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Centralised Sewage Treatment Plant Assisted by Geographic Information System for Electricity Generation

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Municipal wastewater or sewage management is crucial as it is one of the major contributors for greenhouse gas (GHG). The biogas yield from biological treatment in sewage treatment plant (STP) contains about 60 % methane. Existing plant in Malaysia are lacking in capturing this by-product. There is a great potential for capturing biogas and combust it to harness energy. Centralised sewage treatment plant (CSTP) is suggested as long term solution for the increasing number of population and environment concern. Optimum location is an important criterion in building new CSTP in order to keep up with rapid development. The main objective of this study is to develop multi-period planning of centralised sewage treatment plant (CSTP) for electricity generation in Iskandar Malaysia. It can be divided into 5 stages; data gathering, problem formulation and superstructure construction, mathematical modelling, General Algebraic Modeling System (GAMS) coding and result analysis. In this study, GIS is used as preliminary step to generate and prepare data for mathematical model. It should plot the sources, substation and new location of CSTP. The software provides the distance between sources of sewage and new plant plus. The plant is able to produce 8 GWh/y of electricity. The model is capable of proposing location of new centralised sewage treatment plant, technology selection and its capacity.

1. Introduction

Renewable energy is starting to take place as reliable energy provider throughout the world. Nevertheless, the demand of fossil fuel is still high although it is known to be main source of greenhouse gas. Apart from wind and solar energy, biogas yield from anaerobic digestion of sewage is an alternative energy. This abundant supply is untapped. In conventional approach, sewage sludge is dewatered, yielding sludge cake as final product. It is later transport by lorry and dump at nearest landfill. As shown in Figure 1, the dot green box represents the alternative pathway where the biogas is combusted, thus producing electricity. Population growths indirectly affecting the volume of sewage produce. Due to scattered STP, it is necessary to find location and build new CSTP as a solution.

Finding the best location for STP is a challenge. Previous study has presented an application of eco-suitability evaluation, solving the location of STP and outfalls (Zhao et al., 2009). A study in Upper Mahaweli Catchment, Sri Lanka uses GIS integrated with local factor (Ratnapriya et al., 2009) while in Tamil Nadu, India applied suitability score based on planning and design constraints (Benujah and Devi, 2013). The latest research combines GIS and Analytical Hierarchy Process (AHP).The latter is a method used to determine the weight of parameter (Mansouri et al., 2013). Another study use GIS as data input for MSW management (Tan et al., 2014). Based on the literature, GIS is vastly used to find the optimum location for new STP. This is acceptable because the authors are focusing on the geographical and ecological criteria. It lacks the discussion on the sewage network, the incurred cost to build the STP and the location of new CSTP with respect to existing small STP. There is a gap in finding the location to build new STP with the minimum cost without jeopardising the environmental aspect. This is the continuation of preliminary study on multi period planning on CSTP (Tarmizi et al., 2015).

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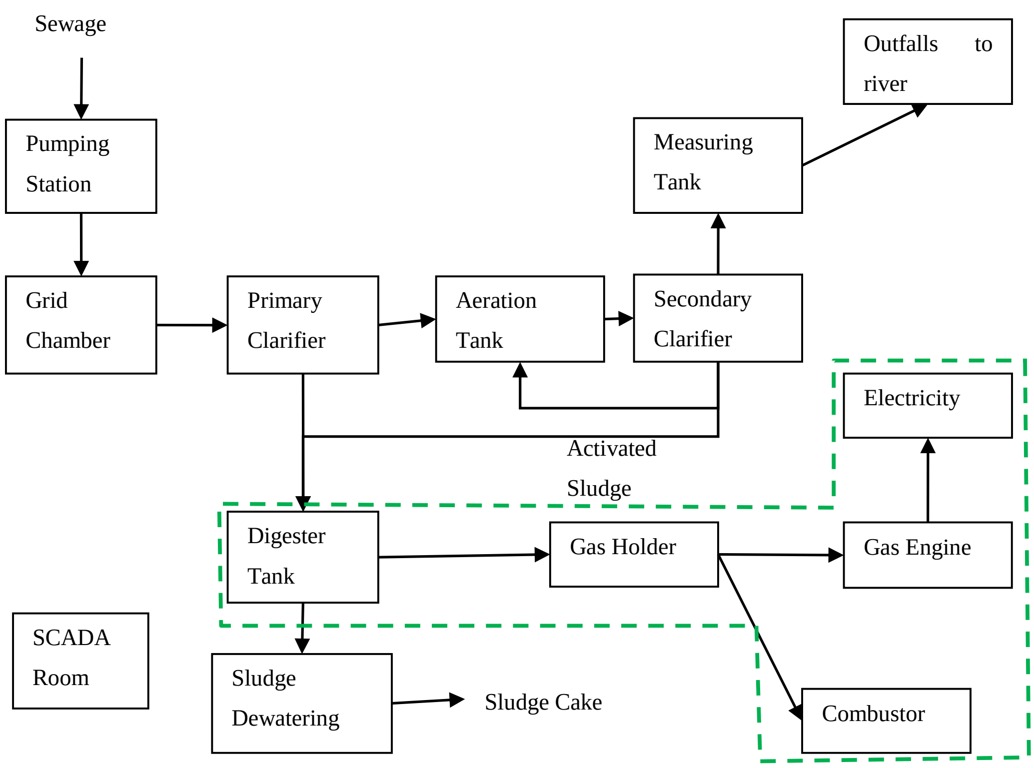

Figure 1: A typical schematic of modern mechanised STP process flow in Malaysia (Palanisamy and Shamsuddin, 2013)

2. Methodology

Figure 2 shows the process flow of this study. The first step is to collect data from dependable sources, then problem formulation and superstructure construction. A superstructure is constructed to represent the entire concept of electricity generation from sewage by connecting sources, location, technologies and end product. Based on the designed superstructure, a mathematical model comprises of two important components is developed: the objective function and constraints. An optimisation software, General Algebraic Modeling System (GAMS) is used to code the model, producing output data.

2.1 Case Study

In this work, Kulai district in Johor is used as the case study area as shown in Figure 3. Location and flowrate of 70 sources of existing STP is obtained from local authority (Indah Water Konsortium). Geographical Information Systems (GIS) is used to plot the locations of the existing STP and substation. Apart from that the new CSTP location 2 substations and 10 identified new centralised STP locations were studied. In order to have better result, the distance between existing STP and new centralised STP were estimated along driving road. In practice, sewage pipe are embedded beneath road. For locations of new CSTP, the potential site identification was conducted using GIS. It should be 200 m from residential area and located beside river to aid removal of treated water effluent.
This study just assumed using one standard anaerobic reactor with constant efficiency. Other type of reactor can be included in future study. According to literature, there were 2 types of biogas engine that are commonly used; internal combustion engine and gas turbine (Coelho et al., 2011). The time range covers 10 y period from 2016 until 2025. General Algebraic Modelling System (GAMS) version 23.7 is used in this study and CPLEX solver is applied to solve the model.

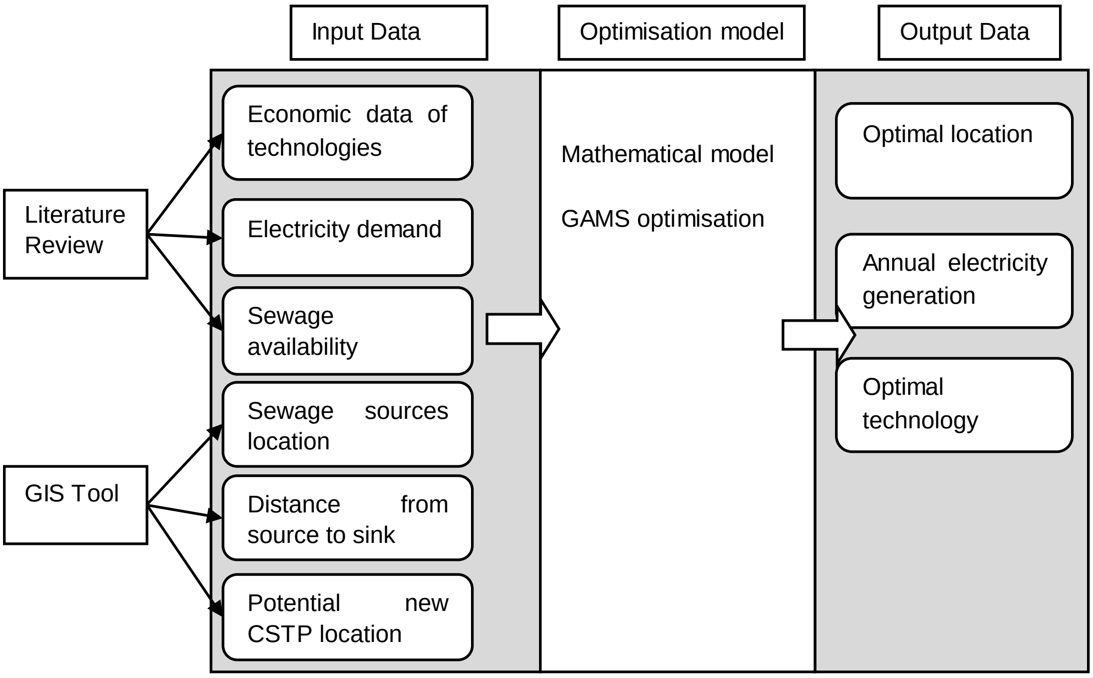

Figure 2: Process flow of this study

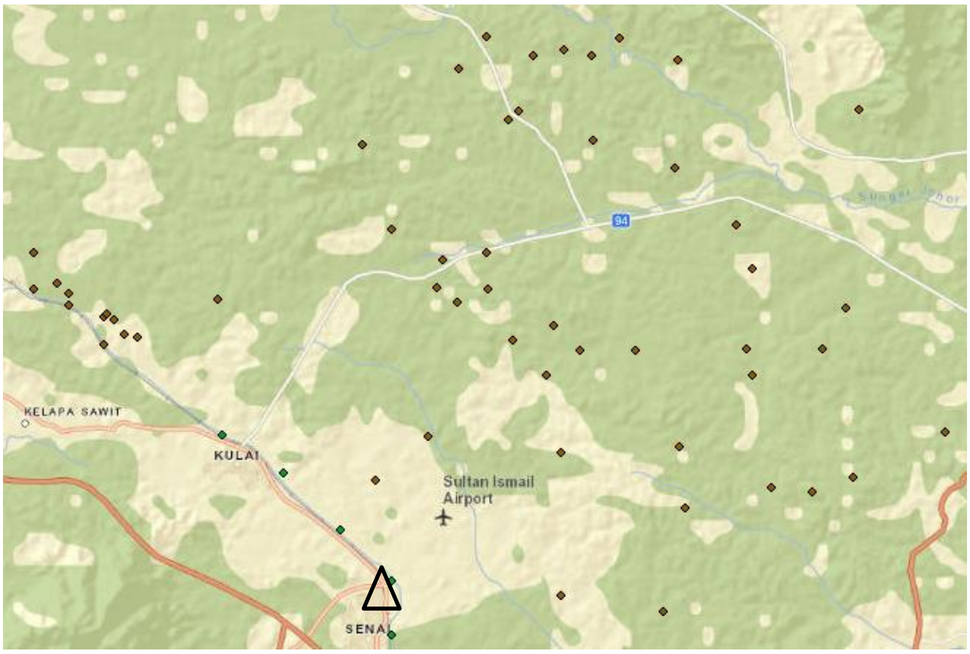

Figure 3: Case study area plotted using ArcGIS (brown-existing STP; green-new CSTP)

2.2 Mathematical formulation

The model consists of an objective function and several constraints. The objective function is to minimise the total cost of electricity generation. It consist of capital and O&M cost of building CSTP, anaerobic digester and biogas engine and cost for pumping, piping and transmission line (Tarmizi et al., 2015).

$$\min\ COST = \underbrace{\sum_{i,l,tm} FW_{i,l,tm} \times cost_l}_{\text{Capital cost for sewage treatment}} + \underbrace{O\&M_l}_{\text{O\&M cost for sewage treatment}} + \underbrace{\sum_{l,r,tm} FSin_{l,r,tm} \times cost_r}_{\text{Capital cost for digester}} + \underbrace{O\&M_r}_{\text{O\&M cost for digester}} +$$
$$\underbrace{\sum_{l,p,t,g,tm} FG_{l,p,t,g,tm} \times cost_t}_{\text{Capital cost for biogas engine}} + \underbrace{O\&M_t}_{\text{O\&M cost for biogas engine}} + \underbrace{\sum_{i,l} dist1_{i,l} \times cost1 \times yl(l)}_{\text{Pumping and piping cost}} \tag{1}$$
$$+ \underbrace{\sum_{l,ss} dist2_{l,ss} \times cost2 \times ylss(l,ss)}_{\text{Transmission cost}}$$

The balance equation is formulated from the mass balance model of STP, and the average daily flow, adf_i is shown in Eq(2).

$$adf_i = \sum_l FW_{i,l} \times yl(l) \quad \forall i \tag{2}$$

where $FW_{i,l}$ is flowrate of domestic wastewater from source, l, to location, l (m^3/d). yl(l) represents the binary variable to select the location, l.
The domestic wastewater undergoes primary treatment to separate solids from the water is written in Eq(3).

$$FW_{i,l} \times treat = FE_{i,l} \quad \forall i, \forall l \tag{3}$$

where $FE_{i,l}$ is flow rate of water effluent after treatment at location, l, from source, i; and treat is the fraction of water effluent produce during treatment at location, l. Its value is assumed to be the same at each location. The flow rate of sewage sludge, $FS_{i,l}$, as the by-product from source, i, at location, l, as stated in Eq(4).

$$FS_{i,l} = FW_{i,l} - FE_{i,l} \quad \forall i, \forall l \tag{4}$$

The total flow rate of sewage sludge $FSin_{l,r}$ from location, l, entering reactor, r, is formulated in Eq(5).

$$\sum_i FS_{i,l} = \sum_r FSin_{l,r} \quad \forall l \tag{5}$$

The flow rate $FP_{l,r,p}$ at location, l, of product, p, yield from reactor, r is indicated in Eq(6).

$$FSin_{l,r} \times yield_{r,p} = FP_{l,r,p} \quad \forall l, \forall r, \forall p \tag{6}$$

where $yield_{r,p}$ is yield of product, p, produce from reactor, r. The flow rate $FPin_{l,p,t}$ at location, l, of product, p, from reactor, r, to technology, t, is stated in Eq(7).

$$\sum_r FP_{l,r,p} = \sum_t FPin_{l,p,t} \quad \forall l, \forall p \tag{7}$$

The flow rate $FG_{l,p,t,g}$ at location, l, of generation, g, from product, p, using technology, t, is shown in Eq(8).

$$FPin_{l,p,t} \times conv_{p,t,g} = FG_{l,p,t,g} \quad \forall j, \forall p, \forall t, \forall g \tag{8}$$

where $conv_{p,t,g}$ is conversion of product, p, using technology, t, to generate g. The flow rate $FGin_{l,g,ss}$ from location, l, of generation, g, to substation, ss, is shown in Eq(9).

$$\sum_{p,t} FG_{l,p,t,g} = \sum_{ss} FGin_{l,g,ss} \quad \forall l, \forall g \tag{9}$$

3. Results and discussions

The result obtained from the preliminary study shows that location 3 (marked with black triangle) is optimal economically as shown in Figure 3. It depends mostly on the distance towards location of the new CSTP and headed to substation. The total cost for building CSTP is RM 308,416,734 which will cater around 400,000 PE. By breaking down the cost, the fraction for piping and pumping is around 25 % of total cost. This is usually not considered in normal plant calculation. This gives overview of retrofitting sewage pipe cost compared to conventional method. The list of parameters and results are summarised in Table 1 and 2.

The biogas yield is 9,388 m^3/d producing 22,533 kWh/d of electricity approximately 0.94 MW/y. This is assuming that the plant run 24/7 continuously for a year with maximum sludge recovered, 3 %. In normal condition, the fraction of sludge is only around 1 % and the rest are water. Most of the energy is loss in form of heat because of technology modest efficiency. Any way necessary to recover it such as co-generation system is beneficial. This is highly favourable in cold country as it can be supplied to nearest residential area in winter. The electricity produce can also be utilised for in-house purpose such running plant equipment and lightning (Malik and Bharti, 2009). The model selected internal combustion engine (ICE) which is common biogas engine over gas turbine. This is influenced by cost and in term of environmental friendly, the gas turbine is preferable as stated in literature. A model that includes pollutant release should be developed in future.

Table 1: List of sets, variables and parameters

Sets	
I	Source of sewage
T	Type of technology
L	Location to build new CSTP
Ss	Substation
r	Type of Anaerobic Digester reactor
tm	Time period
Decision Variables	
$FW_{i,l}$	flowrate of raw domestic wastewater from source i to location l (m^3/day)
$FE_{i,l}$	flowrate of water effluent after treatment at location l from source i
$FS_{i,l}$	flowrate of sewage sludge as by-product from source i at location l
$FSin_{l,r}$	flowrate of sewage sludge from location l entering reactor r
$FP_{l,r,p}$	flowrate at location l of product p yield from reactor r
$FPin_{l,p,t}$	flowrate at location l of product p from reactor r to technology t
$FG_{l,p,t,g}$	flowrate at location l of generation g from product p using technology t
$FGin_{l,g,ss}$	flowrate from location l of generation g to substation ss
Parameters	
$cost_l$	Capital cost for plant (RM/m^3)
$cost_r$	Capital cost for reactor (RM/m^3)
$cost_t$	Capital cost for biogas engine (RM/kWh)
$O\&M_l$	Operation and maintenance cost for plant (RM/m^3)
$O\&M_r$	Operation and maintenance cost for reactor (RM/m^3)
$O\&M_t$	Operation and maintenance cost for biogas engine (RM/kWh)
$cost1$	cost for piping and pumping from source i to location l (RM/km)
$cost2$	cost for electricity transmission from location l to substation ss (RM/km)
$dist1_{i,l}$	Distance from existing STP to new CSTP (km)
$dist2_{l,ss}$	Distance from location of CSTP to substation location (km)
$avai_i$	Population Equivalent availability
Binary variable	
$yl(l)$	Choosing location
$ylss(l, ss)$	Choosing substation
$yt(t)$	Choosing technology

Table 2: Result summary

Location	Type of engine	Year to construct new biomass power plant	Capacity to be build (MW)	Annual operating capacity in MW					
				2016	2017	2018	2019	2020	2025
3	ICE	2016	0.94	0	0.24	0.24	0.24	0.94	0.94

4. Conclusion

A model for the multi-period planning on electricity generation from centralised sewage treatment plant is developed. It is able to select the plant capacity, location technology and propose future planning. The plant is able to produce 8 GWh/y of electricity. The selected location and substation is influenced by lowest distance. Selected technology is based on cost and its efficiency. Different scenario results in different result, such as the selection of gas turbine over ICE due to the environmental constraint. The electricity potential is quite low compared to the huge investment. It is significant in the next few years when the price of fossil fuel rise and economically viable technology. Continuous research is required to meet the energy demand. In the future, having real life data, the model is able to propose more realistic model.

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