GAS SYSTEM CASCADE ANALYSIS FRAMEWORK FOR OPTIMAL DESIGN OF BIOGAS SYSTEM

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Dedicated specially to my mother (Siti Sareah Binti Japri) and my father (Othman Bin Yusoff)

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ABSTRACT

The main objective of this research is to develop a new framework called Gas System Cascade Analysis (GASCA) based on Time-Based Pinch Analysis (TBPA) principle. In additional, there are 4 sub-objectives in this study which is to determine the optimal capacity (energy equivalent) of anaerobic digester (AD) and biogas storage, to examine the impacts of supply-demand variation in selected region, to evaluate the impact of incorporating biogas system on carbon emission reduction and to estimate the cost-benefit analysis for biogas system. Prior to applying GASCA framework, the superstructure of biogas distributed energy system design is introduced to show the overall system operational scenario followed by data collection and extraction. The TBPA was then conducted to determine the optimal capacity of AD, biogas storage, and operation (charging and discharging of biogas from biogas storage). Based on the case study, the optimal capacity of AD was 4,629.52 MJ/h with maximum energy capacity at biogas storage of 16,988.61 MJ/h. Sensitivity analysis was conducted to examine the impact of supply-demand variation on the capacity of AD and biogas storage. The carbon emission reduction contributed by the proposed framework was up to 131,011 kg CO_{2eq} per day. For cost-benefit analysis, the calculated Net Present Value was 18.73 %. In conclusion, GASCA framework has been applied successfully to determine the optimal capacity (energy equivalent) of AD and biogas storage.

ABSTRAK

Objektif utama kajian ini adalah untuk membangunkan satu rangka kerja baru yang dikenali sebagai Analisa Lata Sistem Gas (GASCA) berdasarkan prinsip Analisa Jepit Berasaskan Masa (TBPA). Tambahan pula, terdapat 4 sub-objektif dalam kajian ini iaitu untuk menentukan kapasiti (tenaga setara) pencernaan anaerobik (AD) dan penyimpanan biogas yang optimum, untuk memeriksa kesan perubahan bekalan-permintaan dalam kawasan terpilih, untuk menilai kesan gabungan sistem biogas kepada pengurangan perlepasan karbon dan untuk menganggarkan analisa kos faedah untuk sistem biogas. Sebelum rangka kerja GASCA digunakan, struktur sistem reka bentuk pembahagian tenaga biogas diperkenalkan untuk menunjukkan keseluruhan senario sistem operasi diikuti pengumpulan data dan pengekstrakan. TBPA kemudian dijalankan untuk menentukan kapasiti AD, penyimpanan biogas dan operasi (cas dan nyahcas biogas daripada penyimpanan biogas) yang optimum. Berdasarkan kajian kes, kapasiti AD yang optimum adalah 4,629.52 MJ/h dengan kapasiti tenaga maksimum pada penyimpanan biogas adalah 16,988.61 MJ/h. Analisa kepekaan telah dijalankan untuk mengkaji kesan perubahan bekalan-permintaan pada kapasiti AD dan simpanan biogas. Rangka kerja yang dicadangkan menyumbang pengurangan perlepasan karbon sehingga 131.011 kg CO_{2eq} sehari. Untuk analisa kos-faedah, pengiraan Nilai Kini Bersih adalah 18.73%. Kesimpulannya, rangka kerja GASCA berjaya digunakan untuk menentukan kapasiti AD (tenaga setara) dan simpanan biogas yang optimum.

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LIST OF ABBREVIATIONS

AD	-	Anaerobic Digester
CHP	-	Combined Heat Power
CSTR	-	Continuous Stirred Tank Reactor
CPO	-	Crude Palm Oil
COD	-	Chemical Oxygen Demand
DM	-	Dry Matter
DEG	-	Distributed Energy Generation
DH	-	District Heating
ESCA	-	Electricity System Cascade Analysis
GHG	-	Greenhouse Gas
GASCA	-	Gas System Cascade Analysis
GCC	-	Grand Composite Curve
IRR	-	Internal Rate Of Return
LCFA	-	Long-Chain Fatty Acid
LIES	-	Locally Integrated Energy Systems
LCA	-	Life Cycle Analysis
LPG	-	Liquefied Petroleum Gas
MSW	-	Municipal Solid Waste
MILP	-	Mixed Integer Linear Programming
NGV	-	Natural Gas Vehicle
NPV	-	Net Present Value
OpTiGas	-	On-Peak Time Generation and Storage

PFR	-	Plug Flow Reactor
PSA	-	Pressure Swing Adsorption
PV	-	Photovoltaic
POME	-	Palm Oil Mill Effluent
RE	-	Renewable energy
TBPA	-	Time-Based Pinch Analysis
TS	-	Total Solid
VS	-	Volatile Solid
VFA	-	Volatile Fatty Acid
VPP	-	Virtual Power Plant

LIST OF SYMBOLS

B_t	-	Annual Benefit Cost (USD)
C_t	-	Charging Energy (MJ)
CH_4	-	Methane
CO_2	-	Carbon Dioxide
CH_3COOH	-	Acetic Acid
CHON	-	Mnemonic Acronym (Carbon-Hydrogen-Oxygen-Nitrogen)
d	-	Day
D_t.	-	Discharging Energy (MJ)
$D_{k,z,t}$	-	Final Applications z Which Require Different Biogas Purity Levels *k* (MJ)
f_i	-	Biomass Feedstock
$f_{i,t}$	-	Different Biomass Feedstock
$f_{k,z}^{appl}$	-	Conversion Factor To Account For Energy Loss Factor For Applications (%)
f_k^{upgr}	-	Conversion Factor To Account For Energy Change Due To Biogas Upgrading (%)
$fp_{k,t}$	-	Energy Equivalence For Consumption Rate Of Biogas Feedstock Of Purity Level k (MJ)
$fp_{raw\ k,t}$	-	Energy Equivalence For Consumption Rate Of Raw Biogas (MJ)
f_{chg}	-	Charging Losses (%)

f_{dischg}	-	Discharging Losses (%)
G_t	-	Biogas Generation Form Anaerobic Digester (MJ)
$G_{t,new}$	-	New Guess Biogas Generation (MJ)
$G_{t,old}$	-	Old Guess Biogas Generation (MJ)
$G_{t,final}$	-	Biogas Generation Capacity (MJ)
$G_{t,feedstock}$	-	Biogas Generation From Feedstock (MJ)
H_2	-	Hydrogen
H_2S	-	Hydrogen Sulphide
H_2O	-	Water Vapour
Ir	-	Interest Rate (%)
k	-	Purity Level (Raw Biogas or Upgraded Biogas)
L_t	-	Total Gas Demand (MJ)
N_2	-	Nitrogen
NH_3	-	Ammonia
N_t	-	Net Gas Demand (MJ)
p_j	-	Purification Processing Stage *j*
P_t	-	Biogas Production
Q_t	-	Cumulative Gas Energy At Each Time Slice *t* (MJ)
Q_{t-1}	-	Cumulative Gas Energy At Each Previous Time Slice *t*
$Q_{initial}$	-	Initial Inventory (MJ)
Q_{final}	-	Final Inventory (MJ)
R_t	-	Annual Running Cost (USD)
S_{biogas}	-	Storage Capacity (MJ)
SO_2	-	Sulphur Dioxide
t	-	Time Slice
t-1	-	Previous Time Slice
T	-	Total Period of Analysis
x	-	Number from 1, 2, 3,..
$y_{biogas,i}$	-	Biogas Yield From Feedstock
z	-	Final Application of Biogas (Electricity, cooking gas and NGV)

CHAPTER 1

INTRODUCTION

This chapter provides an overview of current global energy scenario and the challenge faced by the society. This is followed by an introduction of the research background, problem statement, objectives of study, scope of study, significant of the study and summary of this thesis. The aims of this study to develop a new method called Gas System Cascade Analysis (GASCA) framework based on Time-Based Pinch Analysis (TBPA) principle. The four key specific contributions from this research are also presented in this chapter.

1.1 Background of The Study

Nowadays, energy is fundamentally generated from several source categories including fossil fuel combustion, nuclear power and renewable energy (RE). Yet the fossil fuels (i.e. petroleum, coal and natural gas) are still the dominant solution meeting around 88 % of the global energy demand, hitherto comprising the major source of greenhouse gas (GHG) emissions (Olivier et al., 2015). Back in 2008, contribution of RE to energy generation profile is almost negligible (Deublein and Steinhauser, 2008). However, the renewable energy share of global final energy consumption has increased 11 % to 19.2 % in 2014 (Lins et al., 2014). Among the identified RE categories, biogas is considered to be highly potential resource due to its production-and-use cycle and generates almost zero carbon dioxide others than high energy content (calorific value) and ease of storage (Wilfert and Schattauer, 2004).

To promote the implementation of biogas energy systems, several strategies have been highlighted, including: (i) implementing simple process with improved yield to produce more biogas; (ii) researching and developing co-digestion of various feedstocks, especially Municipal Solid Waste (MSW) stream and agri-food industry waste; (iii) encouraging biogas utilisation through incentives to biogas plant, e.g. reasonable feed-in tariff (FIT) and improved access to electricity and gas grid infrastructures (Poeschl et al., 2010). According to Lantz *et al.* (2007), the incentives affecting the biogas utilisation in terms of heat production, combined heat and power (CHP) generation and vehicle fuel production include policy objectives, legislation, taxes, financial subsidies, and other policy instruments; whereas the barriers are constituted by lack of market (i.e. high cost of biogas), existence of competing treatment technologies, and limited public acceptance level.

With proper methane capturing and upgrading system, it is capable of capturing methane gas for the subsequent ‘Biogas-To-Energy’ utilisations (e.g. electricity, natural gas vehicle (NGV) and cooking gas) (Münster and Meibom, 2011). Moreover, other than producing biogas, the system also produces digestate (which could be applied as compost or soil amendment) whose quality depends on the feedstock type. Biogas is produced through biological anaerobic digestion process, which involves microbial break-down of fed substrates in the absence of oxygen. This process is mostly used in industry that deals with wastewater sludge treatment. This process provides volume and mass reductions of the input material by converting it into an energy-rich biogas (Curry and Pillay, 2012).

The proper utilisation of biogas can enhance local economic capabilities, reduce rate of unemployment in rural areas and increase purchasing power in a particular region. In addition, it leads to better living standards, and increased economic and social developments (Surendra et al., 2013). In addition, biogas process has been considered an optimal sustainable solution in waste management that are eco-friendly, socially acceptable and cost-effective (Stehlík, 2009).

A part from that, the implementation of biogas energy technology will also contributed significantly in reduction of GHG and air pollution. As predicted, every year methane gas will release 590-800 million tons into atmosphere due to biodegradation of organic matter under anaerobic digestion (Bond and Templeton, 2011). Thus, biogas system technology is a promising solution to control production of methane that will affect the GHG emission reduction.

1.2 Problem Statement

Design method for biogas system is of growing interest as the fossil fuel reserve availability declines. Over the past years, researchers design biogas system (anaerobic digester (AD) and biogas storage) based on production of methane (CH_3) (Koudache and Yala, 2008), AD design consideration such as organic loading rate, hydraulic retention time and etc (Hilkiah Igoni et al., 2008) and developed dynamic model based on network framework (Minott, 2014). Unfortunately, many of the existing research in designing biogas system have their complexity when came to preliminary macro-analysis.

The application of TBPA is limited for power system specifically for designing an isolated energy system (photovoltaic-battery system and wind-battery system) (Bandyopadhyay, 2011), and optimum sizing of hydrogen generator and storage tank (Ghosh et al., 2015). In addition, Electricity System Cascade Analysis (ESCA) was developed for Distributed Energy Generation (DEG) system design involving non-intermittent biomass power generators (Ho et al., 2012) and intermittent solar photovoltaic (PV) system (Ho et al., 2014). However, to date, TBPA principle has not been extended and there is no research/study on the designing of biogas energy system.

Other than focusing on TBPA principle, concern towards GHG emissions and its impact on climate change has increased significantly. Since the relative impact of methane gas towards climate change (i.e. global warming potential) is about 25 times greater than that of carbon dioxide, the implementation of various biogas technologies will contribute to significant mitigation of GHG emissions (Poeschl et al., 2010). Given a set of biogas demand profile for different biogas quality levels, biogas processing technologies with different performance, feedstock with different biogas potential, it is desired to develop a new method to target the optimal capacity of AD and biogas storage based on TBPA principle. The system will consider configuration biogas energy system and parameters (i.e. conversion factors).

1.3 Objectives of Study

The main objective of this research is to develop a new method called GASCA framework based on TBPA principle. The sub-objectives include the following:

1. To determine the optimal capacity (energy equivalent) of anaerobic digester and biogas storage systems for satisfying known total hybrid energy demand.
2. To examine the impacts of demand variations on biogas system design and regional feedstock selection (food waste, animal manure and palm oil mill effluent (POME)).
3. To evaluate the impact of incorporating biogas energy system on carbon emissions reduction.
4. To estimate the cost-benefit analysis for biogas energy system.

1.4 Scope of Study

The scopes of this study are as follows:

1. Identifying the biogas energy system configuration, biogas purity levels, and types of biogas-final applications for low-quality biogas (electricity) and high-quality biogas (cooking gas and NGV)
2. Collection data; Raw demand of electricity and cooking gas, parameters/values involved in sensitivity analysis (source of feedstock, carbon emission and cost benefit) is based on cited literature review. Raw demand of NGV from Senai Airport Petrol Station (In-situ site).

3. Processing raw data to derive the model estimation parameters i.e. conversion factors
4. Designing optimal sizes of AD and biogas storage systems based on the identified energy demands (final applications)
5. Analysing the impact of biogas-based demand and supply (food waste, animal manure and POME) variation in the selected regional boundary (Senai City)
6. Evaluating the impact of incorporating biogas system on the carbon emissions reduction
7. Estimating the cost benefit of biogas energy system based on optimised capacity of AD

1.5 Significance of Study

The key specific contributions from this research are as follows:

1. GASCA framework based on TBPA will be a simplified biogas energy system design tool that aids in optimal sizing of AD and biogas storage systems
2. GASCA framework will be useful to overcome the complexity encountered from biogas distributed system when designing optimal AD and biogas storage.
3. GASCA framework is capable of supply-demand targeting to satisfy the biogas generation target of selected community. Other than that, it reduces the cost by having optimal sizes for both AD and biogas storage systems
4. GASCA framework enables proper utilisation of biomass to reduce carbon emissions and provide necessary insight for preliminary cost benefits of biogas energy system

1.6 Summary of this Thesis

This thesis consists of five chapters, which includes Chapter 1 that provides the introduction, background of the study, problem statement, objectives of study and the scope of study. Chapter 2 describes the existing biogas system design approach such as design consideration of AD, mathematical model and modelling and simulation development and review the history and research development on TBPA applications. The subsequent sub-section in Chapter 2 covered the research gaps for the current development of the study. Chapter 3 presents the overall methodology of the GASCA framework algorithm and general design equations included cost-benefit analysis step.

In addition, Chapter 4 explain the detailed case study (applied at Senai City) for demonstrating the GASCA framework and the results that comprises four sections; optimal capacity of AD and biogas storage, sensitivity analysis for demand-supply variations, impact of biogas energy system on the carbon emission reduction and cost-benefit analysis for biogas energy system. Last but not least, Chapter 5 concludes this research work and provides recommendations for future works.

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