IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 14, 2020, accepted October 30, 2020, date of publication November 3, 2020, date of current version November 18, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3035702

Economic Analysis of Improving the Energy Efficiency of Nanogrid Solar Road Lighting Using Adaptive Lighting Control

PATHOMTHAT CHIRADEJA[1], SUNTITI YOOMAK[2], (Member, IEEE), AND ATTHAPOL NGAOPITAKKUL[2], (Member, IEEE)
[1]Faculty of Engineering, Srinakharinwirot University, Bangkok 10110, Thailand
[2]Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand

Corresponding author: Atthapol Ngaopitakkul (atthapol.ng@kmitl.ac.th)

This work was supported by The Royal Golden Jubilee (RGJ) Ph.D. Scholarship, Thailand, under Grant PHD/0171/2559.

ABSTRACT This paper presents a road lighting control system that uses a light-dependent resistor sensor cooperating with an Internet protocol camera to the lower energy consumption during unnecessary use of a lighting system. A microcontroller was used as a control circuit to automatically control the brightness of a light-emitting diode (LED) luminaire, increasing or decreasing the brightness depending on traffic density. The proposed lighting control system was integrated into a nanogrid solar road lighting system and analysed through an experimental setup. Furthermore, nanogrid solar road lighting systems in LED solar stand-alone and grid-connected operations, with and without the proposed lighting control, were investigated and compared with a conventional existing road lighting system in terms of economic feasibility, based on the following indicators: discounted payback period, net present value, internal rate of return, and profitability index. The results indicate that the use of the Internet protocol camera with the LED sensor can automatically control the on/off state or illuminance levels of the LED luminaire, thereby lowering the energy consumption of the road lighting system when lighting is not required. The economic assessment results indicate that the nanogrid solar road lighting system in LED solar stand-alone and grid-connected road lighting modes exhibit feasibility for investment; the latter provides more economic feasibility. However, when the proposed lighting control is included, the nanogrid solar road lighting system in both modes have lower initial investment costs and save more energy. Consequently, the economic results are improved. The use of the proposed lighting control is thus economically feasible for road lighting systems.

INDEX TERMS Nanogrid, solar systems, LED luminaires, road lighting systems, economic evaluation, adaptive lighting control.

I. INTRODUCTION

A road lighting system is designed to provide safety and visual clarity for drivers throughout the night. Sufficient lighting can decrease night-time accidents by 30–35% compared with an inefficient road lighting system [1], [2]. However, the quality of a large scale road lighting system is brought to the required standard [3] by providing high electrical energy utilization; sometimes, this exceeds 40% of total energy demand in cities [4], [5]. In Thailand, the energy consumption of road lighting systems is an increasing burden on the government authority's budgets in the free-of-charge services, which was approximately 211 GWh in 2019 [6].

In practice, the consumption of road lighting relies on the type of luminaire used. Existing several road lighting systems in Thailand still use conventional light sources, and the light is on continuously during the dark, leading to high energy consumption. These concerns were addressed by introducing light-emitting diode (LED) luminaires to minimize the energy consumption; LED luminaires are more effective compared with conventional luminaires in terms of lighting quality, lifetime, colour rendering, light distribution efficacy, and energy saving [7], [8]. However, the introduction of LED road lighting systems is only a first step, because energy

The associate editor coordinating the review of this manuscript and approving it for publication was Canbing Li.

consumption in road lighting systems can be decreased further using intelligent controls.

In addition to the energy efficiency of LED technologies, automatic on/off control has generated new opportunities for minimizing energy consumption in road lighting systems [9]–[14]. Here, road lighting systems are controlled to activate and deactivate according to the presence of natural light and object detection using embedded sensors, such as light-dependent resistors (LDRs) [9], [14], infrared (IR) sensors [10]–[12], [14], and cameras [13]. The LDR sensor controls the road lighting function completely based on the availability of natural light [9], [14]. The IR and camera are used to detect objects such as vehicles and pedestrians on the road [10]–[14]. In addition, the camera can provide other benefits of monitoring [15], [16] such as crime detection [9] and dimming control [17], [18]. However, the automatic on/off control still cannot vary light intensity based on traffic volumes, causing excessive energy consumption during unnecessary utilization.

Owing to the rapid convergence of new technologies such as LED lighting, sensors, and small-size controllers, smart lighting control has become feasible. The brightness of road lighting systems can control on/off functions and the light intensity depending on use [19]–[29] to decrease unnecessary utilization, and hence save more energy. Ref. [21] adopted passive infrared (PIR) sensors to track vehicle movement to optimize the illuminance levels of a road lighting system. Refs. [26] and [22] investigated intelligent control strategies for energy optimization. Additionally, improved reliability, enhanced safety, lower cost, and more user satisfaction were discussed. The proposed strategies can save energy by 66–82% depending on the variations in daylight hours. Moreover, wireless sensor networks were applied to dim road lighting systems to achieve high energy efficiency and low implementation costs [25]. In Ref. [23], a deterministic model for a light on demand (LoD) system was employed to control the intensity of road lights in relation to real-time traffic volumes.

Furthermore, smart lighting control systems are integrated with other attractive features based on innovations in Internet-of-Things (IoT) technologies [10], [19], [28], [30] and soft computing methods [15], [20], resulting in lower energy consumption, better energy management, higher visual comfort, and higher safety. For instance, an IoT technique for a control network to control the light intensity of road lighting systems was presented in [19], [30]. In addition, the IoT technologies provided services for road comfort and safety to the driver. In addition to using IoT to control road lighting systems, Ref, [28] adopted an IoT network with wireless control based on a mesh communication network to address environmental detection, security, maintenance, and energy management improvement. Furthermore, soft computing methods used in road lighting systems include artificial intelligence (AI), artificial neural networks (ANNs), and fuzzy logic controllers (FLCs). Ref. [15] employed AI to design intelligent management for road lighting systems to lower electricity costs and maintain maximum visual comfort in required traffic areas. Ref. [20] used an ANN and FLC to create an efficient decision process using sensors for demand based on road utilization and to avoid the unnecessary use of road lighting systems. In that study, a 13.5% reduction in energy consumption was achieved.

Although, as previously mentioned, the use of LED technologies and smart lighting control systems can result in many benefits of lower energy consumption [7]–[30], road lighting systems still consume a significant share of energy from electrical grids. Hence, this results in high energy costs and greenhouse emissions. This is addressed by integrating solar systems into the road lighting system; these convert solar energy into electrical energy to supply the road lighting system [7], [11], [27]–[32], [36], [37]. In Ref. [31], replacing a conventional road lighting system with a solar system resulted in benefits such as cost effectiveness, energy efficiency, high durability, higher lumen output, and environmental friendliness. An economic evaluation to investigate the integration of a solar system into a road lighting system was discussed in [32]. The study observed that, if a road lighting system already exists and requires no modernization, there is satisfied for investment. For smart solar road lighting systems, Ref. [11] claimed that using automatic on/off lighting control with the use of solar energy can be an effective solution for saving energy. Ref. [29] conducted control-based traffic detection to adjust light intensity to decrease lighting consumption for a solar stand-alone road lighting system. Through this technique, the energy cost and energy utilization can be reduced by 29 and 47%, respectively. In conclusion, integrating solar systems into the road lighting systems could be a promising solution for increasing the energy efficiency of these systems [7], [11], [27]–[32], [36], [37]. However, owing to the high initial and operation costs of additional solar systems, their economic feasibility proves unsatisfactory for investment [36], [37].

In practice, many papers focus on the economic evaluation of refurbished road lighting [32]–[35]. An investigation of the economic benefits of investing in a solar system and LED technologies in existing or developed road lighting systems were discussed in [32]. Economic indicators such as the internal rate of return (IRR), profitability index (PI), discounted payback period (DPP), and net present value (NPV) were used to compare the developed road lighting systems. The study claimed that the integration of a solar system into a road lighting system can be achieved if the latter already exists and requires no modernization. Reference [33] presented an economic evaluation model for replacing conventional luminaires with LED ones in a road lighting system. Although the cost of LED luminaires is still the main barrier to investment, their use is economically advisable owing to decreased maintenance and low energy consumption. Reference [34] proposed a step-by-step process for the lighting, energy, and economic analysis of road lighting refurbishment designs. When road lighting systems are refurbished, the annual costs could be reduced by up to 33% because of the decrease in electricity and maintenance costs. Hence, the economic evaluation based on a payback indicator demonstrated acceptable investments. However, the payback value is sensitive to variations in electricity cost. Another paper [35] on adopting LED technologies proved that using LED luminaires as substitutes for conventional light sources is economically worthy based on the analysis of various factors: power consumption, maintenance costs, carbon dioxide emissions, and road safety. From paper [32]–[37], it is pointed that although the solar road lighting systems with lighting control systems provide significant energy saving, the additional investment costs of these technologies require to be considered.

In this field, we proposed improving road lighting energy efficiency through economic analysis, by adopting LED technologies to replace conventional light sources [7], investigating the feasibility of various energy storage systems for LED solar stand-alone road lighting systems [36], and developing road lighting systems using nano-grid technologies [37], [41]. However, our papers state that the integration of a solar stand-alone system into a road lighting system provides an unsatisfactory economic aspect owing to high initial investment costs of the additional solar system. In this study, we applied smart lighting control to dim solar road lighting systems according to vehicle detection to lower the energy consumption during unnecessary utilization. Furthermore, the economic analysis of the solar road lighting systems with and without the proposed lighting control is discussed in the paper.

The contributions of this paper are summarized as follows:

- To cope with high installation costs in the nanogrid solar road lighting system due to a large demand of the lighting system operation at nighttime, a road-lighting control based on adaptive traffic conditions using an LDR sensor in conjunction with an Internet protocol (IP) camera to eliminate unnecessary energy consumption is proposed.
- The adaptive lighting control integrated into the nanogrid solar road lighting system in LED solar stand-alone and grid-connected modes was designed and tested by using an experimental setup. Additionally, the energy efficiency of using the proposed lighting control system was also compared to the system without light control.
- To prove the energy efficiency and economic feasibility of the proposed control lighting system, we studied the economic feasibility of nanogrid solar road lighting systems in LED solar stand-alone and LED solar grid-connected modes, both with and without the proposed lighting control adopted, were analysed and compared with the conventional road lighting system.

The remainder of the paper is structured as follows. Section 2 provides nanogrid solar road lighting systems integrated with a lighting control concept, encompassing road lighting control, nanogrid solar road lighting systems with and without lighting control. Section 3 introduces experimental setup and results in cases of nanogrid solar road lighting with and without lighting control. In Section 4, an economic feasibility analysis, including the investigation outline, system component design, and economic evaluation results, is described. Section 5 presents the discussion of economic aspects. Finally, Section 6 presents the conclusions, summarizing the main contributions and suggesting directions for future studies.

II. NANOGRID ROAD LIGHTING SYSTEMS INTEGRATED WITH LIGHTING CONTROL CONCEPT

A. NANOGRID SYSTEMS WITHOUT CONTROL

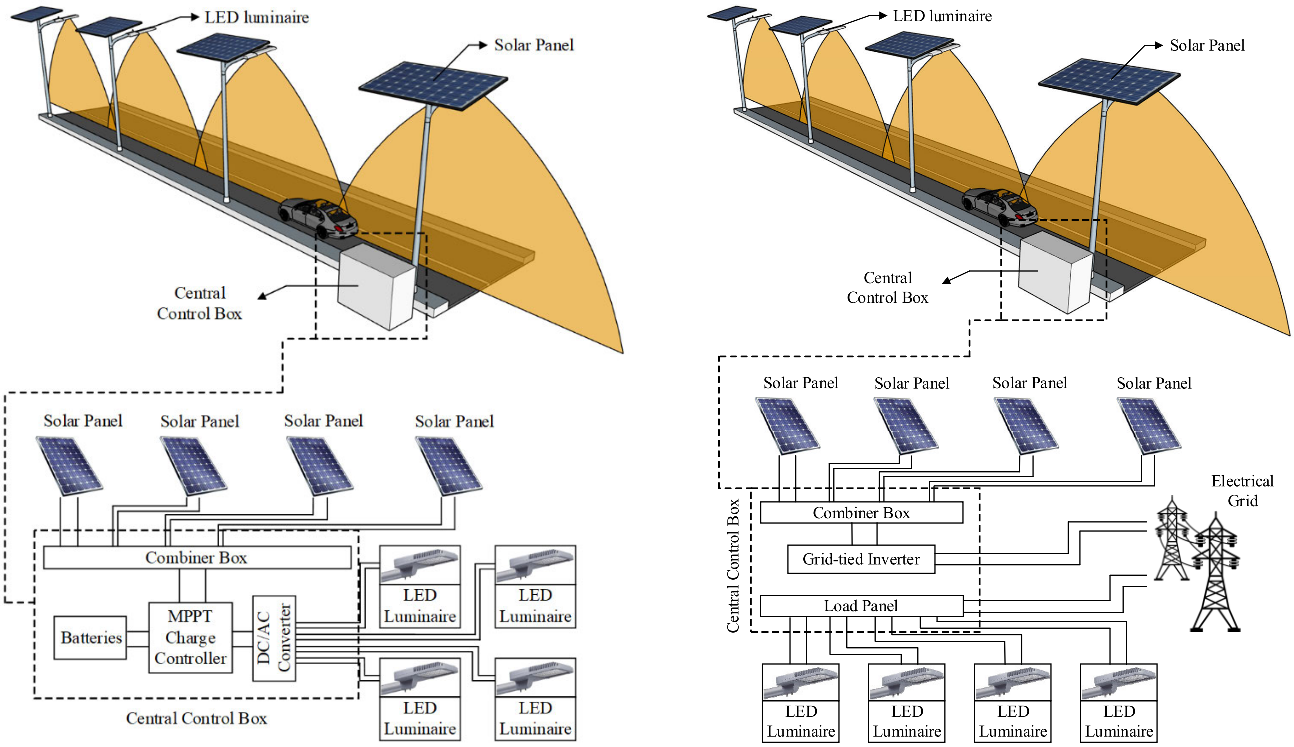
In this research, the concept of a nanogrid solar road lighting system is a road lighting system that uses a solar system to generate electrical energy, enabling operation in stand-alone and grid connection modes [37], [41], is undertaken.

Two major infrastructures for installing solar cell systems with road lighting systems exist: solar systems to generate power to supply the road lighting systems during the dark, which is an LED solar stand-alone road lighting system, and feeding it to the electrical grid, which is a LED solar grid-connected road lighting system. Thus, the latter systems do not relate to the operation of road lighting systems. Both solar road lighting systems have features that provide different advantages and disadvantages depending on the purpose of use.

Fig. 1 show the integration of nanogrid solar systems into road lighting systems which can operate in the LED solar stand-alone and grid-connected road lighting modes. The former operation comprises solar panels, a solar charger, an energy storage system, LED luminaires, and an inverter as shown Fig. 1(a). During the daytime, electrical energy generated from solar panels is stored in the central energy storage system using the solar charger, which controls the voltage and power for charging. The solar charger is employed to extract electrical energy from the energy storage system to supply the LED luminaires via the inverter, which is used to convert direct current into alternating current. In comparison, the LED solar grid-connected road lighting system operation consists of solar panels, a central grid-tied inverter, and LED luminaires as shown Fig. 1(b). During the daytime, if the electrical energy generated from the solar panels is more than the energy used in the road lighting system, the surplus energy will be sent into the electrical grid via the central grid-tied inverter. At night, the system has ability to draws electric energy from the electrical grid to supply the road lighting system when the batteries are run out.

B. NANOGRID SYSTEMS WITH LIGHTING CONTROL

The nanogrid solar road lighting system operated in LED solar stand-alone and grid-connected modes can be integrated with the proposed lighting control using an Internet protocol camera, as shown in Figs. 2(a) and (b), respectively. As the figure shows, a vehicle is moving forward at a high speed on the main road. Road lighting systems are installed



(a) Solar stand-alone road lighting system operation

(b) Solar grid-connection road lighting system operation

FIGURE 1. Diagram of nanogrid solar system application.

symmetrically. Thus, installing detection devices, i.e. IP camera and LDR sensor, on every road lighting pole is not necessary. The LED luminaires are grouped to receive control signals from the central control system. The LDR sensor is used to switch the LED luminaires on or off based on ambient light, while the IP camera is employed to detect vehicles to adaptively adjust the illuminance of the LED luminaire according to traffic volume. The road lighting systems are not operated at full capacity all the time, which lowers the energy consumption. The required sizes of the solar panels and energy storage systems decrease because of the lower solar system cost.

III. EXPERIMENT AND RESULTS OF THE NANOGRID ROAD LIGHTING SYSTEMS

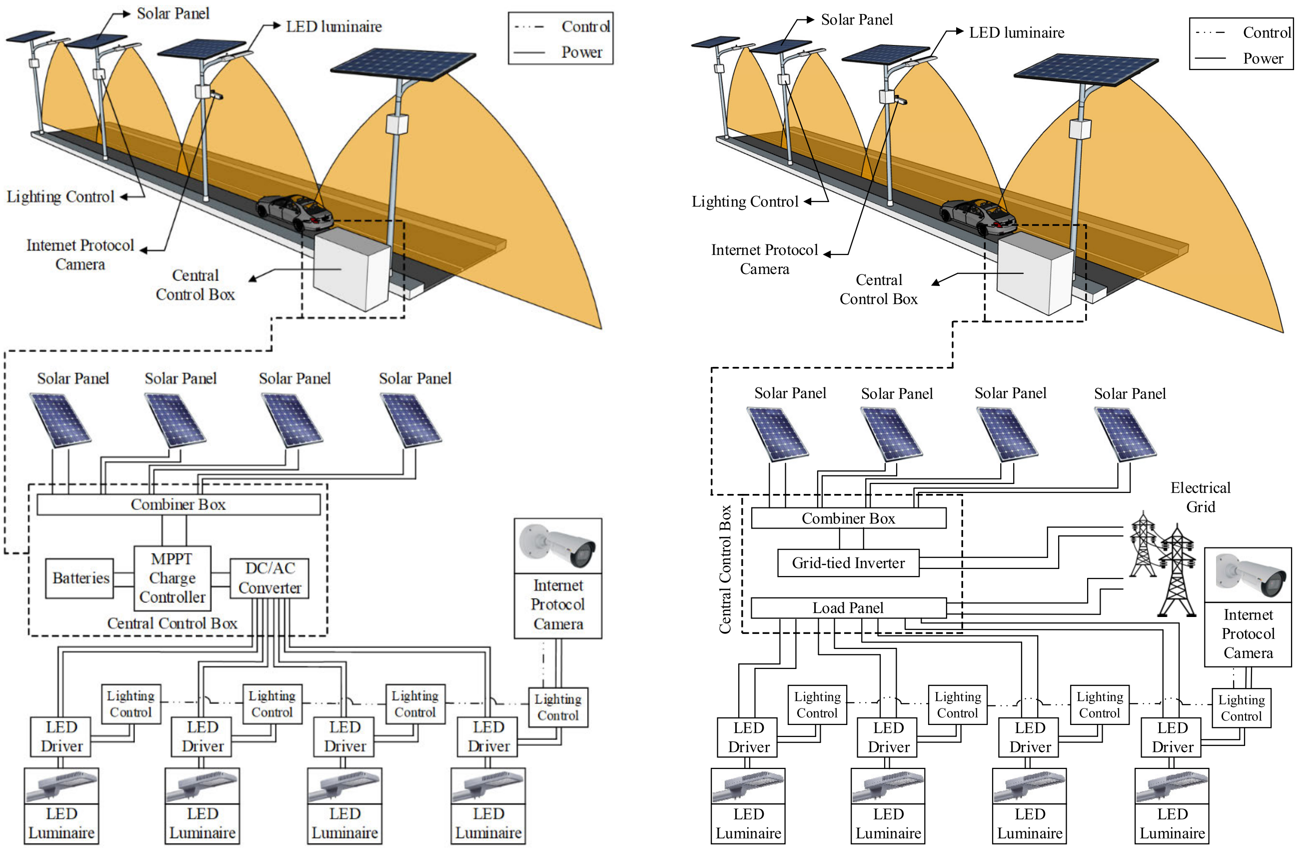
A. NANOGRID SOLAR ROAD LIGHTING SYSTEMS WITHOUT LIGHTING CONTROL

From previous work [37], [41], the proposed nanogrid solar road lighting system was investigated in a laboratory to analyse power quality parameters and its performance. The experimental setup was designed to into two parts: an LED solar stand-alone and an LED solar grid connection operation modes. Fig. 3 presents the schematic diagram of the proposed nanogrid solar road lighting system, consisting of stand-alone operation and grid connection operation as depicted in Figs. 3(a) and (b), respectively.

For the nanogrid solar road lighting system based on stand-alone operation (see Fig. 3(a)), The experimental setup received three-phase voltage (AC) of 400/230 V (denoted by number 1) from a laboratory to supply the PV simulator (denoted by number 2); a PV simulator was used to simulate a solar panel of 300 W. The 24 V, 120 Ah lead-acid battery (denoted by number 7) was used as an energy storage system. The battery was charged by electrical energy from the PV simulator by the 24 V, 30-amp charge controller (denoted by number 6). The 120 W LED luminaire (denoted by number 5) was supplied by the electrical energy from the battery using the charge controller through a 500 W pure sine wave inverter (denoted by number 8) to convert the battery's DC into AC.

In Fig. 3(b), the nanogrid solar road lighting system based on grid connection operation was presented. The experimental setup received three-phase voltages (denoted by number 1) from the laboratory to supply the PV simulator (denoted by number 2). Thus, the characteristic of a 300 W solar panel was determined to be an energy source. The energy generated from the PV simulator was fed into the electrical grid (denoted by number 7) with a voltage of 220 V and frequency of 50 Hz related to the electrical grid conditions. A 250 W microinverter (denoted by number 6) was used to convert the direct current of the solar energy system into the alternating current of the electrical grid. For the road lighting system, the 120 W LED luminaire (denoted by number 5) was supplied by the electrical grid.

The power quality meter (denoted by number 3) was employed to measure and record data, while the current



(a) LED solar stand-alone road lighting system operation

(b) LED solar grid-connection road lighting system operation

FIGURE 2. Diagram of nanogrid solar road lighting systems with lighting control.

TABLE 1. Power quality parameters of a 120 w led luminaire

The LED solar stand-alone mode

Parameters	I (A)	V (V)	P (W)	Q (var)	S (VA)	p.f.	f (Hz)	% THD_i	% THD_v
LED	0.55	228.2	121	-22	126	0.96	50	17.5	1.31

The LED solar grid connection mode

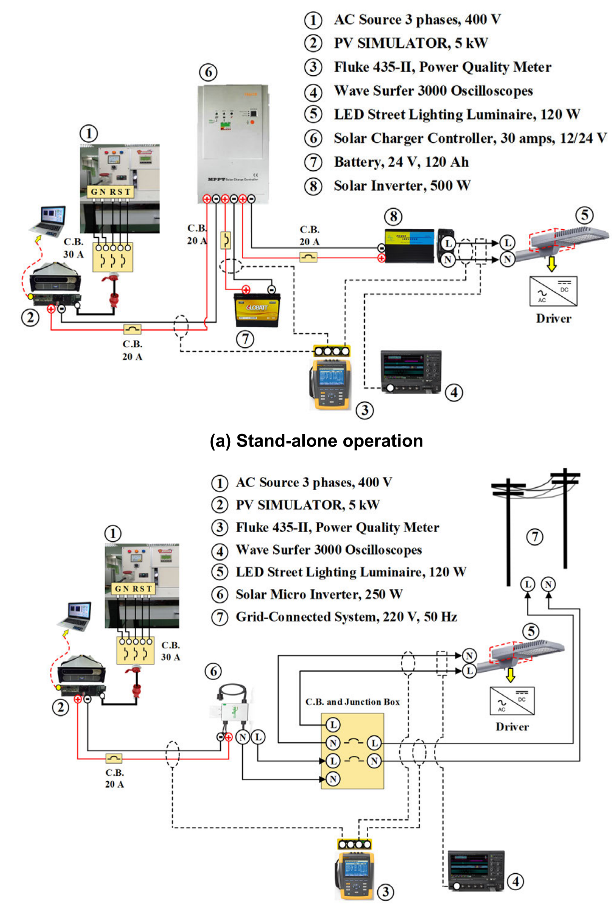
Parameters	I (A)	V (V)	P (W)	Q (var)	S (VA)	p.f.	f (Hz)	% THD_i	% THD_v
LED	0.56	224.7	121	−21	124	0.97	50	13.7	1

waveform was also observed using the oscilloscopes denoted by number 4.

The measurement results of a 120 W LED luminaire based on the LED solar stand-alone and the grid connection operation were presented in Tables I. It is found that whether the systems operate in stand-alone or grid connection modes, the system must supply the active power for the luminaire equal to 121 W. Although LED luminaires are used in road lighting systems to save energy, they provide a constant light value at their rated value. However, the road does not always contain a high traffic density; thus, there is an energy loss. For this reason, a lighting control system dependable on traffic usage is necessary for saving energy consumption in the nanogrid solar road lighting system. Additionally, further results like power quality, battery charging, solar generation, and electrical grid impacts has caried out and discussed in [37], [41].

B. NANOGRID SOLAR ROAD LIGHTING SYSTEMS WITH LIGHTING CONTROL

By considering a lighting control system applied for the nanogrid solar road lighting system, Fig.4 shows a schematic of lighting control based on an IP camera in the nanogrid solar road lighting system divided into stand-alone and grid connection modes (see in Figs. 4(a) and (b) respectively). A 1-phase AC source (denoted as 1) used to supply an LED luminaire and LED driver. When the nanogrid solar road lighting system operated in stand-alone mode, the AC source from batteries is employed. However, when batteries are run out, the nanogrid solar road lighting system will be operated in grid connection mode. Thus, the AC source from the electrical grid is utilized. The light control system comprises the following: a 1-phase AC source (denoted as 1) used to supply an LED luminaire and LED driver; a power quality meter (2) used to measure electrical parameters; an oscilloscope (3) used to record the waveforms; an LED luminaire (4) used as the light source for the road lighting system; an LED driver (5) used to convert high voltages of alternating



(b) Grid connection operation

FIGURE 3. The schematic diagram of the proposed nanogrid solar road lighting system.

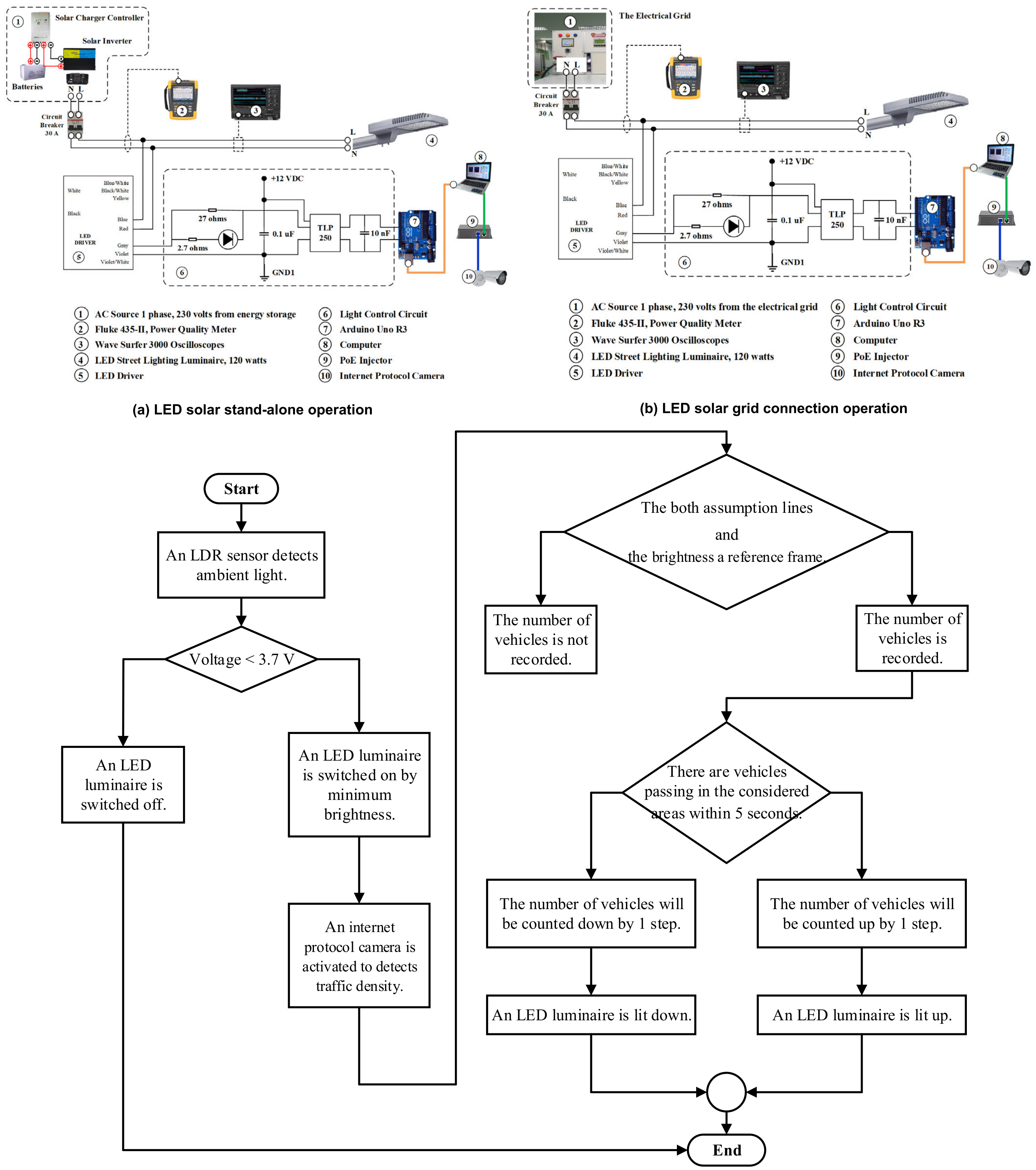
current to low voltages of direct current and to maintain the voltage and current flowing through the LED circuit at their rated levels; a light control circuit (6) cooperating with an Arduino Uno R3 microcontroller (7); a computer (8) used to process the data obtained from the IP camera; a power-over-Ethernet (PoE) injector (9) used to supply power to the camera and split the signals from the camera to the computer; and an IP camera (10) used to detect moveable objects such as vehicles with high accuracy using infrared light, making it useable under low-brightness conditions. The IP camera constitutes a closed-circuit television (CCTV) with a network system, consisting of image processing, compression video analysis, and network functions. In the case study, a bullet-style Axis P1425-LE camera was used to provide high-definition images. The camera features include a power-efficient infrared LED technology for automatic illumination of a scene in complete darkness of 0.25 lx and a controllable frame rate of 25–30 s. The outdoor-ready camera includes the international protection rating 66 (IP 66).

An AVR microcontroller board (Arduino) of the UNO R3 model was employed as the control circuit to control the brightness of the LED luminaire. The IP camera was used as a sensor to detect signals from traffic conditions. It perceived the movement of a vehicle before it arrived at a road lighting pole, by observing the headlights and movement of the vehicle using LabVIEW software. The LabVIEW software was employed to create commands for the IP camera to detect the movement and headlights of vehicles, enabling it to distinguish which objects were vehicles or pedestrians. Subsequently, the signal from the LabVIEW software was sent to the AVR microcontroller to control the brightness via a light control circuit. When several vehicles moved through the detection area, the brightness of the road lighting system was increased. In contrast, the brightness was decreased if an insufficient number of vehicles passed through the detection area. Furthermore, the microcontroller was connected to an LDR sensor installed in the light control circuit of the LED luminaire and was used to control the on/off switching of the LED luminaire automatically depending on the ambient light.

Fig. 4 (c) shows the flowchart of the proposed road lighting control. The operation of the light control circuit began with the LDR sensor detecting the brightness from the external environment. If the voltage generated from the LED sensor was less than 3.7 V, the microcontroller sent a signal to switch on the LED luminaire to the lowest brightness. Subsequently, the IP camera detected traffic density to control the light intensity of the luminaire to make it suitable for driving in each period. The traffic density detection comprised two conditions: vehicles moving over both assumption lines written in the LabVIEW software (Fig. 5(a)) and brightness values in a reference frame as high as the determined value (Fig. 5(b)). The former condition was used to identify object movement and the latter to check whether the object was a vehicle. When both conditions were satisfied, the software began counting vehicles and timers. If vehicles passed by within the following 5 s, the number of vehicles was counted up. By contrast, if vehicles disappeared, the number of vehicles was counted down by one. Hence, the number of vehicles detected by the camera varied with the brightness of the road lighting system. When the brightness of daylight increased until the LDR sensor receives voltage values greater than 3.7 V, the light control circuit sent signals to turn off the LED luminaire.

The signal used to control the LED luminaire was a pulse width modulation (PWM) signal from the AVR microcontroller and was generated by mixing triangle and sine wave signals. The result of the mixing of such signals were pulse signals that had two statuses: an open state or a high signal (1) which meant the LED luminaire was fully lit, and a closed status or a low signal (0) which meant the LED luminaire was turned off

By observing the high-frequency control signal used to adjust the brightness of the LED luminaire, the microcontroller generated the control signal, i.e. the PWM signal in the term of duty cycle adjustment, from a comparison of the signal with a sawtooth waveform. When the latter was less than the former, the PWM signal was in a high state (1), and the LED luminaire was switched on. Otherwise, it was in the low state (0), and the LED luminaire was switched off.



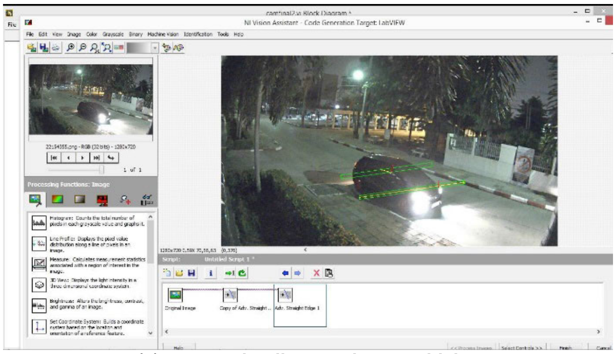
(a) LED solar stand-alone operation

(b) LED solar grid connection operation

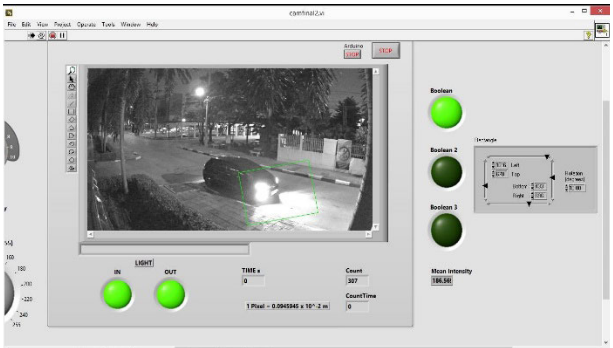
(c) Flowchart of LED road lighting control

FIGURE 4. The schematic diagram of light control with an internet protocol camera.

The power quality from the light control of the road lighting system with the IP camera was measured using an oscilloscope. The oscilloscope observed the input voltage of the LED driver, while the brightness was controlled by adjusting a duty cycle (Fig. 6). The PWM signal used to control the LED luminaire's brightness was smooth and had no ripples. Thus, the light control circuit applied for the LED road lighting system did not cause a severe voltage spike when the LED luminaire was dimmed. We confirmed that, although the used PWM signal had a high frequency, i.e. 489.649 Hz, it did not



(a) assumption lines to detect vehicles



)b(the reference frame used to detect the headlight of vehicles

FIGURE 5. The traffic density detection concept.

affect the LED luminaire lifetime. In addition, the lighting control system operated at high-frequency ranges, leading to a fast-response brightness control. Hence, it did not harm the lighting quality for drivers.

If the LDR sensor observed an ambient light lower than the set value, the LED luminaire was ignited by the designed control system and was controlled to the lowest illuminance (Table II)—an illuminance value of 24.69 lx, controlled by a voltage of 2.99 V. When a vehicle moved into the detection zone, the designed light control circuit automatically increased the voltage according to the specified conditions. As a result, the road lighting system had more brightness. The increased illuminance values were varied according to the number of vehicles that the IP camera could detect. We observed that the designed road lighting system could adjust brightness depending on traffic density to be suit each period. However, higher brightness caused higher energy consumption.

In terms of energy efficiency, the proposed light control system using the IP camera could significantly decrease energy consumption, as it was not always necessary for the nanogrid solar road lighting system to provide the maximum brightness. When no vehicle passed through the detected area, the illuminance was controlled to the minimum value of 24.69 lx. However, when vehicle movement was detected, the illuminance was increased to a value between 34.13 and 55.11 lx, depending on the traffic density.

With the proposed lighting control system, the nanogrid solar road lighting system could save the maximum amount of energy consumption, up to 60%. Additionally, an economic

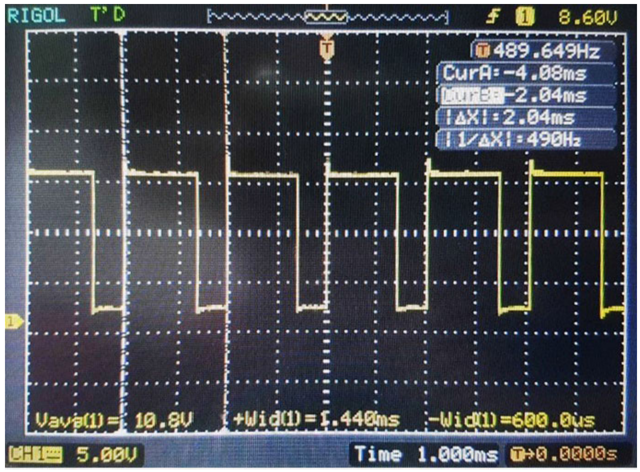


FIGURE 6. Duty cycle signal of LED driver used to control brightness.

TABLE 2. The power quality of the nanogrid solar road lighting system based on the number of vehicles.

The voltage of LED Driver	The number of vehicles	Illuminance (Lux)	Current (A)	Power (W)	Power factor
2.99	0	24.69	0.24	47	0.91
4.00	1	34.13	0.33	68	0.94
5.01	2	42.73	0.42	87	0.96
6.00	3	49.79	0.50	105	0.97
7.02	4	55.11	0.56	119	0.97
8.01	< 4	55.18	0.56	119	0.97

evaluation of the nanogrid solar road lighting systems in the LED solar stand-alone and grid-connection modes with the proposed lighting control is presented here. Owing to the movement characteristics of vehicles travelling in the same direction, the IP camera was used to detect vehicles in a wide range based on the proposed technique. Consequently, installing an IP camera on every road lighting pole to control the lighting was not necessary. In addition, the IP camera had a network system feature to send output signals to the control circuit installed with the LED luminaire(s) to control the illuminance levels of the LED luminaires under consideration.

IV. ECONOMIC FEASIBILITY ANALYSIS

This section analyses the economic feasibility of using the proposed lighting control for the nanogrid solar road lighting system. However, in order to evaluate economic feasibility of the proposed lighting control, the nanogrid solar road lighting system is taken separately to consider LED solar stand-alone and grid-connected systems, which can apparently verify the economic gain benefits of each system operation. A conventional road lighting system in Thailand is used to compare the energy efficiency of the proposed systems.

A main road lighting system implemented on an M2-type road with four lanes and an average traffic flow of 90 km/h were considered for the case study. The lighting quality used for road safety and visual comfort for the driver based on standard installations of main roadways in Thailand was set

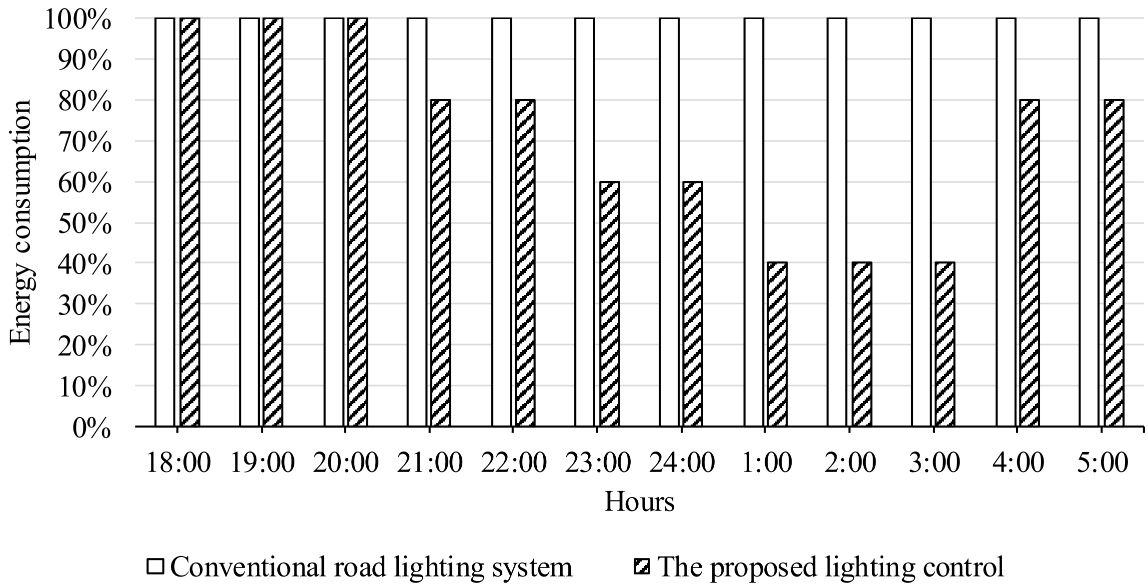


FIGURE 7. The energy consumption of the road lighting system using the proposed lighting control compared to the conventional one.

to have minimum average illuminance of 21.5 lx and uniformity of 0.4 [7-8]. In this category, 250-W HPS luminaires, which had a staggered-pole arrangement, light pole heights of 9 m, and distances between light poles of 36 m were installed [7-8]. Owing to the difficulty of finding historical data of traffic volume in Thailand to adjust the brightness of an area, the energy consumption of the road lighting systems with the lighting control system was assumed as shown in Fig. 7. The proposed lighting control was observed to reduce energy consumption by up to 30%.

The economic evaluation was performed based on the geography of Thailand, which is a tropical country located near the Equator. Several areas in Thailand have great solar power potential, with solar irradiation of 17–20 MJ/m^2 per day [39]. The average solar irradiation throughout the year of Thailand is 17.6 MJ/m^2 per day, which is reduced from the previous solar power potential report [38]. Hence, the brightness of the road lighting systems relied on natural light from 6 a.m. to 6 p.m. during the day. Thus, road lighting systems can function 12 h a day, for approximately 4380 h over annual operation. This location has a large solar irradiance, resulting in high solar generation performance, with an average of 1000 W/m^2 for approximately 5 h per day. The economic study used dynamic methods to account for the time value of money by discounting the cash inflows of the project, which are the DPP, NPV, IRR, and PI. The economic indicator formulas were already derived as indicated in [39].

In the economic evaluation, a 1-km road distance was considered. Staggered pole arrangements with a distance of 36 m between light poles were used. Thus, there were 56 luminaires in total. For solar road lighting systems, central energy storage and energy management were implemented because of lower investment costs than using individual storage and management systems [36]. One group was designed to cater to 14 luminaires. Thus, there were four groups in the 1-km roadway.

Tables III and IV show the investment costs and details of different road lighting systems, i.e. the conventional, LED solar stand-alone, and LED solar grid-connected road lighting systems with and without lighting control. The investment costs are divided into road lighting costs, solar system costs, lighting control costs, and operation and maintenance (O&M) costs.

A. CONVENTIONAL ROAD LIGHTING SYSTEM

Most road lighting systems in Thailand use HPS luminaires owing to their high luminous efficiency against the energy used. However, the use of HPS luminaires results in low energy efficiency, leading to high energy consumption.

1) ROAD LIGHTING COMPONENT

A 250-W HPS luminaire is typically used on the main roads in Thailand, as they provide lighting quality satisfying the standard. However, the power required to use an HPS luminaire is 289 W in total owing to a ballast loss within the luminaire. Thus, the conventional road lighting system consumes an energy of 70886 Wh per year. Furthermore, the use of grid electrical energy has hidden costs, which are fuel energy, transmission lines, transformers, protection systems, etc., used to produce and distribute electrical energy from a power plant to the road lighting system. For this reason, installation costs for electric generators were considered.

2) ROAD LIGHTING SYSTEM COST

Road lighting system cost comprises the costs of luminaires, light poles, power wire, electric generator installation, and electrical equipment (other). As Tables III and IV, although the HPS luminaire had a lower cost than the LED luminaire, the total cost of road lighting using the LED luminaire was

TABLE 3. Costs of different road lighting systems without lighting control

Details	Without lighting control					
	Traditional road lighting (250 W HPS)		LED solar stand-alone		LED solar grid-connected	
	Unit price (USD)	Total price (USD)	Unit price (USD)	Total price (USD)	Unit price (USD)	Total price (USD)
Road lighting cost						
Luminaire cost	98/luminaire	5,488	150/luminaire	8,400	150/luminaire	8,400
Light pole cost	500/luminaire	28,000	500/luminaire	28,000	500/luminaire	28,000
Power wire cost	0.9/m	4,500	250/set	1,000	0.2/m	1,000
Electric generator installation cost	0.9/W	10,012			0.9/W	6,048
Other	10/luminaire	560	10/luminaire	560	10/luminaire	560
Total road lighting cost	48,560		37,960		44,008	
Solar system cost						
Solar panel cost	-	-	1,820/set	7,280	1,820/set	7,280
Battery cost	-	-	3,470/set	13,880		
Charge controller cost	-	-	610/set	2,440		
Inverter cost	-	-	400/set	1,600	1,320/set	5,280
Power wire cost	-	-	560/set	2,240	280/set	1,120
Others	-	-	306/set	1,224	180/set	720
Total solar system cost	-		28,664		14,400	
Lighting control cost						
Internet protocol camera cost	-	-	-	-	-	-
LDR sensor	-	-	-	-	-	-
Arduino Uno R3	-	-	-	-	-	-
Others	-	-	-	-	-	-
Total lighting control cost	-		-		-	
Operation and maintenance (O&M) cost						
Labour cost	22/luminaire	1,232	40/luminaire	2,240	40/luminaire	2,240
Maintenance cost	478/year	9,360	2,835/year	56,700	712/year	14,240
Total O&M cost	-	10,592	-	58,940	-	16,480
Total investment cost	59,152		125,564		74,888	

lower. The LED luminaire is energy efficient, leading to lower electrical power consumption than the conventional luminaire. Hence, the power wire cost decreased.

3) OPERATION AND MAINTENANCE COST

The labour cost used in the case study referred to the Ministry of Labour in Thailand. The conventional road lighting system is a general lighting system installation, which has an average cost of 22 USD per luminaire.

The maintenance cost of the conventional road lighting system was calculated as 10% of the initial installation cost combined with the cost of HPS lamp replacement. The HPS lamp has a lifespan of 20000 h. Therefore, in a project period of 20 years, the HPS lamp must be replaced four times.

B. LED SOLAR STAND-ALONE ROAD LIGHTING SYSTEM WITHOUT LIGHTING CONTROL

The system was designed to produce electrical energy from a solar system and use the generated electrical energy for a road lighting system during the night. Hence, the electrical energy produced from the solar system was sufficient for a one-day backup of the road lighting system.

1) ROAD LIGHTING COMPONENT

A 120-W LED luminaire was selected as it has already been proven to be an efficient replacement for the conventional 250-W HPS luminaire on the main road [7-8]. The road lighting system was designed to operate for 12 h per day, resulting in a daily energy consumption of 1440 Wh.

2) ROAD LIGHTING SYSTEM COST

The LED solar stand-alone road lighting system provided a lower road lighting system cost, as the road lighting system used electrical energy produced from the solar system. Thus, no installation cost for the electric generators was incurred. However, the LED solar stand-alone road lighting system still had a power wire cost as with other road lighting systems, because the stand-alone solar system installed on the road lighting system is a central system. As a result, the power wire was used to transmit electrical energy from the energy storage system to road lighting systems

3) SOLAR SYSTEM COMPONENT

The solar system components consisted of solar panels, batteries, a charge controller, and an inverter. The power of the solar system depended on the solar panel size and system location. In the case study, the solar irradiance of Thailand was employed, which is 20 MJ/m^2 or 5.6 kWh/m^2 per day [38]. A monocrystalline solar panel providing an average efficiency of 20% was selected. The size of a solar panel for the daily energy consumption of the luminaire was calculated using Thailand's solar irradiance of 5.6 kWh/m^2 per day,

TABLE 4. Costs of different road lighting systems with lighting control

Details	With lighting control			
	LED solar stand-alone		LED solar grid-connected	
	Unit price (USD)	Total price (USD)	Unit price (USD)	Total price (USD)
Road lighting cost				
Luminaire cost	150/luminaire	8,400	150/luminaire	8,400
Light pole cost	500/luminaire	28,000	500/luminaire	28,000
Power wire cost	250/set	1,000	0.2/m	1,000
Electric generator installation cost	-	-	0.9/W	6,048
Other	10/luminaire	560	10/luminaire	560
Total road lighting cost	37,960		44,008	
Solar system cost				
Solar panel cost	1,500/set	6,000	1,500/set	6,000
Battery cost	2,320/set	9,280	-	-
Charge controller cost	372/set	1,488	-	-
Inverter cost	400/set	1,600	950/set	3,800
Power wire cost	560/set	2,240	280/set	1,120
Others	306/set	1,224	180/set	720
Total solar system cost	21,832		11,640	
Lighting control cost				
Internet protocol camera cost	350/set	1,400	350/set	1,400
LDR sensor	1.3/set	5	1.3/set	5
Arduino Uno R3	23/set	92	23/set	92
Others	10/set	40	10/set	40
Total lighting control cost	1,537		1,537	
Operation and maintenance (O&M) cost				
Labour cost	40/luminaire	2,240	40/luminaire	2,240
Maintenance cost	2,110/year	42,200	706/year	14,120
Total O&M cost	-	44,440	-	16,360
Total investment cost	105,769		73,545	

a solar panel efficiency of 20%, and a power loss factor of 0.8. Thus, a 300-Wp solar panel (dimension of 1640 × 992 × 35 mm) was used.

Central energy storage systems were used to store energy produced from solar panels. One group of the energy storage system was designed to cater to four solar road lighting systems. Thus, there were four groups of energy storage systems for the 1-km road. The deep-cycle lead-acid battery was the recommended type for use in the solar stand-alone road lighting system. In the case study, the batteries were designed for one-day backup. The daily energy consumption of each set was 20160 Wh. The daily energy consumption used was divided by 0.7 for battery losses and to avoid the depth of discharge which causes a decrease in a battery's lifetime. Therefore, the battery capacity required for one set was 28800 Wh per day. A total of 16 lead-acid batteries of 150 Ah and 12 V were selected. The batteries were connected in series (150 Ah, 192 V) to lower the current rate of the system, leading to a system voltage of 192 V.

The solar charge controller size was calculated from the maximum current generated from one set of solar panels and the voltage level depending on the battery size. Therefore, a 40 A/192 V charge controller was selected. An inverter was used to convert the DC voltage from the batteries to supply the LED luminaires with AC voltage. Thus, the size of the inverter was determined by the size of the LED luminaires, which was higher than 1680 W. Hence, a 2000 W inverter was used in the study.

4) SOLAR SYSTEM COSTS

The solar system in the LED solar stand-alone road lighting system had a higher initial installation cost than the grid-connected one because of the additional cost of the energy storage system, i.e. batteries, inverters, and solar charge controllers (Tables III and IV). However, the inverters used in the LED solar stand-alone road lighting system were cheaper than the other one because they are only used to convert power from the energy storage systems to supply the road lighting system without the grid connection function. By considering the costs of the power wire, the stand-alone system had higher power wire costs than the grid-connected system because of the limitations of the DC voltage system design which relate the voltage levels of the solar charge controllers and batteries. In this case study, a 192-V DC voltage system was employed.

5) OPERATION AND MAINTENANCE COST

The road lighting systems that integrated solar systems required to employ engineering skills with specific knowledge to control the installation, resulting in an increase of costs to 40 USD per luminaire.

The LED luminaire has a lifespan of more than 50000 h. Thus, the LED luminaire would be replaced once during the project period. However, replacing an LED luminaire has a higher cost than replacing an HPS lamp replacement, as the LED luminaire is expensive. Thus, using LED luminaire results in a higher maintenance cost than the use of the HPS luminaire.

For the solar system, maintenance costs arise from solar panels, energy storage devices, solar charge controllers, inverters, wiring, connection, etc. The energy storage devices have a lifetime less than 20 years (approximately 5 years for a deep cycle lead-acid battery [36]). In addition, battery life relies on the state of charge and charge-discharge current. Thus, the energy storage devices are assumed to require replacement three times throughout the project lifetime to maintain the efficiency of energy storage; this results in a high maintenance cost.

C. LED GRID-CONNECTED ROAD LIGHTING SYSTEM WITHOUT LIGHTING CONTROL

The system was designed to install solar panels on a road lighting pole. In this scenario, the electrical energy generated from the solar system was supplied directly into the electrical grid. At night, the road lighting system was supplied with the electrical energy from the electrical grid. Thus, the initial investment costs of an energy storage system were eliminated.

1) ROAD LIGHTING COMPONENT

A 120 W-LED luminaire was used in the road lighting system, which was supplied power from the electrical grid. Hence, the installation costs of an electric generator were included.

2) ROAD LIGHTING SYSTEM COST

The cost of the road lighting system cost did not differ from that of the conventional road lighting system using LED luminaires because the system still required electrical energy from the electrical grid to supply the LED luminaires.

3) SOLAR SYSTEM COMPONENT

Solar system components consist of solar panels and grid-tied inverters. Because the size of the solar system size does not depend on road lighting energy consumption, the sizes of solar panels can be designed as required. However, for comparison with the scenario of the stand-alone solar system, a 300-W solar panel was installed on the light pole. The grid-tied inverter size was determined by the used solar panel capacity. One set of the grid-tied inverter was designed to cater to 14 solar road lighting systems. Thus, the required rating for the grid-tied inverter was 4200 W. A 5000-W grid-tied inverter was selected.

4) SOLAR SYSTEM COSTS

The main cost of LED solar grid-connected system was caused by solar panel and inverters. In addition, the solar system was designed to send the power to the electrical grid. Thus, the cost of an energy storage system was cut off, resulting in lower costs than the stand-alone system. Furthermore, the DC voltage level of the grid-connected system can be independently designed based on the maximum voltage input of the grid-tied inverter. Thus, the solar panels in one group were connected in series to increase the voltage level, which had a DC voltage level of 510 V. Thus, the grid-connected system required a lower current, resulting in a cheaper power wire cost.

5) OPERATION AND MAINTENANCE COST

Similarly, the road lighting systems that integrated solar systems required to employ engineering skills with specific knowledge to control the installation, resulting in an increase of costs to 40 USD per luminaire.

For the solar system, there is increase in maintenance costs from solar panels, inverters, power wire, etc. However, the maintenance cost of an LED solar grid-connected road lighting system is lower than that of the stand-alone system because the solar system does not require an energy storage system, lowering maintenance costs in this aspect.

D. LED SOLAR STAND-ALONE ROAD LIGHTING SYSTEM WITH LIGHTING CONTROL

The system was designed as the same function as the LED solar stand-alone road lighting system, but there was the application of the proposed lighting control in the system (see Table IV).

1) ROAD LIGHTING COMPONENT

A 120 W-LED luminaire was employed in the road lighting system, which was a function similar to the LED solar stand-alone road lighting system.

2) ROAD LIGHTING SYSTEM COST

The cost of road lighting system was similar to the case of LED solar standalone road lighting system without lighting control, as adopting the proposed lighting control does not had an effect on sizes of luminaires, power wire, and the others.

3) SOLAR SYSTEM COMPONENT

Owing to the use of the proposed lighting control, which can save energy up to 30%, the sizes of solar and energy storage systems could be designed to be smaller. Initially, the road lighting required the power of 120 W for 12 h, which was a consumption of 1440 Wh. With the proposed lighting control, the system could save energy by 30%. Therefore, the energy consumption of road lighting system was lowered to 1000 Wh per day. Thus, a 200-Wp monocrystalline solar panel with an average efficiency of 20% (dimension of 1320×992×35 mm) was employed.

The size of the central energy storage system for one backup day decreased, as the energy consumption of one set decreased, which was 14000 Wh. With the battery loss and avoiding of the depth of discharge factor, the battery capacity used for one set was 20000 Wh per day. Eight lead-acid batteries of 200 Ah and 12 V were employed. Thus, the system voltage was determined to be 96 V. The solar charge controller size based on the maximum current of solar panels and the battery voltage was 40 A/ 96 V. Because the size of an inverter determined is by the size of the LED luminaires, a 2000 W inverter was selected.

4) SOLAR SYSTEM COSTS

The use of the proposed lighting control resulted in a decrease in road lighting energy consumption. Hence, as Tables IV shows, the solar systems were designed to be smaller, thus decreasing the size of the solar panels, solar charge controllers, and inverters. Thus, the initial investment costs of solar systems for the LED solar stand-alone road lighting system were minimized.

5) LIGHTING CONTROL COMPONENT

The proposed lighting control was designed to control the luminaires in a group related to the central solar energy management of the stand-alone system. The lighting control and processing systems were installed with the central energy management of the solar energy systems. Thus, one group of the road lighting systems had central solar energy management and central lighting control systems, which was convenient for energy management, road lighting control, and maintenance. One group of the proposed lighting control system had the IP camera and LDR sensor, which were installed on the first road lighting pole to detect traffic volumes and ambient light.

6) LIGHTING CONTROL SYSTEM COSTS

In addition to the cost of the road lighting and the solar systems, there was an additional lighting control cost. In this case study, the road lighting system was implemented on a main road, on which vehicles move at high speeds in the forward direction. Thus, sensor devices were not required to be installed on every road lighting pole. The sensor devices were installed on the first lighting pole to detect the traffic volumes and send the data for processing at a central control system which controlled the brightness of grouped luminaires. In the case study, the proposed lighting control was determined to control fourteen 120W-LED luminaires. Thus, the road distance of 1 km with a staggered-pole arrangement offered the lighting control of four groups.

7) OPERATION AND MAINTENANCE COST

For LED solar stand-alone road lighting system with the proposed lighting control, in addition to the maintenance costs of the road lighting and solar systems, the maintenance costs of the proposed control lighting are considered. However, LED solar stand-alone road lighting systems with lighting control require lower maintenance costs than the system without lighting control because the systems consume less energy. The capacity of the devices, including batteries, is decreased, resulting in less maintenance and replacement costs.

E. LED GRID-CONNECTED ROAD LIGHTING SYSTEM WITH LIGHTING CONTROL

The system was designed as the same function as the LED solar grid-connected road lighting system, but there was the application of the proposed lighting control in the system (see Table IV).

1) ROAD LIGHTING COMPONENT

A 120 W-LED luminaire was employed in the road lighting system, which was a function similar to the LED solar grid-connected road lighting system.

2) ROAD LIGHTING SYSTEM COST

The road lighting system cost had not changed compared to the LED grid-connected road lighting system without lighting control. Consequently, using the lighting control did not have an influence on the road lighting system cost,

3) SOLAR SYSTEM COMPONENT

A solar panel of 200-W was installed on the light pole. Hence, the required grid-tied inverter rating for one set was 2800 W. A 3000 W grid-tied inverter was selected.

4) SOLAR SYSTEM COSTS

The use of the proposed lighting control resulted in a decrease in road lighting energy consumption. Hence, as Tables IV shows, the solar systems were designed to be smaller, thus decreasing the size of the solar panels and grid-tied inverters. Thus, the initial investment costs of solar systems for LED solar grid-connected road lighting system were minimized.

5) LIGHTING CONTROL COMPONENT

The lighting control was designed which have a similar function to the LED solar stand-alone road lighting system. For this reason, one group of the road lighting systems had a

TABLE 5. Cost analysis and economic assessment results

Details	Traditional road lighting system (250 W HPS)	Without lighting control		With lighting control	
		LED solar stand-alone system	LED solar grid-connected system	LED solar stand-alone system	LED solar grid-connected system
Initial investment cost (USD)	59,152	125,564	74,888	105,769	73,545
Annual energy consumption (Wh)	70,886	29,434	29,434	20,604	20,604
Annual electricity cost (USD)	12,051	no	5,004	no	3,503
Annual electricity saving cost (USD)	base	12,051	7,047	12,051	8,548
Annual energy generated into grid (Wh)	no	no	30,047	no	24,119
Annual energy generated into grid cost (USD)	no	no	5,108	no	4,100
Total annual benefit cost (USD)	no	12,051	12,155	12,051	12,648
DPP (years)	base	8.4	1.5	5.1	1.3
IRR (%)	base	17%	77%	26%	88%
NPV (USD)	base	32,895	79,769	50,891	84,806
PI	base	1.5	6.1	2.1	6.9

central lighting control system consisting of the IP camera and LDR sensor.

6) LIGHTING CONTROL SYSTEM COSTS

Because the design and installation of the lighting control system was no different from the stand-alone system with lighting control, the cost of the lighting control system used in economic evaluation was the same as the LED solar stand-alone road lighting system with lighting control.

7) OPERATION AND MAINTENANCE COST

In addition to the operation and maintenance costs from road lighting and solar systems, the operation and maintenance costs of using the proposed lighting control are implemented. However, in this case, the maintenance cost was hardly different from the system without lighting control, since the reduced solar panels and grid-tied inverter capacity did not significantly affect maintenance costs.

V. DISCUSSION

The cost analysis and economic evaluation of solar road lighting systems with and without the proposed control systems compared with the conventional road lighting system are shown in Table V. The economic indexes are calculated based on the project lifetime of 20 years and considering a discounted rate of 10%. Additionally, the electricity cost, which, including value-added tax (VAT) in Thailand, is 0.167 USD/kWh, is evaluated [40].

Although the conventional road lighting system exhibits the lowest initial investment cost, it consumes the highest annual energy, resulting in the highest annual electricity cost. LED solar stand-alone systems with and without control systems exhibited high initial installation costs compared with solar grid-connected systems because of the additional energy storage system costs. However, using the proposed lighting control system can lower the road lighting energy consumption, leading to solar panels and energy storage systems designed to be smaller. Hence, initial investment costs are decreased. However, the initial investment costs of the LED solar grid-connected system with and without light control systems are not significantly different as smaller solar panels and grid-tied do not differ in price.

The high annual energy consumption of the LED solar stand-alone and grid-connected road lighting system result from the use of 120-W LED luminaires. The use of the proposed control system results in energy saving up to 30%. Thus, the annual energy consumption of both LED solar road lighting systems with the lighting control system is lower than for scenarios without it. The LED solar stand-alone systems consume electrical energy produced from their solar systems, leading to non-annual electricity costs. By contrast, the LED solar grid-connected systems still consume electrical energy from the electrical grid, resulting in annual electricity costs. However, the LED solar grid-connected system with the lighting control system results in lower annual electricity costs compared with the other systems, as a result of its higher energy saving.

The annual electricity-saving costs are quantified through comparison with the annual electricity cost of the traditional road lighting system. The LED solar stand-alone systems with and without the proposed lighting control system exhibits the same and highest annual electricity-saving costs because they do not use electrical energy from the electrical grid. Thus, they exhibit the best efficient energy saving. The LED solar grid-connected systems can save electricity cost because of the use of LED luminaires, which can save energy compared with conventional ones. Furthermore, the use of the proposed lighting control system can lower road lighting energy consumption, positively affecting the saving of the annual electricity cost. In addition, the LED solar grid-connected systems are outstanding for feeding the electrical energy from the solar systems into the electrical grid, receiving annual energy generated into the grid cost. Because the LED solar grid-connected system with the lighting control system offers energy saving, the sizes of used solar panels decreases. Thus, its annual energy generated into the grid cost is lower than that with the lighting control system. The total annual benefit cost is calculated by combining the annual electricity-saving cost and annual energy generated into the grid cost. It shows revenue from energy saving or production obtained from using energy-efficient luminaires, solar systems, and the lighting control system.

The DPP, IRR, NPV, and PI were employed and compared for economic analysis. The LED solar stand-alone road lighting system, which encompasses solar and energy storage systems, had higher initial installation and maintenance costs because of battery replacement. Thus, it exhibits a long DPP of 8.4 years, a low IRR of 17%, a small NPV of 32,895 USD, and a low PI of 1.5. However, it has still provided economic feasibility for investment. Subsequently, the LED solar grid-connected road lighting system indicates satisfactory economic feasibility than the stand-alone system because of the electrical energy generated from the solar system directly supplied into the electrical grid without requiring to use an energy storage system. Although it requires to consume electrical energy from the electrical grid to supply the luminaires, resulting in an annual electricity cost, it has the advantage of electricity-saving cost and energy generated into grid cost, resulting in a higher total annual benefit cost than the LED solar stand-alone road lighting system. Thus, it can provide a better economic aspect, i.e. a DPP of 1.5 years, an IRR of 77%, an NPV of 79,769 USD, and a PI of 6.1.

With the proposed lighting control system, although using the control system results in additional investment cost, the energy consumption of the road lighting system decreases, which is dependable on traffic conditions. Thus, the sizes of the solar panel and energy storage system are decreased, leading to a decrease in solar system costs. By considering the LED solar stand-alone road lighting system with the lighting control, the system can result in a lower initial investment cost than the scenario without lighting control. In addition, the system can still save electricity costs in a similar to the scenario without lighting control. Hence, the use of the proposed lighting control has a better economic feasibility, for instance, a lower DPP of 5.1 years, a higher IRR of 26%, a better NPV of 50,891 USD, and a higher PI of 2.1. However, using the lighting control in the LED solar grid-connected lighting system presents an insignificant change compared with the system without lighting control, because the prices of the solar panel and grid-tied inverter are not significantly different when the size of the solar system is minimized. However, the system has the economic benefit of electricity-saving cost from using lighting control. Thus, the economic feasibility evaluation is satisfied and better than the other scenarios: the lowest DPP of 1.3 years, the highest of IRR of 88%, the best NPV of 84,806 USD, and the highest PI of 6.9.

The economic assessment results indicate that the LED solar stand-alone and grid-connected road lighting systems are feasible for investment; the latter exhibits more economic feasibility. However, when the proposed lighting control is included, the LED solar stand-alone and grid-connected road lighting systems have a lower initial investment cost and save more energy. Consequently, the economic results increase. The use of the proposed lighting control exhibits economic feasibility.

VI. CONCLUSION

The proposed technique to control the brightness of the road lighting system based on traffic density can operate efficiently. The signal used to control the LED luminaire's brightness is smooth and has no ripples. Thus, the light control circuit applied for the LED road lighting system does not cause a severe voltage spike when the LED luminaire is dimmed. Furthermore, it does not harm the life of the LED luminaire. The use of the IP camera in cooperation with the LED sensor can automatically control the on/off states or illuminance levels of the LED luminaire, lowering the energy consumption of the road lighting system during times when it is not required.

The application of the lighting control for the nanogrid solar road lighting systems results in an additional investment cost. However, the energy consumption of the road lighting system decreases depending on traffic conditions. Thus, the sizes of the solar panel and energy storage system decrease, leading to a lower solar system cost. By considering the LED solar

road lighting system with the lighting control, the system can result in a lower initial investment cost than without the lighting control. In addition, the system can still save electricity costs in the same manner as the scenario without lighting control. For this reason, the use of the proposed lighting control indicates better economic feasibility. However, using the lighting control in LED solar grid-connected lighting system presents an insignificant change when compared with the system without lighting control because the prices of the solar panel and grid-tied inverter are not significantly different when the size of the solar system is minimized. However, the system has an economic benefit of electricity-saving cost when using lighting control.

In a future study, energy production from various sources and optimal storage systems for road lighting systems will be investigated in terms of the electrical engineering and economic aspects. A feasibility evaluation using wind energy and piezoelectric energy based on vehicle movement will be discussed. Wind turbine location is designed to optimize by considering the optimal distance and position in order to keep the maximum energy production, while the position of piezoelectric device installation is studied for enhanced the electric energy output of power generation pavements. Different energy storage systems, e.g. lead-acid batteries, lithium-ion batteries, and ultracapacitors will be evaluated.

REFERENCES

[1] G. I. Crabb and L. Crinson, *The Impact of Street Lighting on Night-Time Road Casualties*. Wokingham, U.K.: Berkshire, 2008.
[2] M. Jackett and W. Frith, ''Quantifying the impact of road lighting on road safety—A New Zealand study,'' *IATSS Res.*, vol. 36, no. 2, pp. 139–145, Mar. 2013.
[3] *Lighting of Roads for Motor and Predestrain Traffic*, Int. Commission Illumination (CIE), Vienna, Austria, 2010.
[4] M. Richards and D. Carter, ''Good lighting with less energy: Where next?'' *Lighting Res. Technol.*, vol. 41, no. 3, p. 285, 2009.
[5] B. Sun, P. B. Luh, Q.-S. Jia, Z. Jiang, F. Wang, and C. Song, ''Building energy management: Integrated control of active and passive heating, cooling, lighting, shading, and ventilation systems,'' *IEEE Trans. Autom. Sci. Eng.*, vol. 10, no. 3, pp. 588–602, Jul. 2013.
[6] Energy Policy and Planning Office Ministry of Energy. *Electricity Statistic, Electricity Consumption for the Whole Country*. [Online]. Available: http://www.eppo.go.th/index.php/en/en-energystatistics/electricity-statistic
[7] S. Yoomak, C. Jettanasen, A. Ngaopitakkul, S. Bunjongjit, and M. Leelajindakrairerk, ''Comparative study of lighting quality and power quality for LED and HPS luminaires in a roadway lighting system,'' *Energy Buildings*, vol. 159, pp. 542–557, Jan. 2018.
[8] S. Yoomak and A. Ngaopitakkul, ''Optimisation of lighting quality and energy efficiency of LED luminaires in roadway lighting systems on different road surfaces,'' *Sustain. Cities Soc.*, vol. 38, pp. 333–347, Apr. 2018.
[9] S. Priyanka, T. U. Lakshmi, and S. S. Sakthy, ''Web—Based street light system,'' in *Proc. 3rd Int. Conf. Comput. Commun. Technol. (ICCCT)*, Chennai, India, Feb. 2019, pp. 159–162.
[10] V. Prabu and D. Rajendra, ''Internet of Things based intelligent street lighting system for smart city,'' *Int. J. Innov. Res. Sci. Eng. Technol.*, vol. 5, no. 5, pp. 7684–7691, 2016.
[11] M. Abhishek, K. Chetan, and K. Arun, ''Design and implementation of traffic flow based street light control system with effective utilization of solar energy,'' *Int. J. Sci. Eng. Adv. Technol.*, vol. 3, no. 9, pp. 495–499, 2015.
[12] A. M. Sindhu, J. George, S. Roy, and J. Chandra, ''Smart streetlight using IR sensors,'' *IOSR J. Mob. Comput. Appl.*, vol. 3, no. 2, pp. 39–44, 2016.
[13] S. S. Badgelwar and M. H. Pande, ''Survey on energy efficient smart street light system,'' *Asian J. Converg. Technol.*, vol. 3, no. 2350, pp. 866–869, 2017.
[14] K. Muralidhar, M. Agarwal, K. A. Reddy, M. Monica, and E. Thirumaleshwari, ''Design of intelligent street light control system using low cost AT89C51 microcontroller,'' *Int. J. Innov. Res. Comput. Commun. Eng.*, vol. 5, no. 2, pp. 2517–2522, 2017.
[15] J. F. De Paz, J. Bajo, S. Rodríguez, G. Villarrubia, and J. M. Corchado, ''Intelligent system for lighting control in smart cities,'' *Inf. Sci.*, vol. 372, pp. 241–255, Dec. 2016.
[16] O. Yaman and M. Karakose, ''New approach for intelligent street lights using computer vision and wireless sensor networks,'' in *Proc. 7th Int. Istanbul Smart Grids Cities Congr. Fair (ICSG)*, Istanbul, Turkey, Apr. 2019, pp. 81–85.
[17] J. A. Galindo and M. V. Caya, ''Development of street lighting system with object detection,'' in *Proc. IEEE 10th Int. Conf. Humanoid, Nanotechnol., Inf. Technol., Commun. Control, Environ. Manage. (HNICEM)*, Baguio City, Philippines, Nov. 2018, pp. 1–5.
[18] G. Gagliardi, A. Casavola, M. Lupia, G. Cario, F. Tedesco, F. L. Scudo, F. C. Gaccio, and A. Augimeri, ''A smart city adaptive lighting system,'' in *Proc. 3rd Int. Conf. Fog Mobile Edge Comput. (FMEC)*, Barcelona, Apr. 2018, pp. 258–263.
[19] M. A. Rahman, A. T. Asyhari, M. S. Obaidat, I. F. Kurniawan, M. Y. Mukta, and P. Vijayakumar, ''IoT-enabled light intensity-controlled seamless highway lighting system,'' *IEEE Syst. J.*, early access, Mar. 12, 2020, doi: 10.1109/JSYST.2020.2975592.
[20] P. Mohandas, J. S. A. Dhanaraj, and X.-Z. Gao, ''Artificial neural network based smart and energy efficient street lighting system: A case study for residential area in hosur,'' *Sustain. Cities Soc.*, vol. 48, Jul. 2019, Art. no. 101499.
[21] E. Juntunen, E.-M. Sarjanoja, J. Eskeli, H. Pihlajaniemi, and T. Österlund, ''Smart and dynamic route lighting control based on movement tracking,'' *Building Environ.*, vol. 142, pp. 472–483, Sep. 2018.
[22] N. Shlayan, K. Challapali, D. Cavalcanti, T. Oliveira, and Y. Yang, ''A novel illuminance control strategy for roadway lighting based on greenshields macroscopic traffic model,'' *IEEE Photon. J.*, vol. 10, no. 1, Feb. 2018, Art. no. 8200211.
[23] F. Knobloch and N. Braunschweig, ''A traffic-aware moving light system featuring optimal energy efficiency,'' *IEEE Sensors J.*, vol. 17, no. 23, pp. 7731–7740, Dec. 2017.
[24] M. Mahoor, F. R. Salmasi, and T. A. Najafabadi, ''A hierarchical smart street lighting system with brute-force energy optimization,'' *IEEE Sensors J.*, vol. 17, no. 9, pp. 2871–2879, May 2017.
[25] C. A. Tochukwu and O. N. Lois, ''Energy-efficiency improvement on roadway lighting using wireless sensor networks,'' *Int. J. Res. Adv. Eng. Technol.*, vol. 2, no. 4, pp. 1–5, 2016.
[26] G. Shahzad, H. Yang, A. W. Ahmad, and C. Lee, ''Energy-efficient intelligent street lighting system using traffic-adaptive control,'' *IEEE Sensors J.*, vol. 16, no. 13, pp. 5397–5405, Jul. 2016.
[27] C. Vargas, J. Guaman, R. Nogales, and A. Rios, ''Photovoltaic lighting system with intelligent control based on ZigBee and arduino,'' *Energy*, vol. 7, no. 1, pp. 224–233, 2017.
[28] P. Primiceri and P. Visconti, ''Solar-powered LED-based lighting facilities: An overview on recent technologies and embedded IoT devices to obtain wireless control, energy savings and quick maintenance,'' *J. Eng. Appl. Sci.*, vol. 12, pp. 140–150, Jan. 2017.
[29] F. Ramadhani, K. A. Bakar, M. A. Hussain, O. Erixno, and R. Nazir, ''Optimization with traffic-based control for designing standalone streetlight system: A case study,'' *Renew. Energy*, vol. 105, pp. 149–159, May 2017.
[30] M. Y. Mukta, M. A. Rahman, A. T. Asyhari, and M. Z. A. Bhuiyan, ''IoT for energy efficient green highway lighting systems: Challenges and issues,'' *J. Netw. Comput. Appl.*, vol. 158, May 2020, Art. no. 102575.
[31] N. Das, N. Pal, and S. K. Pradip, ''Economic cost analysis of LED over HPS flood lights for an efficient exterior lighting design using solar PV,'' *Building Environ.*, vol. 89, pp. 380–392, Jul. 2015.
[32] G. Pintér, N. Baranyai, A. Wiliams, and H. Zsiborács, ''Study of photovoltaics and LED energy efficiency: Case study in hungary,'' *Energies*, vol. 11, no. 4, p. 790, Mar. 2018.
[33] D. Campisi, S. Gitto, and D. Morea, ''Economic feasibility of energy efficiency improvements in street lighting systems in Rome,'' *J. Cleaner Prod.*, vol. 175, pp. 190–198, Feb. 2018.
[34] M. Beccali, M. Bonomolo, F. Leccese, D. Lista, and G. Salvadori, ''On the impact of safety requirements, energy prices and investment costs in street lighting refurbishment design,'' *Energy*, vol. 165, pp. 739–759, Dec. 2018.
[35] D. Campisi, S. Gitto, and D. Morea, ''Light emitting diodes technology in public light system of the municipality of Rome: An economic and financial analysis,'' *Int. J. Energy Econ. Policy*, vol. 7, no. 1, pp. 200–208, 2017.
[36] S. Yoomak and A. Ngaopitakkul, ''Feasibility analysis of different energy storage systems for solar road lighting systems,'' *IEEE Access*, vol. 7, pp. 101992–102001, 2019.
[37] S. Yoomak and A. Ngaopitakkul, ''Investigation and feasibility evaluation of using nanogrid technology integrated into road lighting system,'' *IEEE Access*, vol. 8, pp. 56739–56754, 2020.
[38] *Department of Alternative Energy Development and Efficiency, Ministry of Energy, the Solar Map. Bangkok: Department of Alternative Energy Development and Efficiency*, Ministry Energy, New Delhi, India, 2017.
[39] S. Yoomak, T. Patcharoen, and A. Ngaopitakkul, ''Performance and economic evaluation of solar rooftop systems in different regions of Thailand,'' *Sustainability*, vol. 11, no. 23, p. 6647, Nov. 2019.
[40] Metropolitan Electricity Authority. *Electricity Rates of Non-Profit Organizations*. Accessed: Jul. 29, 2020. [Online]. Available: https://www.mea.or.th/en/profile/109/259
[41] S. Yoomak and A. Ngaopitakkul, ''Development of sustainable nanogrid road lighting systems,'' *IEEE Trans. Intell. Transp. Syst.*, early access, May 21, 2020, doi: 10.1109/TITS.2020.2994088.