an MINLP optimisation problem implemented in GAMS and solved by DICOPT. Four different operation scenarios are compared, which show the importance of introducing different energy storage systems and hydrogen sub-systems to the RMES. Then, the $\varepsilon$-constrains approach is used as the decision-making method to determine the non-dominated solution among all the generations. A Pareto optimal front is generated, and each of the points represented the best-operating conditions for the system among the objective functions. In this research, only the $\varepsilon$-constrains approach is used as the decision-making method for the multi-objective optimisation. Thus, in the future, multi-criteria methods such as TOPSIS, weighing method, fuzzy uncertainty method, and more can be introduced simultaneously to obtain more accurate multi-objective optimisation results. Also, the system can be extended to form a hydrogen circular economy hub in the future that involves more clean hydrogen production methods and a unique energy generation system.

**Acknowledgements**

The authors would like to thank you for the financial support from Universiti Teknologi Malaysia, Ministry of Education Malaysia through FRGS (R.K130000.7843.5F075) and MRUN TRGS (R.K130000.7843. 4L883). The research has been supported by the project Sustainable Process Integration Laboratory SPIL, funded as project No. CZ.02.1.01/0.0/0.0/15_003/0000456, the Operational Programme Research, Development and Education of the Czech Ministry of Education, Youth and Sports by EU European Structural and Investment Funds, Operational Programme Research, Development and Education under a collaboration agreement with UTM.

## References

Abbasi M., Chahartaghi M., Hashemian S.M., 2018, Energy, exergy, and economic evaluations of a CCHP system by using the internal combustion engines and gas turbine as prime movers, Energy Conversion and Management, 173, 359-374.

Bracco S., Dentici G., Siri S., 2013, Economic and environmental optimisation model for the design and the operation of a combined heat and power distributed generation system in an urban area, Energy, 55, 1014-1024.

Chen X., Liu Q., Xu J., Chen Y., Li W., Yuan Z., Wan Z., Wang X., 2020, Thermodynamic study of a hybrid PEMFC-solar energy multi-generation system combined with SOEC and dual Rankine cycle, Energy Conversion and Management, 226, 113512.

Guo J., Li Y., Shen Y., Li H., 2020, An incentive mechanism design using CCHP-based microgrids for wind power accommodation considering contribution rate, Electric Power Systems Research, 187, 106434.

Javan S., Mohamadi V., Ahmadi P., Hanafizadeh P., 2016, Fluid selection optimisation of a combined cooling, heating and power (CCHP) system for residential applications, Applied Thermal Engineering, 96, 26-38.

Jing R., Zhu X., Zhu Z., Wang W., Meng C., Shah N., Li N., Zhao Y., 2018, A multi-objective optimisation and multi-criteria evaluation integrated framework for distributed energy system optimal planning, Energy Conversion and Management, 166, 445-462.

Mohammadkhani N., Sedighizadeh M., Esmaili M., 2018, Energy and emission management of CCHPs with electric and thermal energy storage and electric vehicle, Thermal Science and Engineering Progress, 8, 494-508.

Nojavan S., Akbari-Dibavar A., Farahmand-Zahed A., Zare K., 2020, Risk-constrained scheduling of a CHP-based microgrid including hydrogen energy storage using robust optimisation approach, International Journal of Hydrogen Energy, 45(56), 32269-32284.

Wu N., Zhan X., Zhu X., Zhang Z., Lin J., Xie S., Meng C., Cao L., Wang X., Shah N., Zheng X., Zhao Y., 2020, Analysis of biomass polygeneration integrated energy system based on a mixed-integer nonlinear programming optimisation method, Journal of Cleaner Production, 271, 122761.

Yong W.N., Liew P.Y., Alwi S.R.W., Klemeš J.J., 2020, Combined Cooling, Heating and Power Integration for Locally Integrated Energy Sectors, Chemical Engineering Transactions, 81, 949-954.