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Optimization with traffic-based control for designing standalone streetlight system: A case study

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ABSTRACT

Standalone street lighting as a preferred application for road lighting faces two important issues: supply performance and energy cost. According to past research, optimization of hybrid renewable energy system (HRES) in street light supply seems the best known approach to deal with these issues. However, the complex design of street light supply with non-linearity of power units and uncertainty of load pattern makes optimization a challenge. This study employs genetic algorithm (GA) optimization to deal with these complex and uncertain systems. In order to optimize streetlight supply, it takes into account the energy cost for a single-objective problem and both the energy cost and supply performance for a multi-objective problem. This study also integrates traffic-based lighting control to overcome the power consumption issue in the load side affecting the optimum design of the streetlight supply. The system including real weather data, real traffic conditions and optimization algorithm are simulated using MATLAB. Based on the results, the proposed method reduces the power consumption by around 47% for a one-year simulation study. Moreover, the optimal design of streetlight supply potentially minimizes power loss by approximately 39% and energy cost by about 29%.

1. Introduction

Street lighting is a valuable public facility long available to increase road user's safety at night [1] and decrease the incidence of criminality in cities [2]. Despite its benefits, the limitation of street light is in its performance [3,4]. The conventional street light design faces two important issues: cost of energy and supply performance. Conventional street lightings are an expensive public utility due to the high cost of its establishment, implementation, and maintenance [3]. Its expensive design cost makes it unpopular for small cities and sparsely populated areas.

Furthermore, the over-consumption of power during operations is significant as the conventional design contributes to the peak load issue given that street light consumes 3.19% of the global electricity consumption [3]. Household supply that interconnects with multiple lighting points contributes to over-consumption affecting performance of supply to satisfy the load demand. An uncontrolled street lighting system operating at high intensity during the night adds to the supply performance issue.

In order to enhance the conventional street lighting design, several refinements have been made. Kostic and Djokic [5] recommended a balance between an acceptable rate of lighting and energy saving. Kotulski et al. [6] suggested using photometric data to optimize the energy efficiency of the street light. In line with that, Gutierrez-Escolar et al. [7] studied government regulations on street lighting in Spain and proposed some suggestions for the device used according to the regulation. Some devices improved were lamps, street light globes, and ballast. The suggested improvements are the change of technology in supply, used lighting patterns and standard of visibility from the street light.

Utilization of hybrid renewable energy system (HRES) is a recent technological innovation for standalone street lighting. HRES is an integrated supply design that combines two or more of renewable

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energy sources. Due to its complex design, HRES needs an ideal size of supply to improve its performance. Several studies have proposed optimization of HRES using cost of energy (COE) as the objective [8–11], while others took into account the supply performance to be optimized in various applications [12–14]. For street lighting applications, HRES optimization was also carried out in several studies [15–17].

Instead of aiming at an integrated improvement for the whole system, most studies have optimized the design on the supply side, yet neglecting the control aspect in the load side. However, based on several studies [12,18,19], load power consumption significantly influenced the supply performance and cost of energy. Thus, load control that adjusts the load power consumption can affect in optimizing the supply to satisfy the load demand. A related research [20] examined six methods of load management in optimizing HRES design to determine the ideal method that can increase supply performance.

The integrated approach to optimize HRES and to apply load side control has not been much studied. For example, Al-Fatlawi et al. [21] investigated the effect of controlled load side to enhance optimum supply capacity using a weather-based controller *i.e.* hybrid optimization of multiple energy resources (HOMER) simulation. Radulovic et al. [22] proposed lighting management in urban areas to study the connection between the optimal intensity and decreasing of carbon emissions from an environmental perspective.

The weaknesses identified above relate to the system design characteristic, including solar radiation and load data. The monthly average data of 30 days used in past research [15–17,21,22] is insufficient to reflect the real technical power flow which is counted in the 8760 h of simulation period. The battery and lighting control methods are not clearly explained and the optimization is carried out by the deterministic iteration approach which can be trapped easily in local optima. Also, the optimization objective just considers the economic view in designing the streetlight supply.

As in previous study [23], the objective of this research is to integrate both design optimization on the supply side and traffic-based control on the load side to generate the optimum size of HRES in the street light supply with better supply performance at the lower cost. This study uses genetic algorithm (GA) method which can deal with multivariable decisions and multi-objective problems in HRES design, and also local optima in the optimization process. Furthermore, traffic-based lighting control was employed in the load side to reduce supply consumption by adjusting lighting intensity to the traffic density condition. The proposed control is expected to significantly influence the optimization of the HRES design. In contrast with previous research [21,22,24], this study considers both the single-objective and multi-objective problems to be optimized applying supply performance and energy cost as the criteria. It applies the actual solar radiation and traffic condition data affecting the load requirement for 8760 h. The algorithm for control and optimization are provided clearly to verify the influence of load control in enhancing power supply optimization. In addition, power flow analysis, including energy excess and losses, are provided in addition to the supply failure ratio in order to improve the system performance analysis.

This paper is arranged as follows: Section 2 describes the methodology of this research including the standalone street light model, optimization in the supply side, and traffic-based control in the load side. Section 3 discusses the optimization results in comparing the HRES design under controlled and uncontrolled loads in single-objective and multi-objective cases. The conclusion is provided in Section 4 which includes future research directions of HRES design for street lighting.

2. Methodology

2.1. Modelling of standalone streetlight

In this study, the street light consists of two sub-systems, *i.e.*, hybrid renewable energy system (HRES) on the supply side and light emitting diode (LED) on the load side. The HRES consists of a photovoltaic (PV) panel, fuel cell (FC) and rechargeable battery. The PV panel serves as the main power source which supplies electricity to the street light depending upon weather conditions, as shown in Fig. 1. The rechargeable battery stores the leftover power from the main source whenever supply exceeds consumption. The street light uses the excess power at night when the PV panel is incapable of producing electricity due to the absence of solar radiation. The fuel cell serves as the main power source to fulfil the lighting load when the battery capacity is low.

The parameters used in the standalone street light simulation are presented in Table 1, based on several assumptions as follows: (1) Calculation of power consumption was based on a standalone power source; (2) Solar radiation data was adopted from actual weather conditions. Since the solar radiation varied every hour, this made a number of negative readings for solar radiation which were assumed to be negligible; (3) Hourly energy cost data was taken from previous studies [16,24,25] which were converted into Malaysian Ringgit (MYR) using the following currency conversion rate, EUR 1 = MYR 4.08 [26]; (4) It was assumed that the electric converter *i.e.* the maximum power point tracking (MPPT) has negligible losses; (5) Carriageway road type for motor vehicles was chosen as the study case. Since carriageways were applicable for high-speed vehicles, the street lighting control focused only on vehicle movements and not of pedestrians.

The maximum and minimum PV power indicates the power range generated by the PV panel which is used as the main source to fulfil the load demands. It shall be noted that this range fluctuates according to changes in weather conditions. The maximum and minimum battery capacity represents the range of storage power that can be used during rainy days when the PV panel is unable to fulfil the load demands. Both the maximum and minimum FC power represents the power range generated by fuel cell. It is determined in case the PV panel and rechargeable battery are unable to supply the load demands for street lighting.

2.1.1. Photovoltaic model

There are three parameters that affect the power generation of the PV model, namely, solar radiation, coverage area and panel efficiency. Solar radiation is the radiant energy emitted by the sun, including electromagnetic energy. The light and heat from the solar radiation are absorbed by the solar cells in order to generate electrical power. The solar radiation (Ins) (W/m^2) varies depending on weather conditions. This study used the hourly solar radiation data in order to determine the PV power. It can be seen from Fig. 2 that the hourly solar radiation data varies over the 1-year simulation period.

The coverage area of the PV panel (A_{PV}) represents an extensive area of solar cell that captures the sunlight radiance. This area captures the sunlight radiance on a single PV panel which is then converted into electrical power per meter square (m^2).

The PV cell technology also influences its power and efficiency. There are three types of PV silicon solar panels commercially available in the market, *i.e.* amorphous, polycrystalline and monocrystalline. Amorphous PV panels are rarely used because of their low efficiency ($\simeq$10%) compared to monocrystalline (25%) and the polycrystalline (20%) PV panels [24]. The choice of the polycrystalline solar panel in this study was to minimize costs, since this solar panel type is cheaper than monocrystalline. Equations (1) and