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Integrated biomass and solar town: Incorporation of load shifting and energy storage

Haslenda Hashim [a,*], Wai Shin Ho [a,b], Jeng Shiun Lim [a], Sandro Macchietto [b]

[a] Process System Engineering Center (PROSPECT), Faculty of Chemical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b] Department of Chemical Engineering, Imperial College London, Roderic Hill Building, South Kensington Campus, London SW7 2AZ, UK

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ABSTRACT

The IBS (Integrated Biomass Solar) town is a concept which encourages local community to utilize biomass waste comprehensively with strong ties between community and local stakeholders. This paper discusses an IBS model and solution for an electrically self-sufficient eco-village with and without LS (load shifting). ES (energy storage) is also incorporated to help reduce electricity demand during peak periods and smooth variations in power generation by variable generation of solar power. Application to a realistic case study shows that substantial technical and economic benefits are achieved through the implementation of IBS with LS and ES. In this study, the LS is used mainly to increase demand during periods of high supply and also shift the load to intervals with low demand. This reduces the size of ES significantly, where the load is subject to distinct weekday and weekend profiles. The study shows that highly competitive electricity prices are obtained and the concept offers the opportunity to spur economic growth and environmental protection through energy efficiency improvement and deployment of low-carbon technologies.

1. Introduction

“Biomass Town” is a low-carbon community that emphasizes sustainability, by utilizing biomass resources in its vicinity to power the local energy system. It is envisaged that a biomass town should be self-sufficient in fulfilling its own energy demand. A biomass-based power plant is typically located in the proximity of biomass sources, to reduce the logistic cost, transmission losses and emission due to the supplementation of fossil fuel with RE (renewable energy) and transportation. The use of biomass which emits zero carbon over its life cycle indeed has the potential to combat global warming issue. However, the biomass available in a region might not be enough to fully satisfy its energy requirements. Also, the emission of pollutant gases such as NO_x (nitrogen oxides) during the biomass combustion stage of power generation is still unavoidable and causes adverse effects on human health. Therefore, to reduce the use of biomass and its harmful environmental impact, one alternative is to have an integrated biomass and solar energy system. Solar energy is an inherently cleaner power generation technology, as it does not involve any combustion process. By integrating solar energy with the biomass power plant, less power is required to be supplied from the power plant, and therefore less emission of pollutant gas from the combustion. The IBS (integrated biomass and solar) energy system is deemed to be a cleaner power generation scheme, at the expense of higher capital cost expenditure on solar. Furthermore, solar energy, depending on sunlight, is clearly not continuous. Thus to further improve the economic performance, an ES (energy storage) system might be incorporated into the IBS (integrated biomass and solar) energy system to reduce the power generation capacity of the energy system. On the other hand, LS (load shifting), a DSM (demand side management) technique has been studied extensively by different researchers [1]. In the case of stand-alone DEG (distributed energy generation) system such as IBS system, shifting the load to periods with high power generation can reduce the size of energy storage [2].

In recent years, numerous studies have been conducted to evaluate the economic feasibility of designing an integrated energy system. Gupta et al. [3] developed a cost minimization model to incorporate a larger variety of RE such as solar-PV, biomass, biogas, hydro as well as fossil fuel generator. Gupta et al. [4] then proposed an optimum control algorithm based on combined dispatch strategies, to achieve the optimal cost of battery incorporated hybrid energy system for electricity generation to solve the model. Gupta et al. [5] then applied the proposed and solving algorithm to

* Corresponding author.
E-mail address: haslenda@cheme.utm.my (H. Hashim).

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perform techno-economic analysis for a cluster of rural villages in India. Kumaravel and Ashok [6] performed an economic analysis to evaluate the economic performance of a hybrid energy system for a rural village in India by using HOMER, an established software. Kusakana [7] similarly perform techno-economic analysis of a hydrokinetic-based hybrid energy system for remote area in South Africa. Bracco et al. [8] optimized the combined heat and power distributed generation systems for a residential district in Italy. A comparative study was performed to quantify the economic savings and CO_2 emission reduction, comparing to the case of using a boiler to supply heat and purchasing electricity from the grid. Zidan and El-Saadany [9] proposed a GA (genetic algorithm) based method to determine the optimal configuration of a DEG system that considers wind power and photovoltaic generation. The formulated probabilistic generation-load model also considered the effect of load variation and stochastic power generation of the energy sources. Voll et al. [10] presented a framework for automated superstructure generation and optimization. The superstructure is generated using a P-graph approach, and then automatically convert into a mathematical model using generic component-based modelling approach. The formulated MILP (mixed integer linear programming) is then optimized to determine the structure, sizing and operation of distributed energy supply systems. Buoro et al. [11] formulated a multi-objective MILP model to determine the optimal design and operation strategy of a DEG system that consists of small-scale CHP systems, large centralized solar plant and thermal storage for an industry area. The authors also examined the effects of electricity carbon intensity variation on the designs of DEG system. Perera et al. [12] formulated a multi-objective MILP that considers levelized energy cost, initial capital cost and greenhouse gas emission to design the DEG system. Doagou-Mojarrad et al. [13] proposed a fuzzy satisfying method to determine the optimize placement and sizing of DEG units in distribution network, with the aim of achieving minimum total electrical energy losses, total electrical energy cost and total pollutant emissions. Mohanty et al. [14] developed an optimal planning model for DEG based micro-grid system that considers PV, a small wind electric generator, a biomass gasifier system, a diesel generator and battery storage. Another study worth mentioning was conducted by Ho et al. [15], who developed a numerical approach known as ESCA (Electricity System Cascade Analysis), to identify the optimal configuration of a DEG system that consists of biomass power generator and ES. Mohammad Rozali et al. [16] propose an alternate numerical method to design of hybrid power systems to determine the maximum power recovery and the battery storage capacity by considering the energy losses during the power system's conversion, transfer and storage. However, none of the studies above incorporated the demand side management such as load shifting feature into their models and assessments.

To address this issue, Dietrich et al. [2] formulated load shifting procedures into a mathematical model and applied it to a wind energy based isolated energy system, to determine the effects of load shifting on operation cost. Gudi et al. [17] performed load shifting for a set of household appliances that are powered by different energy sources by using Particle Swarm Optimization algorithm. In another study, Lujano-Rojas et al. [18] proposed a novel load management strategy for the optimization of a RE system by predicting the wind speed and its corresponding power. However, limited study has been reported to optimize the design an integrated biomass and energy solar system that considers load shifting of the demand side. Hashim et al. [19] present a mathematical model for simultaneous design and scheduling for the DEG system of an IBS town that considers the variation of daily solar intensity profile subject to different weather patterns. The authors evaluate and compare the economic advantages of load shifting on the design and operation of the DEG system. On the demand side, the authors only considered a single type of load profile, i.e. the authors assumed that the routine daily activities of a household will remain the same, regardless whether a specific day is weekend or weekday. Yet in actual scenarios, the daily activities of a typical household are greatly dependent on the nature of day, i.e., weekday and weekend, each having its own distinct load profile.

Thus the objective of this study is to use an optimization modelling approach to determine the optimal design for an IBS energy system that caters for a community electricity demand with different weekday and weekend load profiles. Compared to the previous models, the model considered in this study covers a different set of variability and inter-relationship between the energy load profiles, energy production intermittency, load shifting, and energy storage. The economic performance resulting from incorporating ES and load shifting is therefore discussed in this study.

This article begins by presenting a superstructure that describes the problem statement. Section 2 describes a multi-period mixed integer linear programming formulation to solve the problem statement. Section 3 demonstrates the application of the model to a typical case study and Section 4 analyses the results of the model application.

2. Methodology

In this paper, a model is developed as a MILP (mixed integer linear programming) model to design, schedule and perform load shifting on a DEG system for an IBS energy system. In this section, the mathematical superstructure and the developed model are presented.

2.1. Mathematical superstructure

Fig. 1 shows the superstructure that illustrates the supply and demand sides of IBS energy system. On the supply side, the power generators consist of a solar PV and biomass power plant, from which the hourly generated power can be directly fed to the demand side, or may be stored in the energy storage system first, prior to the discharging. The power generation of the solar PV system depends on the solar intensity and three different weather patterns, i.e., sunny, cloudy and rainy weather are considered. On the demand side, the load is assumed to consist of fixed load and shiftable load. The load profile results from the hourly electrical energy consumption of a set of electrical appliances over the weekdays and weekends. Some load (e.g. lighting) is assumed fixed, whereas some other (e.g. for machine washing) is assumed to be flexible and may be shifted to specific range of time slices, so as to reduce the size of the energy storage system. In this study, time is represented in hourly interval over a period of 24 h (a day).

Thus given a set of process and operating data for the power generators (power generation yield) and energy storage system (charging and discharging efficiency), the weather profile (the hourly solar intensity), cost data (electricity cost, capital cost for power generators and energy storage system) and load profile during weekday and weekend (hourly electricity consumption of a set of electrical appliance), the problem consists of determining:

- the capacity of power generators.
- the power-related and energy related capacity of the energy storage.
- the power generation schedule.
- the charging and discharging schedule of the energy storage system.

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