A LOW-COST IoT - ENABLED SMART LIGHTING SYSTEM FOR ENERGY EFFICIENCY IN DOMESTIC USE

HỆ THỐNG ĐÈN CHIẾU SÁNG THÔNG MINH ỨNG DỤNG CÔNG NGHỆ IoT CHI PHÍ THẤP TIẾT KIỆM NĂNG LƯỢNG SỬ DỤNG TRONG GIA ĐÌNH

Vu Trong Duc Anh[1], Nguyen Xuan Truong[1,*], Hoang Mai Quyen[2]

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ABSTRACT

Regarding current domestic lighting systems, there are two development pathways: the first is integrating Internet of Things (IoT) technology for the convenience and comfortability of users, and hence, enhancing the quality of life. The second one is pushing for a more energy-efficient lighting system to reduce energy consumption, which is a crucial task in the ongoing struggle against climate change. This research addresses these two problems by developing a lighting system that will automatically adjust the light's intensity in domestic use based on the surrounding environment condition to achieve high energy efficiency. A low-cost intelligent lighting instrumentation and automation system are developed based on IoT technology. The system collects and stores environmental data on the cloud, as well as being able to remotely control via the Internet and voice controllable by virtual assistance. This can be conducted by utilising light sensors, an Arduino-based microcontroller, and a cloud platform to facilitate communication between elements of the system.. An experiment will then be conducted to demonstrate that the proposed system can achieve energy-saving in comparison to a conventional scheme.

Keywords: *Energy efficiency, LED, Arduino, smart lighting, IoT technology.*

TÓM TẮT

Để cập tới hệ thống chiếu sáng hiện nay, có hai phương hướng phát triển; đầu tiên là sự tích hợp công nghệ Internet vạn vật nhằm hướng tới sự tiện lợi và thoải mái đối với người dung, do đó nâng cao chất lượng cuộc sống. Thứ hai, thúc đẩy phát triển các hệ thống chiếu sáng hiệu quả sử dụng năng lượng hơn nhằm giảm mức tiêu thụ năng lượng, cũng là một trong các nhiệm vụ quan trọng trong ứng phó sự biến đổi khí hậu. Nghiên cứu này giải quyết cả hai vấn đề bằng cách phát triển một hệ thống chiếu sáng sẽ tự động điều chỉnh cường độ ánh sáng sử dụng trong gia đình theo điều kiện môi trường xung quanh để đạt được hiệu quả sử dụng năng lượng cao. Hệ thống thiết bị chiếu sáng và tự động hóa thông minh chi phí thấp được phát triển dựa trên nền tảng ứng dụng công nghệ IoT. Hệ thống thu thập và lưu trữ dữ liệu môi trường trên đám mây, cũng như có thể điều khiển từ xa qua Internet và điều khiển bằng giọng nói bằng hỗ trợ ảo bằng cách sử dụng cảm biến ánh sáng, bộ vi điều khiển Arduino và nền tảng đám mây để tạo điều kiện giao tiếp giữa các thành phần của hệ thống. Tiếp đó, một thí nghiệm sẽ được tiến hành để chứng minh rằng hệ thống được đề xuất phát triển có thể đạt được mức tiết kiệm năng lượng so với hệ thống đèn chiếu sáng thông thường.

Từ khóa: *Hiệu quả năng lượng, LED, Arduino, hệ thống đèn thông minh, công nghệ IoT.*

[1]Department of Energy, University of Science and Technology of Hanoi, Vietnam Academy of Science and Technology

[2]Faculty of Electrical Engineering, Hanoi University of Industry

[*]Email : nguyen-xuan.truong@usth.edu.vn

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ABBREVIATION

CO_2	Carbon dioxide
NCCS	National Climate Change Strategy
VNEEP	National Energy Efficiency Program
LED	Light-emitting diode
IoT	Internet of Thing
PWM	Pulse Width Modulation

1. INTRODUCTION

It is a consensus that promoting the efficient use of energy is essential in tackling climate change [1], since improving energy efficiency is the least expensive method to expand the energy supply without causing additional CO2 emissions [2]. Overall, electricity from lightning is responsible for nearly 20% of electricity consumption and 6% of carbon dioxide (CO_2) emissions worldwide [3]. Therefore, improving the efficiency of the lighting system is crucial to achieve Net Zero Emissions goals in 2050. To Vietnam, climate change poses an existential threat. Hence, the country has made a strong climate commitment to become Net Zero in 2050 [4] and has already issued the National Climate Change Strategy to 2050, in which improving energy efficiency is recognised as part of the nation's climate strategy [5]. Such priority is realised in the country's National Energy Efficiency Program (VNEEP), with the aim of saving 5.0 - 7.0% of the national energy consumption from 2019 to 2025 through various saving measures, in which improving the nation's lighting efficiency is prioritised [6]. Therefore, improving lighting efficiency is a global necessity, and also a priority in Vietnam. Globally, lighting is one of the few sectors that are currently on track toward the Net Zero Emissions 2050 goal, thanks to the rapid deployment of highly efficient LED, which has already occupied over 50% of the lighting market [7] and is expected to reach 100% by 2025 globally to meet the sectoral target of being Net Zero in 2050 [8].

The Internet of Things (IoT) refers to the interconnection between the network of physical devices, smartphone, home appliances, cameras, medical instruments and human-based on stipulated protocols for a smarter tracking, monitoring, controlling, positioning, saving and administrating [9, 10]. It enables connected devices to "communicate" by using the digital existence of the physical/material aspect. It also includes the dedicated use of the internet: types of connections, databases, networks and wireless canals. If the data is stored a CLOUD or an online database, the choice of the display interface can be adapted to the requirements, as long as the data type is readable. IoT has various applications, in which smart homes and smart lighting have received special attention due to the benefits of efficiency, cost-effectiveness and comfortability [9]. A Smart Lighting System is an autonomous and intelligent lighting system that is comprised of IoT communication protocols, devices, and sensors. The number of IoT devices worldwide is forecast to almost triple from 9.7 billion in 2020 to more than 29 billion IoT devices in 2030 [11].

Table 1. Important components for IoT smart lighting solution deployment [12-15]

Components	Description
LED Lighting	By using the IoT technology, the lighting system can be controlled remotely from users' devices.
Sensor's technologies and Control methods	Smart lighting system is a system that combines sensor technologies and control method. By using sensors such as temperature, motion, occupancy and daylight harvesting sensor or control techniques such dimming and turning off/on the lights, energy efficiency and safety operation can be increased while energy costs can be reduced.
Connectivity platform	The collected data from the sensors can be stored and processed on the IoT platform.
Data analytics	Based on the data collected by the sensors, different operating scenarios can be created for smart energy management **purposes** (home, building), as well as real-time measured parameters can be taken to maximize cost-reduction, energy efficiency.
Smart usage	Smart lighting systems can be enhanced by artificial intelligence. It can can possibly predict future energy consumption and defects in the lighting usage. The benefits of the IoT-based smart lighting are listed as faster deployment, reduction in maintenance cost.

Smart lighting system is a system that is connected to a network and can be controlled **or** monitored from any centralized system or via a cloud remotely [12]. The application of the smart lighting systems has been increasing rapidly in recent years and has potential to be an infrastructure enabling IoT technology. Smart lighting systems in domestics, offices and industries uses can significantly reduce energy costs. An IoT-enabled Smart Lighting System can enhance the system's energy efficiency by 17 - 60% over traditional ones, depending on the user's usage patterns [10]. However, the relatively high initial investment cost remains an obstacle to the widespread implementation of smart energy-saving lighting systems [11-14]. To further exploit the IoT enable-smart lighting as a potential solution of energy efficiency achieving, it is necessary to perform the following important components described in Table 1 [12-15]. Along with the context, this study is conducted to construct a low-cost autonomous lightning system and evaluate its energy-saving potential. The organization of the paper is prepared as follows: Section 2 describes the proposal of an IoT-based smart lighting system, in which the system diagram, the control flowchart and the experimental steps are presented with detailed explanations, respectively. Section 3 shows the experimental works and results. Finally, conclusion remarks with the possible future studies are given in the last section.

2. METHODS AND MATERIALS

2.1. Proposal design of the Smart-Lighting system with Internet of Things features

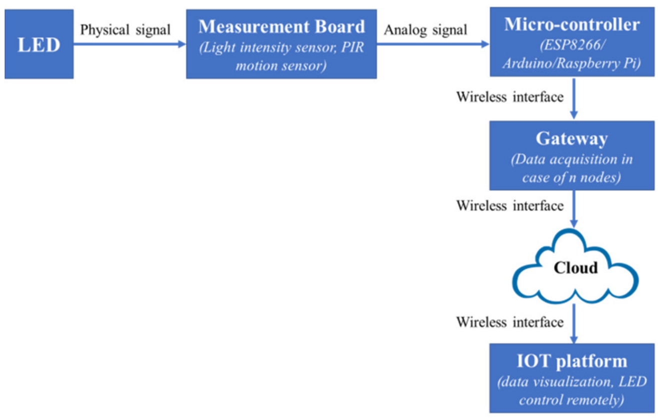

Figure 1. Diagram of the proposal IoT enable Smart Lighting System

In this section, the proposed design IoT-enable Smart Lighting system is composed of measuring devices (light intensity of the LED, ambient illuminance in a room) which receive physical parameters such as light intensity in a room. The parameters are sent a microcontroller as Arduino or ESP8266 chip or Raspberry Pi to adjust the LED's illuminance relay. Then, the parameters are sent another microcontroller to adjust the LED's illuminance relay in accordance with the ambient illuminance sensor reading. The data is then stored in the CLOUD and transferred the communication interface (IOT platform) to interact with the users by showing that analysed results on PC or smartphone screen (Figure 1).

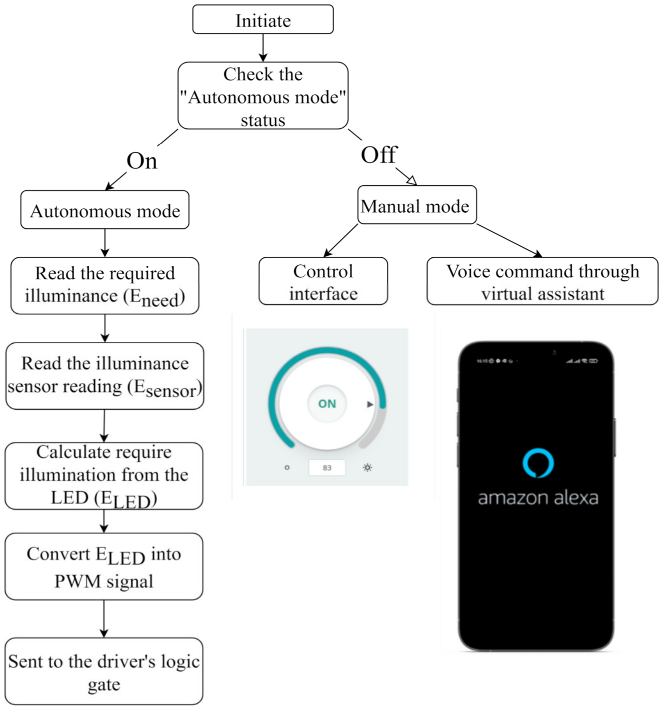

Figure 2. Software control scheme

The LED can be controlled remotely from a control interface in the cloud-based platform, or be controlled by external applications that utilise the cloud-based platform as an intermediary, e.g. a voice assistant. The system consists of six main parts:

- The Microcontroller transfers measurement gauge signals which communication pins and PWM pins.
- Sensor Board (light intensity, PIR motion). Using these board reduces the wiring required to transmit the signal from the source to the sensor and therefore reduces the impact of measurement noise.
- Cable (including power cable and signal cable)
- The communication device (Wi-Fi module, TCP/IP protocol)
- IOT platform (Human Machine Interface such as computer screen, smartphone)
- Power supply (0 - 5VDC; 12VDC)

In the case of Smart Lighting, the IoT takes responsibility for monitoring the light intensity state following the desire of the uses (in any time, from anywhere) with only the Internet connection that exists in many applications. The implementation of Internet of Things technology monitoring systems allows decisions to be based on objective data. The IoT's information chain of the proposed system uses an Arduino IoT cloud (Arduino Web Editor, and Amazon Alexa as the virtual assistant), which functions as the cloud-based platform mentioned in the Figure 1. The Arduino IoT Cloud is an online platform that enables users to create, deploy and monitor IoT projects as well as configuration, write code, upload and visualization. The platform features include Data Monitoring, Variable Synchronisation, Over-The-Air (OTA) Uploads and Amazon Alexa Support. Due to these functions and a relatively user-friendly interface, this platform is a powerful tool for IoT projects [16]. Arduino IoT Cloud only serves as a third-party intermediary service that facilitates the communication between elements in this project, while the control mechanism and interface still must be programmed in C++. The Arduino Web Editor is an IDE (Integrated Development Environment) to write code and upload sketches to Arduino-supported microcontrollers, and operates directly on popular web browsers such as Chrome, Firefox, Safari and Edge. Other secondary features and the compatibility with Arduino IoT Cloud are the rationales for its usage in this research. In Figure 2, the flowchart of process for monitoring and control via IoT platform is presented. Firstly, after initiating, the software control scheme will check for the control mode: whether the user prefers the LED to be autonomously controlled, or manually control by user input. For the manual control scheme, the user simply inputs their desired level of illuminance by a control interface provided in the cloud-based platform or commands the virtual assistant to do so. On the other hand, for the autonomous mode, firstly, the required level of illuminance will be read (E_{need}). This is the overall illuminance required for a certain activity that is established according to the British Standard EN 12464-1 [17] in the aforementioned surface, and also the value that needs to be kept constant regardless of the environment illumination. Since illuminance is an additive value; after having read the ambient illuminances (E_{sensor}), which is the illuminance at the aforementioned surface without taking into account the illuminance of the. Then, the illuminance needed to be emitted by the LED (E_{LED}) will be calculated according to the formula:

$$E_{LED} = E_{need} - E_{sensor} \tag{1}$$

E_{LED} is then converted to the PWM signal that drives the LED, the map () and the analogWrite () function in the Arduino library. In detail, the "analogWrite()" generates a PWM signal to a designated microcontroller pin with the syntax: "analogWrite(pin, value)"

Where:

- pin: the Arduino pin to write to.
- value: the duty cycle: between 0 (always off) and 1024 (always on)

However, to use "analogWrite", E_{LED} must first be converted to the range from 0 to 1024. To do that, the map()function is used, which syntax is: "map(value, fromLow, fromHigh, toLow, toHigh)",

Where:

- "value": the number to map.
- "fromLow": the lower bound of the value's current range.
- "fromHigh": the upper bound of the value's current range.
- "toLow": the lower bound of the value's target range.

● "toHigh": the upper bound of the value's target range.

Hence, assuming the maximum illuminance of the LED is $E_{max\ LED}$, which method to determine will be presented in the later section, and $E_{converted}$ is the value when converting E_{LED} from the range [0, $E_{max\ LED}$] to the range [0,1024], then the syntax will be:

$$E_{converted} = map(E_{LED}, 0, E_{max\ LED}, 0, 1024) \quad (2)$$

2.2. Experimental steps

In order to determine the energy-saving potential of the device, an experiment was conducted in 4 steps (Figure 3).

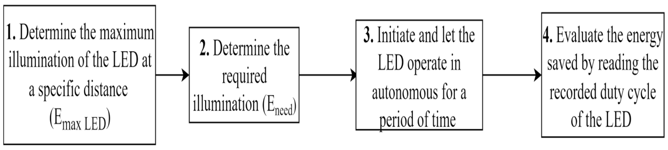

Figure 3. Experiment steps

Step 1: Since the illuminance on a specific surface is distance-dependent, the maximum illuminance the LED can emit can only be specified at a particular distance. However, at a far enough distance, the LED illuminance will be diffused with that of the surrounding environment, causing incorrect measurement. Therefore, the illuminance of the LED operates at maximum power at a distance of 1cm ($E_{max\ LED\ (1)}$) will first be measured, and the maximum illuminance at any other distance will be calculated according to the formula of the inverse square law [18]:

$$E_{max\ LED(d)} = E_{max\ LED(1)} \times (\frac{d}{0.01})^2 \quad (3)$$

Where

● $E_{max\ LED\ (d)}$: The maximum illuminance at distance d from the LED in lux

● d: the distance from the LED to the surface in metres (m)

Step 2: The required illumination (E_{need}) can be set by the user according to some established standards. In this project, the British Standard EN 12464-1 will be used, in which a 300 lux illuminance is recommended for the classroom [19]. Hence, in this experiment, the value E_{need} = 300 lux will be used.

Step 3: After that, the LED is operated in the autonomous mode for a period of time, in which the microcontroller will continuously substitute E_{need} to (1), determine E_{LED} and covert to PWM signal and adjust the LED emitted illuminance each time E_{sensor} change

Step 4: Assuming that energy loss as heat dissipation of the electronics components and energy supply to the microcontroller is negligible, then the energy-saved can deduct from the duty cycle recorded.

In this project, the following hardware components were used: the ESP8266 microcontroller, a BH1750 illuminance sensor, an LM7805 voltage regulator, and L298 Dual Full-bridge Driver, with the description as shown in Table 2.

Table 2. Hardware materials

Hardware	Description
Microcontroller ESP8266	The ESP8266 is a microcontroller designed for IoT application, which capabilities include establishing Wi-Fi TCP/IP connection, while also very inexpensive, and widely popular, which make it a suitable choice for IoT projects and make use of the near-universal coverage of Wi-Fi in buildings
BH1750 illuminance sensor	The Light's illuminance sensor used was the BH1750 photodiode. Its output signal can be read directly in the lux unit and transmitted to the microcontroller by the I2C protocol. This component was chosen for its cost affordability, and availability in the market
LM7805 voltage regulator	LM7805 functions as a Power-Dissipation type voltage regulator. In this project, this module is used to supply 5V voltage to the L298 and the microcontroller, and 12V voltage to drive the LED. Again, its cost-affordability and availability make it suitable for this project
L298 Dual Full-bridge Driver	The L298 is a power electronic integrated circuit that acts as a high voltage, a high current dual full-bridge driver designed to accept controlling PWM signal from the microcontroller. The module requires additional supply voltage to drive the LED since the PWM signal is provided at a lower voltage

3. RESULTS AND DISCUSSION

3.1. IoT-based Smart lighting prototype

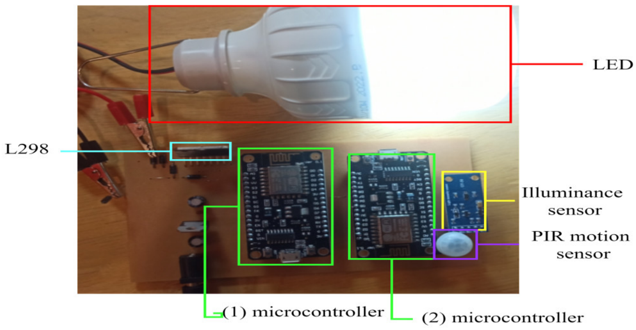

Figure 4. Proposal design prototype

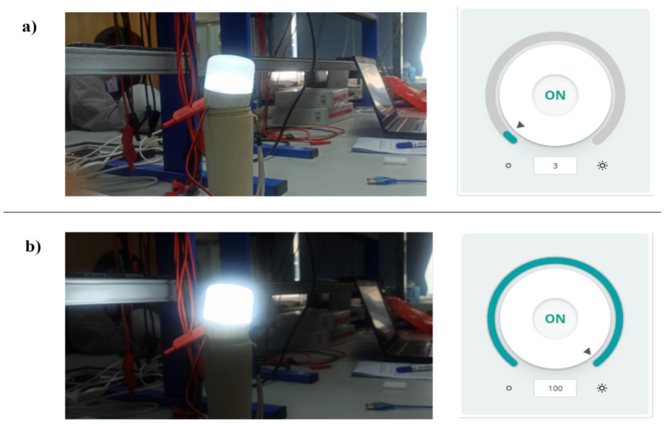

Figure 5. Manual control mode of the prototype device (a) at 3% of the maximum power and (b) at 100%

The proposal design prototype is shown in Figure 4: The device comprises two independent microcontrollers: one to receive the sensor's output (1), and one to control the LED. However, to supply the 12V LED, a voltage regulator and a full-bridge driver are added. To begin with, the device is supplied by an AC/DC adapter that can be directly plugged into the household electrical socket. The 12V DC current supplied by the adapter is then passed through a voltage regulator, which supplies both the microcontrollers and the driver. The PWM signal from the first microcontroller, instead of directly driving the LED, now functions as the input to the logic gate of the driver: when the PWM is at 3V, it signals the driver to "open" the 12V voltage to the LED, and vice versa, the 0V PWM signals the driver to "close", which result in a 0V voltage to the LED.

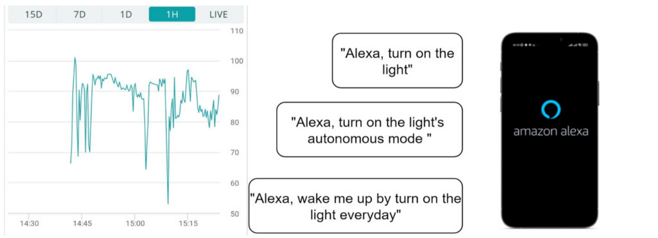

Figure 6. Monitor interface in the Arduino IoT app (left) and the Alexa voice command (right)

Figure 7. Energy monitor dashboard in Alexa

The proposal prototype will have 3 modes of control. As illustrated in Figure 5, the LED can be controlled manually by an online control interface that is available online in the Arduino IoT Cloud dashboard. The adjustable range is from 0 to 100, equivalent to adjusting from 0% to 100% power of the LED. Furthermore, Arduino IoT Cloud is also capable of generating a visualisation of the collected data and display online in real-time. The collected illuminance data from the sensor is displayed in Figure 5. Additionally, Arduino IoT Cloud also provide a smartphone application, which allows users to remotely control and monitor the LED directly from the phone, as shown in Figure 5. Similarly, with Alexa integration through Arduino IoT Cloud as the intermediary, the LED can also be controlled manually by the Alexa app, or via the user's voice command to Alexa. As Alexa is a very popular application in home automation, with already-available integration of numerous IoT devices in the market, its utility from there is enormous, such as some available voice commands to Alexa, as illustrated in Figure 6. It is also worth discussing that, upon the completion of this project, it was discovered that there exist integrated circuits (IC) that can function as LED Driver DC/DC Converters, Constant Current, and PWM generators [20], which can replace both the voltage regulator and the driver in this project, while also provide a more reliable, compact and efficient operation. However, such ICs aren't cheap nor available or obtainable in the Vietnamese market by any means. In the meantime, utilizing widely available and low-cost electronic components for intelligent and energy-efficient lighting systems, as this project has done, might be a potential direction worth investigating and further development.

Another potential of the virtual assistant in energy saving is that Alexa allows users to monitor their energy consumption and optimise their energy consumption behaviour, as shown in Figure 7. Furthermore, Alexa is also capable of coordinating multi-smart device schedules and routines simply by the ease of a voice command, instead of complex coding. This ability to enable personalisation energy optimization routines is a potential energy-saving measure worth investigating in a future where smart devices become more prevalent. For example, one can create routines such as "turn off all devices when I left home", or "turn off the oven in 20 minutes". The saving potential in this means will obviously vary from person-to-person basis.

3.2. Autonomous mode and the energy-saving assessment

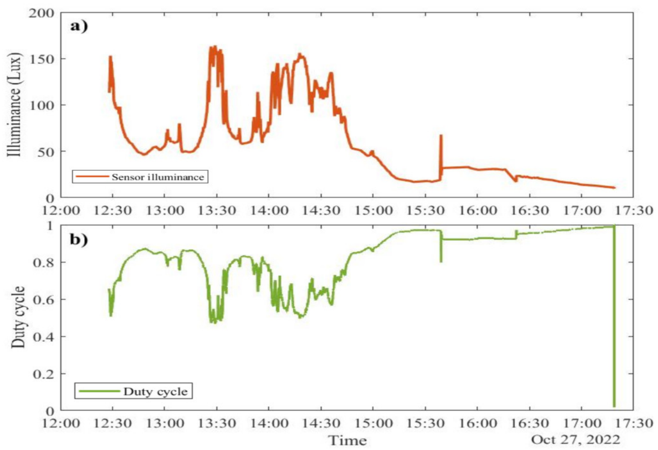

Figure 8. The record in autonomous mode for (a) the illuminance and (b) the LED duty cycle

The experiment was conducted in the Practical Energy Laboratory at the University of Science and Technology of Hanoi, 18 Hoang Quoc Viet, Cau Giay, Ha Noi. Due to the limited power of the LED used, the LED and the emitted surface are placed 4 cm from each other to provide a meaningful illuminance. Through on-site measurements, the maximum illuminance of the LED at the distance of 1cm: $E_{maxLED(1)}$ = 4670 lux. According to (2), the maximum illuminance of the LED at a distance of 4 cm is equal to $E_{maxLED(4)}$ = 291 lux. Also, according to Britsh Standard EN 12464-1, the illuminance of 300 lux is recommended for the classroom [18]; therefore, E_{need} = 300 lux. With the above parameters as inputs, the LED is then left autonomously operated for more than four hours, with the illuminance sensors reading in lux and the duty cycle recorded for analysis. The recorded parameters are shown in Figure 8.

As can be seen, the illuminance line and the duty cycle line run in inverse to each other, which means that when the illuminance value increase, the duty cycle decreases, which reduces the illuminance of the LED so that the overall illuminance is kept constant at 300 lux. As the experiment was conducted on a cloudy day with sunny moments; from 12:30 to 15:00, the ambient illuminance fluctuated greatly and vary from as low as 50 lux to as high as 154 lux, with the duty cycle also fluctuating accordingly. Cloudy weather also affects the overall system performance, as the average duty cycle during the period is $D_{average}$ = 0.81, which means that the LED is "on" for 81% of the time, and with the assumption that no additional energy is lost through other means (power electronics, microcontrollers), this equals an energy consumption of 81% that of uncontrolled LED, which results in a saving of 19%. However, as mentioned, cloudy weather greatly affected the system's performance, since, on less sunny days, more power must be consumed for lightning. Therefore, additional experiments should be conducted under different weather conditions for a more accurate conclusion on the saving of this device. However, due to time constraints, this proposal might be subjected to further studies. It is also observed that, since the voltage regulator LM7805 used in this project is of dissipation type, further development of this project should consider using a buck converter set-up instead for greater efficiency.

4. CONCLUSION

This paper has presented a study to construct a low-cost autonomous lightning system and evaluate its energy-saving potential, including the processes, methods and both hardware and software materials utilised. The results of this study can be summarised as follow: (i) A fully functional smart lighting system that features online real-time monitoring, autonomous illuminance control and virtual assistant voice control using a common, basic and inexpensive hardware electronic set-up with simple and straightforward software architecture is feasible; (ii) The potential of the virtual assistant in terms of energy saving; (iii) On unfavourable cloudy weather, and assuming that no additional energy is lost through other means, such a system can achieve a saving of 19%.

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THÔNG TIN TÁC GIẢ

Vũ Trọng Đức Anh[1], Nguyễn Xuân Trường[1], Hoàng Mai Quyền[2]

[1]Khoa Năng lượng, Trường Đại học Khoa học và Công nghệ Hà Nội, Viện Hàn lâm Khoa học và Công nghệ Việt Nam

[2]Khoa Điện, Trường Đại học Công nghiệp Hà Nội