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The development of a smart traffic light system using a solar-powered standalone photovoltaic system

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Abstract The demand for electricity generation from standalone solar energy is increasing, particularly for the advancement of smart technology like intelligent traffic light systems. A self-contained solar photovoltaic (PV) system can produce, store, and distribute electricity to traffic lights independently of the power grid. In contrast, conventional traffic light systems are often inefficient. The operation of these systems is based on fixed timing intervals for each lane and relies on the grid for power, which can occasionally fail, resulting in traffic accidents. A solution to these problems has been devised in the form of an intelligent traffic signal system that operates using a self-contained solar PV system. The objective of this study is to analyse current traffic signal systems through a comprehensive review of relevant articles, journals, and past studies. The objectives are to design and develop an intelligent traffic light system that incorporates independent solar PV power and to assess the appropriateness of solar panels, charge controllers, batteries, and sensors used in the system. The intelligent traffic light system utilises infrared sensors to accurately detect the level of traffic congestion. The timing of the traffic light system is regulated by an Arduino Nano microcontroller, which adjusts the signals in response to the current vehicle density. LED traffic light modules are used to display the traffic light signals. This technology utilises solar energy to offer a dependable and sustainable solution, guaranteeing uninterrupted operation even in the event of grid power outages. Integrating independent solar PV electricity into the smart traffic light system enhances traffic management and greatly mitigates the danger of road accidents resulting from traffic signal malfunctions. This novel approach showcases the capacity of solar energy to improve public safety and promote the progress of smart city initiatives.

Keywords: PV solar, traffic light, smart system

1. Introduction

The rapid process of urbanisation and the expanding population in metropolitan regions have resulted in a substantial surge in traffic congestion, giving rise to several difficulties, including transportation delays, environmental pollution, and fuel usage. Traditional pre-timed traffic signals have become a hindrance in efficiently controlling this high volume of traffic, especially during peak hours (Agrawal & Paulus, 2020).

Moreover, the number of vehicles on the road has increased proportionally with global population growth, resulting in road congestion, especially in urban cities. This road congestion occurs because conventional traffic light systems use a fixed timer programme to send signals to road users. As a result, drivers need to wait longer for the signals to turn green, even though there are no vehicles at other intersections. The long traffic light timer not only stresses drivers but also results in significant fuel waste and increases carbon dioxide emissions from queued vehicles.

To tackle these problems, researchers have been investigating the use of intelligent traffic signal systems, which utilise cutting-edge technologies to enhance traffic control procedures. Various intelligent traffic light systems have been suggested in the literature. Martínez-rodríguez-osorio et al. (2006) proposed a powerline communication system that enables remote monitoring and control of traffic lights. Abdullah et al. (2010) and AbdelRahman et al. (2011) conducted a study on utilising sensors to identify the presence of vehicles and subsequently modify the timing of traffic signals. Odeh (2013) proposed a system that employs a genetic algorithm to regulate traffic signal durations according to congestion levels, whereas Salehet al. (2017) developed a system that utilises infrared sensors, cameras, and image processing algorithms to regulate traffic lights according to the volume of traffic and to identify vehicles that run red lights. These systems collectively exemplify the capacity of intelligent traffic signal technology to enhance traffic flow, safety, and efficiency.

Electricity is the most crucial component of a traffic signal system's operation, as the traffic control systems can function continuously in the presence of energy. An electrical failure or interruption may impair the system's operation and affect the

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safety of road users. Furthermore, conventional traffic light systems typically use underground and overhead cables to supply electric power, which can sometimes cause malfunctions due to power outages and even road accidents.

Developed and developing countries are increasingly deploying standalone photovoltaic (PV) solar traffic light systems, such as Germany, the United States, Australia, and Canada, to name a few. These countries utilise solar technology to develop traffic management systems that are more resilient and environmentally friendly, thereby contributing to their broader sustainability objectives. Moghbelli et al. (2009) and Hernández et al. (2011) conducted separate studies on the technical and economic implications of adopting these systems in Qatar and Bogotá, respectively. A study revealed that PV-powered LED systems can effectively minimise energy consumption and expenses in comparison to conventional traffic signals. Ciriminna et al. (2017) underscored the considerable potential of solar-powered LED streetlights in both developed and developing nations, emphasising their contribution to sustainability. In his study, Diong (2014) proposed a conceptual design for a power supply architecture that allows for dual input, hence encouraging the use of solar-powered traffic light systems.

By utilising solar energy, a traffic light system can reduce or eliminate its reliance on the electrical grid, improving its dependability and decreasing its operating expenses. Integrating solar power into a traffic light system can also reduce energy consumption and installation costs, particularly in grid-isolated or remote areas. Solar energy is a type of energy obtained directly from the sun and converted to electrical energy. It is the most environmentally friendly form of energy and does not contribute to climate change or energy crises.

Several studies have emphasised the ability of solar energy to improve the sustainability and efficiency of traffic signal systems. Manikandan et al. (2018) and Gourav et al. (2021) highlighted the significance of solar power for conserving energy. Manikandan's technology is designed to automatically shut off during periods of low vehicle density, while Gourav's solution enables signal control through software programmes. Himawan et al. (2020) examined the stability and efficiency of solar power. Their approach involved employing a solar cell to provide a steady supply of energy. Nale's strategy, on the other hand, involved adopting a solar system to increase the amount of electrical energy generated (Nale, 2015).

The two most significant advantages of solar energy are that it has no fuel costs and produces no greenhouse gases throughout the solar energy generation process (Dixit, 2020; Guangul & Chala, 2019; Zerari et al., 2019). Furthermore, a standalone PV solar model integrates all components necessary for electricity generation and supply, including the solar PV panel, battery, charge controller, and load (Guo et al., 2015). A battery is added to store the excess energy generated by the solar panel, which can be utilised at night or on overcast days. A charge controller is connected to the battery to protect it against overcharging and regulate the system's general performance.

The objective of this study is mainly to design and develop a standalone PV solar system to power a smart traffic light system. Infrared (IR) sensors are used in the smart traffic light system to detect the traffic density and transmit the data to the Arduino Nano microcontroller. This microcontroller will vary the timer of the traffic light system based on the vehicle density and change the signal appropriately. Therefore, with the integration of a standalone PV solar system, the generator can provide enough electricity to power the traffic light system and overcome many mishaps on the road due to traffic light malfunctions.

2. Materials and Methods

To achieve the objectives, several methods have been implemented in this project, including the development of a standalone solar PV generator and a smart traffic light system. The block diagram of the overall system as shown in Figure 1 illustrates the standalone PV solar system that supplies the power to the Arduino Nano microcontroller for its operation. When the IR sensor detects a high vehicle density in any lane, it will transmit the signal to the microcontroller. The microcontroller will then process the signal and send the output signal to the LED on the high-density lane to appropriately change the signal of the LED traffic light module to clear the road.

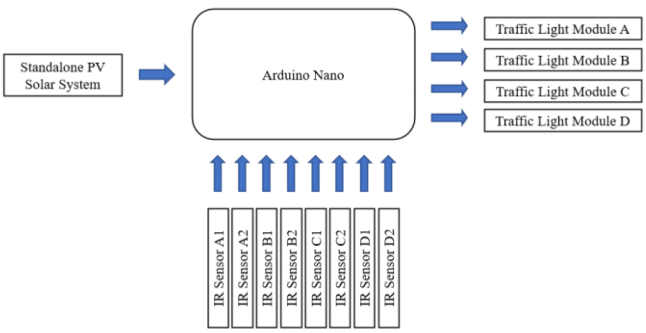

Figure 1 A block diagram of the overall system.

Figure 2 depicts the block diagram of a standalone PV solar generator. When a PV solar panel receives sunlight from the sun, it converts the solar energy into DC power. During the day, the solar panel will directly deliver power to the DC load, while the charge controller will charge the batteries to provide power to the load at night or on cloudy days. The DC-DC converter is used to step up the voltage to power the microcontroller.

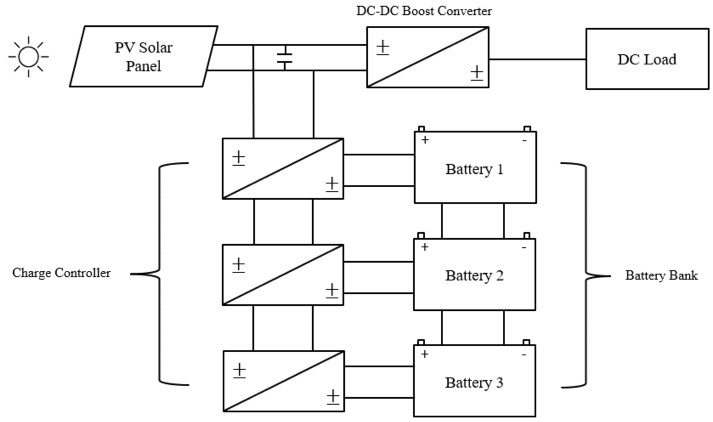

Figure 2 A block diagram of the standalone PV solar generator.

The smart traffic light system is designed to function under three conditions. Figure 3 shows the flow of the smart traffic light system of this study. When the traffic status is normal, or the sensor detects no vehicle density, the relevant traffic lights for lanes A, B, C, and D will be activated and run in the normal sequence of lanes B, D, A, and C. The second condition is met when the vehicle density on a particular lane increases. The traffic light system will change the signal based on the vehicle density to prioritise that high-density lane. Thirdly, when the vehicle density is equal in all lanes, the traffic light system will run in the normal sequence of lanes B, D, A, and C. These three conditions are required to prevent traffic congestion by prioritising the lane with a high density of vehicles.

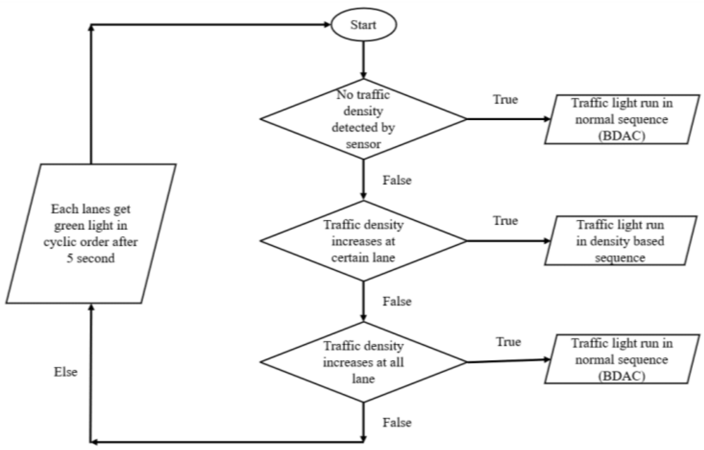

Figure 3 A flowchart of the smart traffic light system.

2.1. Hardware and Software Implementation

The solar PV system is the most crucial part of the project as it produces electricity that will power the smart traffic light system. Several elements are essential in developing the PV solar generator, including solar panels, a charge controller, a battery bank, and a DC-to-DC converter. Polycrystalline PV solar panels are used as they are cost-effective, robust, generate less silicon waste, and perform better in hot climates.

The smart traffic light project utilises a rechargeable lithium-ion battery as its portable power source. The TP4056 charge controller module is responsible for guaranteeing the safe and effective charging of the battery, preventing overcharging and prolonging its lifespan. The DC-DC boost converter module regulates the battery voltage to the necessary levels for the components of the system. The Arduino Nano microcontroller serves as the primary microcontroller, which is responsible for processing information from the IR sensors that identify cars or pedestrians. It utilises the provided input to regulate the LED traffic light module, thereby efficiently controlling the traffic flow at the intersection by adjusting the lights as necessary.

2.2. Project Development

There are two systems connected in this project: a standalone PV solar system and a smart traffic light system. Figure 4 illustrates the drawing of the hardware installation plan.

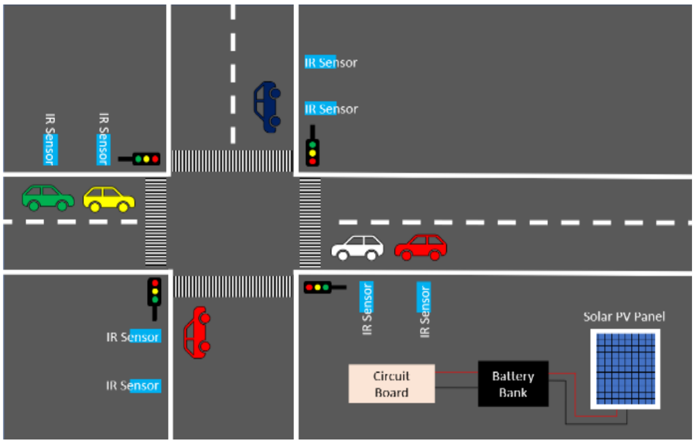

Figure 4 Illustration of the hardware installation plan.

Firstly, the components used for the standalone PV solar systems are a polycrystalline PV solar panel, TP4056 charge controllers, 3.7 V 18650 Li-ion batteries, and a DC-DC boost converter module. In the developed system, the solar panel is connected to the charge controller input port. The TP4056 charge controller is used to charge a single cell of a lithium-ion battery and protect the battery from overcharging or undercharging. Next, the charging port of TP4056 is attached to the battery terminal. The 18650 Li-ion batteries are used as the battery bank for standalone solar systems. The output port of the charge controllers is connected to the DC-DC boost converter module, which is used to step up the voltage to power the microcontrollers. Figure 5 shows the standalone PV solar system proposed in this project.

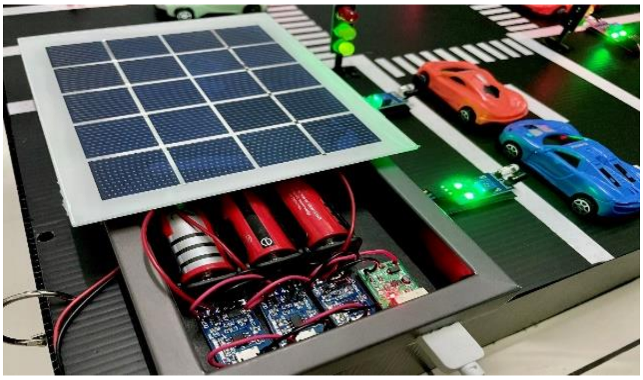

Figure 5 A standalone PV solar system.

Furthermore, several components are used to develop the smart traffic light system, including Arduino Nano, IR sensors, and LED traffic light modules. Based on the circuit design, the IR sensors and traffic light modules are attached to the Arduino Nano ports. The programme of the density-based traffic light systems is uploaded into the Arduino Nano microcontroller. Then, the standalone PV solar system is assembled with the smart traffic light system by connecting the DC-DC converter module's USB port to the Arduino Nano's input port. Precautionary measures are taken to ensure that the connections, especially the components' terminal, are correctly connected to prevent the circuit from blowing up and harming the hardware. Figure 6 shows the completed project prototype.

Figure 6 The completed project prototype.

3. Results and Discussion

The data collection procedure was carried out by conducting experiments for seven consecutive days to test the system's performance and obtain more accurate data. In addition, the data collection process was also carried out every hour for 12 h a day, starting from 7 a.m. until 7 p.m. This procedure ensures that the solar panel can receive maximum sunlight and function properly. Furthermore, the battery bank was tested by connecting the load on the output side to ensure its efficiency based on the calculation.

During data collection, the electrical power formula was used to calculate the value of the power generated by the solar panel. The relationship between solar panel power, voltage, and current is shown in Equation 1. Meanwhile, Equation 2 provides the battery charging time data.

$$P = VI \qquad (1)$$

Where *P* is the solar panel power (mW), *V* is the solar panel voltage (V), and *I* is the solar panel current (mA).

$$T = \frac{C}{R} \qquad (2)$$

Where *T* is the battery bank charging time (h), *C* is the battery bank capacity (mAh), and *R* is the charging current (mA).

The results obtained from the experiment were analysed and calculated to obtain the average data values. The average output of solar panel voltage, current, power, battery voltage, and charging time for each day are presented in Table 1. The solar panel generated the highest power on Day 1 with an average value of 421.82 mW, while the lowest power with an average value of 38.49 mW was recorded on Day 6.

Table 1 Data obtained from the standalone solar system.

Day	Solar Panel Output Voltage (V)	Solar Panel Output Current (mA)	Solar Panel Output Power (mW)	Battery Bank Voltage (V)	Battery Charging Time (h)
1	3.40	105.33	421.82	3.70	6,238.15
2	3.80	12.99	54.02	3.70	2,786.71
3	3.64	67.35	267.26	3.70	3,636.40
4	3.63	94.24	372.82	3.70	749.57
5	3.68	95.68	382.23	3.70	394.81
6	3.52	9.69	38.49	3.70	5,196.13
7	3.66	94.34	382.13	3.70	495.61

Figure 7 illustrates the relationship between the average solar panel power and the average solar panel current for each of the seven days. The solar panel power increases as the solar panel current increases.

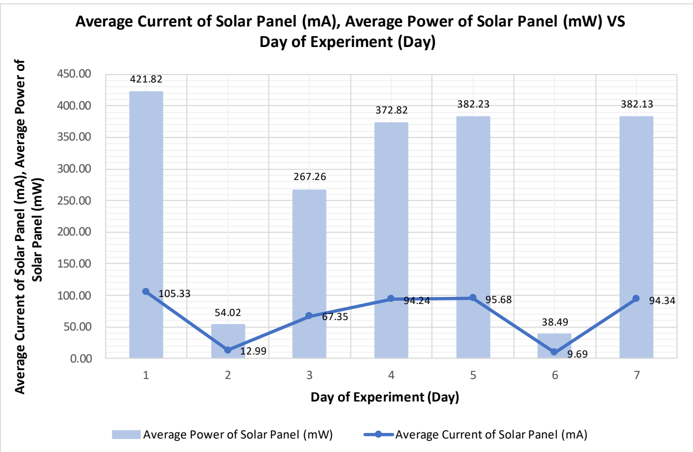

Figure 7 The relationship between the average solar panel current and the average solar panel power.

As the prototype testing was conducted near the end of the year (i.e., during the rainy season in Malaysia), the 7-day average daily intensity of solar radiation was relatively low. Thus, there is a major difference in the data taken each day as the Malaysian Meteorological Department and various studies on tropical climate conditions in Malaysia highlight that during monsoon seasons, typically from November to March and June to September, solar radiation is significantly lower due to heavy cloud cover, which directly affects the performance of solar PV systems (Sopian et al., 2024). Hence, several challenges have been faced during the prototype testing of the project, where the weather during the project was predominantly gloomy and rainy.

Besides, the suggested size of this project's solar panel is another element that contributes to the low output current of the solar panel. Based on the solar panel PV sizing calculation, the peak sun hour specified in the calculation is 4 h, as the experiment is expected to be conducted on a bright sunny day. These 4 peak sun hours align with standard calculations for a bright sunny day by Bensaha et al. (2020), who studied the design and optimisation of standalone PV systems. Nonetheless, on the day of testing, the weather was mostly cloudy for the entire week, which affected the PV solar panel output. On a sunny day, the proposed 2 W, 5 V PV solar panel should be able to produce a maximum current output of 400 mA. However, this PV solar panel cannot reach its maximum output current in overcast weather and only produces a small current due to the incompatibility of PV solar panel specifications. As a result, the solar panel's ability to convert more sunlight into electricity is diminished. Based on the experimental data obtained, the highest average output power produced by the solar panel is only 421.82 mW, with an average output current of 105.33 mA.

The charge controller is the most important element when charging a lithium-ion battery. The charge controller regulates the voltage and current entering the battery, preventing overcharging and deep discharging, which are critical for maintaining battery health and longevity. In systems using lithium-ion batteries, these controllers are crucial because they ensure safe operation and enhance the overall efficiency of energy storage systems, making them indispensable in battery management (Ali et al., 2022). Based on the experimental data in Table 1, the battery bank took a long time to fully charge, which is more than 24 h. As the output current from the panel is low, the charge controller module does not work correctly. This issue happened because the three parallel TP4056 modules need at least 4 A of input current to quickly and safely charge the 3.6 A battery bank.

Figure 8 depicts the relationship between the daily average solar panel current and the battery bank charging time. The charging time of the battery bank decreases as the average solar panel output current increases. This relationship suggests that the higher the output current produced by the solar panel, the shorter it takes for the battery bank to fully charge.

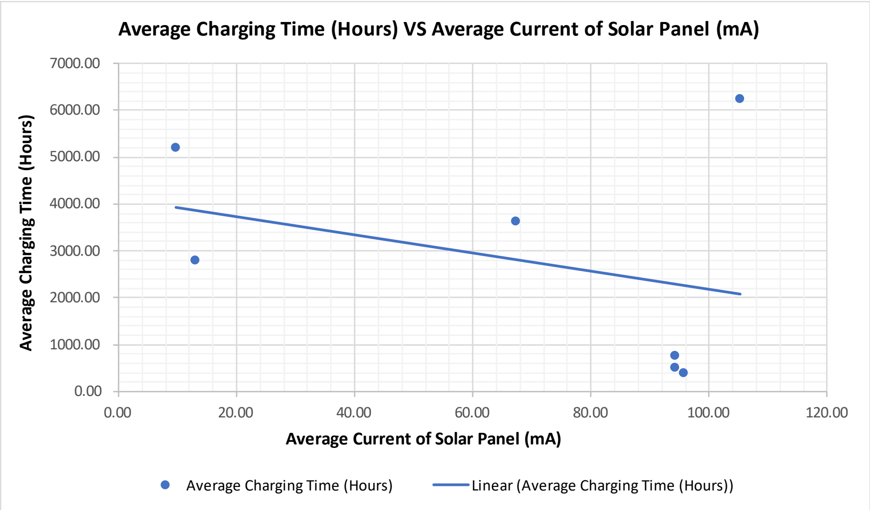

Figure 8 The relationship between the average battery bank charging time and the average solar panel current.

Due to the inability of the PV solar panel to convert sunlight into electricity at its optimum capacity, it takes a long time to charge the battery bank during the experiment. However, this issue is resolved by connecting the charge controller's micro-USB input port directly to the 4 A current source. Consequently, the time required to fully charge the battery bank is shortened.

In addition, the battery's endurance has been considered and analysed to ensure that the battery bank can power the load at its maximum capacity. The battery bank's endurance is the maximum amount of time it can support the load on its own, which can be obtained using Equation 3 as follows:

$$\text{Battery Bank Endurance} = \frac{V_{dc} \times Ah}{\text{load}} \tag{3}$$

The battery's endurance can be determined by using the battery's specifications used in this project. Assuming the capacity of the battery is at its optimal capacity:

$$\text{Battery Bank Endurance} = \frac{3.7V \times 3.6Ah}{3.3\ W} = 4.04\ \text{Hours} \tag{4}$$

According to Equation 4, the battery bank can theoretically power the system for up to 4.0364 h. On average, battery banks perform at 85% of their claimed efficiency. A study published by Zhang & Ramadass (2012) indicated that the typical efficiency rates of lithium-ion battery banks, particularly those using 18650 cells, are often operated at about 85% efficiency due to various factors, such as internal resistance and energy losses during charge and discharge cycles. This efficiency rate is a common benchmark when evaluating battery performance in practical applications. Therefore, the actual battery endurance is considered as follows:

$$\text{Battery Bank Endurance} = \frac{3.7V \times 3.6Ah}{3.3\ W} \times 85\% = 3.43\ \text{Hours} \quad (5)$$

According to Equation 5, the actual battery bank endurance is 3.43 h, with a capacity loss of approximately 0.54 Ah. However, during testing, the battery bank could only power the smart traffic light system for 45 min, or 0.75 h. The battery bank should be able to power the load for up to 3 h, as targeted. However, according to the 18650 lithium-ion battery specification, the battery has a cut-off voltage range of approximately 2.0–2.5 V. The battery bank will stop discharging when its voltage reaches its cut-off current. Thus, the 18650 lithium-ion battery type is unsuitable to be used as a battery bank in this project due to its limited specification.

A smart traffic light system is an intelligent traffic management system that uses solar power as its primary energy source and advanced algorithms to optimise traffic flow and reduce congestion. Alharbi et al. (2021) highlighted the use of dynamic smart traffic management systems that incorporate solar power and advanced algorithms to manage traffic efficiently, significantly reducing congestion. The effectiveness of this system is attributed to its ability to adapt to real-time traffic conditions, demonstrating a clear advantage over conventional traffic systems. Recent research highlights the potential of machine learning (ML) in optimising traffic management and promoting sustainable energy solutions. Furthermore, ML algorithms can analyse traffic data to predict congestion, optimise routes, and improve traffic flow, leading to reduced travel times and better overall management (Leen et al., 2023).

Moreover, ML techniques have been applied to accelerate advances in renewable energy harvesting, storage, conversion, and management, supporting the transition from fossil fuels to sustainable energy sources (Yao et al., 2023). These smart systems not only improve traffic management but also contribute to environmental sustainability by utilising clean energy. These findings reinforce the claim that smart traffic light systems represent a significant advancement over traditional systems, primarily due to their intelligent design and reliance on renewable energy sources.

This system consists of three significant elements: the Arduino Nano microcontroller, IR sensors, and LED traffic light modules. All these elements consume about 3.3 W of power per hour. The IR sensors are connected to the Arduino Nano microcontroller to control the traffic light system based on traffic density. After the traffic light system is loaded, digital IR sensors detect the traffic density. The IR sensors identify vehicles based on the light they reflect. These sensors emit IR beams towards the detection area, and when a vehicle passes through, the light reflects off the vehicle's surface back to the sensor. The sensor then processes this reflected light to determine the presence, speed, and sometimes the size of the vehicle. This method is highly effective because IR light is less susceptible to interference from ambient lighting conditions and can operate reliably in various weather scenarios.

In traffic management systems, IR sensors have proven effective in detecting and classifying vehicles. The reflex-type setups with retro-reflective markers, as described by Garner et al. (1990), enable these sensors to precisely count vehicle tires, measure speed, and determine axle spacing. The utilisation of IR technology in overhead laser sensors has demonstrated exceptional precision (98.5%) in categorising vehicles at toll plazas, even in adverse weather conditions (Tropartz, Hoerber, & Gruener, 1999). Researchers have created active and passive IR sensors for vehicles, which can also be used in pedestrian sensing systems at controlled crossings (Clark, Kidson, & Hodge, 1990). This research emphasises the adaptability and dependability of IR sensors in traffic control, providing non-invasive installation choices and the capability to function well in different environmental circumstances.

The sensors are installed adjacent to the road and facing the lane to measure the traffic density. In addition, the IR sensors are placed at a considerable distance from the lane to detect stopped traffic once a predetermined threshold has been achieved. Table 2 shows that the IR sensors are programmed to detect obstacles representing traffic density.

Table 2 Condition of IR sensors.

Sensor's Condition	Time for the Sensor to Respond (s)
Starting (the sensor is loading once the system starts)	1
Indicator ON (sensor detects obstacles)	1
Indicator OFF (no obstacle is detected)	1

The IR sensor required 1 s to load during the system's initialisation. Once the sensor has been loaded, it is ready to work. Table 3 shows the green traffic light signal duration based on the traffic density. When an obstacle is detected, the IR sensors transmit the signal to the Arduino Nano microcontroller to change the traffic light modules on the high-density lane to green for 5 s. However, if any vehicle density is still detected on the same road, the traffic light module on that road will keep showing green until the road is clear. When no density is detected, the IR sensor indicator will turn off and send a signal to the microcontroller to change the traffic light module to red and rotate the sequence until the lane with the high-density vehicle is detected again.

Furthermore, this smart traffic light system could reduce congestion and improve traffic flow. Road users do not need to wait long even though there is no vehicle on the other lane, as the traffic light automatically runs in a density-based system and prioritises the lane with high density. A non-conventional energy source, standalone PV solar system power, also supplies this smart traffic light system. Table 4 shows a comparison between the conventional traffic light system and the proposed smart traffic light system.

Table 3 Duration of green traffic light signal based on the traffic density.

Traffic Density	Duration of Green Traffic Light's Signal (s)
Low (1 sensor ON on a particular lane)	5
High (2 sensors ON on a particular lane)	≥ 10

Table 4 Comparison of conventional and smart traffic light systems.

Criteria	Conventional Traffic Light System	Proposed Smart Traffic Light System
Time	Unnecessary time wastage	Save time
Power	High power consumption	Low power consumption
Energy source	Conventional	Non-conventional
Control system	Manual	Automatic

4. Conclusions

In summary, the development of a solar-powered intelligent traffic light system is a remarkably efficient and environmentally beneficial resolution for contemporary traffic control. This cutting-edge system utilises plentiful solar energy to autonomously operate traffic lights, guaranteeing dependable and uninterrupted functionality even in distant or underdeveloped regions with limited or unreliable access to traditional grid electricity.

Smart technology integration greatly improves the functionality of traffic signals by allowing adaptive control that is based on real-time traffic circumstances. Throughout the day, the PV solar system transforms sunlight into electrical energy, which is used to operate the smart traffic lights and also to recharge a battery bank that is located on board. During periods of sunlight absence, the traffic lights derive their power from this stored energy. The system dynamically modifies traffic light phases based on the density of vehicles in each lane, giving priority to lanes with greater traffic in order to enhance traffic flow and alleviate congestion. As a consequence, this leads to enhanced traffic control, reduced journey durations, and enhanced road security.

Furthermore, the system's autonomy from the conventional power grid improves its ability to withstand power failures and reduces dependence on fossil fuels, resulting in lower greenhouse gas emissions and a smaller carbon footprint. This strategy demonstrates the capacity to combine environmentally friendly technology with smart infrastructure to promote the growth of sustainable cities.

The effective implementation of such a system has substantial economic, environmental, and social advantages. From an economic standpoint, it reduces the expenses associated with infrastructure upkeep and energy usage. From an environmental perspective, it facilitates the shift towards sustainable energy sources and aids in the reduction of climate change impacts. From a social perspective, it improves the effectiveness and safety of traffic, ultimately resulting in an improved quality of life for people living in metropolitan areas.

In order to enhance the efficiency and expand the capacity of these intelligent traffic solutions, future research should prioritise the optimisation of PV system performance, the refinement of traffic management algorithms, and the exploration of alternative renewable energy sources. Progress in these domains would not only enhance the dependability of intelligent traffic signal systems but also broaden their suitability to many contexts, facilitating the development of more intelligent and environmentally friendly urban spaces.

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Ethical considerations

Not applicable.

Conflict of Interest

The authors declare no conflicts of interest.

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