CHEMICAL ENGINEERING TRANSACTIONS
VOL. 81, 2020

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

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216
DOI: 10.3303/CET2081159

Combined Cooling, Heating and Power Integration for Locally Integrated Energy Sector

Wen Ni Yong[a], Peng Yen Liew[a,b]*, Sharifah Rafidah Wan Alwi[b], Jiří Jaromír Klemeš[c]

[a]Malaysia – Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia
[b]Process Systems Engineering Centre (PROSPECT), Research Institute for Sustainable Environment, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor Malaysia
[c]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

A huge amount of energy is consumed by residential, industrial, workplace and service sector. The operating units in Locally Integrated Energy Sectors (LIES) contributes negatively to global greenhouse gases emission. Energy efficiency is particularly important to overcome the growth of energy demand. Many countries in the world have implemented a number of methods to increase energy efficiencies. Combined Cooling, Heat and Power system (CCHP) is also known as the tri-generation system has been proven to be more efficient on sustainability and environmentally as compare to conventional generating system in terms of energy consumption, operational costs, heat loss and greenhouse gases emission. CCHP system tends to produce more products using waste heat. The expected outputs of tri-generation systems are power, heating utility system, cooling down utility system and waste heat. Process Integration through Pinch analysis is a tool for reducing energy consumptions and maximizing energy recovery. Total Site Heat Integration (TSHI) is an extended methodology of the individual process Pinch Analysis on heating targeting. Power Pinch Analysis (PoPA) is used to optimize the power from process, tri-generation and co-generation systems. CCHP Integration can be connected to form a comprehensive energy integration network among the energy supply and demand within a local area, as proposed by LIES. The new methodology deals with variable heating, chilling and power supply and demand, with a heat and battery storage system. The system is connected to a trigeneration energy system for optimizing the operation of the proposed system. The trigeneration system provides great flexibility for the optimization of the energy system. A case study is performed for verifying the proposed methodology, whereby energy recovery (cooling, heat and power) opportunities are found from the system studied. The case study showed 100 % reduction of steam, chilled water and electricity demand. The system managed to produce more electricity than required. This developing methodology provides better guidance to engineers, especially during the design stage on the performance limitations and specific compromises within a system.

1. Introduction

Environmental pollution, climate change and fast energy depletion are the examples caused by rapid industrialization and increased global population. A continuing increase in carbon dioxide emissions and crude oil usage has become the main focus for industrial energy efficiency. Process Integration (PI) combines several processes to reduce resources consumption while minimising the emissions and environmental impacts (Klemeš et al., 2018). In the energy crisis on 1970s, this concept was introduced as a heat integration. The methodology is then widely used in the processing and power generating industry over the last 30 y for energy saving on reducing the amount of external heating and cooling requirements.
Heat Integration (HI) using Pinch Technology is a firstly developed part of Process Integration and provides the design foundation for combined heat and power systems, refrigeration, air conditioning and heating with pump systems (Chew et al., 2015). Heat Integration between several processes with the centralized utility system is then termed as Total Site Heat Integration (TSHI) (Liew et al., 2017). TSHI integrates several individual

Paper Received: 05/04/2020; Revised: 16/04/2020; Accepted: 24/04/2020
Please cite this article as: Yong W.N., Liew P.Y., Wan Alwi S.R., Klemeš J.J., 2020, Combined Cooling, Heating and Power Integration for Locally Integrated Energy Sector, Chemical Engineering Transactions, 81, 949-954 DOI:10.3303/CET2081159

processes to recover heat indirectly by a common utility system, which offers additional inter-process heat recovery through consumption and generation of utilities. Locally Integrated Energy Sectors (LIES) is a concept that extended from TSHI concept (Perry et al., 2008). It provides energy integration with end users from various sectors such as the industrial, services, residential, agriculture, transportation and public sectors within a local area. This approach helps to increase the energy efficiency on heat and power. Heat Integration (HI) and Power Integration (PI) can be connected to form a bigger energy integration network among all of the facilities within a local area (Lee et al., 2019).

The extension of the Pinch Methodology to power systems analysis recently emerged and is now rapidly developing. Wan Alwi et al. (2012) extended the Pinch Analysis concept used in Process Integration to determine the minimum power in electricity targets for systems comprising hybrid renewable energy sources. Cogeneration or combined heat and power (CHP) production is the use of a heat engine or power station to simultaneously generate electricity and useful heat (Ng et al., 2017). In this sequential energy production, both heat and power requirements are satisfied from a single fuel source. Tri-generation or Combined Heating, Cooling and Power (CCHP) is one step ahead of cogeneration (Liu et al., 2013), referring to the concurrent generation of electricity, useful heating, and cooling from a single fuel source. Comparative to CHP, the waste heat is collected and used to generate heating, cooling and powerful effect. CCHP systems can attain higher overall efficiencies than traditional power plants or cogeneration, especially on energy saving and reduce the emission of pollutants to the environment. (Al-Sulaiman et al., 2011).

The new methodology proposes the extension of Total Site (TS) or LIES concepts, considers the fluctuation of energy supply and demands, to include tri-generation power plant as energy supply and cogeneration facility for waste heat recovery. A CCHP Integration methodology is proposed in this study. This work aims to optimise the heating, cooling and power energy system of an industrial TS or LIES, as shown in Figure 1. The productions of electricity and chilled water are targeted based on the heating requirement by the overall system. This methodology could design an efficient tri-generation energy supply system for LIES.

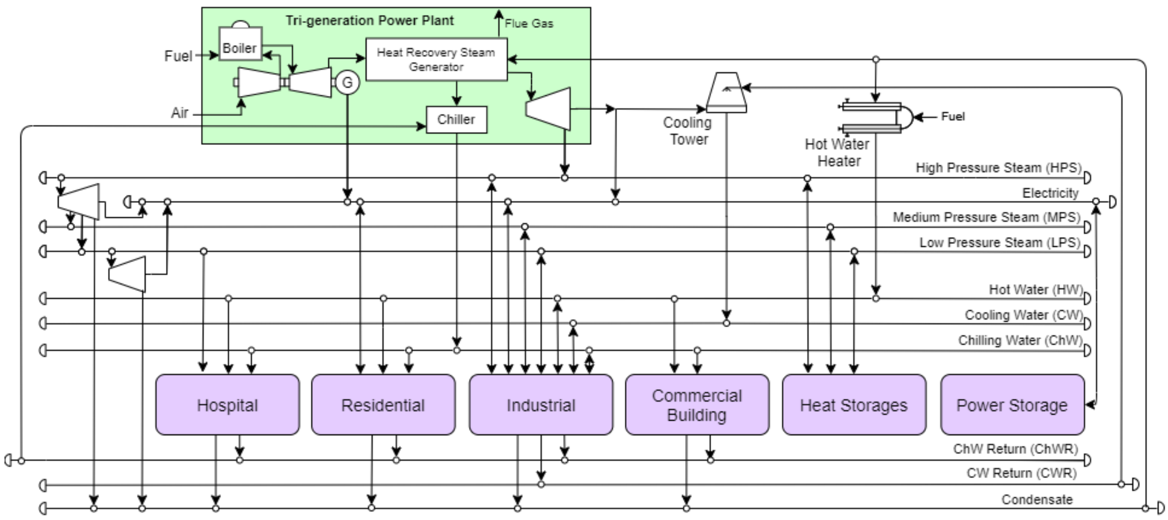

Figure 1: Locally Integrated Energy Sectors with heat, power and refrigeration optimisation

2. Methodology

This research developed a locally integrated heating, chilling and power targeting methodology for Total Site system with a tri-generation power plant based on Pinch-based method which covers all utilities available in a process site. This study involved Total Site Heat Integration and Power Pinch Analysis with heat storage and power storage, as shown in Figure 2 with the implementation of a tri-generation power plant in LIES to compare the energy saving. This novel methodology is to improve the energy efficiency of a local area with the concept of LIES by using CCHP Integration.

2.1 Data Extraction

LIES helps to promote the relationship between industry and local area to enhance their overall system energy efficiency. The data such as Starting Temperature (T_s), Target Temperature (T_t), Enthalpy (ΔH) and Heat Capacity (C_p) are required to maximize the heat recovery in LIES. For power data, the power rating and consumption and supply timing should be recorded. After extracting these data, each stream data is classified as Time Slide (TSL). This TSL method can solve the variation or fluctuation of huge energy data in a massive CCHP Integration problem.

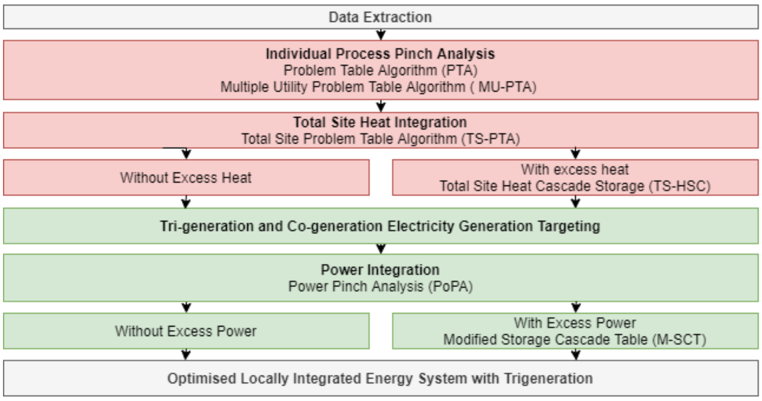

Figure 2: The proposed CCHP Integration methodology for LIES.

2.2 Individual Process Pinch Analysis

Pinch analysis is a methodology for reducing the energy consumption of processes by calculating thermodynamically feasible energy targets (or minimum energy consumption). Heat integration is used to recover the heat energy from the system. After the stream data categorized into different TSL, Problem Table Algorithm (PTA) is used to determine the individual heat recovery in each stream through the pinch point. Ts and Tt from the extracted data are shifted to Shifted Starting Temperature (T_s') and Shifted Target Temperature (T_t') based on a minimum temperature difference for the process to process ($\Delta T_{min,pp}$). After determining the pinch point, the heat sink is the heat above pinch point, and the heat source is the heat below pinch point. This concept of PTA is further extended to Multiple Utility Problem Table Algorithm (MU-PTA) by Liew et al. (2018). MU-PTA uses the minimum temperature difference for the utility to process ($\Delta T_{min,up}$) to determine the Pinch Point of the required utility at multiple levels.

2.3 Total Site Heat Integration

LIES extends Total Site Heat Integration (TSHI) to Total Site Problem Table Algorithmn (TS-PTA) which helps to optimise the energy system for centralized of multiple industrial processes as well as other process heat demands in proximity. TSHI has many opportunities to be explored for energy savings and also to overcome constraints. Total Site Heat Integration (TSHI) has received growing interest since its inception in the ’90s (Klemeš et al., 1997). Heat storage is then integrated with TS-PTA to become Total Site-Heat Storage Cascade (TS-HSC) by Liew et al. (2018). Heat energy losses from charging and discharging the heat storage are considered.

2.4 Tri-generation and Co-generation Utility Generation Targeting

The power generated from the tri-generation system and waste heat from cogeneration is targeted to undergo a power integration. The general concept of a trigeneration system is presented in Figure 3. Natural gas is used as an input in a boiler to produce hot gas to go through the gas turbine, then heat up feed water in the heat recovery steam generator. The output of the gas turbine system is electricity and Useful Thermal (UT). This UT can be used as a Very High-Pressure Steam (VHPS) and to produce cooling by entering an absorption chiller. The electricity, steam and chilled water produced from the tri-generation system is used to fulfil the utility demand.

Figure 3 shows an example of the tri-generation system with an output of 30 % of electricity and 55 % of UT (Afonso and Rocha, 2016). The UT is further to produce heating and cooling by using the heating unit and chiller inside the tri-generation system. Heating unit efficiency and chiller Coefficient of Performance (COP) are considered into the calculation. The utility generations from the tri-generation are targeted according to the highest demands among heating, cooling and electricity demand.

The VHPS produced from the tri-generation system is typically used at various pressure level, whereby the backpressure turbine system is used to create usable electrical energy from this pressure reduction. The power generated is then used for satisfying the power consumption in the system. Excess steam from the system is considered for power generation through a condensing turbine, for maximizing the energy recovery in the overall system.

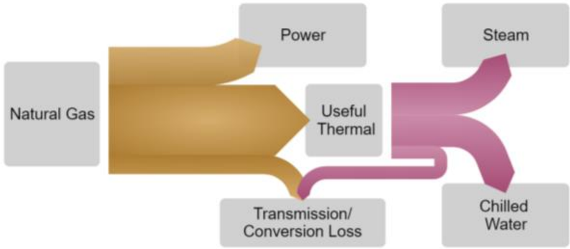

Figure 3: General trigeneration concept

2.5 Power Integration

The extension of the Pinch Methodology to power systems analysis recently emerged and is now rapidly developing. The power from the tri-generation system and cogeneration system is integrated by using a method called Power Pinch Analysis (PoPA). PoPA is further extended to a Modified Storage Cascade Table (M-SCT) by Mohammad Rozali et al. (2013), when the excess power is available. M-SCT is battery storage which considered the charging and discharging energy losses during the power storage process. By assuming all Energy Supply and Demand is Alternating Current (AC) and battery storage is Direct Current (DC), inverter efficiency is considered.

2.6 Energy Saving Analysis

An energy-saving analysis is analysed based on a table to compare or summarize the external heating, chilling and power sources required to fulfil the heating, chilling and power demand. The more external sources used indicates that the least optimize is the system as more waste heat is released to the atmosphere, which shows the lower in energy efficiency.

3. Case Study

A case study is presented to demonstrate the comprehensive framework to optimise heating, chilling and power for a LIES. Generally, LIES can be separated into 2 sections which are heat and cooling integration, as well as power integration. The energy demand data are extracted from industrial plants, hospital, residential and commercial building. The case study is proposed under 2 scenarios, as shown in Table 1, whereby Scenario 1 served as a base case to compare the total energy saving. The minimum temperature difference between the process streams and the utility ($\Delta T_{min,up}$) is assumed to be 12 °C and the minimum temperature difference between the process streams ($\Delta T_{min,pp}$) is 12 °C for Process A, B, C, D and 8 °C for Process E. Five types of utilities are available in the existing industrial processes, which includes Medium Pressure Steam (MPS) at 220 °C, Low Pressure Steam (LPS) at 130 °C, Hot Water (HW) at 50-70 °C, cooling water (CW) at 15 °C and Chilled Water (ChW) at 8-11°C. Time slice (TSL) model is used for handling the process stream intermittency.

Table 1: Summary of the methods used for both scenarios

Scenario	PTA	MU-PTA	TS-PTA	TS-HSC	PoPA	M-SCT
1 (Base)	√	√	√	X	X	X
2	√	√	√	√	√	√

3.1 Heat Pinch Analysis (Individual Process and Total Site)

From Table 2, all the positive values shown are representing the demands after TS-PTA. For the negative value of -1,791 kWh in LPS from TSL 2 is representing, there are excess LPS from the system. External heating, cooling and power supply are used to fulfil the heating, chilling and power demand after TS-PTA. In Scenario 2, if there are excess heat available, the heat is then stored into thermal storage system for later use. After performing TS-HSC for MPS and LPS level, storage at LPS level shows excess 500 kWh in the TSL 2.

3.2 Tri-generation and Co-generation Electricity Generation Targeting

In this case study, a tri-generation system is used, whereby natural gas fed into the boiler. The system produces 30 % of electricity and 55 % of UT (Afonso and Rocha, 2016). This UT energy is flexible for usage as steam or feed into adsorption chiller to produce ChW. The system is assumed to have a thermal efficiency of 0.56 and chiller Coefficient of Performance (COP) of 0.85 (Afonso and Rocha, 2016). The output of the tri-generation system is used to satisfy the heating, chilling and electricity demands. For targeting the tri-generation capacity for this case study, the calculation is based on the largest demand (between heating, cooling and electricity), whereby the value is then used to calculate the other two types of energy produced concurrently.

Table 2: Summary of all the energy demands from Scenario 1 after TS-PTA

TSL	Time	MPS (kWh)	LPS (kWh)	HW (kWh)	CW (kWh)	ChW (kWh)	Electricity (kWh)
1	20:00-06:00	17	585	817	442	0	232
2	06:00-17:00	2	-1,791	0	10,938	17,820	385
3	17:00-18:00	0	24	172	1,844	1,620	28
4	18:00-20:00	0	48	343	89	0	46
Total		19	-1,134	1,332	13,313	19,440	691

It is found that electricity was the major demand on TSL 1 & 4, while chilled water is the major demand on TSL 2 & 3. In order to satisfy the electricity demand (12.75 MWh) and satisfying the chilling demand (19.44 MWh), the Very High Pressure Steam (VHPS - 90 bar, 500 °C) produced from the trigeneration is 0.29 MWh, whereby requires 43.89 MWh of natural gas as shown in Table 3.
Cogeneration system is also used to transform waste heat in the system into the useful heating and power which helps to increase the energy efficiency of the system. For this case study, 3 cogeneration systems with 0.8 turbine efficiency are used. Cogeneration system 1 used a backpressure turbine which converted 22 kWh of VHPS into 19 kWh of MPS and 2 kWh of electricity. Backpressure turbine is used to convert VHPS into various pressure steams depends on the steam demand with the ability of producing extra usable electricity. In this case, 19 kWh of MPS is used to fulfill the MPS demand from LIES. By using a cogeneration system, condensing turbine is used and these excess waste streams are converted to condensate for the aim of producing more usable electricity. The cogeneration system 2 used a condensing turbine which converted 26 kWh of excess VHPS generated from the tri-generation system into 148 kWh of condensate and 94 kWh of electricity. Besides that, cogeneration system 3 used a condensing turbine which converted 500 kWh of excess LPS from heating storage into 381 kWh of condensate and 95 kWh of electricity. The total power generation targeted from the cogeneration system is 0.19 MWh.

Table 3: Summary of the input and output of tri-generation and cogeneration systems in a day

		Tri-generation System	Cogeneration System 1	Cogeneration System 2	Cogeneration System 3
Input	Natural Gas (kWh)	43,891	-	-	-
	HPS (kWh)	-	22	265	-
	LPS (kWh)	-	-	-	500
Output	HPS (kWh)	287	-	-	-
	MPS (kWh)	-	19	-	-
	Condensate (kWh)	-	-	148	381
	ChW (kWh)	19,440	-	-	-
	Electricity (kWh)	12,754	2	94	95

3.3 Power Integration and Energy Saving Analysis

Electricity generation from Tri- and Co-generation system is considered for the PoPA and energy saving analysis. Table 4 shows excess electricity generated from PoPA. It could be stored in battery storage for later use when the electricity is a deficit. This could be analysed using M-SCT by considering a charging/discharging efficiency of 0.9 and AC-DC inverter efficiency of 0.95. However, in this case, M-SCT is not required as there is no TSL with deficit of electricity, which it is recommended to be sold or used immediately at another system.
Table 4 summarised the energy requirement for the system after considering CCHP Integration (Scenario 2),

Table 4: Summary of all the energy demands after PoPA (Scenario 2)

TSL	Time	MPS (kWh)	LPS (kWh)	HW (kWh)	CW (kWh)	ChW (kWh)	Electricity (kWh)
1	20:00-06:00	0	0	817	442	0	-79
2	06:00-17:00	0	0	0	10,938	0	-11,147
3	17:00-18:00	0	0	172	1,844	0	-1,012
4	18:00-20:00	0	0	343	89	0	-17
Total		0	0	1,332	13,313	0	-12,255

while Table 2 shows the requirement with only TSHI (Scenario 1). For Scenario 1, all the demands required to be fulfilled by external sources. For Scenario 2, with the help of a tri-generation power plant, all the demands have been fulfilled except for HW and CW. The demand of HW and CW from Table 4 required external heat exchanger and cooling tower to fulfill the demand. All of the demands are fully fulfilled by the tri-generation system, cogeneration system, heat exchanger, cooling tower, heat storage and power storage in Scenario 2.

4. Conclusions

A new optimization framework for CCHP Integration is developed in this research. Heating, chilling, and power system is integrated into LIES by using TSHI and PoPA to increase the energy efficiency, while cooling recovery is considered within TSLs. The case study shows a 100 % reduction of steam, chilled water and electricity demand. The system managed to produce more electricity than required. The proposed framework provides a more practical tool for researchers and engineers to deal with the LIES energy efficiency optimization by sustainably adding a tri-generation power plant. Tri-generation and cogeneration system integration in LIES provides a novel framework for achieving minimal overall energy (cooling, heat and power) requirements. Heat storage and power storage in LIES are also contributing to maximizing the heat or power recovery in the system. This comprehensive CCHP Integration framework helps engineers to design the centralised utility system for improving system-wide energy efficiency. The future work will extend the search to perform a detailed cost-benefit analysis, especially on capital and utility cost.

Acknowledgements

The authors would like to thank 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, Malaysia.

References

Afonso C., Rocha C., 2016, Evaluation of the economic viability of the application of a trigeneration system in a small hotel, Future Cities and Environment, 2(1), 2.

Al-Sulaiman F.A., Hamdullahpur F., Dincer I., 2011, Performance comparison of three trigeneration systems using organic rankine cycles, Energy, 36(9), 5741-5754.

Chew K.H., Klemeš J.J., Wan Alwi S.R., Manan Z.A., 2015, Process modifications to maximise energy savings in total site heat integration, Applied Thermal Engineering, 78, 731-739.

Klemeš J.J., Dhole V.R., Raissi K., Perry S.J., Puigjaner L., 1997, Targeting and design methodology for reduction of fuel, power and CO2 on total sites, Applied Thermal Engineering, 17(8), 993-1003.

Klemeš J.J., Varbanov P.S., Walmsley T.G., Jia X., 2018, New directions in the implementation of Pinch Methodology (PM), Renewable and Sustainable Energy Reviews, 98, 439-468.

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., Theo W.L., Wan Alwi S.R., Lim J.S., Abdul Manan Z., Klemeš J.J., Varbanov P.S., 2017, Total Site Heat Integration planning and design for industrial, urban and renewable systems, Renewable and Sustainable Energy Reviews, 68, 964-985.

Liew P.Y., Wan Alwi S.R., Ho W.S., Abdul Manan Z., Varbanov P.S., Klemeš J.J., 2018, Multi-period energy targeting for total site and locally integrated energy sectors with cascade pinch analysis, Energy, 155, 370-380.

Liu M., Shi Y., Fang F., 2013, Optimal power flow and PGU capacity of CCHP systems using a matrix modeling approach, Applied Energy, 102, 794-802.

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

Ng R.T.L., Loo J.S.W., Ng D.K.S., Foo D.C.Y., Kim J.-K., Tan R.R., 2017, Targeting for cogeneration potential and steam allocation for steam distribution network, Applied Thermal Engineering, 113, 1610-1621.

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.

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.