MULTIPLE-RESOURCES TARGETING USING WATER-ENERGY NEXUS CASCADE ANALYSIS AND MATHEMATICAL MODELLING

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ABSTRACT

Energy and water are two valuable resources that are mainly utilized in all sectors, from residential consumption to industrial processes. As conservation of resources are crucial, optimisation of energy and water system is becoming important. Pinch technology is an outstanding methodology and well known for its simplicity among the various targeting techniques. Previous targeting problems which are solved using the pinch analysis only focused on optimisation of single resource which may lead to under-sizing of system, as systems may rely on one another to operate. The water-energy nexus cascade analysis is introduced with the purpose to concurrently target both water and energy system. A case study involving a residential community comprising of 50,000 household unit with daily electricity demand of 343,750 kWh and water demand of 150,000 m3 is adapted. An integrated gasifier fuel cell is used to meet electricity demand while a water treatment plant is used to meet clean water demand. The results show the highest difference of 9.1% of the system capacities compared to methodology using single resource targeting method such as electric system cascade analysis. Sensitivity analysis is also performed to study the significance of capacity differences if higher water or energy conversion rate is imposed. Nevertheless, water-energy nexus cascade analysis, similar with other pinch and cascade analysis, it lacks the capability to consider other variables such as cost in its analysis. As such, a mathematical model is developed to provide a more holistic approach to the targeting problem. It’s revealed that using the mathematical modelling, the capacity of the system is larger. The resulting cost of the system is MYR 516.65 million. Apart from identifying the optimal capacity of the system, the study concluded that the higher the interdependency of resources, the differences becomes more significant. Therefore, when analysing system that shows an inter-dependent nature, it is important to consider both resources and target them simultaneously to prevent the system from being under-designed.

ABSTRAK

Tenaga dan air adalah dua sumber berharga yang digunakan secara besar-besaran di semua sektor, dari penggunaan kediaman ke proses perindustrian. Oleh kerana keabadian sumber menjadi keutamaan, pengoptimuman sistem tenaga dan sistem air menjadi penting. Teknologi jepit adalah kaedah yang terbaik dan dikenali kerana ianya mudah diguna berbanding pelbagai teknik sasaran yang lain. Masalah sasaran sebelumnya yang diselesaikan menggunakan analisis jepit hanya memberi tumpuan kepada sasaran sumber tunggal yang mungkin akan menjadikan sistem mungkin terkurang saiz, kerana sistem mungkin bergantung kepada satu sama lain untuk beroperasi. Analisis lata air-tenaga diperkenalkan dengan tujuan untuk sasar kedua-dua sistem air dan tenaga secara serentak. Satu kajian kes melibatkan komuniti kediaman yang terdiri daripada 50,000 unit rumah dengan bekalan elektrik harian 343,750 kWJ dan permintaan air sebanyak 150,000 m3 adalah digunakan. Suatu sel bahan api gas bersepadu digunakan untuk memenuhi permintaan elektrik manakala loji rawatan air digunakan untuk memenuhi permintaan air bersih. Hasilnya menunjukkan perbezaan tertinggi 9.1% daripada kapasiti sistem berbanding metodologi menggunakan kaedah sasaran sumber tunggal seperti analisis lata sistem elektrik. Analisis sensitiviti juga dilakukan untuk mengkaji kepentingan perbezaan kapasiti jika kadar penukaran air atau tenaga yang lebih tinggi dikenakan. Walau bagaimanapun, analisis lata air-tenaga adalah sama dengan analisis jepit dan lata yang lain, ia tidak mempunyai keupayaan untuk mempertimbangkan pembolehubah lain seperti kos dalam analisisnya. Oleh itu, model matematik dibangunkan untuk menyediakan pendekatan yang lebih holistik kepada masalah sasaran. Penggunaan permodalan matematik mendedahkan bahawa kapasiti sistem adalah besar. Kos yang terhasil adalah sebanyak MYR 516.65 juta. Selain daripada mengenal pasti keupayaan optimum sistem, kajian menyimpulkan bahawa semakin tinggi saling kebergantungan sumber, perbezaan menjadi lebih penting. Oleh itu, apabila menganalisis sistem yang menunjukkan sifat saling bergantung, adalah penting untuk mempertimbang kedua-dua sumber dan mensasarkan mereka secara serentak untuk mengelakkan daripada sistem tersasar daripada yang direkabentuk..

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LIST OF ABBREVIATIONS

BAU	-	Business as Usual
CEPA	-	Carbon Emission Pinch Analysis
CO_2	-	Carbon Dioxide
COSM	-	Cost-Optimisation Superstructure Model
CSCC	-	Carbon Storage Composite Curve
ES	-	Energy Storage
ESCA	-	Energy Storage Cascade Analysis
GAMS	-	General Algebraic Modelling System
GDP	-	Gross Domestic Product
GHG	-	Green-House Gas
IGFC	-	Integrated Gasification Fuel Cell
LFP	-	Lithium-Iron Phosphate
LMO	-	Lithium Manganese Oxide
LP	-	Linear Programming
MILP	-	Mixed Integer Linear Programming
MINLP	-	Mixed Integer Non-Linear Programming
NBP	-	National Biofuel Policy
NLP	-	Non- Linear Programming
NMC	-	Nickel Manganese Cobalt Oxide
PEMFC	-	Proton Exchange Membrane Fuel Cell
WAMPA	-	Waste Management Pinch Analysis
WENCA	-	Water-Energy Nexus Cascade Analysis
WS	-	Water Storage
WTP	-	Water Treatment Plant

LIST OF SYMBOLS

S_t	-	Total resource supply
N_t	-	Resource demand
D_t	-	Total demand
C_t	-	Cumulative resource
CN_t	-	New cumulative
P	-	Percentage of differences
i	-	Number of iteration
t_n	-	Time
DP_t	-	Demand by power plant
DM_t	-	Demand by pump

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CHAPTER 1

INTRODUCTION

1.1 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. The recent emergence of the phenomenon as a critical issue is significant for the understanding of nexus nature. Chapter 1 gives an overview introduction on the water-energy nexus nature. The next sub-chapter 1.2 present the research background about Water-Energy Nexus as well as the problem statement. Next, section 1.3 and section 1.4 revealed the objectives and scope of this study. Finally, the significance of this research is presented in section 1.5.

1.2 Research Background

Water and energy are fundamental to human existence. Both resources have shaped the development of societies during the history of mankind: water resources have influenced human settlement patterns; and energy has been an important enabler to perform routines. Both resources have been ineradicably utilized since decades ago; from the early use of animal and waterpower, to more technically advanced forms such as steam power and later revolution of electricity generation. In a modern society, water and electricity are interdependent. Water is critical for electricity generation, and electricity is critical for water treatment and transportation. For example, over 41% of world electricity generation relies on water-intensive coal-fired power stations and water transportation consume approximately 7% of the energy produced worldwide

(Meldrum, et al., 2013). The fundamental role of both infrastructure industries for general economic development and social wellbeing further strengthens the importance of the interdependency between the two.

Energy is widely recognized to be a critical enabler of modern society. Yet, energy drives a nation's development. From basic living requirement to the operations in industrial and commercial activities, energy plays a vital role. In 2014, world primary energy supply amounted to 155,481 terawatt-hour (TWh) or 13,541 million tonnes oil equivalent (Mtoe) [IEA, 2016]. This demand was met from a variety of primary sources including approximately 31.5% from oil, 28.8% from coal, 21.3% from natural gas, 10.0% from biomass, 5.1% from nuclear fission, 2.3% from hydroelectric, and 1.0% from all other miscellaneous sources including wind, solar photovoltaic, solar thermal and geothermal. Important questions include how will this demand will likely change going forward, how the demand will likely be met, and what might be some of the challenges and consequences in meeting that demand. In this subtopic, the world energy outlook is overviewed and later the discussion is scoped down to national (Malaysia) level.

Figure 1.1 explains the trend of global primary energy consumption from 1965 to 2013 according to its resources. As analyzed, the global energy demand has continued to grow, mainly from fossil fuels. While within fossil fuels, coal shows a tremendous increase compared to others. Fossil fuel supply was up 183 Mtoe in 2013 while new renewable supply was up 42 Mtoe from 2012. In 2003, new renewables (wind, solar, geothermal, biofuels etc) accounted for 0.82% of total primary energy and by 2013 this had grown to 2.69%. In 2003, nuclear power accounted for 6.01% and this fell to 4.40% in 2013. The 1.87% growth in share of new renewables almost matches the 1.61% fall in the share of nuclear power.

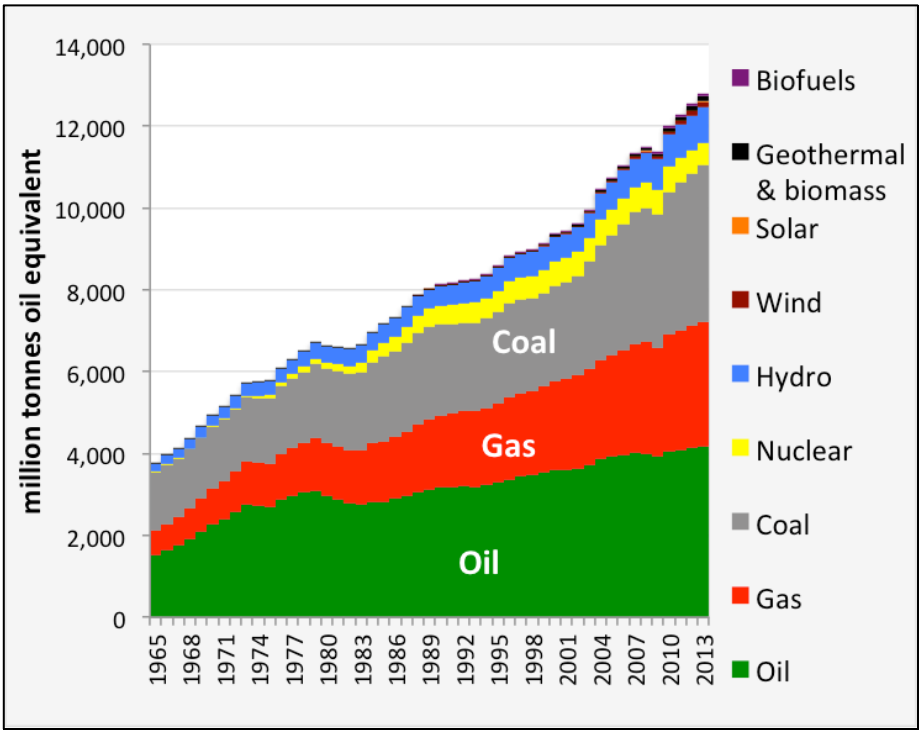

Figure 1.1 Global primary energy consumption (IEA, 2016)

Besides, fresh water is a critical resource for humanity and the ecosystem. In general, water resources can be partitioned into two major categories: blue water and green water (Falkenmark and Rockström 2006). Precipitation that runs off or percolates into the deep aquifer is defined as blue water, and precipitation that filtrates into soil, which eventually returns to the atmosphere as evaporation, is called green water (Hoekstra et al. 2011). For human purposes, green water is almost exclusively used for agricultural production, but blue water can be used for multiple competing sectors, such as irrigation and municipal water.

Since population distribution, climatic and hydrologic conditions vary significantly around the world (Kummu *et al.* 2014), there is often a mismatch between water demand and water supply. In fact, most populated regions are also water-scarce areas (Kummu and Varis 2011). In order to quantify to what extent water supply may fall short of human and environmental needs, a diverse set of water availability indicators has been developed over the past 30 years. Major categories of indexes include water crowding indexes and various demand- to-supply ratios.

At global level, the withdrawal ratios are 69 percent agricultural, 12 percent municipal and 19 percent industrial. These numbers, however, are biased strongly by the few countries, which have very high water withdrawals. Averaging the ratios of each individual country, its suitable to describe "for any given country" these ratios are 59, 23 and 18 percent respectively (Kummu *et al.* 2014). At global level, amount of water consumption had increased tremendously over the decades. The described trend according to sectors is further illustrated in Figure 1.2 below.

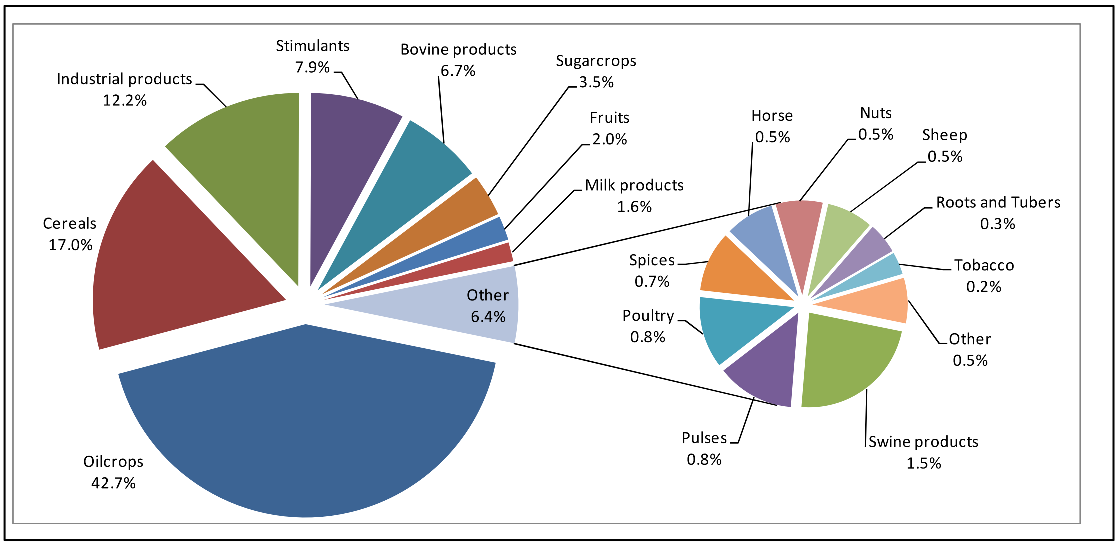

Figure 1.2 Contribution of different product categories to the global virtual water flows (Meknonnen and Hoekstra, 2011)

The largest share of the international virtual water flows relates to trade in oil crops (including cotton, soybean, oil palm, sunflower, rapeseed and others) and derived products. This category accounts for 43% of the total sum of international virtual water flows. More than half of this amount relates to trade in cotton products; about one fifth relates to trade in soybean. The other products with a large share in the global virtual water flows are cereals (17%), industrial products (12.2%), stimulants (7.9%) and beef cattle products (6.7%) (Meknonnen and Hoekstra, 2011).

With the statistics of increasing demand mentioned above, it is becoming a challenge to continuously meet these demand due to environmental impact as well resource scarcity or depletion. Sustainable technologies which may solve both environmental and resource scarcity is not as competitive compared to conventional technologies in the aspect of economics and efficiency. Hence, optimisation study is essential to ensure the system built can run in optimum parameters without shortfall. This is further studied in process systems engineering and will be explained in the next subchapter.

With the growing concern for water and energy security globally, research and understanding on interdependency between water and energy is receiving incredible attention as an effort to conserve both resources. Countries across the globe had developed policies to ensure the sustainability of water and energy, and is calling for more detailed studies on water-energy nexus to be done to improve the policies that existed today (Healy *et al.*, 2015). The links between water and energy are many and varied, connecting different functions to cater the supply-demand process. Generally, energy is required to extract, purify, deliver, heat or cool, treat and discharge of water or wastewater. Energy generation consumes water either to process the raw materials used in the facility or to generate the electricity itself. Conserving energy can lower the demand on water resources; and increasing water treatment efficiency can also reduce the amount of energy consumed to transport, heat and treat water (Dai *et al.*, 2018).

Whereas, the interdependency between water and energy, sometimes called the water-energy nexus, is growing in importance as demand for both water and energy increases. Figure 1.3 shows the water-energy nexus, it can be seen that water is required in fuel production, power generation (as hydropower), extraction and refining process as well as for thermos-electric cooling. Energy on the other hand is also required for fuel production, extraction and transmission, wastewater treatment and drinking water treatment (Cabezas & Huang, 2015). This nature shows that especially in the context of targeting and designing of a water-energy system, both resources must be considered simultaneously.

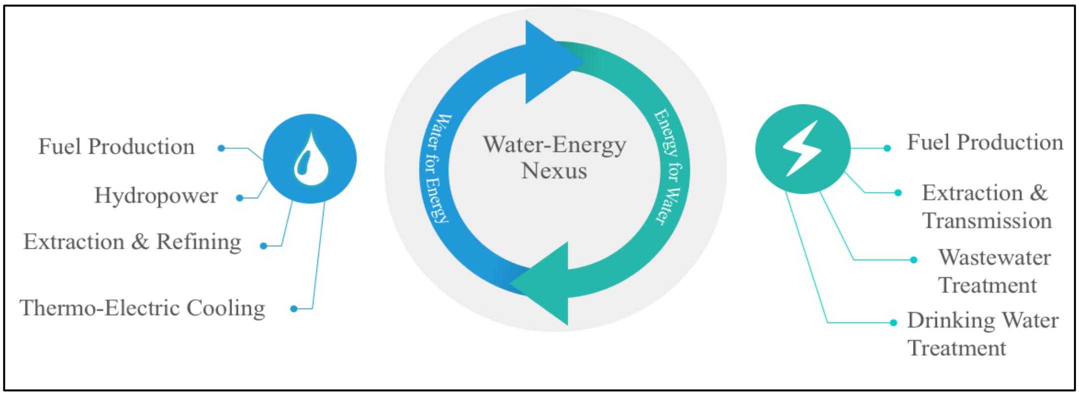

Figure 1.3 The relationship between water and energy using nexus theory

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. On the other hand, 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. Advances throughout the technology advancement from research and development, demonstration and deployment can address key challenges. Potential applications of interest for technology solutions cover several broad areas, including water efficiency in energy systems, energy efficiency in water systems, and productive use of non-traditional waters such as reused water (NETL, 2018).

The next step is to conduct a technology research portfolio analysis, addressing risk, performance targets, potential impacts, R&D pathways, and learning curves. A strong analysis will highlight potential synergies for technologies that span multiple programs. Hence, this research is conducted to further identify the relationship between water-energy nexus relationship in an Integrated Gasification Fuel Cell (IGFC) to supply electricity for residential demand coupled with water treatment plant to supply water. The study will focus on developing methodology to identify preliminary design capacities or sizing of water and energy system.

1.3 Problem Statement

Renewable technologies that can ensure resource sustainability is often expensive and lower in efficiency compared to conventional systems. In order to improve the efficiency of the system, researchers has suggested resource integration and targeting of such system to achieve optimality in resource management and consumption. Among the techniques, mathematical modelling often used to provide holistic and optimal solution to the design and operation of an integrated system. However mathematical modelling lack of illustration in term of its approach in determining the optimal result. Pinch Analysis on the other hand, although lack the capability to consider multiple variables in its analysis, are still widely utilized as a go-to targeting method and option as it provides users with full illustration on how the optimal result is determined.

Previous study on water and energy system using Pinch Analysis has been designed as a separate system. Conventionally, given a specific energy demand, Electricity System Cascade Analysis (ESCA) can be used to determine the required capacity of the power plant and the energy storage in order to ensure smooth operation of the plant (Ho et al., 2012). On the contrary, if given a specific water demand, similar cascade table can be applied to determine the water treatment and water storage tank capacity. Individual assessment of both resources in the design stage might leads to both systems being undersized. When a system is undersized, this will affect the system as overall and in worst case scenario, the system need to be re-designed as there will complicated issues during operation. This will then affect the economic value of the production making it infeasible for profit. Under-designed systems that fall short of the required design specification can put personnel or workers at risk. Consequently, this will further generate big expenses from loss of production time, lost time injuries, worker-compensation costs and fines.

In order to improve the result provided by Pinch Analysis, this work presents a new targeting and designing method to enhance Pinch Analysis approach in designing an energy and water system. The technique can be used to simultaneously target and determine the optimal capacity of both water and energy system to meet a specific water and energy demand. The new technique is known as Water-Energy Nexus Cascade Analysis (WENCA).

In addition to that, in order to provide a more holistic investigation of the system, a mathematical model is also developed and programmed using General Algebraic Modeling System (GAMS) to identify the optimal capacity of both systems as well the total cost of the system.

1.4 Objectives of The Study

Based on the problem statements, the main purpose of this work is to develop a novel technique to design water system and energy system in an integrated methodology using water-energy nexus principles. The objectives and the sub-objectives covered in this research are as follows:

1. To develop a new numerical Pinch Analysis method for an integrated application of water-energy nexus known as Water-Energy Nexus Cascade Analysis (WENCA).

2. To develop a mathematical model to target energy and water network system. The sub-objectives of the mathematical model are as below:
   a) To design and identify the capacity of power plant, water treatment plant, energy storage system, and water storage system
   b) To optimally schedule the supply-demand of the energy and water network

1.5 Scopes of The Study

To achieve the intended research objectives, the scope of work has been drawn as follows:

1. Studying the state-of-art analysis for numerical optimisation of water-energy nexus including its feature, gaps, and potential improvement.

2. Developing a targeting technique which allow users to target two inter-related resources such as water and energy using a simple tool based on Pinch Analysis. Specific scope includes:
   a) Developing a new numerical method based on Pinch Analysis by using Microsoft Excel
   b) Apply the introduced method to a case study comprising of an integrated water and energy system
   c) Determining optimal sizing of the system capacities
   d) Comparing the results obtained with the existing methodology such as Electricity Storage Cascade Analysis and Water Supply Cascade Analysis
   e) Perform scenario analysis such as introducing different demand load during seasonal changes and compare the results with original scenario

3. Developing a mathematical model for designing a resource-integrated system (water system and energy system). Specific scope includes:
   a) Developing a Mixed Integer Linear Programming (MILP) model for the similar case study in second objective
   b) Programming the MILP model in General Algebraic Modelling System (GAMS)
   c) Revealing the optimal capacity of water system and energy system using GAMS
   d) Determining the total annual cost of the system that includes amortized investment cost and annual operation cost.

1.6 Significance of The Study

This study will be significant endeavor in promoting an effective and easy way to identify resource capacity at a preliminary stage. The newly introduced numerical pinch method as well as the mathematical model developed for energy and water system can provide an optimal solution for resource use with the aim towards achieving strategic resource management. Through this research work, several key contributions can be drawn as follows:

1. Contribution towards the Water-Energy Nexus studies.

   The idea of nexus was first conceived by the World Economic Forum (2011) to promote the inseparable links between the use of resources to provide basic and universal rights to basic needs of life such as food, water and energy security. The idea of nexus is based on systems thinking, which means it does not view the sectors such as water and energy sectors independently but takes the perspective that all the considered sectors should be governed together. Since studies using nexus theory is very new and need an in-depth research, this study will contribute towards the better understanding Water-Energy Nexus in identifying the optimal solution for system design. Till to date that this study has been conducted, there is no studies has been presented with similar method of identifying system capacities using Water-Energy Nexus principles.

2. Contribution towards the advancement of numerical analysis; namely Pinch Analysis and cascade analysis.

   a) A new application of Pinch Analysis which inclusive of an integrated water-energy nexus system known as WENCA is developed. The methodology is capable to identify the optimal size of the operating units and optimal operation of the system studied. The system is subjected to the most optimum operation as well as worst-case scenario to ensure the system operates in a reliable mode at all condition. WENCA is developed based on ESCA that is capable to identify the optimal sizing of two resources in a single loop. This is the main contribution of the study since ESCA is only able to identify only identify the capacity for a single resource i.e. energy storage system.

b) This study also reveals the capability of the method to identify the system capacity taking account the changes of demand during seasonal changes. This feature will able the method to be used anywhere around the world provided that the demand data is available.

3. Contribution towards the field of mathematical model by designing a resource-integrated system using MILP modelling.

   New MILP model is developed to design water and energy system that is considered as multi-resource targeting method. The model is capable to determine the optimal sizing of the water system and energy system to cater the specified demand. The objective of the model developed is to reveal the cost of the system that includes amortized investment cost and annual operation cost.

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