CHEMICAL ENGINEERING TRANSACTIONS

VOL. 63, 2018

A publication of AIDIC

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

Guest Editors: Jeng Shiun Lim, Wai Shin Ho, Jiří J. Klemeš

ISBN 978-88-95608-61-7; **ISSN** 2283-9216

DOI: 10.3303/CET1863046

Water-Energy Nexus Cascade Analysis (WENCA) for Simultaneous Water-Energy System Optimisation

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This paper presents a new numerical method called the Water-Energy Nexus Cascade Analysis (WENCA), developed based on the principal of Pinch Analysis. Water and energy are both valuable resources that are majorly used in industrial processes. Both water and energy are interdependent where increasing water demand will increase the energy demand and vice versa. In this paper, WENCA is introduced to simultaneously optimise both water and energy system that is interdependent. The methodology applies Cascade Analysis to individually optimise both system. As both systems are interdependent, altering one of the system will result in a change to the other system. An iterative method is then introduced to converge the analysis to obtain the optimal result for both systems. A case study comprising of both electricity and water demand of 6,875 kWh and 3,000 m^3 from a residential area with 1,000 unit of houses is applied in this work. The electricity demand is met using fuel cell where hydrogen is produced through coal gasification (which utilised water as it raw material), a water treatment plant (WTP) is also introduced for water treatment to fulfil the water demands. The optimal result reveals that the WTP capacity is 3,200.73 m^3, its corresponding water storage tank capacity is 175 m^3, hydrogen power plant is 9 MW and its corresponding energy storage capacity is 4.13 MW.

1. Introduction

Pinch Analysis (PA) is a technique to predict optimal performance of a process prior to actual synthesis and design. It is a technique best used at preliminary design stage to assist in decision-making process. Due to this advantage, PA has evolved over the decade from a tool for energy conservation (Linnholff et al., 1982) into an analytical tool for process integration and optimisation. PA can be categorised under two models. The first model as introduced by Linnholff et al. (1982), known as supply-demand model, presents a Pinch method with quality versus quantity without considering time factor. The second model presents a model that relate quantity within a period of time (quality) (Singhvi and Shenoy, 2002).

In addition to these fields of work, Ho et al. (2012) has demonstrated a numerical method based on PA called the Electricity System Cascading Analysis (ESCA). This methodology is very useful for designing and optimising power generators (biomass, biogas, solar and more) and energy storage for energy system.

Previous studies on PA including ESCA only considers a single source of resource during the analysis. In a case of integrating and designing system consisting of multiple resources, there is the possibility that both resource may be intercorrelated affecting the design of the system. For example, water and energy resource in a hydrogen production plant (where the hydrogen is used to produce electricity); pure water is required to produce hydrogen (energy) which then requires electricity for the treatment process, creating an explicit interaction between the both resources. Increasing the demand of electricity (in a hydrogen plant) will increase the demand of water for producing water which will further increase the demand of electricity (to treat water).

There are a clear interdependency of water and energy in many processes. This intrinsic relationship is

Please cite this article as: Ahmad Muzammil Idris, Wai Shin Ho, Liu Wen Hui, Ahmad Fakrul Ramli, Aminullah Mohtar, Haslenda Hashim, Zarina Ab Muis, Jeng Shiun Lim, Peng Yen Liew, 2018, Water-energy nexus cascade analysis (wenca) for simultaneous water-energy system optimisation, Chemical Engineering Transactions, 63, 271-276 DOI:10.3303/CET1863046

commonly known as the water-energy nexus. The water-energy nexus captures the interdependency between the two resources and focuses not only the sustainability of the system (Samanaseh, 2017) but also conserves energy and minimises related greenhouse gas (GHG) emissions. The nexus manifests itself in many ways, revealing substantial trade-offs and opportunity costs involving the ways we use water and energy.

This study will present a new technique to optimise the usage of water and energy through cascade analysis called Water-Energy-Nexus Cascade Analysis (WENCA). WENCA is a modified technique from ESCA, which serve as a resource optimisation tool for processes that has an intrinsic relationship of water-energy nexus. These interactions were not explored in previous studies, as considering the relation between water and energy can improve the design parameter resulting in a more accurate result. Synergies between water and energy systems offer opportunities to compound benefits of new technologies.

2. Methodology

Aim of WENCA is to simultaneously optimise both water and energy system. This chapter will illustrate the step-by-step methodology for conducting WENCA. Noted that the methodology presented below is a generic methodology and water and energy resource is presented as “first resource” and “second resource”. This indicates that the methodology can be applied for any interdependent resources other than water and energy.

Step 1: The first step of WENCA is to determine the system configuration, period of analysis (usually 24 hours) and identifying the two interdependent resources for integration and optimisation. Once the system configuration is determined, then the corresponding data is to be collected. Common data required for WENCA includes, energy and water demand of the system, total energy requirement to operate the water system (kWh/m^3 or kJ/m^3) and total water requirement to operate the energy system (m^3/kWh or kJ/kWh).

Step 2: Start the cascade analysis by selecting one of the resources (hereby refers as the first resource). Estimate an initial capacity of the plant and conduct the cascade analysis for the first resource based on the demand requirement of the first resource. The cascade analysis is based on ESCA (Ho et al., 2012).

Step 3: Calculate the requirement of the other resource (hereby refers as the second resource) required to operate the plant base on the capacity obtain in Step 2. Conduct the cascade analysis for the second resource.

Step 4: Calculate the requirement of the first resource to operate the plant of the second resource. Repeat cascade analysis of the first resource to determine the new plant capacity. Based on the new plant capacity, repeat Step 3 and determine the new plant capacity of the second resource.

Step 5: Compare the new result with the old result, if the difference is less than 5 %, the new results is determined as the optimal capacity of the plant. The corresponding storage capacity for both systems is then extracted. If the difference is more than 5 %, repeat Step 4 and Step 5 until the differences is less than 5 %. For more accurate results, the limit of 5 % can be further reduced depending on the user.

To construct the cascade table, the first column (Column 1) aligns the duration, T, of the analysis (commonly, interval of one hour is use) in a timely manner. Column 2 lists the supply of the resource accordingly to the capacity of the plant, it is assumed that the generation is equal to the capacity of the plant. The total supply, $\mathrm{S_t}$, of the resource can be estimated using Eq(1). $\mathrm{D_t}$ is the total demand of the resource.

$$\mathrm{S_t} = \frac{\sum \mathrm{D_t}}{24} \tag{1}$$

Column 3 list the demands of the resources, with the last sub-column indicating the total demand, $\mathrm{D_t}$. Column 4 list the net demand of the resource, $\mathrm{N_t}$, which can be calculated using Eq(2).

$$\mathrm{N_t} = \mathrm{S} - \mathrm{D_t} \tag{2}$$

If the value is positive (surplus), place the value in Column 5 (charge to storage, $\mathrm{R_t}$). If the value is negative (deficit), place the value in Column 6 (discharge from storage, $\mathrm{DC_t}$). Calculate the cumulative resource in the storage and list it in Column 7. The cumulative resource, $\mathrm{C_t}$ can be calculated using Eq(3).

$$\mathrm{C_t} = \mathrm{C_{t-1}} + \mathrm{R_t} + \mathrm{DC_t} \tag{3}$$

Identify the largest negative value in Column 7 and place it at the top of Column 8 as new cumulative ($\mathrm{CN_t}$), repeat the calculation using Eq(4). The Pinch Point can be identified at the time when the storage is empty.

$$\mathrm{CN_t} = \mathrm{CN_{t-1}} + \mathrm{R_t} + \mathrm{DC_t} \tag{4}$$

The percentage differences, P can be calculated using Eq(5)

$$\mathrm{P} = \frac{|\mathrm{S_{i+1}} - \mathrm{S_i}|}{\mathrm{S_i}} \tag{5}$$

where i is the number of iteration.

3. Case Study, Results, and Discussion

In this work, WENCA is applied to design for a water treatment plant (WTP) and a coal gasification - fuel cell system for power generation. Figure 1a shows the configuration of the water treatment plant and the coal gasification – fuel cell system depicted for this study. In this system configuration, coal is reacted with steam to produce hydrogen, H_2 to produce electricity for a residential area of 1,000 households. Figure 1b shows a conventional process scheme to produce hydrogen by coal gasification. A synthesis gas containing carbon monoxide, CO, H_2, carbon dioxide, CO_2, and water, H_2O is produced by reacting coal with H_2O and oxygen, O_2 above 1000 °C. CO in the synthesis gas is then reacted with H_2O in a Water-Gas Shift (WGS) reactor to produce CO_2 and H_2 (Bell et al., 2011). H_2 is then recovered to produce electricity as shown in Figure 1a, while CO_2 can be captured and stored to prevent its emission to the environment. This study does not include the discussion of CO_2 capture and storage. An external source of river water will be treated and used for gasification process and as supply for residential demand, the excess will be stored.

A typical household with a daily consumption of 165 kWh is estimated for this study. The power plant will also produce electricity to operate the water storage system as well as the water treatment plant. Similarly, the water treatment plant is primarily used to supply water for the residential area with an estimated daily water consumption of 3 m^3 per house. Figure 2 shows the daily water and electric demand for 1,000 houses. Both electricity and water storage are included to store excess energy and water when the demand is low. The energy, DR_t^E and water demand, DR_t^W by the residential are as shown in Figure 2. According to Batelle (2014), 1 m^3 of water can produce up to 2.9 kWh of electricity (through coal gasification and fuel cell conversion). To treat 1 m^3 of water requires 0.6604 kWh of electricity using conventional treatment method (Pabi et al., 2013) (Step 1). For the pump, 0.05 kWh of electricity needed to pump water for an average 10 m long pipe (CottonInfo, 2015).

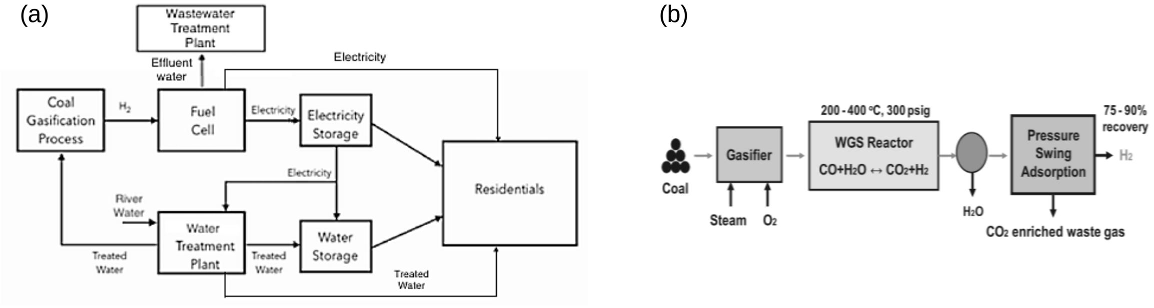

Figure 1: System configuration and process flow of a) Water treatment plant and coal gasification – fuel cell system b) Conventional process of hydrogen production from coal gasification process (Bell et al., 2011)

The analysis begins by performing the cascade analysis for the WTP (water resource). The initial estimation of the WTP is 360 m^3/h of water production, while the resulting WTP capacity is 485 m^3/h (Step 2) In Step 3, the corresponding energy required to operate the WTP is calculated as 320.30 kWh. The energy demand by the WTP is added into the residential energy demand and ESCA is conducted. It was identified that the hydrogen power plant capacity is 7,198.84 kW. In Step 4, the new WTP capacity of 2,607.36 m^3 and hydrogen power plant capacity of 8,600.44 kW was identified. Overall 4 iterations were conducted and the final capacity of the WTP is revealed as 3,200.73 m^3 and the hydrogen power plant capacity is 8,992.3 kW, the water tank storage capacity is extracted and revealed as 175 m^3, while the energy storage capacity is 4125.21 kWh (Step 5).

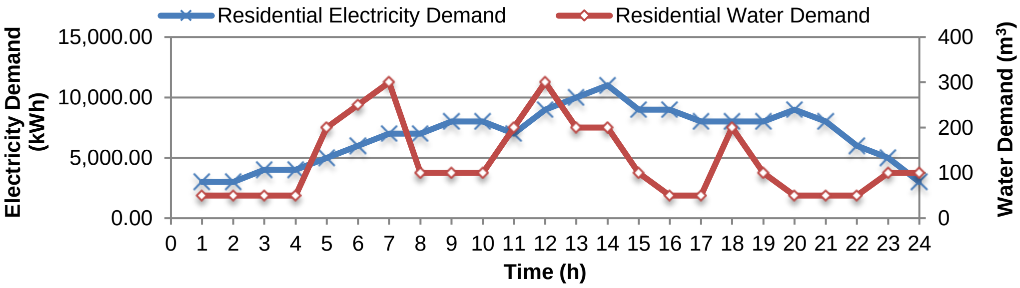

Figure 2: Estimated water and energy demand of residential area with 1,000 households

The summary of the iteration and corresponding capacity for each iteration is as shown in Table 1. Table 2 and Table 3 show the final cascade analysis for the WTP and the hydrogen power plant. The electricity demand of the WTP, DP_t^E is calculated using Eq(6) while the water requirement for the hydrogen power plant, DP_t^W is calculated using Eq(7). The electricity requirement for the pumps, DM_t^E is calculated using Eq(8). The superscript, E represent the hydrogen power plant and superscript, W represent the WTP, including the one presented in cascade tables.

$$\mathrm{DP}_t^E = (0.6604)\mathrm{S}_t^W \tag{6}$$

$$\mathrm{DP}_t^W = \frac{\mathrm{S}_t^E}{2.9} \tag{7}$$

$$\mathrm{DM}_t^E = \mathrm{N}_t^W(0.05) \tag{8}$$

Table 1: Summarised result of Water and Electric Cascade Analysis

Number of Iteration	WTP capacity (m^3)	Water storage capacity (m^3)	Hydrogen power plant capacity (kW)	Energy storage capacity (kWh)
1	485	175	7,198.8	4,125.2
2	2,607.4	175	8,600.4	4,125.2
3	3,090.7	175	8,919.6	4,125.2
4	3,200.7	175	8,992.3	4,125.2

Table 2: WTP Cascade Analysis

Time (h), t_n	S_t^W(m^3)	Water Treatment Demand			N_t^W (m^3)	R_t^W(m^3)	DC_t^W (m^3),	C_t^W (m^3)	CN_t^W (m^3)
		DP_t^W(m^3)	DR_t^W (m^3)	D_t^W (m^3)					
									400
1	3,200.7	3,075.7	50	3,125.7	75	75	0	75	475
2	3,200.7	3,075.7	50	3,125.7	75	75	0	150	550
3	3,200.7	3,075.7	50	3,125.7	75	75	0	225	625
4	3,200.7	3,075.7	50	3,125.7	75	75	0	300	700
5	3,200.7	3,075.7	200	3,275.7	-75	0	-75	225	625
6	3,200.7	3,075.7	250	3,325.7	-125	0	-125	100	500
7	3,200.7	3,075.7	300	3,375.7	-175	0	-175	-75	325
8	3,200.7	3,075.7	100	3,175.7	25	25	0	-50	350
9	3,200.7	3,075.7	100	3,175.7	25	25	0	-25	375
10	3,200.7	3,075.7	100	3,175.7	25	25	0	0	400
11	3,200.7	3,075.7	200	3,275.7	-75	0	-75	-75	325
12	3,200.7	3,075.7	300	3,375.7	-175	0	-175	-250	150
13	3,200.7	3,075.7	200	3,275.7	-75	0	-75	-325	75
14	3,200.7	3,075.7	200	3,275.7	-75	0	-75	-400 (Largest negative)	0 (Pinch Point)
15	3,200.7	3,075.7	100	3,175.7	25	25	0	-375	25
16	3,200.7	3,075.7	50	3,125.7	75	75	0	-300	100
17	3,200.7	3,075.7	50	3,125.7	75	75	0	-225	175
18	3,200.7	3,075.7	200	3,275.7	-75	0	-75	-300	100
19	3,200.7	3,075.7	100	3,175.7	25	25	0	-275	125
20	3,200.7	3,075.7	50	3,125.7	75	75	0	-200	200
21	3,200.7	3,075.7	50	3,125.7	75	75	0	-125	275
22	3,200.7	3,075.7	50	3,125.7	75	75	0	-50	350
23	3,200.7	3,075.7	100	3,175.7	25	25	0	-25	375
24	3,200.7	3,075.7	100	3,175.7	25	25	0	0	400

Table 3: Hydrogen power plant Cascade Analysis

Time, T (h)	S_t^E(kWh)h),	Electricity Demand (kWh)				N_t^E(kWh)	R_t^E (kWh)	DC_t^E(kWh)	C_t^E(kWh)	CN_t^E(kWh)
		DP_t^E	DR_t^E	DM_t^E	D_t^E					
										6629.4
1	8,992.3	2,113.7	3,000	3.7	5,117.5	3,874.8	3,874.8	0	3,874.8	10,504.2
2	8,992.3	2,113.7	3,000	3.7	5,117.5	3,874.8	3,874.8	0	7,749.6	14,378.9
3	8,992.3	2,113.7	4,000	3.	6,117.5	2,874.8	2,874.8	0	10,624.4	17,253.7
4	8,992.3	2,113.7	4,000	3.7	6,117.5	2,874.8	2,874.8	0	13,499.2	20,128.5
5	8,992.3	2,113.7	5,000	3.7	7,117.5	1,874.8	1,874.8	0	15,374	22,003.3
6	8,992.3	2,113.7	6,000	6.2	8,120	872.3	872.3	0	16,246.2	22,875.6
7	8,992.3	2,113.7	7,000	8.7	9,122.5	-130.2	0	-130.2	16,116	22,745.4
8	8,992.3	2,113.7	7,000	1.2	9,115.	-122.7	0	-122.7	15,993.3	22,622.7
9	8,992.3	2,113.7	8,000	1.2	10,115	-1,122.7	0	-1,122.7	14,870.6	21,500
10	8,992.3	2,113.7	8,000	1.2	10,115	-1,122.7	0	-1,122.7	13,747.9	20,377.3
11	8,992.3	2,113.7	7,000	3.7	9,117.5	-125.2	0	-125.2	13,622.7	20,252.1
12	8,992.3	2,113.7	9,000	8.7	11,122.5	-2,130.2	0	-2,130.2	11,492.5	18,121.9
13	8,992.3	2,113.7	10,000	3.7	12,117.5	-3,125.2	0	-3,125.2	8,367.3	14,996.7
14	8,992.3	2,113.7	11,000	3.7	13,117.5	-4,125.2	0	-4,125.2	4,243	10,871.4
15	8,992.3	2,113.7	9,000	1.2	11,115	-2,122.7	0	-2,122.7	2,119.4	8,748.7
16	8,992.3	2,113.7	9,000	3.7	11,117.5	-2,125.2	0	-2,125.2	-5.8	6,623.5
17	8,992.3	2,113.7	8,000	3.7	10,117.5	-1,125.2	0	-1,125.2	-1,131.0	5,498.3
18	8,992.3	2,113.7	8,000	3.7	10,117.5	-1,125.2	0	-1,125.2	-2,256.2	4,373.1
19	8,992.3	2,113.7	8,000	1.2	10,115	-1,122.7	0	-1,122.7	-3,379	3,250.4
20	8,992.3	2,113.7	9,000	3.7	11,117.5	-2,125.2	0	-2,125.2	-5,505	1,125.2
21	8,992.3	2,113.7	8,000	3.7	10,117.5	-1,125.2	0	-1,125.2	-6,629.4 (Largest negative)	0 (Pinch Point)
22	8,992.30	2,113.76	6,000	3.75	8,117.51	874.79	874.8	0	-5,754.6	874.8
23	8,992.30	2,113.76	5,000	1.25	7,115.01	1,877.3	1,877.3	0	-3,877.3	2,752.1
24	8,992.30	2,113.76	3,000	1.25	5,115.01	3,877.3	3,877.3	0	0	6,629.4

Table 4 shows the design capacity comparison if the system configuration use water and energy integration through WENCA analysis and without integration (water and energy operate in silo or on its own process). With integration of the resources, the result shows a very high amount compared to without integration. For example, WPT capacity and Hydrogen power plant capacity shows a very high result due to the supply for the residential is only considered if the resource integration has been done. Where as, battery is only needed for storage purpose if the integration is considered in the system. This modification within the process with integration of energy and water can be termed as dual generation of water and power and thus can be further considered for coal gasification plant that located near residential.

Table 4: Design capacity comparison with integration and without integration of water and energy

Method	WTP capacity (m^3)	Water storage capacity (m^3)	Hydrogen power plant capacity (kWh)	Battery capacity (kWh)
With Integration	3,200.7	175	8,992.3	4,125.2
Without integration (Residential)	125	175	-	-
Without integration (Power Plant)	-	-	3,139.4	-

4. Conclusion

Since water and energy systems are interdependent and closely related, more comprehensive macro-level studies that aim to provide a holistic view of WEN at a specific industry and simultaneously consider water for energy and energy for water – as performed in this case study are needed to increase our current knowledge on how to help design engineers and decision-makers resolve issues in regional resource management. Continuous research and methodology is also needed to ensure the WEN studies able to prevent the resource scarcity as the main objective. Introducing new methodology would able the researchers and engineers to understand better on nexus thinking and provide better solution specially to reduce GHG emissions due to resource consumption.

In this paper, a new and novel technique of water-energy nexus through integration using cascade analysis called WENCA is presented. Through the case study, it can be concluded that WENCA is capable to determine the WTP capacity, water storage capacity, fuel cell capacity and battery capacity with better accuracy. This is particularly useful for design engineers to develop an integrated system between water and energy to optimise resources usage through water-energy nexus theory. While WENCA is able to reveal the optimal capacity and scheduling of the system, further improvement is required to enhance the capability of WENCA. Efficiency losses of the water and energy system should be considered.

The future work on WENCA will include efficiency losses and possible interdependency of other resources other than water and energy.

Acknowledgments

This research paper is financially supported by the Universiti Teknologi Malaysia (UTM) under the Grant vot no. Q.J130000.2446.03G61 and Grant vot no. Q.J130000.2546.12H89.

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