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Multi-period Planning of Centralized Sewage Treatment Plant for Electricity Generation in Iskandar Malaysia

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Electricity has become one of human basic needs beside food and water. The demands increase significantly with rapid industries and advance technology development. Currently, Malaysia is depending mostly on fossil fuels to generate electricity particularly from natural gas which will eventually deplete soon. However, the process of generating electricity extensively from fossil fuels produce greenhouse gas especially carbon dioxide. Therefore, a sustainable electricity generation is required. One sources of energy that started to get attention is biogas release from sewage treatment plant (STP) which contains up to 70 % methane. Unfortunately, the biogas is commonly flared or release to atmosphere. The main objective of this study is to develop multi-period planning of centralized sewage treatment plant (CSTP) for electricity generation in Iskandar Malaysia. It can be divided into 5 stages; problem formulation and superstructure construction, data gathering, mathematical modelling, General Algebraic Modeling System (GAMS) coding and result analysis. This model is used to propose the optimal network and location to build CSTP which can meet electricity demand.

1. Introduction

Fossil fuels, the major source for generating electricity will deplete soon. Furthermore, the extensive usage of these non renewable fuels contributes to greenhouse gas. As result, it triggers worldwide research on renewable energy. One of the alternative energy comes from biogas yield from anaerobic digestion of sewage sludge. A study discovers that incoming raw sewage contains 9.3 times of energy needed to treat it (Shizas et al., 2004). Unfortunately, this enormous energy is untapped. In order to harness this abundance energy, centralized sewage treatment plant (STP) is proposed. In Malaysia, STP are scattered in a district due to the nature of current practice. New treatment plant is built by the developer for each new housing development. Moreover, the main aim is to treat sewage until it meet required standard (Indah Water Konsortium, 2013). A significant amount of biogas to generate electricity is achievable by centralized the plant. The capacity, location and the technology for the plant is crucial to be decided.
Previously, multi period study is on CO_2 emissions consideration from power plant (Mirzaesmaeeli et al., 2010). It discusses the planning of power plant with respect to CO_2 emission. There are optimizations on network of waste to energy which applied mathematical model. One study proposed optimal processing configuration from waste generation to energy (Ng et al. 2013). Another work cover the logistics network for waste batteries by minimize its total present value in different scenario (Donmez and Turkay, 2013). In addition, similar framework is practiced for rice network synthesis on resources and utility (Lim et al., 2013). There is a gap where all of above concepts can be applied to STP as macro scale planning. Optimizations on sewage treatment plant are usually done on micro scale which concern on plant efficiency and cost. Preliminary study was done in previous conference paper for single period on macro scale (Tarmizi et al., 2014). Proper future planning is crucial to ensure energy security. Based on current pace, renewable energy is predicted to have large generation mix alongside fossil fuel in years to come. Therefore, this study propose multi-period mixed integer non-linear programming (MINLP) for electricity generation from centralized sewage treatment plant by meeting the demand at the lowest cost possible.

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2. Methodology

2.1 Problem Formulation and Superstructure development

The first step is to understand the problem by developing superstructure diagram. Given a set of sewage source i, scattered in a district. The composition or its quality is assumed to be the same. This sewage is piped and pumped to a set of new CSTP location l. At the new plant, primary treatment occur where water and solid is separated. The by-product, sewage sludge enters a set of anaerobic reactor r, yielding product p. Later, it is feed into gas engine technology t, producing value added product g. Finally, it is injected to nearest substation ss. A strategic location of CSTP is crucial to minimize the cost for piping and pumping. The location of CSTP and favourable technology will be determined by optimization model. From that, a sewage network design is produced. The feasibility of sewage management method for area of case study is to be investigated. This study is expected to assist and guide the decision maker to select the suitable technology, by considering the trade-off between economic and process performance. The general superstructure is illustrated in Figure 1.

2.2 Mathematical modelling

Theoretically, this model is mixed-integer non-linear programming (MINLP) due to the multiplication of positive variable with binary variable. In order to avoid difficulties encountered with large convex non-linear models, linearization is performed by multiplying the binary with large value.

Objective function

The main objective is to minimize cost for the new centralized STP. Below is the equation:

$$\min \ COST = \underbrace{\textstyle\sum_{i,l,tm} FW_{i,l,tm} \times cost_l}_{\text{Capital cost for sewage treatment}} + \underbrace{O\&M_l}_{\text{O\&M cost for sewage treatment}} + \underbrace{\textstyle\sum_{l,r,tm} FSin_{l,r,tm} \times cost_r}_{\text{Capital cost for digester}} + \underbrace{O\&M_r}_{\text{O\&M cost for digester}} +$$

$$\underbrace{\textstyle\sum_{l,p,t,g,tm} FG_{l,p,t,g,tm} \times cost_t}_{\text{Capital cost for biogas engine}} + \underbrace{O\&M_t}_{\text{O\&M cost for biogas engine}} + \underbrace{\textstyle\sum_{i,l} dist1_{i,l} \times cost1 \times yl(l)}_{\text{Pumping and piping cost}}$$

$$+ \underbrace{\textstyle\sum_{l,ss} dist2_{l,ss} \times cost2 \times ylss(l,ss)}_{\text{Transmission cost}} \tag{1}$$

Constraint

Electricity demand

This constraint ensure that the plant produce an amount of electricity that can cover the demand at year *tm*.

$$\textstyle\sum_{l,g,ss} FGin_{l,g,ss,tm} \geq dem_{tm} \tag{2}$$

PE availability

This PE availability, $avai_i$ is converted into average daily flow at different location, adf_i using Eq(3) stated in Malaysian Standard 1228 (1991).

$$adf(i) \leq fpc \times avai(i) \tag{3}$$

where fpc, flow per capita (m^3 wastewater/day/ person).

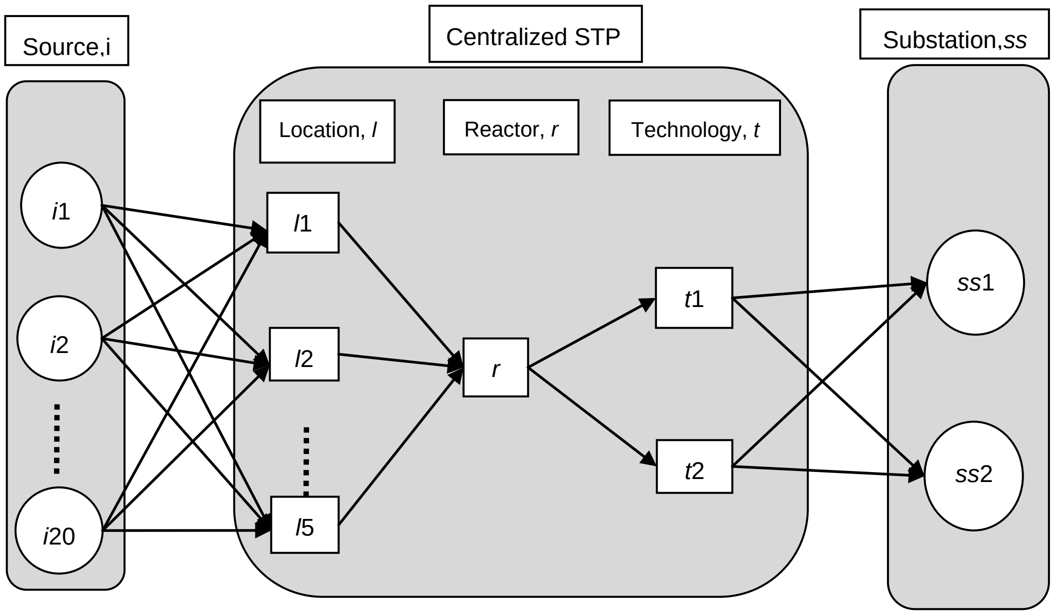

Figure 1: Superstructure for this case study

Construction lead time

For new plant, no power is generated until the construction of the building completed. Therefore, to address this issue, the matrix method is used (Sirikitputtisak et al. 2009).

$$FG_{l,p,t,g} \leq \sum_{l,p,t,g} FG_{l,p,t,g}\ y_m \tag{4}$$

$$\sum_{tmc} y_m \leq 1 \tag{5}$$

Balance

$$adf_i = \sum_l FW_{i,l} \times\ yl(l) \quad \forall i \tag{6}$$

where fpc, flow per capita (m^3 wastewater/day/ person) while $FW_{i,l}$ is flowrate of domestic wastewater from source *i* to location *l* (m^3/day). The binary variable to select location *l* is $yl(l)$. The domestic wastewater undergoes primary treatment to separate solid from water show in Eq(7).

$$FW_{i,l} \times treat = FE_{i,l} \quad \forall i, \forall l \tag{7}$$

where $FE_{i,l}$ is flowrate of water effluent after treatment at location *l* from source *i*; $treat$ is the fraction of water effluent produce during treatment at location *l*. Its value is expected to be the same at each location. The flowrate of sewage sludge as by-product from source *i* at location *l*, $FS_{i,l}$ is stated in Eq(8).

$$FS_{i,l} = FW_{i,l} - FE_{i,l} \quad \forall i, \forall l \tag{8}$$

The total flowrate of sewage sludge from location *l* entering reactor r, $\mathrm{FSin}_{l,r}$ is stated in Eq(9).

$$\sum_i FS_{i,l} = \sum_r FSin_{l,r} \quad \forall l \tag{9}$$

The flowrate at location *l* of product *p* yield from reactor *r*, $FP_{l,r,p}$ is stated in Eq(10).

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

$$FSin_{l,r} \times yield_{r,p} = FP_{l,r,p} \quad \forall l, \forall r, \forall p \tag{10}$$

where $yield_{r,p}$ is yield of product *p* produce from reactor *r*. The flowrate at location *l* of product *p* from reactor *r* to technology *t*, $FPin_{l,p,t}$ is stated in Eq(11).

$$\sum_r FP_{l,r,p} = \sum_t FPin_{l,p,t} \quad \forall l, \forall p \tag{11}$$

The flowrate at location *l* of generation *g* from product *p* using technology *a*,$\mathrm{FG}_{\mathrm{l,p,t,g}}$ is shown in Eq(12).

$$FPin_{l,p,t} \times conv_{p,t,g} = FG_{l,p,t,g} \quad \forall j, \forall p, \forall t, \forall g \tag{12}$$

where $\mathrm{conv}_{\mathrm{p,t,g}}$ is conversion of product *p* using technology *t* to generate *g*. The flowrate from location *l* of generation *g* to substation *ss*, $FGin_{l,g,ss}$ is shown in Eq(13).

$$\sum_{p,t} FG_{l,p,t,g} = \sum_{ss} FGin_{l,g,ss} \quad \forall l, \forall g \tag{13}$$

3. Case study and discussion

Kulai district, Johor is used as the case study area. The time range covers 3 y period from 2015 until 2017. General Algebraic Modelling System (GAMS) version 23.7 is used in this study and CPLEX solver is applied to solve the model. For this case study, 20 sources of existing STP were studied with 5 identified new centralized STP locations. There were 2 types of biogas engine which are internal combustion engine and gas turbine. However, this study just assumed using one standard anaerobic reactor. Two nearest substations is included in this research. In order to have better result, the distance between existing STP and new centralized STP were estimated along driving road. In practice, sewage pipe are embedded beneath road.

3.1 Assumptions

Several assumptions have been made and are listed below:

1. The effect of different elevation towards piping and pumping cost is neglected.
2. Operation and maintenance cost is constant.
3. 1 y period for building STP with electricity generating capabilities before fully operate.
4. Technology efficiency and cost is assumed constant.
5. The population equivalent is constant

3.2 Results and discussion

The result obtained from the preliminary study shows that location 3 is optimal economically as shown in Figure 2. It depends mostly on the distance towards location of the new CSTP and headed to substation. The total cost for building CSTP is RM 217,416,734 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 results is summarize in Table 2.

The biogas yield is 6,583 m^3/d producing 15,801 kWh per day of electricity approximately 0.7 MW per year. 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. Actually, most of the energy is loss in form of heat because of technology modest efficiency. Therefore, 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 utilize 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. Theoretically, this is influenced by cost and in term of environmental friendly, the gas turbine is preferable as stated in literature. Therefore, a model that includes pollutant release should be developed in future.

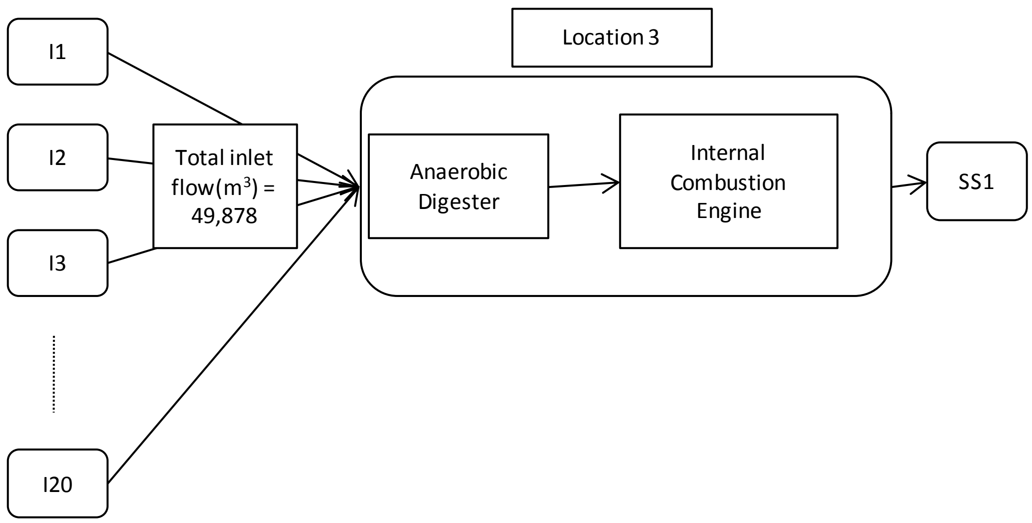

Figure 2: Diagram summary

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		
				2015	2016	2017
3	ICE	2015	0.24	0	0.24	0.24

4. Conclusions

A Mixed Integer Linear Programming (MILP) model for the multi-period planning on electricity generation from centralized sewage treatment plant is developed. It is able to select the plant capacity, location technology and propose future planning. Basically, the selected location and substation is influenced by lowest distance. On the other hand, selected technology is based on cost and its efficiency. Bear in mind that different scenario resulting in different result such as the selection of gas turbine over ICE due to environmental constraint. Currently, the electricity potential is quite low compared to the huge investment. However, it is significant in the next few years when the price of fossil fuel rise and economically viable technology. Therefore, continuous research is required to meet the energy demand. In future, having significant amount of data, the model are be able to propose a multi objective and have more realistic model.

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