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Optimal Sizing and Costing of Water-Energy Nexus System

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Energy as well as water are two valuable resources that are majorly utilized in all sectors, from residential consumption to industrial processes. As conservation of resources are becoming a priority, optimization of energy or water system for residential and industrial usage is becoming more important. Previous optimization problems solved using Pinch Analysis only focused on optimization of single resource which may lead to under-sizing of system, as systems may rely on one another to operate. By using pinch analysis, it lacks the capability to consider other variables such as cost in its analysis. As such, a MILP model is developed in this study to provide a more holistic approach to the optimization problem. 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 results revealed the capacity of the system is larger compared to the similar case study done using pinch analysis. The resulting cost of the system is MYR 516,650,000.00. Apart from identifying the optimal capacity and cost of the system, the study concluded that the higher the interdependency of resources, the differences become more significant. When analysing system that shows an inter-dependent or nexus nature, it is important to consider both resources and target them simultaneously to prevent the system being under-designed.

1. Introduction

Energy and water are essential for physical, social and economic wellbeing. In recent times, changes to the energy and water industries; have brought into sharp focus the link between the two - termed energy-water nexus. With the growing demand of the most valuable resources of water and energy, further research and understanding of the concept of water and energy interdependency is receiving more attention with the aim to conserve both resources. What appears to be lacking is an informed understanding of the nature of the nexus and policy tools to assist decision makers develop more integrated energy and water policies. The establishment of the nexus understanding is also still at surface. Understanding the challenges and developing solutions will necessitate early engagement with proper stakeholders, including federal agencies, state and local governments and international partners.
Previous study on water and energy system using Pinch Analysis has been designed as a separate system. Conventionally, Electricity System Cascade Analysis (ESCA) methodology can be used to calculate the design capacity of a power plant along with its energy storage (Ho et al., 2012) by using pinch analysis concept. Similar cascade table can be also applied to calculate the design capacity of water treatment system along with its water storage tank capacity. DiMartino et al. (2021) studied about optimization framework for the design of reverse osmosis desalination plants under food-energy-water nexus considerations. A Pareto Front for minimizing operational cost and maximizing the permeate flow for water for irrigation was proposed in their study. Idris et al. (2018) introduced an integrated dual resources optimization called Water-Energy Nexus Cascade Analysis (WENCA). The study was also later extended to consider the nexus of product and energy (Idris et al., 2019). The study has concluded that conducting individual assessment of both resources during the

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design stage might result to both systems being undersized. This is majorly due to the reason that the interdependency between these two most critical resources has been ignored. When a system is undersized, this will affect the system as overall and in worst case scenario, the system needs to be re-designed as there will complicated issues during operation. The limitation of WENCA (and as general for Pinch Analysis); it only capable to illustrate two-dimensional analysis. Feasibility, economic relevance and detailed technical consideration of the processes are key drivers of the decision process concerning optimisation studies. These factors such as costing and applying feasible design constraints could not be inclusively comprehended in Pinch Analysis. Due to such limitations and to take into count economic factors, this study will present a MILP model with the objective to model optimal sizing and calculate the overall costing of water-energy nexus system. A case study will be presented to compare the results obtained using the mathematical model with WENCA.

2. Methodology

This section describes the model formulated for this study. The list of indices, parameters and variables of the model is shown in Table 2.1. In this work, the case study was depicted from Idris et al., (2021), using fuel cell system to represent the water-energy nexus. The case study used to design a water treatment plant (WTP) as a water system and an integrated gasification-fuel cell (IGFC) system for power generation. 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. 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 1,000 °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 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. 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 Idris et al., (2021). Both electricity and water storage are included to store excess energy and water when the demand is low.

The objective function of the MILP model is to minimize the total cost of the system. The formulation is shown in Eq(1). The details of each cost breakdown (annual operating cost, AOC and amortized investment cost, AIC) are shown in Eq(2) and Eq(3). The amortized investment cost on the other hand consists of capital costs of IGFC Power Plant, and ES (based on power-related and energy-related capital cost). The annual operating cost consist of the IGFC Power Plant fixed O&M cost, ES fixed O&M cost, WTP fixed O&M cost and WS fixed O&M cost. These costs are amortized monthly and multiplied by the total months to obtain the annual investment cost.

For energy system, the cost per kW (ic) is multiplied with the IGFC capacity (IGFCCap) and its amortization factors. This is then added with storage cost (sce) with its energy capacity with its amortization factor. The equation also considers water system in which wc is water storage cost per m^3 and wt is water treatment cost per m^3 multiply by their respective capacity, WSCap and WTPCap along with amortization factor. Operations and maintenance cost for each system represented as om1 for IGFC, om2 for ES, om3 for WS and om4 for WTP multiplied by each capacity to get the annual operation cost, AOC.

$$\text{Annual Cost (AC)} = \text{Annual Investment Cost (AIC)} + \text{Amortized Operating Cost} \tag{1}$$

$$AIC = ic \cdot IGFCCap \cdot af \cdot m + sce \cdot ESCapE \cdot af \cdot m + ESCapP \cdot scp \cdot af \cdot m + wc \cdot WSCap \cdot af \cdot m + wt \cdot WTPCap \cdot af \cdot m \tag{2}$$

$$AOC = om1 \cdot IGFCCap + om2 \cdot ESCapP + om3 \cdot wc \cdot WSCapP + om4 \cdot WTPCapP \tag{3}$$

The operation of IGFC Power Plant is formulated as a set of energy balances (equality constraints). Residential energy demand is supplied by IGFC (E1) and ES (E3) as in Eq(4). WTP energy demand as in Eq(5) explains the water supply from WTP which is W1, W2 and W5 multiplied with its conversion factor fwtoe. Each demand is then divided with pump efficiency, pumpeff. Then this water amount is converted into energy using fpump conversion. WTP energy supply from IGFC and ES is shown in Eq(6) and WS energy supply from IGFC and ES as in Eq(7) as well as energy required by pump Eq(8). Eq(9) shows the total energy demands, E1, E2, E4 and E5. In Eq(10), total energy demand is summed along with power plant reserve (fres) of 20 % and energy required by the power plant itself (fpp). In Eq(11), IGFC Capacity is specified.

$$rese = E1 + E3 \tag{4}$$

$$WTPEd = ((W1+W5+W2)\cdot fwtoe)+((W1/pumpeff)\cdot fpump)+((W5/pumpeff)\cdot fpump)+((W2 /pumpeff)\cdot fpump) \tag{5}$$

$$WTPEd = E4 + E6 \tag{6}$$

$$WSEd = E5 + E7 \tag{7}$$

$$WSEd = ((W3 /pumpeff)\cdot fpump) + ((W4/pumpeff)\cdot fpump) \tag{8}$$

$$IGFCESTot = E1 + E2 + E4 +E5 \tag{9}$$

$$IGFCES = IGFCESTot +(IGFCESTot \cdot fpp) + (IGFCESTot \cdot fres) \tag{10}$$

$$IGFCCap \geq IGFCES \tag{11}$$

With regards to ES operation constraints, Eq(12) states the cumulative amount of energy in ES, ESCum. With the assumption that the ES operated in a daily continuous cycle, there is a need to ensure that the operation of the ES could run continuously and stable regardless of changing weather and day. Eq(13) constrain the power-related ES capacity, ESCapP (charging/discharging of ES per hour must be equal or less than the power-related ES capacity). Eq(14) is formulated such that the initial content of the ES is of the same amount as initialamountE. Eq(15) bounds the operation of the ES between charging and discharging state (only one state at a time), where binary variable $energyin_{t,}$ indicates the charging status (1 charging, 0 otherwise) and binary variable $energyout_t$ indicates the discharging status (1 discharging, 0 otherwise). Eq(16) and Eq(17) are formulated to avoid non-linear terms in the model where ln is a very large value (Mirzaesmaeeli et al., 2010). Lastly, Eq(18) limits the energy-related ES capacity (total energy accumulated in the ES, ESCum must be equal to or less than the energy-related ES capacity, ESCapE with consideration of depth of discharge, esdod).

$$ESCum = ESCum + (E2\cdot eseff) - (E3+E6+E7/pumpeff) \tag{12}$$

$$ESCapP \geq E3 + E7 + E6 \tag{13}$$

$$ESCum = initialamountE \tag{14}$$

$$Energyin + Energyout = 1 \tag{15}$$

$$E2 \leq Energyin \cdot ln \tag{16}$$

$$E3 + E7 + E6 \leq Energyout\cdot ln \tag{17}$$

$$ESCapE \geq ESCum/esdod \tag{18}$$

For WTP operations, Eq(19) shows the water supply to residential, resw from WTP (W4) and WS (W5). Whereas, Eq(21) shows the water supply to IGFC, IGFCWd power plant from similar sources as residential. Eq(21) shows the conversion of energy to water, fetow for IGFC Power Plant (IGFCES). Lastly, Eq(22) limits the WTP capacity, WTPCap (WTP capacity must be larger than the total water supply, WTPWs).

$$resw = W4 + W5 \tag{19}$$

$$IGFCWd = W1 + W3 \tag{20}$$

$$IGFCWd = IGFCES \cdot fetow \tag{21}$$

$$WTPWs \le WTPCap \tag{22}$$

With regards to WS operation constraints, Eq(23) shows the cumulative amount of water in WS, WSCum. Eq(24) limits the WTP capacity (WTP capacity must be larger than the total water supply). Similar to ES operation, WSCum in Eq(25) is formulated such that the initial content of the WS is of the same amount.

$$WSCum = WSCum + W2 - W3 - W4 \tag{23}$$

$$WSCum = initialamountW \tag{24}$$

The mathematical model was coded in General Algebraic Modelling System (GAMS) and with the objective to minimise the total annual cost, the model is solved via CPLEX 12.3.0.0. The GAMS model statistics are shown in Table 5.7. To run the GAMS software, the machine used to run on an Apple MacbookPro (64-bit) with MacOS High Sierra Operating System with an Intel Core i7 @ 2.8 GHz processor, and an installed memory of 4 GB. The program run about 20 seconds to solve the model.

3. Results and discussion

This case study involves the design of an integrated system of water and energy supply for residential. A typical family household (double story house) with 165 kWh of daily consumption has been estimated based on the case study by Idris et al. (2021). The power plant will not only produce electricity for the operation of water storage system but also for the operation of the water treatment plant. The water treatment plant is estimated to supply an amount of 3 m^3 of water per house (for their daily consumption) and electricity for 50,000 unit of houses. Excess energy and water are stored by both electricity and water storage during low demand. The system components consist of IGFC plant and Lithium-Ion (Li-ion) ES system. To meet the residential load demands, the system will be supplied with electricity generated from the IGFC and/or stored in the Li-ion battery unit. Note that any energy drawn from the Li-ion battery unit must have been previously stored on it; utilizing energy generated from the IGFC. Electricity supplied from IGFC to the Li-ion storage system has to be inverted from AC to DC before it can be stored, while energy supplied from the Li-ion battery to the demand load has to be inverted from DC to AC. Similarly, water is obtained from river and processed to produce potable water for residential and power plant. The excess water will be storage in WS system.

For the capital cost of the system, the investment is assumed to be amortized monthly for 30 y at an interest rate of 7 % (Ho et al., 2012). The process configuration within the IGFC power plant is divided into 5 main plant sections, which is gasifier, gas cleaning, air separation unit, steam cycle and fuel cell island. Coal as received has a high heating value (HHV) of 27,113 kJ/kg (Bell et al., 2011). With such system, NETL (2009) reported an overall cost of 1,773 USD/kW. Considering inflation rate for 10 y (from 2009 to 2019), the price is 2,000 USD USD/kW. Fu et al. (2018) in their study summarizes the capital cost of Li-ion Energy Storage System with 780 /kW. This price is then converted to local currency giving a rate of 3,260 MYR/kW (based on first week of June 2021 average currency exchange rate with 4.18 MYR/USD). While the fixed O&M cost resulted in 37.3 MYR /kW. The charging and discharging efficiency of ES is assumed as 92.2 % while ESDOD is 80 % (Ho et al., 2012). For the WTP, the system delivers water to a single distribution zone at approximately 75 psig, which is typical for water treatment systems. The total building cost for an average capacity of 10,000 m^3 to 12,000 m^3 is estimated of USD 14,900,000 after inflation (Rogers, 2008). This is then converted to local currency to MYR 62,200,000. The capital cost of ground level storage tank is 800 MYR/m^3 while the O&M cost is 10 % of the capital cost for every 5 y (CECTanks, 2019).

The results shows that total annual cost for the system is MYR 516,650,000. This cost is including amortized investment cost of MYR 404,520,000 and annual operation cost of MYR 112,140,000. The results obtained also is compared with WENCA case study results. The summarized sizing or capacity of each subcomponent in this case study by using mathematical model is shown in Table 1 below.

For the capacity, the analysis of each capacity programmed in the mathematical model will be discussed. The results obtained from this case study using mathematical modeling shows different results in terms of capacity compared to the one achieved using WENCA methodology.

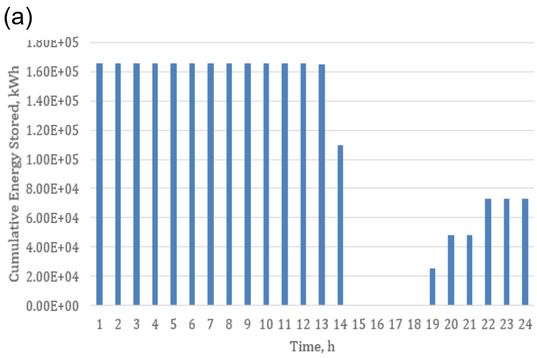
The result shows that the IGFC capacity achieved is 495,366.91 kW. The result shows a difference of 29.5 % compared to WENCA. This is due to three main reasons. Firstly, the IGFC power plant efficiency has been considered in this case study that is 37.7 %. This efficiency percentage has been incorporated in the mathematical model and not in WENCA case study due to the simplicity of the method. Secondly, the higher difference is also due to the consideration of 10 % power plant reserve. In general, power plant is best to have a reserve capacity up to 20 % of its maximum demand (Ramli et al., 2018). Since this case study has ES which functions to store excess energy produced by IGFC power plant, only 10 % of the reserve has been considered. This consideration causes the power plant capacity achieved in this case study to be higher compared to WENCA. The capacity of IGFC power plant is higher since the energy storage size achieved in this case study is smaller compared to WENCA. The reduced size of ES is compensated with some higher capacity of IGFC power plant. It has been identified that, the capacity for ES in this study has reduce to almost half of the size achieved in WENCA. This is mainly due to the fact that the capital cost to build ES and also the operating cost of ES is higher compared to building and operation of IGFC power plant. The model has optimally identified the optimum capacity of IGFC and ES so as to minimize the total cost. Hence, the capacity of ES achieved in this case study is smaller compared to the one achieved in WENCA case study. The cumulative energy content of the ES is shown in Figure 1 below.

Based on Figure 1a, the Lithium-ion battery is being charged continuously from 1st hour till the 12th hour. Then, there is a small drop at the 13th hour while a significant drop of the energy content is seen at the 14th hour. While almost all the energy stored is been utilized at the 15th hour and there is no reserved energy from 16th hour till 18th hour. Energy is then stored again at the 19th hour with significantly increasing amount of storage till the final hour of the day. From the energy demand for residential, it can be divided into three parts of trends i.e. base load, intermediate load and peak load as shown in Figure 1b.

Referring to Figure 1b, the demand is at peak starting from the 12th hour of the day. Then the highest load at the 14th hour till the 17th hour of the day. Also at the 19th hour continuously for two hours. The demand is then dropping to intermediate load region, then with significant low demand causing it to reach to base load.

Table 1: Capacity of each subsystem

Capacity Type	Unit	Capacity (Mathematical Model)	Capacity (WENCA)
IGFC Power Plant	kW	495,366.91	359,782.49
ES Storage (Energy)	kWh	107,509.88	206,260.42
ES Storage (Power)	kW	100,681.82	-
Water Treatment Plant	m^3	10,973.86	7,207
Water Storage	m^3	48,345.33	35,000



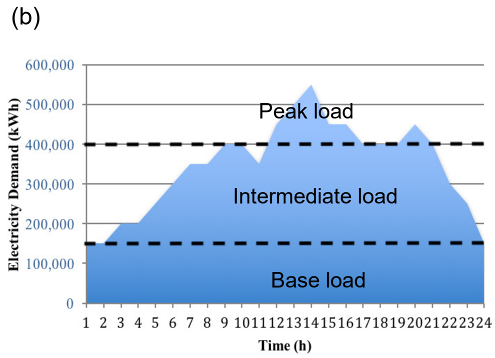


Figure 1: (a) Cumulative energy content in ES and (b) Sectionalized electricity demand for 24 h

As shown in Figure 1b, during peak load, the power plant will supply electricity to the highest possible amount. When there is deficit amount electricity needed to cater the demand, ES will then supply electricity from the storage. Hence, there is a significant drop of cumulative energy in storage during the peak demand. On the other hand, the energy stored during the 24th hour is 73,400 kWh (the final hour of the day). However, the energy stored on the first hour of the following day, the amount reached to the maximum capacity (160,000 kWh). Theoretically, this is still achievable by the ES system since the charging capacity or ES capacity (by power) is 100,681 kW.

The sizing of WTP resulted in 10,973.86 m^3, that shows a difference of 52.3 % compared to case study using WENCA methodology. This huge difference is mainly due to the fact that the IGFC consumption is doubled in this case study with 37.7 % increment. Since similar conversion factor has been used in this case study, this increment can be concluded is due to the increased capacity of IGFC that leads to further increment of water consumption by IGFC. This proves that the model has applied the water-energy nexus conversion and proving that with the increment of one resource capacity will affect another resource's capacity. The capacity achieved is also comparatively higher than achieved in WENCA case study. Since the system considered the inter-relation between water and energy, changing one capacity will lead to change of another resource's capacity. If this inter-relation such as explained in water-energy nexus theory is not considered, neither the capacity of water system nor energy will be affected if any of the system is introduced with changes. WS capacity achieved in this case study is 48,345.33 m^3. Similar to energy system configuration, during the peak demand of water; water treatment plant will supply water to the highest possible amount. When there is deficit amount water needed to cater the demand, water is then will be supplied from the storage. The capacity of WS using mathematical model is higher compared to WENCA. This is also due to the fact that in latter case study, the energy capacity is higher, making the amount of water demand will be higher as well. This proves that when the water-energy nexus method is considered, the increment of one resource capacity will affect the second resource's capacity.

4. Conclusion

Since water and energy systems are interdependent and closely related, more comprehensive macro-level studies are needed to increase our current knowledge on how to help design engineers and decision-makers resolve issues in regional resource management. In this paper, an MILP model has been proposed to optimize water and energy in a single model. The results from this case study show that the achieved capacities are higher compared to the one achieved in WENCA case study. The highest differences achieved are by WTP capacity with 52.3 % of difference compared to WENCA case study. This is due to the increased capacity of IGFC Power Plant leading to increased amount of water required making the capacities of WTP; consequently, WS will be higher. Since the system considered the inter-relation between water and energy, changing one capacity will lead to the change of another resource's capacity. This implies that the consideration of water and energy interdependency must be taken account while designing a system involving both resources.

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