CHEMICAL ENGINEERING TRANSACTIONS

VOL. 83, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-81-5; **ISSN** 2283-9216

DOI: 10.3303/CET2183007

Integration of Combined Heat and Power Energy Systems with Gas Turbine in Locally Integrated Energy Sectors

Emily Amy Authin[a], Peng Yen Liew[a,*], Jiří Jaromír Klemeš[b], Wai Shin Ho[c], Nurfatehah Wahyuny Che Jusoh[a], Nor Erniza Mohammad Rozali[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]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
[c]School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor Malaysia.
[d]Department of Chemical Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia
pyliew@utm.my

World energy consumption has been increasing drastically due to the increment world population, with the high consumption from industry, residential, commercial and community service buildings. Locally Integrated Energy Sector (LIES) is introduced to minimize the energy consumption for the commercial and residential units integrated. The LIES concept extended from the Pinch Analysis-based multiple-processes Heat Integration considers energy intermittency and storage. The LIES started from thermal energy conservation, then extended to power and heat energy optimisation. The methodology aimed to maximize the energy recovery between processes across time for minimizing the overall energy consumption, which lead to energy and operating cost saving. The system integrates with steam turbines and energy storages (heat and power) to minimize the waste heat available in the LIES system. This research focuses on the energy source for overall LIES system, which the conventional boiler is replaced with a combined cycle CHP system with gas turbine. The CHP system consumes natural gas to generate heat and power energy for the system. The sequence of heat and power optimisation, via heat and power integration, is also studied in this research. The design and operating parameter of the gas turbine system is affected by the sequences of optimisation. The CHP system operates to fulfil the heat demand or power demand at the first place, which leads to different overall consumptions. The integration options are compared based on the overall energy consumption and operating costs. Result shows that the power-to-heat optimisation has the least overall energy consumption (1,434 kW/y), which contributes to the highest annual energy saving and operation cost saving (203,397 USD/y).

1. Introduction

As the world population is increasing, the threats of climate change caused by rapidly growing world energy consumption and CO_2 emissions. To date, the global average energy consumption per capita has increased by approximately 45 % compared to 1970 (Ritchie and Roser, 2020). The global final energy consumption from industrial sector, residential areas, commercial and community service buildings contribute up to 64 % in 2017 (International Energy Agency, 2020).The idea to conserve energy in various sectors is vital to maximize energy recovery and minimize energy demand.
Total Site Heat Integration (TSHI) offers a great heat recovery potential for multiple individual process with a utility system (Dhole and Linnhoff, 1993). The LIES concept, as the extension of TSHI, has been introduced for incorporating renewable energy and district heating system with industrial processes and local energy sectors to enhance overall energy efficiency (Perry et al., 2008). Varbanov and Klemeš (2011) introduced Total Site Cascade for analysing energy consumption of LIES considering the energy availability of commercial or residential buildings as well as renewable energy sources. Liew et al. (2016) has demonstrated the integration of distinct cooling system in LIES system as an option to utilise the industrial low-grade waste heat. Lee et al.

Paper Received: 11/05/2020; Revised: 08/08/2020; Accepted: 10/08/2020
Please cite this article as: Authin E.A., Liew P.Y., Klemeš J.J., Ho W.S., Che Jusoh N.W., Mohammad Rozali N.E., 2021, Integration of Combined Heat and Power Energy Systems with Gas Turbine in Locally Integrated Energy Sectors, Chemical Engineering Transactions, 83, 37-42 DOI:10.3303/CET2183007

(2019) integrated the methodology of TSHI with Power Pinch Analysis (PoPA) to sequentially optimize heat and power in LIES with conventional boiler and steam turbine.
Combined heat and power (CHP) or cogeneration production are the use of a heat engine or power station to simultaneously generate electricity and useful heat. CHP with gas turbine has been recognized since 1980s to conserve energy. Low capacity gas turbine (typically less than 50 MW) are suitable for cogeneration due to low capital cost and less mechanical complexity (Heppenstall, 1998). A basic gas turbine-based cogeneration system consists of a gas turbine cycle (compressor, combustion chamber and expander), a Heat Recovery Steam Generator (HRSG) for steam production and a steam turbine (Najjar, 2000). Natural gas is introduced into combustion chamber of gas turbine where combustion takes place with compressed air coming out from compressor. Hot exhaust flue gases from the turbine is the heat source for process heat production. The quantity and quality of process heat produced depend on the temperature of hot exhaust gases enter the HRSG. High Pressure Steam (HPS) or Medium Pressure steam (MPS) produced can be used either for process heat or electric power that is generated by steam turbine or both. At the same time, lower temperature exhaust gases from HRSG can be used for process heat as well to minimize waste heat release to the atmosphere. Townsend and Linnhoff (1983) has developed a methodology to size gas turbine cogeneration system by matching Grand Composite Curve (GCC) of the process with flue gas profile to minimize energy use. Najjar (2000) reviewed advanced thermodynamic cycles for gas turbine cogeneration system to improve efficiency. Bade and Bandyopadhyay (2015) developed methodology based on pinch analysis to integrate CHP system with gas turbine and regenerator in a process plant to minimize fuel consumption. Many established methodologies are developed for implementation of CHP system with gas turbine in industrial site. However, the importance of CHP with gas turbine system for maximising energy savings in LIES for heat and power could explored.
The overview of CHP with gas turbine system in LIES is shown in Figure 1, which local sectors are integrated with industrial processes for their heat and power energy system. The heat and power energy are supplied by a CHP with gas turbine, which the ratio of heat and power energy productions could be adjusted based on the demands from LIES. This paper addresses some novelties as follows: (1) Heat and power energy systems optimisation for LIES with variable energy supply and demand and energy storages (2) CHP with gas turbine system optimisation to replace the conventional boiler in the LIES (3) impact study of sequence between heat and power integration for LIES with the CHP and gas turbine integration.

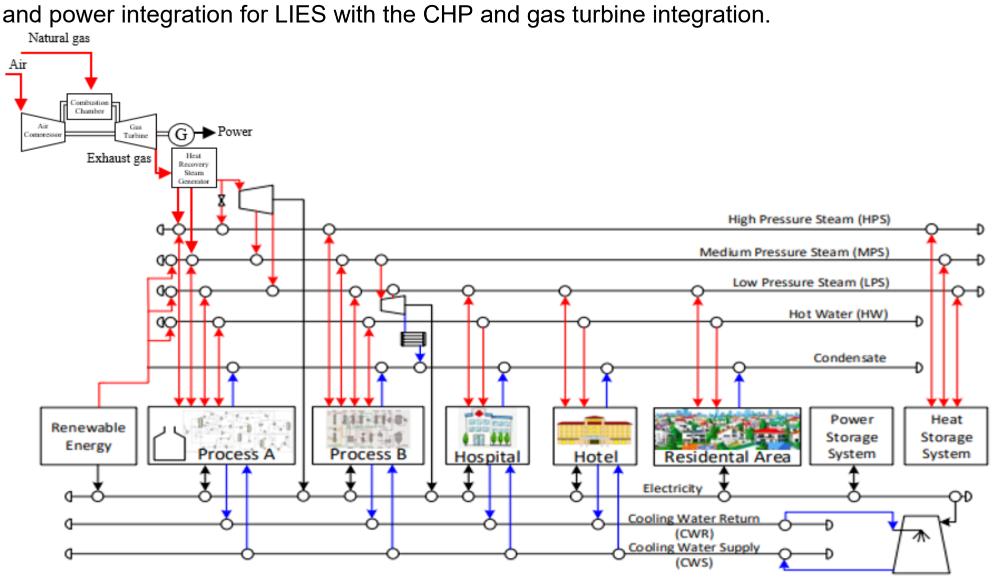

Figure 1: Overview of CHP system with gas turbine in Locally Integrated Energy Sectors (Perry et al., 2008)

2. Methodology

A comprehensive framework to optimize heat and power energy systems for LIES via heat and power integration along with heat and power energy storage is shown in Figure 2. The proposed methodology aimed to maximize the energy recovery between processes across time, while minimizing the overall energy consumption. The sequence of heat and power optimisation may affect the design and operating parameter of the gas turbine system. The CHP with gas turbine system can operate to fulfill the heat demand or power demand in LIES, eventually lead to reduction of overall energy consumptions.

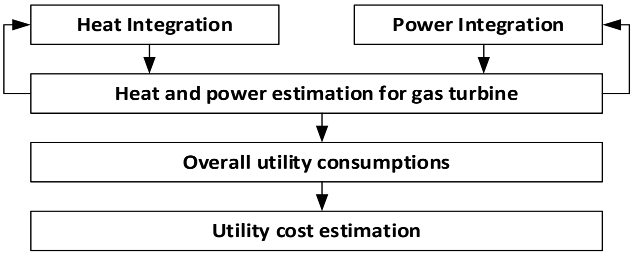

Figure 2: Heat and power integration methodology in LIES with CHP and gas turbine

2.1 Heat Integration

2.1.1 Data extraction

Multiple processes stream data such as source temperature, target temperature, heat capacity flowrate. heat duty and operation time duration are extracted. All the processes stream data have been categorized into different Time Slices (TSLs) based on their operating hours.

2.1.2 Individual Process Pinch Analysis

The data obtained at each time slices are analyzed using Problem Table Algorithm (PTA) to obtain the pinch point of the plant in a TSL. After cascaded of heat energy from highest temperature to lowest temperature, the pinch point will show the temperature where the maximum energy recovery takes place. Heat source which is the amount of heat energy required to be cooled off and heat sink which is the minimum heat energy required to fulfill the heat demand are identified. The results obtained from PTA are used to target the exact amount of utilities required within the given temperature ranges of utilities using Multiple Utility Problem Table Algorithm (MU-PTA). Through heat cascading for multiple utilities level, the amount of heat utility required to be consumed is the amount of multiple utility required above pinch region while the amount of heat utility that can be produced is the amount of multiple utility required below pinch region.

2.1.3 Total Site Heat Integration

The utility generation and consumption for each plant in Total Site (TS) (Liew et al., 2012) are targeting using Total Site - Problem Table Algorithm (TS-PTA) and summarized for each TSL. After the generation and consumption targeted matched at each utility level, the amount of external utility required to fulfill the heat demands in the site at each utility level is determined from the final cascade in TS-PTA. Total Site - Heat Storage Cascade (TS-HSC) (Liew et al., 2014) simulate the storage of excess heat utility from the a TSL and discharges to satisfy the heat demand of the same utility in later TSLs. External utility is required when the heat energy in the heat storage is insufficient to fully satisfy the heat demand in processes. This study assumed for the use of thermochemical heat storage system, which self-discharge energy loss is assumed negligible. However, the heat storage will lose 5 % of energy during charging and 10 % of energy during discharging.

2.2 Power Integration

2.2.1 Data extraction

The power supply from renewable energies (solar, wind and biomass) and power demand should be recorded according to their power rating and it’s duration.

2.2.2 Power Pinch Analysis

Through Power Cascade Analysis (PoCA), the amount of power source is maximized from the integration of renewable energies into power network for satisfying the power demand from various appliances in facilities and households (Mohammad Rozali et al., 2013b). The outsourced electricity needed at each time slice, excess electricity let down to battery storage, time interval where the maximum power demand occurs is identified.

2.2.3 Power storage

Modified Storage Cascade Table (Modified SCT) is used in this study for simulating the potential power recovery across time through the usage of battery storage system (Mohammad Rozali et al., 2013a). The Sodium Sulfur (NaS) battery system is assumed in this study. The depth of discharge of battery is assumed as 80 %, inverter efficiency of battery is assumed as 90 %, charging and discharging efficiency of the battery on the other hand is assumed as 95 % (Ho et al., 2012). The excess energy from PoCA is charged into the battery while insufficient energy generated to meet the load, additional source is required from the battery system.

2.3 Heat and power cogeneration estimation

In this study, 45 MW General Electric (GE) LM6000 turboshaft gas turbine has additions and modifications designed to make it more suitable for industrial heat and power generation (Darrow et al., 2015). The technical specifications of gas turbine for CHP operation in this work are assumed as electrical efficiency, CHP efficiency, thermal output and electric output as fraction of fuel input are assumed 35.96 %, 68.80 %, 0.33 and 0.36 (Darrow et al., 2015). The heat and power cogenerated by gas turbine can be calculated using the Eqs(1) to (4):

$$F_{in} = Q_T / \eta_T \quad (1)$$

$$F_{in} = E / \eta_E \quad (2)$$

$$\eta_{CHP} = (E_{cogen} + Q_T) / F_{in} \quad (3)$$

At temperature 25 ℃, the range of Lower Heating Value (LHV) of natural gas is about 38,000 kJ/kg to 50,000 kJ/kg (Soares, 2014). The total fuel used per hour is calculated using the equation below:

$$\dot{m}_{fuel} = (CE_{fuel}\ x\ 3600)/(LHV\ x\ 1.10) \quad (4)$$

2.4 Overall utility consumption and economic analysis

The amount of outsourced electricity from the grid, electricity consumption for cooling tower, natural gas consumption for gas turbine are used to estimate the operating cost. The economic analysis is done by comparing the total energy consumption and operating cost of the integration options to evaluate their feasibility.

3. Case study

A case study with 3 scenarios is presented to demonstrate the methodology proposed. The hypothetical case study consists multiple processes of industrial plants, residential areas, commercial buildings and community service buildings. The thermal energy demand data is adapted from Liew et al. (2014), while power demand data is modified from (Ho et al., 2012). On the other hand, power supply from various renewable energy, such as solar energy, wind energy and biomass energy are assumed based on Wan Alwi et al. (2012). In order to study the sequence of heat and power optimisation via heat integration and power integration, the case study has been analyzed based on 3 scenarios. Scenario 1 is the base reference case, no cogeneration with gas turbine and energy storage system. Scenario 2 involves gas turbine cogenerated power supply without heat storage and with battery storage while Scenario 3 involves gas turbine cogenerated heat supply with both heat storage and battery storage. Table 1 shows the summary of the system configuration for all scenarios.

Table 1: Summary of system configurations for all the scenarios

Scenario	Heat Integration	Heat Storage	Gas Turbine	Power Integration	Battery Storage	Heat-to-Power	Power-to-Heat
1	√	X	X	√	X	X	X
2	√	X	√	√	√	√	X
3	√	√	√	√	√	X	√

For TSHI, the utilities obtained on different TSLs are Medium Pressure Steam (MPS) at 220 ℃, Low Pressure Steam (LPS) at 130 ℃, Hot Water utility (HW) at 50 ℃ and Cooling Water utility (CW) at 15 ℃. Based on the summarized result from TS-PTA, the above pinch region indicates the energy demand to be fulfilled by central utility system through either conventional boiler or gas turbine cogenerated thermal energy source. The result obtained can be used to estimate the fuel input to the system. The fuel input for conventional boiler is referred to boiler load. Besides that, the fuel input for gas turbine is referred to gas turbine load, it can be estimated by using Eq(1) or Eq(2) and the thermal energy source cogenerated can be obtained through Eq(3). On the other hand, the below Pinch region indicates the energy excess to be cooled down by cooling tower. The result obtained can be used to estimate the cooling tower load.

For PoPA, the amount of electricity surplus and deficit for each hour are calculated. The electricity is outsourced from the grid during deficit of electricity (negative value) to fulfil the power demand and excess of electricity during surplus of electricity (positive value) after fulfilling the power demand is then sold to the grid again. The power energy source cogenerated by gas turbine can be estimated by using Eq(3).

For economy analysis, the assumed price for natural gas to fulfil the boiler load and gas turbine load is 162 USD/kW.y and 28.45 USD/kW.y for electricity consumption of cooling tower (Liew et al., 2016). The outsourced electricity purchased from grid and excess electricity sold to the grid are in the same rate, 121.76 USD/kW.y (Statista, 2020). The total utility consumption and operation cost are summarized in Table 2 and 3.

Table 2: Summary of total energy consumption for various utilities

Utility		Unit	Scenario 1	Scenario 2	Scenario 3
MPS	Outsourced	kW	11.55	-	-
	Excess	kW	-	-	-
LPS	Outsourced	kW	114.57	-	-
	Excess	kW	319.83	281.69	-
HW	Outsourced	kW	50.82	-	-
	Excess	kW	619.40	616.40	-
CW	Outsourced	kW	-	-	-
	Excess	kW	201.62	248.22	248.22
Electricity	Outsourced	kW	422.50	385.00	-
	Excess	kW	4.00	-	-
Boiler Load		kW	176.94	-	-
Cooling Tower Load		kW	1,140.85	1,146.31	248.22
Gas Turbine Load		kW	-	145.83	1,186.04
Total Utility		kW	1,740.29	1,677.14	1,434.26

Table 3: Summary of economic analysis for the case study

Utility		Unit	Scenario 1	Scenario 2	Scenario 3
Electricity	Outsourced	USD/y	296,561	207,239	-
	Excess	USD/y	2,808	-	-
Boiler Load		USD/y	28,665	-	-
Cooling Tower Load		USD/y	32,457	32,613	7,062
Gas Turbine Load		USD/y	-	17,757	144,417
Total Operation Cost		USD/y	354,876	320,608	151,479
Total Cost Saving		USD/y	-	34,267	203,397

Based on Table 2 and 3, the base case of this case study, Scenario 1, has the highest utility consumption of 1,740 kW and highest operation cost of 354,875 USD/y. After the integration of gas turbine, Scenario 2 and 3 has lower utility consumption compare to scenario 1.

For Scenario 2, the lower utility consumption of 1,6177 kW, eventually leads to lower operation cost of 320,608 USD/y when compare with Scenario 1. The amount of outsourced electricity of 385 kW indicates that the additional power supply cogenerated by gas turbine from TSHI is not sufficient to cope with the power demand in PoPA. If the battery storage is available, the electricity excess will not be sold to the grid but store in battery storage for future usage. Without the heat storage, excess heat utilities will be cooled off in cooling tower. Scenario 3 has the least utility consumption of 1,434 kW and least operation cost of 151,479 USD/y. The result indicated that the additional thermal supply cogenerated by gas turbine from PoPA successfully cope with part of the heat demand in TSHI. Electricity excess is first considered for storage in battery storage, then sold to the grid. The heat storage facilities are assumed available for MPS storage, LPS storage and HW storage. The excess heat of MPS, LPS and HW are stored in the storages for future usage, only CW will release to cooling tower. Based on this case study, the sequence of power-to-heat optimisation could provide bigger saving of overall energy consumption and operation cost than the sequence of heat-to-power optimisation.

4. Conclusions

A new methodology for integrating CHP with gas turbine system in LIES with variable supply and demand and energy storages for heat and power energy systems is introduced in this study. The sequence of heat and power integration is studied for the proposed energy system to maximise the heat and power energy recovery between processes across time. The case study demonstrates that the overall energy consumption and operation cost has reduced with the proposed energy system configuration. The sequence of power-to-heat optimisation provides the higher annual saving of operation cost of 203,397 USD/y compared to 34,267 USD/y for sequence of heat-to-power optimisation via heat integration and power integration. A detailed capital cost for the CHP with gas turbine system should be considered in future study.

Acknowledgments

The authors would like to thank for the financial support from Universiti Teknologi Malaysia and Ministry of Education through the Fundamental Research Grant Scheme - FRGS (R.K130000.7843.5F075) and MRUN Translational Research Grant Scheme (R.K130000.7843. 4L883). The research has also 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

Bade M.H., Bandyopadhyay S., 2015, Analysis of gas turbine integrated cogeneration plant: Process integration approach, Applied Thermal Engineering, 78, 118-128.

Darrow K., Tidball R., Wang J., Hampson A., 2015, Catalog of CHP Technologies, Section 3. Technology Characterization – Combustion Turbines, US Environmental Protection Agency, Washington, US.

Dhole V.R., Linnhoff B., 1993, Total site targets for fuel, co-generation, emissions, and cooling, Computers & Chemical Engineering, 17, S101-S109.

Heppenstall T., 1998, Advanced gas turbine cycles for power generation: a critical review, Applied Thermal Engineering, 18(9), 837-846.

Ho W.S., Hashim H., Hassim M.H., Muis Z.A., Shamsuddin N.L.M., 2012, Design of distributed energy system through Electric System Cascade Analysis (ESCA), Applied Energy, 99, 309-315.

International Energy Agency, 2020, Key World Energy Statistics 2019 <www.iea.org/reports/key-world-energy-statistics-2019> Accessed on 15/04/2020.

Lee P.Y., Liew P.Y., Walmsley T.G., Klemeš J.J., 2019, Cogeneration Optimisation for Locally Integrated Energy Systems, Chemical Engineering Transactions, 76, 79-84.

Liew P.Y., Alwi S.R.W., Varbanov P.S., Manan Z.A., Klemeš J.J., 2012, A numerical technique for total site sensitivity analysis, Applied Thermal Engineering, 40, 397-408.

Liew P.Y., Walmsley T.G., Wan Alwi S.R., Abdul Manan Z., Klemeš J.J., Varbanov P.S., 2016, Integrating district cooling systems in Locally Integrated Energy Sectors through Total Site Heat Integration, Applied Energy, 184, 1350-1363.

Liew P.Y., Wan Alwi S.R., Klemeš J.J., Varbanov P.S., Abdul Manan Z., 2014, Algorithmic targeting for Total Site Heat Integration with variable energy supply/demand, Applied Thermal Engineering, 70(2), 1073-1083.

Mohammad Rozali N.E., Wan Alwi S.R., Abdul Manan Z., Klemeš J.J., Hassan M.Y., 2013a, Process integration of hybrid power systems with energy losses considerations, Energy, 55, 38-45.

Mohammad Rozali N.E., Wan Alwi S.R., Manan Z.A., Klemeš J.J., Hassan M.Y., 2013b, Process Integration techniques for optimal design of hybrid power systems, Applied Thermal Engineering, 61(1), 26-35.

Najjar Y.S.H., 2000, Gas turbine cogeneration systems: a review of some novel cycles, Applied Thermal Engineering, 20(2), 179-197.

Perry S., Klemeš J., Bulatov I., 2008, Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors, Energy, 33(10), 1489-1497.

Ritchie H., Roser M., 2020, Energy <ourworldindata.org/energy> Accessed on 25/04/2020.

Soares C.M., 2014, Gas Turbines: A Handbook of Air, Land and Sea Applications, Butterworth-Heinemann, Oxford, UK.

Statista, 2020, Natural gas prices for industry worldwide as of 2018 <www.statista.com/statistics/253047/natural-gas-prices-in-selected-countries/> Accessed on 15/04/2020.

Townsend D.W., Linnhoff B., 1983, Heat and power networks in process design. Part II: Design procedure for equipment selection and process matching, AIChE Journal, 29(5), 748-771.

Varbanov P.S., Klemeš J.J., 2011, Integration and management of renewables into Total Sites with variable supply and demand, Computers & Chemical Engineering, 35(9), 1815-1826.

Wan Alwi S.R., Mohammad Rozali N.E., Abdul-Manan Z., Klemeš J.J., 2012, A process integration targeting method for hybrid power systems, Energy, 44(1), 6-10.