CHEMICAL ENGINEERING TRANSACTIONS

VOL. 72, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Jeng Shiun Lim, Azizul Azri Mustaffa, Nur Nabila Abdul Hamid, Jiří Jaromír Klemeš

ISBN 978-88-95608-69-3; **ISSN** 2283-9216

DOI: 10.3303/CET1972052

Integrated Optimisation of Energy-Water Nexus for Industrial Site Planning

Ezah Abdul Aziz, Haslenda Hashim*

Process Systems Engineering Centre (PROSPECT), Research Institute of Sustainability Environment (RISE), Universiti Teknologi Malaysia, 81310 UTM, Johor Bahru, Malaysia.
haslenda@cheme.utm.my

Energy and water are inextricably linked. The energy-water nexus shows the interwoven of energy and water in terms of resources use. Energy is vital to extract, treat and deliver water meanwhile water is consumed in energy production and electricity generation at multiple phases of industrial chain. The robust existed interlink has called for increasing focuses due to the facts that demands for energy and water are growing rapidly. This paper presents an attempt to develop a model for the synthesis of energy-integrated water nexus in an industrial site addressing industrial symbiosis via viable inter-plant integration among multiple plants with centralised utility system and water regeneration system. A mixed integer non-linear programming (MINLP) is formulated to satisfy the heat, power and water demand with an objective function to minimise the electricity and water requirement in terms of cost under the condition that all the operational requirements are met. The model for the water-energy nexus in an industrial site was optimised using GAMS software and resulted in an optimised external power demand of 2,331.4 kWh with 30 % savings and 9,133.1 kg/s for chilled water with 98.5 % savings. Generator 1 is selected as optimal steam power generator with optimised cost of 917.42 MYR. The approach demonstrates that optimised water-energy nexus in industrial site can give significant savings and resource conservation rather than stand-alone plant integration and optimisation.

1. Introduction

The "energy-water nexus" is a broad label for the set of interactions caused when humans develop and use water and energy (Halstead et al., 2014). The nexus manifests itself in many ways, revealing substantial trade-offs and opportunity costs associated with the ways of water and energy usage. The trade-offs among water generation/consumption and energy generation/consumption can result in significant reduction of energy use and environmental impact. Recently, Wang et al. (2018) have briefly analysed current and future development trends of water footprint (WF) methodology in a few topics including "WF and energy" since water-energy nexus has always been two pillars of environmental and ecological systems. It is important to promote the overall level of resource conservation by exploiting the cooperative utilisation in an industrial site through an optimised energy-water network (Hamiche et al., 2016). Boix et al. (2015) reviewed the methods and progress for the design of various process systems within eco-industrial park (EIP), including water, energy, material, etc. Meanwhile, Kastner et al. (2015) reviewed recent quantitative tools and methods by cultivating industrial symbiotic exchanges in existing industrial parks as well as minimising energy and material consumption. Pan et al. (2016) explained and proposed a series of systematic approaches for multi-level modelling and optimisation construction process in EIP. Quantitative tools and methods have been developed to identify and cultivate industrial symbiotic exchanges in existing industrial parks to minimise overall energy and material consumption (Kastner et al., 2015). Computer-based method is used simultaneously with novel mathematical methods in design and optimisation of EIP in order to blend into the new era of Industry 4.0 (Pan et al., 2015). Recently, Song et al. (2017) presented a methodology for inter-plant heat-integrated water allocation network (IHIWAN) synthesis via both direct and indirect schemes of cross-plant water reuse into consideration. Later, Liu et al. (2018) presented a methodology for IHIWAN synthesis via coupling scheme of water allocation and heat exchange. Song et al. (2017) and Liu et al. (2018) both formulated a non-linear programming model (NLP) for the synthesis via two optimisation solution approaches which are sequential

Paper Received: 24 September 2018; Revised: 02 October 2018; Accepted: 27 October 2018

Please cite this article as: Aziz E.A., Hashim H., 2019, Integrated optimisation of energy-water nexus for industrial site planning, Chemical Engineering Transactions, 72, 307-312 DOI:10.3303/CET1972052

and simultaneous design. Despite numerous studies have been developed for heat-water combined network, yet the integrated energy-water nexus (energy in terms of heat and power) has not been adequately investigated. Strategies for inter-plant integration of heat-power-water are not yet explored. This paper aims to optimise water-energy nexus in an industrial site by utilising the concept of symbiosis that demonstrate viable inter-plant integration of heat, power as well as water resources for an industrial site.

2. Superstructure

The superstructure of the energy-integrated water synthesis problem is illustrated as in Figure 1. Given an industrial site consists mix of five industrial plants with known heat and power demand and supply supplied by an existing utility system. The industrial site also consists of known number of processes with known freshwater demand and wastewater discharge. The system is required to incorporate heat, power, and water integration analysis to establish the maximum of heat, power, and water recovery among the plants in the industrial site with centralised utility system. Steam headers are allocated according to the steam temperature and pressure of high-pressure steam (HPS), medium pressure steam (MPS), low pressure steam (LPS) and cooling water (CW). Surplus heat from plants that act as heat sources are supplied to the respective headers which will be used to satisfy the heat demand for each plant under the limitations of total heat supply available. The deficit HPS, MPS and LPS demands after total site heat integration via the headers would be further satisfied by the centralised steam system which uses the regenerated waste water (x_4) as the source for steam formation denoted as x_{3a}, x_{3b} and x_{3c}. The cooling water demand for each plant is supplied from the CW header in which the deficit cooling water after heat integration would be contributed by the chilled water which is purchased from outsource denoted as x_5. Excess water demand could also contribute to additional chilled water requirements. The waste water generated by the site and the excess water in CW header flows into the wastewater (WW) header which will be regenerated for energy applications. Water regeneration is an important element in the water-energy nexus. Regenerated wastewater, (x_4) is split into streams that act as the sources for centralised steam system and steam power generator. Three streams with different mass flow rate (kg), x_{4a}, x_{4b} and x_{4c}, are converted to HPS, MPS and LPS and supplied to the respective headers in heat (kW) x_{3a}, x_{3b} and x_{3c}. The power required in each plant is supplied by the electricity header. The source for the header could be from the purchased external power, (x_2) or potentially satisfied by a steam power generator or both. In this case study, two steam power generators, Gen 1 and Gen 2 are available with different efficiency to convert regenerated water into electricity to meet the power requirements in the site in order to minimise the external power required. x_{1a} and x_{1b} represent the power generated by Gen 1 and Gen 2 by utilising stream x_{4d} and x_{4e}. In this study, only one steam power generator should be installed for the power source alternative. The results from solving the mathematical model using GAMS would provide the optimal selection for the steam power generator with the objective function of minimising the external power requirement, (x_2) and chilled water requirement, (x_5) in terms of cost simultaneously. The optimal values of heat inter-changed between plants via the headers and the amount of heat supplied by the centralised steam system would also be obtained for design references to achieve minimum water and energy consumption. The development of an optimised water-energy nexus is essential to implement the concept of industrial symbiosis that demonstrate viable inter-plant exchanges.

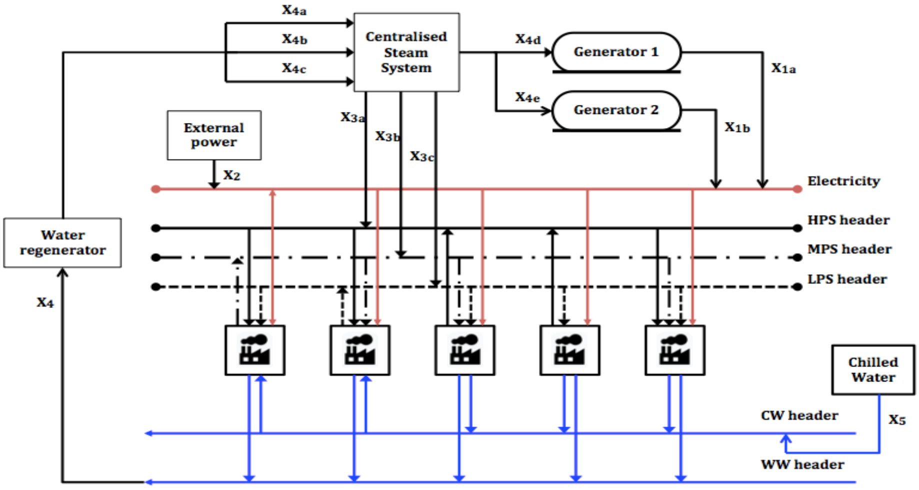

Figure 1: Superstructure for Energy-Water Nexus in an Industrial Site

3. Mathematical model formulation

The objective function of the MINLP model is to minimise the cost for external water and electricity requirement (z). The formulation is described in Eq(1) consists of cost of electricity ($Cost_P$) cost for chilled water ($Cost_W$), external power demand (x_2) and chilled water demand (x_5). Indices in this model include *i* for header (HPS, MPS, LPS, CW), and *j* for plant (1, 2, 3, 4, 5).

$$z = Cost_p \cdot x_2 + Cost_w \cdot x_5 \tag{1}$$

The heat supply availability S for each header *i* limits the amount of heat that could be interchanged between plants *j* through HPS, MPS, LPS and CW headers as shown in Eq(2). The summation of heat interchanged (x_{ij}) for each header *j* should not exceed the heat source availability S_i at respective header

$$\sum_j x_{ij} \leq S_i \qquad \forall i \tag{2}$$

The heat demand D for each plant *j* limits the amount of heat that should be transferred to the plant through HPS, MPS, LPS and CW headers as shown in Eq(3). The summation of heat interchanged (x_{ij}) for each plant *i* should not exceed the total heat demand D_j at respective plant.

$$\sum_i x_{ij} \leq D_j \qquad \forall j \tag{3}$$

The heat demand parameters (c_{ij}) limit the amount of heat that can be interchanged between plants *j* via headers *i* (x_{ij}) as described in Eq(4). The transfer of heat higher than the demand at specific plant will result in excess waste heat and insufficient heat supply for other plant's heat demands.

$$x_{ij} \leq c_{ij} \tag{4}$$

The external heat requirements of HPS, MPS, LPS and CW from the centralised steam system are determined as described in Eq(5). By subtracting the amount of heat interchanged between plants via headers (x_{ij}) from the heat demand parameters (c_{ij}) associated for each plant, the amount of deficit heat after heat integration (r_{ij}) will be supplied by the centralised steam system.

$$x_{ij} - c_{ij} = r_{ij} \tag{5}$$

The summation of unmet heat demand (r_{ij}) from all plants determines the external heat requirements from centralised steam system for HPS header (x_{3a}), MPS header (x_{3b}), and LPS header (x_{3c}) as shown in Eq(6), (7) and (8). The total unmet cooling water demand is supplied by the external cooling water demand (x_{cw}) multiplied by the enthalpy of the cooling water as described in Eq(9).

$$\sum_{j=HPS}^{i} r_{ij} = x_{3a} \tag{6}$$

$$\sum_{j=MPS}^{i} r_{ij} = x_{3b} \tag{7}$$

$$\sum_{j=LPS}^{i} r_{ij} = x_{3c} \tag{8}$$

$$\sum_{j=CW}^{i} r_{ij} = x_{CW} \times CW_{enthalpy} \tag{9}$$

The water to steam conversion factor (k_{steam}) determines the amount of water consumed (x_{4a}, x_{4b}, x_{4c}) for each type of steam generated (HPS, MPS, LPS) through the centralised steam system. The regenerated water streams in unit kg/s (x_{4a}, x_{4b}, x_{4c}) are converted to HPS, MPS and LPS for external heat supply in unit kW (x_{3a}, x_{3b}, x_{3c}) to their respective headers using the Eq(10).

$$\frac{x_{4a}}{x_{3a}}, \frac{x_{4b}}{x_{3b}}, \frac{x_{4c}}{x_{3c}} = k_{steam} \tag{10}$$

The conversion factor for steam power generator Gen 1 and Gen 2 ($k_{power,G1}$, $k_{power,G2}$) determines the amount of water consumed in kg/s (x_{4d}, x_{4e}) for generation of electricity through Gen 1 or Gen 2. The regenerated water streams (x_{4d}, x_{4e}) are converted to power via Gen 1 or Gen 2 in kWh (x_{1a}, x_{1b}) using the Eq(11) and Eq(12).

$$\frac{x_{4d}}{x_{1a}} = k_{power,G1} \tag{11}$$

$$\frac{x_{4e}}{x_{2a}} = k_{power,G2} \quad (12)$$

The maximum power demand (Pmax) serves as the limiting factor for the external power demand (x_2) and the alternative power generated from either Gen 1 or Gen 2 (x_{1a}, x_{1b}). The binary parameter y_1 determines whether the amount of power generated by Gen 1 (x_{1a}) is utilised as the alternative power source to meet the maximum power demand. Gen 1 is selected when parameter y_1 equals to 1. Same goes to parameter y_2 which indicates the selection of Gen 2. The summation of the external power demand (x_2) and alternative power supplied by steam power generator (x_{1a} or x_{1b}) should not exceed the maximum power demand (P_{max}) as described in Eq(13).

$$y_1 \cdot x_{1a} + y_2 \cdot x_{1b} + x_2 = P_{max} \quad (13)$$

The maximum power capacities for Gen 1 and Gen 2 (C_{G1}, C_{G2}) limit the alternative power generated from Gen 1 or Gen 2 (x_{1a}, x_{1b}) and act as one of the determining factors for the selection of steam power generator. The binary parameter y_1 determines whether the generator capacity constraint for Gen 1 should be complied. The capacity constraint for Gen 1 is met when parameter y_1 equals to 1. Same goes to parameter y_2 which indicates the inequality constraint of Gen 2. The alternative power supplied by steam power generator (x_{1a} or x_{1b}) should not exceed the maximum power capacity (C_{G1}, C_{G2}) as described in Eq(14) and (15).

$$x_{1a} \leq C_{G1} \cdot y_1 \quad (14)$$

$$x_{1b} \leq C_{G2} \cdot y_2 \quad (15)$$

The mass balance for the amount of wastewater in the WW header is described in Eq(16). The amount of wastewater available for regeneration (x_4) equals to the summation of the external chilled water demand (x_5) and wastewater generated (WWG) excluding the fresh water demand (FWD) and cooling water demand (x_{cw}) in the site.

$$x_4 = x_5 - x_{CW} - FWD + WWG \quad (16)$$

The mass balance for the amount of regenerated wastewater for energy generation is described in Eq(17). The amount of regenerated wastewater is distributed for the steam generation in the centralised steam system (x_{4a}, x_{4b}, x_{4c}) and for the power generation via Gen 1 or Gen 2 (x_{4d}, x_{4e}). The wastewater that is not utilised in any energy conversion technology is wasted as the final wastewater (x_{4f}).

$$x_4 = x_{4a} + x_{4b} + x_{4c} + x_{4d} + x_{4e} + x_{4f} \quad (17)$$

The minimum requirement of the external chilled water demand (x_5) depends on the cooling water demand for the site after heat integration between plants (x_{cw}) as described in Eq(18).

$$x_5 \geq x_{CW} \quad (18)$$

Table 1 lists all the parameters used in this mathematical formulation as follows.

Table 1: List of parameters for mathematical formulation

Parameter	Unit	Description	Value
k_{steam}	kg/kW	Water to steam conversion factor in centralized steam system for HPS, MPS and LPS steams	1.8
$k_{power,G1}$	kg/kWh	Water to power conversion factor in Gen 1	4.536
$k_{power,G2}$	kg/kW	Water to power conversion factor in Gen 2	5.52
C_{G1}	kW	Maximum power capacity of Gen 1	1,000
C_{G2}	kW	Maximum power capacity of Gen 2	1,000
$Cost_P$	MYR/kWh	Cost for electricity	0.37
$Cost_w$	MYR/kg	Cost for chilled water	0.006
P_{max}	kW	Maximum power demand	3,331.4
FWD	kg	Fresh water demand	20.75
WWG	kg	Wastewater generation	652.65
$CW_{enthalpy}$	kJ/kg	Cooling water enthalpy	163
y_1	-	Binary parameter (1 if Gen 1 is selected, 0 if otherwise)	1 or 0
y_2	-	Binary parameter (1 if Gen 2 is selected, 0 if otherwise)	1 or 0

4. Results and discussion

Baseline study was conducted at first to collect data on amount of resources either being generated or consumed. The quality measure of heat, power and water resources were systematically investigated in terms of flow rate, temperature, pressure and multiple contaminant concentration. For heat resources, the quality measure of steam such as low pressure (LP), medium pressure (MP), and high pressure (HP) is crucial to be measured for proper heat distribution. As for power, the quality measure involving the power rating consumption and time interval. As for water, the quality parameter will be measured from the aspect of temperature, flow rate and contaminant concentration. The quality measures of water supply, receiving water, wastewater treatment, and disposal have to be monitored to ensure environmental standards are being met as well as to investigate the suitability of water quality for regenerating, reuse or disposal. Based on the data collected, the unit of plants in the industrial area was identified by the capability to become either source or sink. Following this, multiple integration strategies were conducted on an illustrated case study involving total site of heat, power and water integration to establish the maximum heat, power, and water recovery among the plants in the site. Next, an optimal energy-water nexus was developed with minimum cost under the condition that all the operational requirements were met. The model for the water-energy nexus in an industrial site was optimised using CPLEX solver of GAMS software (version 25.1.1). The optimal solution for external power requirement (x_2) was 2,331.4 kWh and external chilled water demand (x_5) was 9,133 kWh with installation of generator 1 as the steam power generator and the optimal cost was 917.42 MYR. The optimal values for heat interchanged between plants (x_{ij}) and unmet heat demand (r_{ij}) are compiled in Table 2 and Table 3 below.

Table 2: Optimal values for x_{ij}

Header	Heat Exchanged between plants, x_{ij}					Heat availability, S(*ij*), (kW)
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	
HPS header	453.5	0	0	0	393.5	847
MPS header	0	231	551	0	635	1,417
LPS header	196	0	0	0	0	196
CW header	366	352	0	0	0	951
Total	2,026	1,227	1,048	105	1,677	

Table 3: Optimal values for r_{ij}

Header	Unmet heat demand, r_{ij}					Heat availability, S(*ij*), (kW)
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	
HPS header	356.5	250	0	0	356.5	847
MPS header	0	394	0	0	0	1,417
LPS header	497	105	292	0	0	196
CW header	0	0	0	0	0	951
Total	2,026	1,227	1,048	105	1,677	

The optimal solution for other variables is listed in Table 4. Based on the findings, industrial site planner can reduce the cost of external power and water requirement by designing a centralised steam system with greater water to steam conversion factor or by installing a steam power generator with higher conversion factor that will yield greater power output. The reduction of outsource demand can greatly minimise the cost. The installation of water regeneration system is also efficient in reducing fresh water consumption. Efficient conservation efforts via reuse, recycling, retreat are tokens that lead to sustainable use of resources that move align with government motivation to foster sustainable green economy development. Reduction consumption of energy and water will reduce the dependency on fossil fuels simultaneously will reduce the carbon emissions. This could also reduce the amount of carbon taxes that need to be paid by the government. The efficacy of heat and water recovery will reduce industrial operation and capital costs thus inspire more industrial partners to contribute to symbiotic variety of resources exchange. Industrial symbiosis offers significant contribution towards further improved resources efficiency and is a key driver in establishing circular economies.

Table 4: Optimal values for other variables

Notation	Value	Unit	Description
x_{1a}	1,000.0	kWh	Power generated from Gen 1
x_{1b}	0	kWh	Power generated from Gen 2
x_{3a}	963.0	kW	External HPS supplied from centralised steam system
x_{3b}	394.0	kW	External MPS supplied from centralised steam system
x_{3c}	1,548.0	kW	External LPS supplied from centralised steam system
x_{4a}	1,733.4	kg/s	Water consumed by centralised steam system to produce HPS
x_{4b}	709.2	kg/s	Water consumed by centralised steam system to produce MPS
x_{4c}	2,786.4	kg/s	Water consumed by centralised steam system to produce LPS
x_{4d}	4,536.0	kg/s	Water consumed by Gen 1 to generate electricity
x_{4e}	0	kg/s	Water consumed by Gen 2 to generate electricity
x_{4f}	0	kg/s	Final wastewater amount after energy generation
x_4	9,765.0	kg/s	Regenerated wastewater from WW header
x_5	9,133.0	kg/s	External chilled water demand
x_{cw}	0	kg/s	External cooling water demand

5. Conclusion

A model for optimal energy-integrated water network configuration has been developed to satisfy the demand with minimum cost under the condition that all the operational requirements are met. Total site of heat, power and water integration were established by addressing the synergy of symbiosis in an industrial site simultaneously maximise energy and water recovery as illustrated in the superstructure. The approach enables the acceptance of energy-water nexus in an industrial site by utilising the concept of symbiosis that demonstrate viable inter-plant exchanges. The model was optimised using GAMS software and resulted in an optimised external power demand and chilled water demand with savings of 30 % and 98.5 %. The optimisation model is expected to capture a holistic intra-plant and inter-plant for optimal energy-water nexus integration. The creation of energy and water symbiosis can lead towards reduction of fossil fuel as well as mitigation adverse effects of climate change. Industrial symbiosis motivates industrial entities to develop beneficial relationships and is a key driver towards establishing circular economies and green growth. The development of designed symbiosis networks is said to be persistent and technically practical, economically feasible, environmentally sustainable and socially adaptable. The development of proper infrastructure and mechanism for industrial symbiosis will lead towards improved efficiency, zero emissions as well as other income generation and job creation within the industrial site.

References

Boix, M., Montastruc, L., Azzaro-Pantel, C., Domenech, S., 2015, Optimization methods applied to the design of eco-industrial parks: A literature review, Journal of Cleaner Production, 87, 303-317.

General Algebraic Modeling System (GAMS), Release 25.1.2, 2018, GAMS Development Corporation, Washington, DC, USA.

Halstead, M., Kober, T., Van Der Zwaan, B., 2014, Understanding the energy-water nexus (September), ECN-E14-046, Energy Research Centre of The Netherlands (ECN), Patten, The Netherlands.

Hamiche, A.M., Boudghene, A., Flazi, S., 2016, A review of the water-energy nexus, Renewable and Sustainable Energy Reviews, Elsevier, 65, 319–331.

Kastner, C.A., Lau, R., Kraft, M., 2015, Quantitative tools for cultivating symbiosis in industrial parks: A literature review, Applied Energy, 155, 599–612.

Liu, L., Song, H., Zhang, L., Du, J., 2018, Heat-integrated water allocation network synthesis for industrial parks with sequential and simultaneous design, Computers & Chemical Engineering, 108, 408-424.

Pan, M., Sikorski, J., Kastner, C.A., Akroyd, J., Mosbach, S., Lau, R., Kraft, M., 2015, Applying Industry 4.0 to the Jurong Island eEco-industrial Park, Energy Procedia, 75, 1536–1541.

Pan, M., Sikorski, J., Akroyd, J., Mosbach, S., Lau, R., Kraft, M., 2016, Design technologies for eco-industrial parks: From unit operations to processes, plants and industrial networks, Applied Energy, 175, 305-323.

Song, H., Liu, L., Du, J., 2017, Heat-integrated water allocation network synthesis for industrial parks, Chemical Engineering Transactions, 61, 475-480.

Wang, X., Klemeš, J.J., Walmsley, T.G., Wang, Y., Yu, H., 2018, Recent Developments of Water Footprint Methodology, Chemical Engineering Transactions, 70, 511-516.