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Optimisation and targeting of supply-demand of biogas system through gas system cascade analysis (GASCA) framework

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ABSTRACT

Biogas decentralised energy system is an important technology in developed countries nowadays as one of the energy efficient and eco-friendly techniques for production of bioenergy besides giving significant impact towards reduction of disposed waste volume and greenhouse gas (GHG). The aim of this article is to present a new numerical method, i.e., Gas System Cascading Analysis (GASCA), based on Time Based Pinch Analysis (TBPA) principle. GASCA is capable of targeting the biogas supply-demand chain, as well as optimal capacities of anaerobic digestion (AD) and biogas storage systems for a known total demand profile, with the consideration of energy conversion efficiency for different biogas qualities, charging and discharging efficiencies and losses. In the illustrative case study, the optimal capacity of AD was 4629.52 MJ/h, with initial energy content and maximum energy capacity at biogas storage of 8737.19 MJ/h and 16,988.61 MJ/h. The simulation study also revealed that application of GASCA-optimised biogas energy system could potentially reduce carbon emission by up to 138 t $CO_{2\ eq}$/d. Moreover, a sensitivity analysis was conducted to examine the impacts of demand variations on biogas system design and regional feedstock selection.

1. Introduction

Global energy demand has seen continual increment in response to population expansion and industrial intensification (Trivedi, 2012). Yet the conventional fossil fuel is still the dominant solution meeting around 88% of the global energy demand, and would definitely be the major source of greenhouse gas (GHG) emissions (Olivier et al., 2015). Utilisation of conventional renewable resource (such as biomass and hydropower plant) and new renewable resource (such as solar energy, wind, geothermal, etc.) for electrical, heat and mechanical power generation is a promising solution to reduce the GHG emissions (Mijakovski et al., 2016).

Being one of the biofuels derived from biomass resources, biogas is seen as a more sustainable and environmentally friendly alternative for generating decentralised energy source (Lijó et al., 2014). It was reported to help improve energy security, reduce GHG emissions (Poeschl et al., 2010), and manage organic waste (Wang et al., 2014). Raw biogas resource has been applied for generation of electricity and thermal energy, while upgraded one is benefited for vehicle fuel application and natural gas substitute (Olsson and Fallde, 2014).

In global perspectives, there have been huge potentials for biogas generation and utilisation worldwide. In 2013 European countries had collectively observed a tremendous biogas generation potential of 156 TWh (EurObserv'ER, 2014), while biogas production in United States was estimated to be up to 103 TWh (U.S. Environmental Protection Agency, 2014). The biogas production capacities were estimated to be 141 TWh in China (Li, 2014) and 13.2 TWh in India (Abhishek, 2015), assuming an average biogas calorific value of 23 MJ/m^3 (Frost and Gilkinson, 2010). For ASEAN countries actively engaged in integrating biogas into sustainable energy system, the approximate overall biogas production potential in the period of 2010–2012 was 141 TWh.

Biogas in Malaysia is typically derived from the anaerobic digestion (AD) of biomass feedstock (Siddique et al., 2015).

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Common biomass feedstock comprises of organic fraction of municipal solid waste (MSW), sewage sludge, animal by-products, as well as palm oil mill effluent (POME) (Ng et al., 2012). In the present situation the recovery of biogas through anaerobic treatment of POME is more predominant in Malaysia, driven by the fifth entry point project (EPP5) of palm oil National Key Economic Area (NKEA) programme, which intends to install biogas systems in all palm oil mills in Malaysia by 2020 (Malaysian Palm Oil Board, 2011). In order to support the EPP 5, formulation of a comprehensive design framework for biogas-based distributed energy system would be imperative. The overall process flow diagram for biogas distributed energy system, with illustration of multiple demand types, is as shown in Fig. 1.

Conventional biogas plant design approach is typically based on heuristics (Wu, 2015), design equations, material selection guidelines, and financial databases (Kuria, 2008). Practically used simulation-based design tools include C spark (C#) programme (Samer, 2010) and On-Peak Time Generation and Storage (OpTiGaS) system (Minott, 2014). Seeing that biogas system design involves batch process concept, Time-Based Pinch Analysis (TBPA) could be a handy yet simplified approach (Klemes et al., 2013).

One of these TBPA design approaches includes supply chain aggregate planning using Pinch Analysis (i.e. Grand Composite Curve (GCC)) for meeting the demand over specific timeframe with maximum profit (Singhvi and Shenoy, 2002). It was also applied in carbon emissions and energy footprint problem management (Tan and Foo, 2009), in-campus paper recycling network design (Kit et al., 2011), as well as water and power system optimal planning and management (Klemes et al., 2010). For power system optimisation specifically, TBPA was applied for designing and optimizing 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 (DEG) (Ho et al., 2012) and intermittent solar PV system (Ho et al., 2014).

In terms of work for renewable energy planning and utilisation in towns and regions, Varbanov and Klemes (2010) further extended the Total Site approach to Locally Integrated Energy Systems (LIES) using TBPA for including renewables and fluctuating supply and demand. Similarly, Wan Alwi et al. (2012) developed numerical tool for integrating renewable energy into total sites. Significant breakthroughs in LIES development featured total site district cooling system design optimisation by Liew et al. (2015) and inter-municipality renewable management network for LIES reliability enhancement (Kostevšek et al., 2015). Metrics for evaluating LIES sustainability were also developed to assess the wood biomass-based district heating (DH) system in Slovenian municipality (Kostevsek et al., 2015).

In terms of biogas system planning, Pierie et al. (2016) introduced a new approach for designing decentralised biogas energy system using material flow analysis, material and energy flow analysis and life cycle analysis (LCA), with evaluation of its environmental sustainability and energy efficiency. With regional database and risk management consideration, Chauhan and Saini (2016) applied discrete harmony search algorithm to optimise the integrated renewable energy system (with incorporation of biogas production) for Indian rural community. For supporting the development of decentralised biogas system, financial-oriented optimisation of biogas delivery grid for integrating AD systems in different zones was conducted in the Netherlands (Hengeveld et al., 2016). In Turkey, multi-objective mixed integer linear programming (MILP) approach was applied to optimise biogas-based district heating system with thermal storage technology (Balaman and Selim, 2016). Seasonal fluctuations of biomass availability and biogas plant operational parameters were captured in this study. Moreover, Pechmann et al. (2016) evaluated the financial feasibility of biogas plant-integrated virtual power plant (VPP) using dynamic simulation approach in the planning phase, whereas Karschin and

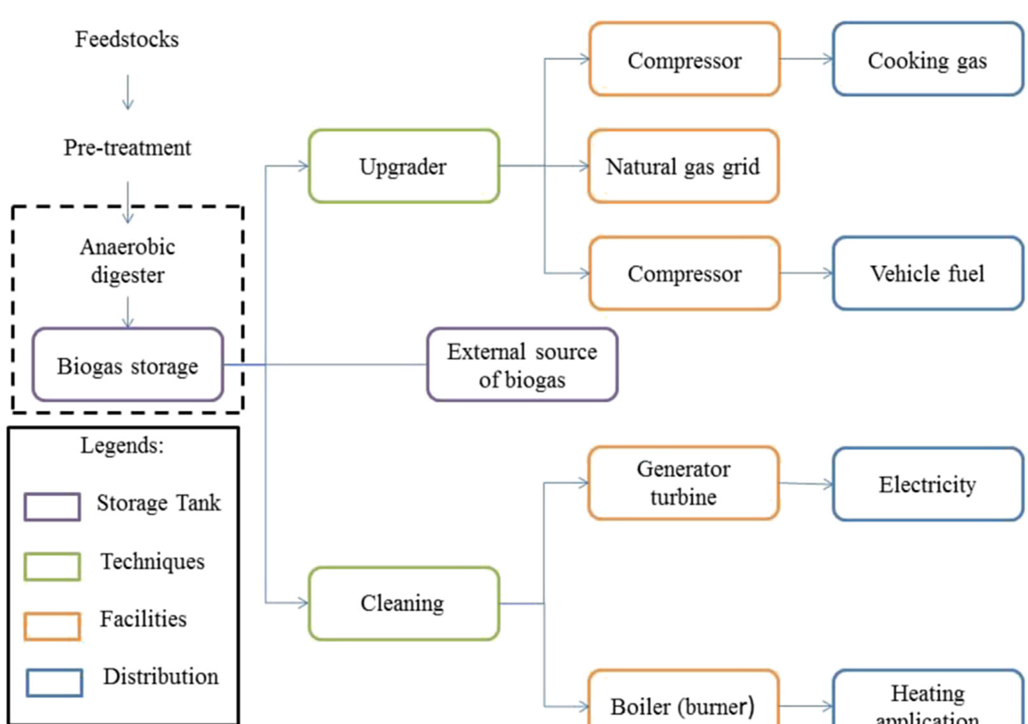

Fig. 1. Process flow diagram of biogas energy system.