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%.

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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 (HRES) model. Radunovic 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 is 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 fulfill 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) Carriage way 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 fulfill 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 fulfill 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 panel, 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/m²) 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 (∆APV) 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 (m²).

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 (~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...
(2) are used to describe the photovoltaic mathematical model \[23,25\] as follows,

\[ GPV = \eta_{PV} \times APV = PPV / Ins \] (1)

\[ PPV = \eta_{PV} \times APV \times Ins \] (2)

In these equations, \( PPV \) refers to the power generated by the PV panel at any given hour of the year, \( \eta_{PV} \) is the PV panel efficiency, \( APV \) is the coverage area of the PV panel that captures solar radiation, and \( Ins \) represents the hourly average radiation intensity of sunlight.

2.1.2. Battery model

The battery capacity model \[27\] was calculated based on its charge and discharge conditions. The PV panel supplies the lighting load during daytime and also charges the battery. In charging conditions, the power stored with respect to time is dependent on the self-charging efficiency \( \eta_{S} \), efficiency of the inverter \( \eta_{C} \), battery efficiency \( \eta_{B} \), and PV power \( PPV \). The battery capacity was used to determine the maximum value of the power captured. Equation (3) below was used to calculate the battery power \( PB \) for the current hour.

\[ PB(t) = PB(t - 1) \times (1 - \eta_{S}) + \left( PPV(t) - \frac{PB(t)}{\eta_{C}} \right) \times \eta_{B} \] (3)
The rechargeable battery will discharge its power to supply the lighting load (P_L) at night. The battery capacity is a variable that affects the discharging rate and time to supply the lighting load. The minimum rate of battery capacity to supply the lighting load is approximately 20%. If the battery capacity is low, the battery is incapable of supplying the lighting load and therefore, the power source will be switched to the FC power. The power of the battery in the discharge condition for any given hour of the year is expressed by Equation (4):

\[ P_B(t) = P_B \left( t - 1 \right) \times \left( 1 - \eta_S \right) + \left( P_{PV}(t) - P_L(t) \right) / \eta_{FC} \]  

(4)

The percentage of the battery capacity was determined by the amount of power stored at the time using the State of Charge (SOC) equation. The SOC represents the rate of the battery power (P_B) which is influenced by the battery capacity (C_B) and battery voltage (V_Ra). The SOC is given by Equation (5) [27]:

\[ SOC(t) = P_B(t) / (C_B \times V_{Ra}) \]  

(5)

### 2.1.3. Fuel cell model

The fuel cell is the power source that converts hydrogen into electrical power. In this study, the FC serves as the back-up power supply when the PV and rechargeable battery cannot fulfill the lighting demands. This study selects the proton exchange membrane fuel cell (PEMFC) since it has compact design, high current density and high efficiency in normal temperatures as compared to the other types of fuel cells [24]. PEMFC is also advantageous because of its ability to start up quickly. Moreover, PEMFC generates more power within a shorter time frame [23,24]. The commercialized PEMFC (i.e. Nexa FC from Ballard company) [23,24] was used to back up the PV-battery system for street lighting. Based on previous designs, the FC tank was placed inside the box of the street light controller and the tank was refueled by changing the hydrogen tank every 1½ to 2 years depending on the hydrogen consumption [24].

From Equations (6) and (7), which represent the mathematical model of the PEMFC, the power generated by the fuel cell (P_FC) and the amount of the hydrogen consumed (Q_H2) for each hour are given by:

\[ P_{FC} = n \times V_L / I_u \]  

(6)

\[ Q_{H2} = \int P_{FC} / \eta_{FC} \, dt \]  

(7)

where n is the number of cells in the PEMFC stack, V_L is the voltage of the cell, I_u represents the current density of the cell, Q_H2 is the amount of hydrogen supply used to generate power in the PEMFC stack, and \( \eta_{FC} \) is the power efficiency of the PEMFC stack.

### 2.1.4. Traffic and lighting model

For the case study, the actual traffic density data in Johor Bahru (one of the major towns in Malaysia) was used for the standalone street lighting system. It was chosen with respect to the traffic density as the control variable for the lighting load where the average daily traffic density in the area is about 294 vehicles/day. Moreover, the single carriageway was studied as the road type for motor vehicles [28] since it is the most relevant type representing the traffic density in Johor Bahru. The input of the lighting control system (i.e. traffic data) was plotted hourly per day for the 1-year simulation (8760 h). The traffic data per day for a 1-week period is shown in Fig. 3.

### 2.1.5. Trafic flow

Since traffic was the main source of the illumination cost, a traffic flow simulation (8760 h). The traffic flow was calculated using the POVM method in order to reduce power consumption in the lighting load. The optimization results for both controlled and uncontrolled loads were compared to determine the effect of implementing traffic control in the optimization of HRES for street lighting application. This study investigated four cases, which are: (1) Case 1: single-objective with uncontrolled load, (2) Case 2: multi-objective with uncontrolled load, (3) Case 3: single-objective with controlled load, and (4) Case 4: multi-objective with controlled load.

#### 2.2.1. Genetic algorithm (GA) method

**Genetic algorithm (GA)** is an advanced optimization method that effectively solves complex problems with multiple objectives and a large number of parameters [30]. This study faced conflicting objectives (i.e. maximizing the LPSP and minimizing the energy cost), which is difficult to be solved using simple optimization methods. Moreover, the process to attain these objectives is complicated and involves a non-linear problem (which is dependent on weather and traffic conditions) [31]. For these reasons, GA method is highly suitable since it is an attractive optimization method due to its simplicity in solving complex problems and best when dealing with conflicting objectives [23].

The HRES design consists of three decision variables, i.e. PV power, battery capacity and FC power. These variables represent the rate of power supply used to maximize the supply performance at the lowest cost. The three decision variables were optimized based on the range of generated/stored power. The set of limits were arranged for PV power, battery capacity and FC power to be within the range as presented in Table 3.

In the GA process, the variables and their respective values that were set into solutions called ‘individuals’, were evaluated with respect to the objective value. The street light simulation, including the HRES and lighting load components, were used in the evaluation process to calculate the fitness value with respect to the given objective. The optimization features such as maximum generation, variations of individual, selection method, probability of mutation and crossover are presented in Table 4.

The flow chart of the optimization process is shown in Fig. 4. The flow chart shows the two algorithms for the HRES optimization: (A) single-objective optimization cases (with uncontrolled load for case 1 and controlled load for case 3) and (B) multi-objective optimization cases (with uncontrolled load for case 2 and controlled load for case 4), respectively. For single-objective cases, the energy cost was used as the objective function, whereas for multi-objective cases, the decision variables must fulfill the conflicting objectives in terms of supply performance and
In general for all cases, the streetlight supply was modelled using Equations (1)–(7) based on actual weather and traffic data. The range of the decision variables i.e. PV power, battery capacity, and FC power were set as given in Table 3 for each case. The GA operators, namely, generation, population and probability of mutation and crossover were set and started by initiating the generation and population. The initial population consists of solutions called ‘individuals’. These solutions were evaluated in order to fulfil the objectives. The load profile was generated in the evaluation process for each case study. For the uncontrolled load cases (1&2), the power consumption was initiated at its highest rate during its operation, whereas for controlled load cases (3&4), the consumption was based on the lighting load control algorithm, as described in Section 2.3. Once the best solution was reached, the solution was kept in while others were selected using roulette wheel method. The selected solutions were modified using crossover and mutation operators in order to generate better solutions. The process was repeated until the maximum generation was reached.

### Table 2

<table>
<thead>
<tr>
<th>Characteristic of lighting</th>
<th>Value [23]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working voltage</td>
<td>Volts 12</td>
</tr>
<tr>
<td>Power rate</td>
<td>Watts 120</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Luminous per watts 72</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ppv(W)</th>
<th>Cb(Ah)</th>
<th>Pfc(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>1</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>Minimum</td>
<td>500</td>
<td>5833</td>
<td>500</td>
</tr>
</tbody>
</table>

### Table 4

<table>
<thead>
<tr>
<th>Parameter of GA</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum generation</td>
<td>100</td>
</tr>
<tr>
<td>Variations of individual</td>
<td>3</td>
</tr>
<tr>
<td>Bit of individual</td>
<td>10</td>
</tr>
<tr>
<td>Individuals per generation</td>
<td>40</td>
</tr>
<tr>
<td>Probability of mutation</td>
<td>0.1</td>
</tr>
<tr>
<td>Probability of crossover</td>
<td>0.9</td>
</tr>
</tbody>
</table>

2.2.2. Objectives function for power optimization

Optimization the street lighting model was conducted in order to maximize the supply performance and minimize the energy cost. This study used the cost of energy (COE) to measure the energy cost of the system whereas the supply performance was calculated using the loss of power supply probability (LPSP).

The COE is an estimate of the total cost of the annual generated energy (kWh) over its lifetime [32], whereby the unit cost (COEunit) represents the total cost for each unit of supply. This includes the installation cost, maintenance cost and charge rate, divided by the annual generated energy. Thus, the total unit cost (COEtotal) describes the accumulation of the cost of supply for the entire system. The COEunit and COEtotal is given by Equations (8) and (9), respectively [24,25] i.e.

$$COE_{\text{total}} = \frac{\text{Coe}_\text{total}}{\text{Total annual generated energy (kWh)}}$$

$$COE_{\text{total}} = COE_{\text{PV}} + COE_{\text{B}} + COE_{\text{FC}}$$

where $COE_{\text{PV}}, COE_{\text{B}}$ and $COE_{\text{FC}}$ are the cost of energy for the PV, battery, and FC power, respectively. The COE calculated for each power source taken from Refs. [23,26] is summarized in Table 5.

The LPSP, which is a measure of supply performance as suggested in several studies [12–14,19], is defined as the ratio of the number of hours when the system fails to supply the load to the total number of operating hours [27]. The LPSP indicates the number of times the power produced cannot satisfy the load demands. The LPSP was determined using Equations (10) and (11):

$$P_{\text{Loss}} = P_{\text{PV}} + P_{\text{B}} + P_{\text{FC}} - P_L$$

$$LPSP = \sum_{t=1}^{T} P_{\text{Loss}(t)} / T$$

where $P_{\text{Loss}(t)}$ is the number of hours when power loss occurred ($P_{\text{Loss}} < 0$) at the T times of simulation periods (maximum value is 8760). The power loss refers to the difference between the power produced (consisting of the PV power ($P_{\text{PV}}$), battery power ($P_{\text{B}}$), and FC power ($P_{\text{FC}}$) and the power consumed ($P_L$). In order to assess the supply performance, the loss ratio of the system was calculated with respect to time. An LPSP value of 0 indicates that the supply satisfies the load throughout the period whereas an LPSP value of 1 indicates that the supply does not satisfy the load at any time.

2.2.3. Fitness evaluation and constraints

In this study, performance of street light was simulated over a 1-
year period, taking into account the supply performance and energy cost as the objective functions. It accounted for the power flow analysis of the simulated street lighting using the parameters in Table 6 as well as its fitness calculation in order to optimize the supply.

In the single objective cases, the fitness values were calculated from 0 to 1 and this range represents the highest energy cost value of the street light system. The calculation of fitness value for energy cost objective function is expressed in Equation (13) as follows,

**Fig. 4.** HRES optimization algorithm for (A) Single-objective optimization cases (with uncontrolled load and controlled load) and (B) Multi-objective optimization cases (with uncontrolled load and controlled load).

**Table 5**

<table>
<thead>
<tr>
<th>Item</th>
<th>Price (RM/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaic (PV)</td>
<td>15.57</td>
</tr>
<tr>
<td>Battery (B)</td>
<td>0.66</td>
</tr>
<tr>
<td>Fuel cell (FC)</td>
<td>19.46</td>
</tr>
<tr>
<td>Hydrogen (H₂)</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

**Table 6**

<table>
<thead>
<tr>
<th>Evaluation criterion</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of power supply</td>
<td>Percentage losses (%)</td>
</tr>
<tr>
<td>Energy cost of system</td>
<td>Cost of energy (RM)</td>
</tr>
<tr>
<td>Excess and losses energy</td>
<td>Annual energy calculation (kWh)</td>
</tr>
</tbody>
</table>
Here, COE denotes the energy cost of the street light. For the multi-objective cases, the fitness values were calculated based on the energy cost and supply performance function using the weight sum approach. In this study, a weightage of 30% and 70% were used for supply performance and cost of the system, respectively. It was designed since a system with lower cost is given the higher priority.

The fitness value was determined using Equation (14):

$$fitness = \frac{(101 - coe)}{59721.47} + 1$$

(13)

Here, COE denotes the energy cost of the street light. For the multi-objective cases, the fitness values were calculated based on the energy cost and supply performance function using the weight sum approach. In this study, a weightage of 30% and 70% were used for supply performance and cost of the system, respectively. It was designed since a system with lower cost is given the higher priority.

The fitness value was determined using Equation (14):

$$fitness = 0.3\times (1 - cal_{lpp}) + 0.7\times \left(\frac{(101 - coe)}{59721.47} + 1\right)$$

(14)

The Excess and Losses (EoL) energy was also calculated as part of the supply performance evaluation. The EoL is the difference between energy supply ($P_s$) and energy consumption ($P_L$) which is expressed with positive and negative values where $P_s$ represents the annual generated energy, while $P_L$ refers to the annual energy consumption of the lighting load. Equation (15) was used to determine the supply power, comprising the PV, battery and FC power while Equation (16) was used to determine estimates of the EoL value in the street light simulation as follows,

$$P_s = P_{PV} + P_B + P_{FC}$$

(15)

$$EoL = \sum_{t=1}^{8760} P_L(t) - P_s(t)$$

(16)

It should be noted that the constraints refer to the range of decision variables which need to be considered in generating the set of solutions [14]. There are several constraints considered in generating the optimum HRES design, which are expressed as follows:

$$P_{Bmin} < P_B < P_{Bmax}$$

(17)

$$0 < P_{FC} < P_{FCmax}$$

(18)

where $P_B$ is the battery power and $P_{FC}$ is the FC power.

2.3. Traffic-based lighting control method on the load side

In designing an advanced street lighting system, lamp control is essential since it plays a vital role in energy savings. Several parameters (e.g. daylight/night time conditions, weather conditions and pedestrian/vehicle conditions) have been used to control the lamp to its appropriate intensity. The results of previous studies [3,5,33–37] have shown that it is possible to adjust the light intensity to provide sufficient brightness based on traffic conditions, which improves driving conditions and thus minimize the likelihood of accidents. Traffic count can be used for lamp control, such that the luminance is adjusted to suit the road environment as well as lamp specifications.

This study does not only consider the optimization of HRES but also the lighting load control. It integrates optimization with lighting load control in order to achieve the best supply performance at the lowest energy cost. Lighting load control was conducted by adjusting the light intensity towards the power consumed over a specific period. This method is essentially an on/ off control method that is based on time (i.e. daylight/night time) and vehicle detection. The traffic count were based on the actual traffic density data provided by the Public Works Department of Malaysia [38].

The proposed lighting control is described as follows. Based on the traffic density data, the hourly traffic flow was used to predict how often the light is turned on and hence, how much power is consumed. There are two conditions for lighting control: (1) turn-on state when vehicles appear and (2) turn-off state when there are no vehicles. After turned on for 10 s, the street light will automatically be switched into the standby mode (i.e. 32% from the maximum intensity) when no vehicle is detected and vice versa. The maximum number of vehicles required to simultaneously retain the turn-on condition was determined using Equation (19):

$$Maxv = \frac{T}{Tf}$$

(19)

where $Maxv$ refers to the maximum number of vehicles in 1 h (which corresponds to the turn-on time for 1 h), $T$ is the measured switching period in 1 h and $Tf$ is the on/off control time. Accordingly, if the vehicle density exceeds $Maxv$, then the street light turns on continuously during 1 h in maximum power consumption. On the other hand, if the vehicle density is less than $Maxv$, the hourly power consumed ($P_{h}(t)$) is given by Equation (20):

$$P_{h}(t) = \frac{\left(\frac{Tf(t)\times10\times100}{3600} + \left(3600 - \left(\frac{Tf(t)\times10}{3600}\right)\right)\times10\right)}{\eta_{lum}}$$

(20)

where $Tf(t)$ is the traffic density data for 1 h, $P_{h}(t)$ is the load consumption of the street light and $\eta_{lum}$ is the luminance efficiency of the street light. Based on this concept, the lighting load control can reduce the power consumption of the street light and hence, the power supply requirement. In this study, the lighting load control was implemented at night from 07:00 p.m. to 07:00 a.m [24], while the street light is switched off during the day. The power consumption was determined by the length of time that the lamp is turned on, and the controlled load profile was based on the power consumption. Fig. 5 shows the algorithm used for the lighting load control.

The hourly power consumed for the controlled load based on Equation (20) is shown in Fig. 6. The maximum traffic count is 699 vehicles per hour, which consumes 100 W of power for 1 h.
However, if the vehicle density is less than $Maxv$, the lighting load control is worked to adjust the lighting based on the traffic density input which in turn, reduces power consumption.

### 3. Results and discussion

Once the HRES optimization process was completed, evaluation of the optimum configuration was done to obtain the final COE and LPSP values. The results are presented in the next sections with respect to the generated power and consumed power for each of the configurations.

#### 3.1. Optimization with uncontrolled load

The optimum results in the supply side for the single-objective and multi-objective cases (excluding the lighting load control) are presented in the following sub-sections.

##### 3.1.1. Case 1: single-objective optimization

For the single-objective problem, this study optimized the supply design based on the energy cost. For the uncontrolled load, the optimum configuration consists of three power sources: PV, battery and FC. The best configuration (reflected by the best fitness value) was evaluated using the street light simulation. The optimum power supply rate is found to be 75 W, 140 Ah and 40 W for the PV panel, rechargeable battery and FC, respectively. The maximum fitness value using the GA search method is approximately 0.88 for this case.

##### 3.1.2. Case 2: multi-objective optimization

For the multi-objective problem, optimization of the supply design was based on the energy cost and power losses. This study included power losses parameter to account for power failure in the supply. The power supply rate is found to be 69 W, 131 Ah and 172 W for the PV panel, battery and FC, respectively. The maximum fitness value is around 0.92 for this case.

Calculations of the annual generation and consumption were conducted for the energy flow analysis. Based on this analysis, it found that the FC dominates the used power compared to the PV panel and rechargeable battery. However, the power consumed from the FC can fulfill the lighting load, which does not degrade the supply performance in any way. The energy loss for this design is about 127.98 kWh for the 1-year simulated period. It can be deduced that the multi-objective optimum design has lower supply failure since it has a higher supply capacity to fulfill the load. However, this comes at the expense of higher costs to compensate for the increased usage of the fuel cell as compared to the single-objective optimum design.

#### 3.2. Optimization with controlled load

Control mechanism was implemented for the lighting load and the results are discussed in Section 3.2.1. The decrease in the load consumption implies that the lighting load control is effective in enhancing the supply performance while reducing the cost of energy supply. This study presents the optimization results for single-objective and multi-objective problems with controlled load as in Sections 3.2.2 and 3.2.3, respectively.

##### 3.2.1. The load profile of lighting power consumption

The load profile is representative of the power consumption of the street light during its operation. In this study, the street light is operated at night from 07:00 p.m. to 07:00 a.m. and the street light is switched off during the day. Hence, this indicates that the street light consumes power for only 12 h a day. Fig. 7 shows the load profile input for a 1-day simulation period.

Based on Equations (17) and (18), the uncontrolled street light consumes 1.34 kWh and 532.90 kWh of energy respectively for the day and 1-year simulated period. In this study, traffic-based lighting load control was applied to reduce power consumption of street light based on the traffic flow conditions. The light intensity of the street light changes dynamically every hour. Using the proposed method, the light intensity is high during heavy traffic and vice versa for low traffic conditions. In brief, a change in the traffic volume results in a change in the light intensity.

The controlled load reduces to 811.71 Wh of energy per day and decreases to 284.49 kWh of energy over a 1-year period. The load profile with respect to the power consumption affects the power supply design [18,19,23].

##### 3.2.2. Case 3: single-objective optimization

Based on the simulation, the single-objective optimum design with controlled load has higher fitness value compared to that for uncontrolled load. The PV power, battery capacity and FC power are 62 W, 142 Ah and 27 W respectively, and the fitness value is around 0.90.

It can be found that the LPSP is about 38% for a 1-year simulated period. This means the single-objective optimum design with controlled load reduces power failure by roughly 5% for the 1-year simulation period. The energy cost for this design is approximately RM6,316 which is lower than that for the uncontrolled load. Based on annual energy generation and consumption, the energy loss for

![Fig. 6. Comparison between traffic density and hourly power consumption.](image-url)
a 1-year period is 61.506 kWh. It is analyzed that the usage of the FC for controlled load is less than that for uncontrolled load.

### 3.2.3. Case 4: multi-objective optimization

For multi-objective problem, the PV power, battery capacity, and FC power are found to be 62 W, 398 Ah and 27 W, respectively. Based on the results, the usage of the FC for controlled load condition is less than that for uncontrolled load. Hence, the lowest LPSP is about 0.0015, which indicates that the occurrence of supply failure is about 0.15% for the 1-year simulated period. This design incurs an energy cost of RM7,477 which is lower than that for the uncontrolled load. In addition, the street light supply has an excess energy of 69.34 kWh for the 1-year period.

### 3.2.4. Discussion

This study focused on optimizing the supply design and improved the lighting load control in order to maximize supply performance and minimize the energy cost for street lighting. Implementation of GA for both single-objective and multi-objective optimization problems were studied. Table 7 shows that the multi-objective optimum design gives better results than the single-objective optimum design in terms of supply performance and energy cost. Despite the higher energy cost, the multi-objective optimum design enhances the supply performance for the 1-year simulated period, as indicated by the lower LPSP and energy loss. This shows the benefits of considering the supply performance to reduce power supply failure and increase street light performance.

This study also improved the supply performance and reduced energy cost of the street lighting supply design by implementing traffic-based lighting load control. Since the lighting load is a power-consuming component, it affects the supply performance and energy cost of street lighting. The lighting load control approach was proposed to adjust the lamp intensity based on the hourly traffic density which was integrated into the optimization part.

The results reveal that implementation of the lighting load control for the multi-objective optimization case gives the best supply performance and energy cost. The lighting load control also yields energy savings of 70 kWh for the 1-year simulation period, along with the lowest power supply failure and energy cost. Based on these results, it can be deduced that the proposed method gives optimum street lighting supply design and lower energy cost.

### 4. Conclusion

The street light system is simulated to optimize its HRES design, taking into account the supply losses and energy cost issues. The lighting load as the power-consuming component in street lighting is considered to be controlled with adjusting the lamp intensity and hence, power consumption. It can be found that improvements can be made in order to ensure optimum supply. Genetic Algorithm is used for both single-objective and multi-objective optimization problems since it can deal with conflicting objectives (i.e., maximizing the LPSP and minimizing the energy cost). Moreover, the process to attain these objectives is complicated and involves a non-linear problem (which is dependent on weather and traffic conditions). For these reasons, GA method is chosen due to its simplicity in solving complex problem and good performance when dealing with conflicting objectives. It is concluded that the multi-objective optimization gives higher supply performance and lower energy cost compared to the single-objective optimization. This indicates that the proposed lighting load control method increases the street light supply performance while simultaneously producing excess energy for the 1-year simulated period. The proposed lighting load control method also reduces the energy cost and also minimizes the utilization of the fuel cell which has significant contribution for increasing the energy cost. Future studies will look into the development of advanced lighting load control

### Table 7

<table>
<thead>
<tr>
<th>Simulation results</th>
<th>Uncontrolled load</th>
<th>Multi-objective</th>
<th>Controlled load</th>
<th>Multi-objective</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PV (kWh)</strong></td>
<td>89.58</td>
<td>82.41</td>
<td>74.05</td>
<td>75.23</td>
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<tr>
<td><strong>Battery (kWh)</strong></td>
<td>1.68</td>
<td>1.57</td>
<td>1.7</td>
<td>2.38</td>
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<tr>
<td><strong>FC (kWh)</strong></td>
<td>194.19</td>
<td>576.89</td>
<td>147.23</td>
<td>276.22</td>
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<tr>
<td><strong>LPSP (%)</strong></td>
<td>40</td>
<td>0.23</td>
<td>38</td>
<td>0.15</td>
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<tr>
<td><strong>COE (MYR)</strong></td>
<td>7830</td>
<td>10.524</td>
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<td>7477</td>
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<tr>
<td><strong>Excess(+)losses(–) energy (kWh)</strong></td>
<td>[–]247.45</td>
<td>[+]127.96</td>
<td>[–]61.51</td>
<td>[+]693.4</td>
</tr>
</tbody>
</table>

![Fig. 7. Hourly load profiles for uncontrolled and controlled load.](image-url)
methods which to further reduce power consumption, improve supply performance and reduce energy costs. It is also recommended to use other meta-heuristic approaches in order to produce better optimization results. Furthermore, real-time study will be initiated to examine the tangible outcomes obtained from improving HRES design for standalone street lighting.

Acknowledgement

The authors are grateful to the University of Malaya Research Grant (UMRG) “RP006A-13ICT” for providing financial assistance for this project.

List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{pv}$</td>
<td>Gain of Photovoltaic Power</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency (%)</td>
</tr>
<tr>
<td>$l$</td>
<td>Current (A)</td>
</tr>
<tr>
<td>$P$</td>
<td>Power (Watt)</td>
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<tr>
<td>COE</td>
<td>Cost of Energy (MYR)</td>
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<td>$L_{ns}$</td>
<td>Irradiance of Solar (W/m²)</td>
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<td>$SOC$</td>
<td>State of Charge (%)</td>
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<td>$V_{bo}$</td>
<td>Open Voltage of Battery (V)</td>
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<tr>
<td>$Int$</td>
<td>Lighting Intensity (Lm)</td>
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<td>$C$</td>
<td>Capacity (AH)</td>
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<td>$LPSP$</td>
<td>Loss of Supply Probability (%)</td>
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<td>$T$</td>
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<td>$H_{2}$</td>
<td>Hydrogen</td>
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References


