MATHEMATICAL MODELLING OPTIMISATION OF CENTRALISED SEWAGE TREATMENT PLANT FOR ELECTRICITY GENERATION

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ABSTRACT

Electricity has become one of the most basic requirements of human life. Fossil fuel is the world's leading source of gross electricity production. Alternative fuels have been offered the chance to lessen reliance on fossil fuels while also lowering greenhouse gas emissions. Malaysia's government recently announced a plan to seek green energy alternatives and technology for sustainable development. One of the most promising alternative fuels is biogas, which is produced through anaerobic digestion of sewage sludge in treatment plants. The existing decentralised small-scale sewage treatment plant is currently facing a problem due to a lack of input substrate for a biogas facility of sufficient scale. Furthermore, it necessitates a large plot of land and is difficult to manage due to its scattered placement. As a result, a centralised sewage treatment plant (CSTP) is a viable solution to this issue. The main objective of this research is to develop a model for optimal CSTP planning in generating electricity. The general methods can be divided into 5 stages; data gathering, problem formulation and superstructure construction, model development, general algebraic modeling system software coding and result analysis. The first phase includes creating a single-period model with the primary purpose of lowering capital costs. The second phase is the development of a multi-objective model that maximises economic performance while reducing environmental effect. The third phase is to develop a multi-period model for planning till 2035. Biogas from anaerobic digestion is estimated to be capable of producing 2,140 GWh of power in Peninsular Malaysia in 2018. In terms of economics, electricity generation, and sewage management, the model produced significant improvements over current practise. According to the first model, the total cost of building CSTP is RM175,014,755, which will serve around 400,000 population equivalent and produce 5,767 MWh of electricity per year. The second model calculated the total cost as RM250,880,000 with a multi-objective factor, λ, of 0.56 and a capacity of 7,699 MWh electricity per year. The final model concluded that co-digestion is the best solution for increasing biogas production. Two CSTPs were proposed to meet electricity demand and available sewage at a total cost of RM1,217,416,734 and to generate 56,943 MWh of electricity per year. This research can be used as a preliminary study for CSTP by policymakers and government bodies, allowing them to draw conclusions about the technical and environmental aspects of the transition from existing decentralised to centralised systems. This model can be further developed into usable software that assists relevant authorities in making decisions.

ABSTRAK

Elektrik telah menjadi salah satu keperluan asas dalam kehidupan manusia. Bahan api fosil adalah sumber utama pengeluaran elektrik kasar di dunia. Bahan api alternatif telah diberikan peluang untuk mengurangkan pergantungan kepada bahan api fosil di samping mengurangkan pelepasan gas rumah hijau. Kerajaan Malaysia baru-baru ini mengumumkan rancangan untuk mencari alternatif tenaga hijau dan teknologi untuk pembangunan mampan. Salah satu bahan api alternatif yang paling menjanjikan ialah biogas, yang dihasilkan melalui pencernaan anaerobik enapcemar kumbahan di loji rawatan. Loji rawatan kumbahan tidak terpusat berskala kecil sedia ada kini menghadapi masalah kerana kekurangan input substratum untuk loji biogas dalam skala yang mencukupi. Tambahan pula, ia memerlukan sebidang tanah yang luas dan sukar untuk diuruskan kerana penempatannya yang berselerak. Akibatnya, loji rawatan kumbahan terpusat (CSTP) adalah penyelesaian yang sesuai untuk isu ini. Objektif utama kajian ini adalah untuk membangunkan model untuk perancangan CSTP yang optimum dan mampu menjana elektrik. Kaedah umum boleh dibahagikan kepada 5 peringkat; pengumpulan data, perumusan masalah dan pembinaan superstruktur, pembangunan model, pengkodan perisian dan analisa hasil perisian menggunakan perisian sistem pemodelan aljabar umum. Fasa pertama termasuk mencipta model satu kala dengan tujuan utama untuk mengurangkan kos modal. Fasa kedua ialah pembangunan model pelbagai objektif yang memaksimumkan prestasi ekonomi sambil mengurangkan kesan alam sekitar. Fasa ketiga ialah membangunkan model pelbagai kala untuk perancangan sehingga 2035. Biogas daripada pencernaan anaerobik dianggarkan mampu menghasilkan 2,140 GWj kuasa di Semenanjung Malaysia pada tahun 2018. Dari segi ekonomi, penjanaan elektrik, dan pengurusan kumbahan, model menghasilkan peningkatan yang ketara berbanding amalan semasa. Berdasarkan model pertama, jumlah kos pembinaan CSTP ialah RM175,014,755, yang akan memberi perkhidmatan kepada kira-kira 400,000 penduduk setara dan menghasilkan 5,767 MWj elektrik setahun. Model kedua mengira jumlah kos sebanyak RM250,880,000 dengan faktor pelbagai objektif, λ, sebanyak 0.56 dan kapasiti elektrik 7,699 MWj setahun. Model akhir membuat kesimpulan bahawa pencernaan bersama adalah penyelesaian terbaik untuk meningkatkan pengeluaran biogas. Dua CSTP dicadangkan untuk memenuhi permintaan elektrik dan kumbahan yang ada pada kos keseluruhan RM1,217,416,734 dan menjana 56,943 MWj elektrik setahun. Penyelidikan ini boleh digunakan sebagai kajian awal untuk CSTP oleh penggubal dasar dan badan kerajaan, membolehkan mereka membuat kesimpulan tentang aspek teknikal dan alam sekitar tentang peralihan daripada sistem tidak terpusat sedia ada kepada sistem terpusat. Model ini boleh dikembangkan lagi untuk menjadi perisian yang boleh digunakan yang membantu pihak berkuasa yang berkaitan dalam membuat keputusan.

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LIST OF ABBREVIATIONS

STP	-	Sewage Treatment Plant
CSTP	-	Centralised Sewage Treatment Plant
PE	-	Population Equivalent
ICE	-	Internal Combustion Engine
GHG	-	Greenhouse Gas
MILP	-	Mixed Integer Linear Programming
MILNP	-	Mixed Integer Non Linear Programming
GIS	-	Geographical Information System
FIT	-	Feed in Tariff
GAMS	-	General Algebraic Modeling System
IM	-	Iskandar Malaysia
CEPCI	-	Chemical Engineering Plant Cost Index

LIST OF SYMBOLS

δ	-	Minimal error
D, d	-	Diameter
F	-	Force
v	-	Velocity
p	-	Pressure
λ	-	Continuous interdependent variable

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Food and shelter are necessities of life since thousands of years ago. Nowadays, electricity has become part of human basic needs. It is needed to power up computers, mobile phones, electric households, machines, and even traffic lights. Until today, electricity is largely generated by using fossil fuels. According to the latest statistics (International Energy Agency, 2019), fossil fuels dominate as a source of gross electricity production by 63 percent in the year 2018 throughout the world.

Lately, the demands for electricity increase significantly with rapid industries and advanced technology development. For example, the entry of electronic gadgets especially smartphones into society has changed people's lifestyles. People can access information anywhere and anytime using the internet, famously social media which heavily consumes electricity. The increasing numbers of users raise electricity demand. This issue takes place worldwide including in Malaysia. Electricity consumption in Malaysia increases by 59% from 2009 to 2018 (Malaysia Energy Information Hub, 2018). It is high compared to the population growth rate at only 16% during the same period.

Furthermore, the finding of new technology and the fast-growing industrial sector harms the environment. The process of generating electricity extensively from fossil fuels produces greenhouse gas (GHG), especially carbon dioxide (CO_2). In 2018, the world's total CO_2 emission from fossil fuels is approximately 32,285 million metric tonnes (International Energy Agency, 2019). As this poses a threat to the global climate, regulatory agencies have enacted strict regulations to limit GHG emission whereby the Kyoto Protocol was inked in 1997 (Oh and Chua, 2010). In 2015, 197 countries agreed to a new consensus on climate change. Paris climate agreement aims to greatly reduce global greenhouse gas emissions in an effort to limit the global temperature increase in this century to 2 degrees Celsius while pursuing the means to limit the increase to 1.5 degrees. Today, 189 countries have joined the Paris Agreement (United Nation, 2016).

Currently, Malaysia is depending mostly on fossil fuels to generate electricity, particularly from natural gas. Therefore, sustainable electricity generation is required. Malaysia has started to include renewable energy (RE) instead of building new fossil fuel plants. The most potential RE is solar and biomass because Malaysia is situated in the equatorial region and have large palm oil plantation (Shafie et al., 2012). Although a lot of initiative has been done by the government to increase RE in electricity generation, the total RE for electricity generation in 2018 is 16.7%. It is primarily made up of 16.0% hydropower and 0.6% by biomass, biogas, and solar. (Energy Commission, 2018).

There is a new source of electricity that is not fully utilized yet in Malaysia which is biogas from sewage treatment plants (STP). This technology has been implied in the USA and European countries. Biogas produced is captured instead of released to the atmosphere. A study discovers that incoming raw sewage contains 9.3 times of energy needed to treat it (Shizas et al., 2004). Therefore, it is practicable to harness energy from sewage sludge. Currently, extensive research and development are undergoing to extract energy from sewage. The generated electricity can power up the plant itself and produce useful heat.

1.2 Problem Statement

Industrial revolution 4.0 (IR 4.0) is inevitable for Malaysia where the demand for electricity is significantly high. IR 4.0 is the cyber-physical systems that connect digital world and biological systems like human through internet (Department of Statistic Malaysia, 2020). This new technology involving artificial intelligence, internet of things, cloud processing, and big data analysis will require a substantial amount of electricity. Apart from that, Malaysia is looking to increase the share of renewable energy in its installed capacity to 40% by the year 2035 (Malaysian Investment Development Authority, 2021). One of the untapped renewable energy is from sewage or municipal wastewater.

The increased importance of renewable energy has raised considerable interest in the conversion of sewage treatment plant (STP) to energy. To date, STPs in Malaysia currently focus on meeting the effluent standard set by regulators (Indah Water Konsortium., 2013). There are more than 6,000 STPs with over 18,000 km of sewer network that served a population of 37 million in year 2014 (National Water Services Commission., 2015). Small scale STPs for each housing development have caused the majority of plants to be scattered within a district, which consumes much space and land. In addition to the concern of land availability, another major issue is high electricity consumption, with 40% of operation and maintenance costs is dedicated to electricity usage (Baki et al., 2006). A system that uses conventional activated sludge for instance consumes 9,497 kWh/day as reported by Water Environment Partnership in Asia (WEPA). The drawback of the small scale STP could be overcome by a centralised sewage treatment plant (CSTP).

Theoretically, sewage treatments have high energy recovery potential. Unfortunately, this abundant source of energy is not fully utilized. In 2019, Malaysia had a population of 32 million with a population growth of approximately 1.5 percent annually (Department of Statistic Malaysia, 2019). When the population increase, sewage also increase which reflect the continuous supply of substrate. All human wastes are required to undergo treatment before it is released into the environment. In the present day, there are more than 10,000 STP all around Malaysia (National Water

Services Commission, 2018). As of today, STPs are first built by the developer and after that, they will be handed over to the responsible company. Due to this practice, decentralised and unsystematic sewerage systems existed. The sole purpose of the current STP is to meet the environmental standard.

.Sewage sludge, the by-product, can produce biogas during anaerobic digestion. In conventional practice, the biogas is burned or released into the atmosphere. As an alternative, it can be converted to electric power and also produces useful heat. The total estimation population equivalents (PE) are 43 million for Peninsular Malaysia (National Water Services Commission, 2018). From this data, 390,000 m^3 of biogas are estimated to be produced per day or equivalent to 2,140 GWh of electricity in the year 2018.

In 2018, Malaysia had a population of 30 million with a population growth of approximately 1.5 percent annually (Department of Statistic Malaysia, 2019). This large population indeed results in enormous biogas potential from sewage sludge generated from STPs, but this energy is still untapped in Malaysia. In order to harness this abundance of energy, CSTP is proposed to capture the biogas and convert it into electricity. Compared to small STPs, CSTP is running at low capital and operating costs in the same urban area (Abbassi and Baz, 2008). Furthermore, it satisfies the demand of highly populated areas (Ho and Anda, 2004). In addition, a reduction of 20% electricity consumption in STP is possible when recovered biogas is used to produce electricity (Coelho et al., 2011).

A centralised sewage treatment plant (CSTP) is proposed to realise this potential. The capital cost of building a new CSTP is high compared to STP. Long and complex underground piping and pumping are needed to collect raw sewage from sources. Therefore, a systematic approach is needed to deal with sewage and electricity simultaneously. Currently, there are less than 5% CSTP all over Malaysia. Energy recovery from sewage is still new in Malaysia. Among those STPs, there are only 4 which harness the energy from biogas which is Jelutong STP in Penang and 3 in Kuala Lumpur (Pantai STP, Pantai 2 STP, and Bunus STP). All STPs in Kuala Lumpur are upgraded from the existing STP location while Jelutong is built in a reclaimed sea area.

There is a need to plan for a systematic and centralise STPs which connect existing plants.

Building a normal STP used a lower cost and common technology, less piping, and enough to meet the environmental standard. However, it is difficult to monitor due to scattered locations. CSTP is favourable over STP due to the capacity it can treat sewage daily. Although it required high capital cost, it is much easier to monitor compared to scattered decentralised STP.

Based on the literature, Geographic Information Systems (GIS) is vastly used to find the optimum location for STP. Previous literature focuses on geographical and ecological criteria rather than economic which is discussed in subtopic 2.8 in chapter 2 There is a lack of literature discussing the sewage network or the incurred cost to build the STP. Thus, there is a gap in finding the location to build a new CSTP with the minimum cost and follow the sewerage guideline.

Based on the previous literature, an optimisations on the network of waste to energy which applied mathematical model was studied. The focus is mainly on municipal solid waste as it is the largest leftover by human beings worldwide. There is also a study on rice network synthesis on resources and utility. This concept can be applied to the STP. Optimizations on sewage treatment plants are usually done on a micro scale which concerns on efficiency and cost. However, published research lack on optimizing the network of CSTP at the macro level considering the optimum location and converting by-product into electricity. Further research gaps are discussed in chapter 2. It is important to have a proper sewage network in order to keep good sanitation and achieve status as a developed country.

Therefore, this study will propose a model for CSTP that determines its capacity, technology, and location. The model will be able to propose planning with multi objectives to satisfy forecasted demand.

1.3 Research Objective

The main objective of this research is to develop a comprehensive model for optimal planning of centralised sewage treatment plant (CSTP) for electricity generation. The objectives are outlined below:

(a) To develop a single period mathematical model for centralised sewage treatment plant consisting of plant capacity and technology selection considering a simple case scenario.

(b) To develop multi-objective model showing the effect of environmental and economic priority.

(c) To propose multi-period model and satisfy forecasted energy demand for a period of time.

(d) To propose the optimal location for the construction and operation of new CSTP with electricity generation.

1.4 Research Scope

In order to achieve the research objective, the scope of work is listed below:

(a) Data collection

   a. Iskandar Malaysia under IWK jurisdiction only focuses on Kulai and Johor Bahru Tengah District.

   b. Costing data is obtained from literature largely from open-source government agencies and books

   c. Locations and coordinates for existing and new CSTP are obtained from IWK and Johor Geo Portal.

(b) Model development

a. Three types of models; Single objective single period, multi-objective single period, and multi-period with spatial planning.

b. Coding of mathematical model and optimization in General Algebraic Modelling System (GAMS) software.

c. Planning for centralised sewage treatment plant until 2017-2035.

(c) Focus on optimization (macro planning) where the detailed design of STP is not within the scope of this work.

(d) Applying the optimization model on existing STP in Kulai and Johor Bahru Tengah district, as a case study.

(e) Tools used

a. Google Earth software is used for preparing location data in chapter 4. Mapping 20 existing STPs, 5 new CSTPs, 2 substations and manually measuring the distance parameter.

b. Geo portal Johor website to determine new CSTP location. Manually identify the potential location which is still under development.

c. ARCGIS software for preparing data in Chapters 5 and 6. Mapping 272 existing STPs locations, 10 new CSTPs, 30 substations and automatically calculating distance using available function build-in software.

d. GAMS software to code and run the model for each chapter.

(f) Perform sensitivity analysis and evaluate changes of the parameter to the production of biogas quality.

1.5 Significances of Study

This study is expected to:

(a) Assist and guide the decision-maker to select the suitable location, technology, and network, by considering the trade-off between economic and process performance.

(b) Propose the building and planning of centralised sewage treatment plants over a period of time. It helps the decision-maker plan ahead for the future.

(c) Help determine the suitable technology in converting biogas into value-added products; electricity and heat.

(d) Serve other states and locations where scattered existing STP is being transformed into CSTP.

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LIST OF PUBLICATIONS

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1. **Tarmizi, M.S**., Lim, J.S., Hashim, H. and Muis, Z.A. (2015). Multi-period Planning of Centralized Sewage Treatment Plant for Electricity Generation in Iskandar Malaysia. In *Chemical Engineering Transactions*. pp.457–462. **(Indexed by SCOPUS)**

2. **Tarmizi, M.S**., Muis, Z.A., Hashim, H., Lim, J.S. and Ho, W.S. (2017). Centralised sewage treatment plant assisted by geographic information system for electricity generation. *Chemical Engineering Transactions*. 56, 1165–1170. **(Indexed by SCOPUS)**

Non-indexed Journal

1. **Tarmizi, M.S**., Lim, J.S. and Hashim, H. (2014). Optimal Planning of Centralized Sewage Treatment Plant for Electricity Generation in Iskandar Malaysia. International Journal of Chemical and Environmental Engineering. 5(3), 176–179.