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Design and Implementation of a Smart Energy Management System (SEMS) for Food Truck DC Loads in Off-Grid Photovoltaic (OGPV)

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Abstract

Mobile food trucks need diesel generators or gasoline to produce power to operate essential appliances. This leads to increased fuel expenditures, emissions, and noise pollution, which are harms to the environment, as well as customers' and employees' experience. To reduce these burdens, this project was to design and develop a Smart Energy Management System (SEMS) to replace the need for a diesel generator by integrating it with an Off-Grid Photovoltaic (OGPV) to power DC loads more efficiently. An energy demand analysis was conducted on four food trucks located in Kuala Lumpur; the data collected from the appliances was analyzed to create an Excel-based tool that allowed us to determine the optimal sizes of PV panels, batteries, and MPPT charge controllers that provided a two-day autonomy (for cloudy days). The tools were validated using the PVsyst software and the analysis showed an average load demand error of lower than 0.4% which validated the tool's effectiveness. A SEMS prototype with an ESP32 microcontroller was built that utilized voltage, current, light, and rain sensors, and the prototype was able to automate lighting control and monitor real-time data using an LCD display and Arduino IoT Cloud. Testing in the day, night, and rain proved the system's capacity to manage energy very efficiently along with reliable operations and the ability to adapt to variable environments. To summarize, the integrated SEMS-OGPV system provides a real-world user outcome as a practical, sustainable, and scalable energy solution for mobile food operations considering the accurate sizing, optimized efficiencies, and greater environmental considerations.

1. Introduction

Mobile food trucks are now a common aspect of urban landscapes, but they rely on diesel or gasoline generators to provide electrical power for key equipment such as refrigeration, cooking, and lighting. These generators have many disadvantages, including noise, emissions, odor, and fuel consumption, which impact the environment and the customer experience [1][2]. Moreover, fuel prices fluctuate and are often expenses that weigh on operators' economic viability, profits, and flexibility. Off-Grid Photovoltaic (OGPV) systems can be installed to replace these generators utilizing solar energy, which reduces or eliminates fuel use, emissions, and noise [3][4]. Yet, we do not often think of solar energy in variable terms, it is variable and mobile food trucks substantially influence their energy demand into highly variable levels of consumption that depend on weather and operating conditions [5].

All this variability makes it difficult for these types of generators to be adequately fitted without oversizing the system and wasting both money and space. Prior research in renewable energy integration into energy systems has referred to cases of static applications with renewable energy systems on site, or, generic off grid applications with little if any focus on mobile operations directly influenced by weather and requiring real time control of load. Thus, this project is proposing a new integration of an OGPV system with a Smart Energy Management System (SEMS) specifically focused on managing DC loads in a food truck. Unlike existing works, the SEMS in this study incorporates multi-sensor monitoring (light and rain), real-time voltage and current measurement, automated relay-based load control, and IoT-enabled remote monitoring, enabling intelligent, condition-based energy allocation that optimizes performance even under variable environmental conditions. Unlike previous studies, this SEMS integrates light and rain sensors, real-time voltage and current monitoring, automated relay-based load control, and IoT-enabled remote monitoring, enabling intelligent, condition-based energy allocation that optimizes performance under varying environmental conditions. The objectives are to: (1) develop an Excel-based tool for calculating optimal PV panel, battery, and inverter sizes from recorded energy consumption data with two-day autonomy; (2) design and implement a SEMS prototype to monitor and control DC loads; and (3) validate the SEMS performance through hardware testing and simulation. The proposal includes energy demand assessments on four food trucks through interviews, establishing the SEMS hardware using an ESP32 microcontroller with sensors for voltage, current, light, and rain, and testing the systems during the day, night, and rain. Data collection on appliance usage, along with analysis of consumption, is completed using the Excel tool to determine the system sizing; sizing is then validated through PVsyst which is recognized as the industry-standard reference for designing PV systems [6]. The results indicate that the SEMS-OGPV system is adequate to meet energy needs and achieve greater efficiencies while being a practical and replicable renewable energy solution for mobile food truck operations [7][8].

1.1 Renewable Energy

Renewable energy harnesses natural resources such as sunlight, wind, and water to generate power, offering a sustainable alternative to fossil fuels. Solar energy, derived from sunlight, is one of the most abundant and accessible renewable energy sources available globally. It is increasingly utilized in various applications due to its reliability, scalability, and minimal environmental impact [8]. Unlike conventional energy systems, solar energy systems produce zero emissions during operation, making them ideal for addressing climate change and reducing air pollution. This project specifically leverages sunlight to power a food truck, utilizing an Off-Grid Photovoltaic (OGPV) system that is tailored to the truck's energy requirements. As shown in Fig. 1, a solar photovoltaic system operates by converting sunlight into electricity, storing it in batteries, and distributing it to the load, forming the foundation of the OGPV system [9].

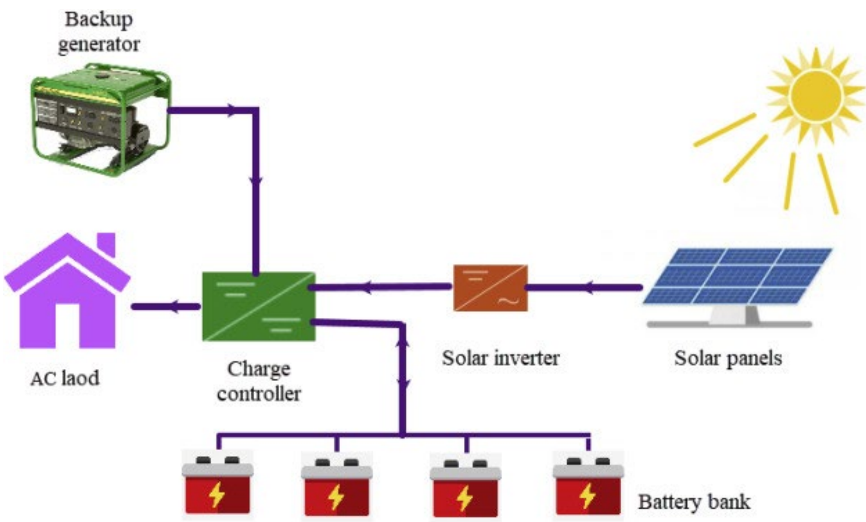

Fig. 1 *Basic working principle of a solar photovoltaic system, including sunlight conversion to electricity [9]*

This project utilizes sunlight as the primary energy source for powering essential food truck appliances, such as refrigeration, lighting, and cooking equipment. To address the challenges of solar variability, the system is integrated with a Smart Energy Management System (SEMS) that monitors energy production, optimizes power allocation, and ensures efficient battery usage. The environmental and economic benefits of this transition are evident when comparing emissions and operational costs between diesel generators and solar-powered systems.

As depicted in Fig. 2, solar-powered systems significantly reduce carbon emissions and operational costs, reinforcing their advantages over traditional fossil fuel-based systems [10].

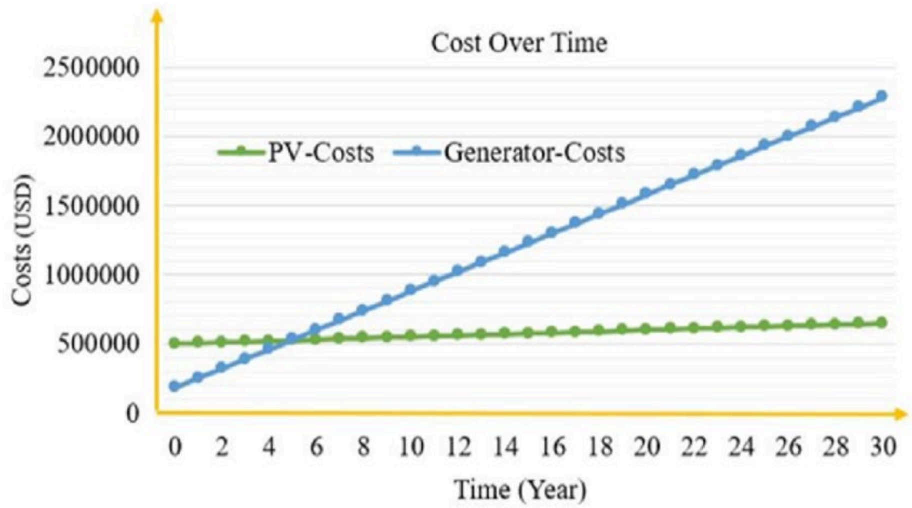

Fig. 2 *Comparison of emissions and costs between diesel generators and solar-powered systems* [10]

2. Materials and Methods

In this section, there are a few stages that lead to the project's success by acknowledging each software and hardware function.

The Smart Energy Management System (SEMS) is a system for controlling and monitoring the DC loads in food trucks. The block diagram in Fig. 3 depicts the SEMS using a NodeMCU ESP32 microcontroller to process inputs from environmental sensors such as a rain sensor and a light sensor primarily for its ability to automatically control lighting appliances, based on former or existing conditions like weather, and ambient light level. SN-B25-VOL for voltage measurement and ACS712 for current measurement relay the power quantities that are supplied to the loads in the food truck prior to real-time monitoring. The voltage sensor data and the current sensor data are displayed at the local level on an LCD I2C 16x2 screen and sent to the Arduino IoT Cloud. This allows food truck operators to monitor the energy behaviour and operational conditions of food trucks; track energy usage; track energy system performance; and monitor load reliability of DC loads operating under varying environmental conditions.

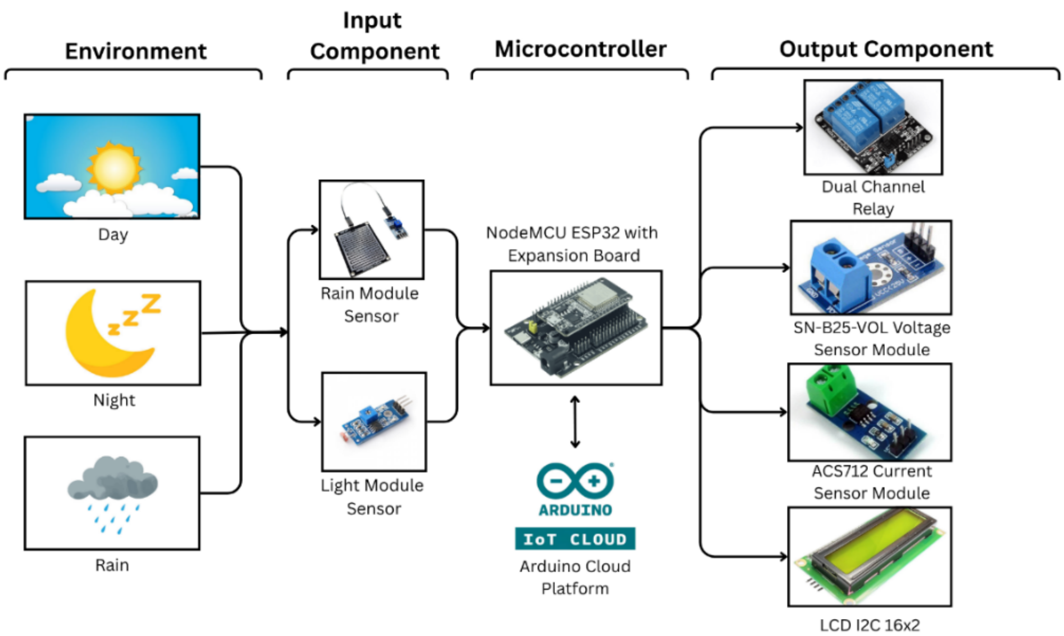

Fig. 3 *Block diagram of SEMS*

All the components used in this project are integrated into a single circuit, as illustrated in Fig. 4. This figure shows the complete circuit diagram of the Smart Energy Management System (SEMS) with Off-Grid Photovoltaic (OGPV) for the food truck application.

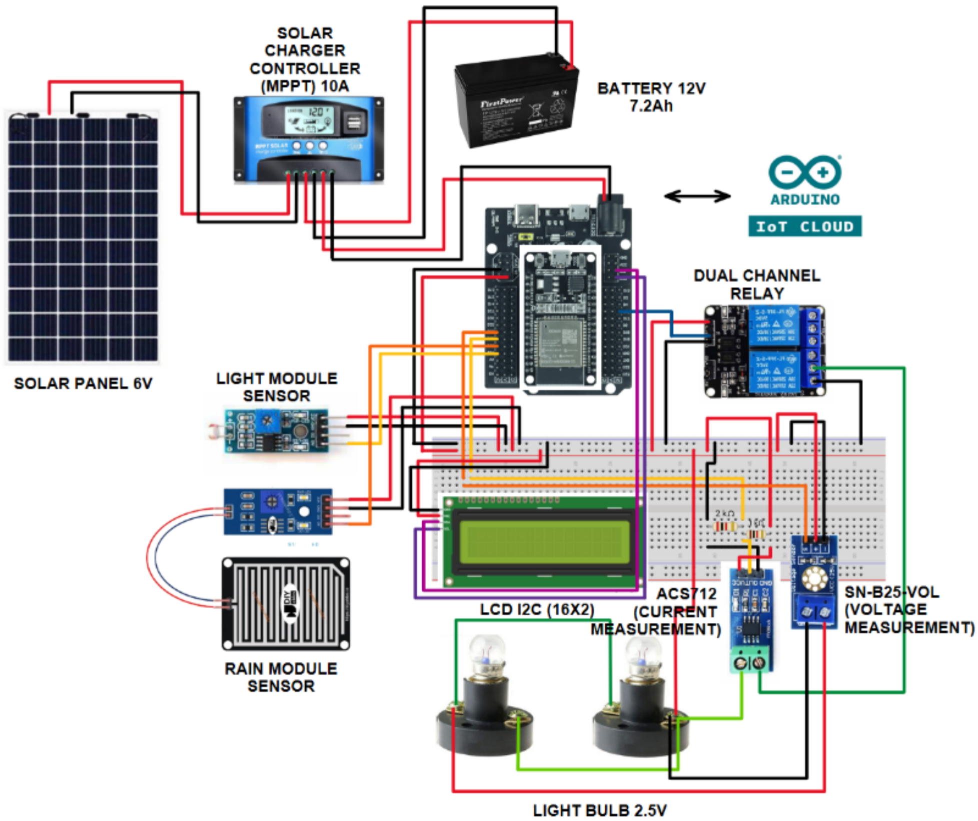

Fig. 4 *Circuit diagram for SEMS with OGPV system*

Fig. 5 illustrates the functional flowchart of the Smart Energy Management System (SEMS) for DC load control in a food truck application. The flowchart provides a clear sequence of steps starting from weather condition detection.

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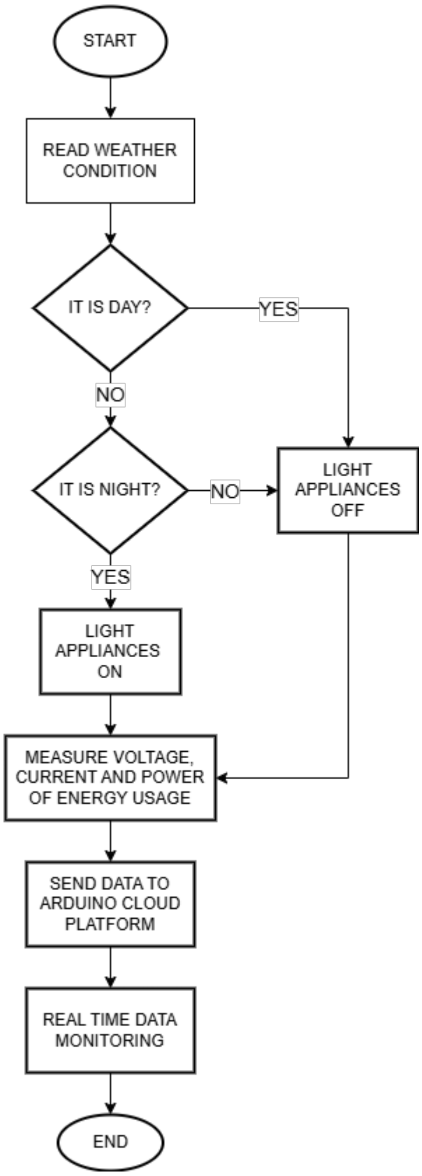

Fig. 5 *Flowchart of functionality of SEMS for DC load*

2.1 Data Collection and Energy Analysis

Fig. 6 displays an interview session at MaTiC Lot, Kuala Lumpur with Mrs. Ninie, the site organizer, and the owner of the lokching food truck at Taman Universiti Parit Raja. At the MaTiC Lot site, energy data was obtained from four food trucks (Nasi Lemak Stall, Sate Warisan Stall, Dutch Lady Stall, and Coconut Shake Stall) through observation and interviews. Mrs. Ninie explained that the food trucks at MaTiC use power from a sub-distribution box to the main grid, limited to 2000 watts per truck and operate from 4 PM to 12 AM daily. This data was important to perform a load analysis and input into the excel tool. An interview with the lokching food truck operator at Parit Raja provided their experiences with a generator, including high petrol costs (RM15/week), breakdowns and maintenance over RM1000/year. The owner was interested in proceeding to a solar power system. All the site interview combinations demonstrated information on operational loading, costs and motivation for using an OGPV system with SEMS for energy management.

Fig. 6 *Interview session at MaTiC Lot, Kuala Lumpur with Mrs. Ninie and with the owner of lokching's food truck*

2.2 Formula of Excel Based Tool

The development of an Excel-based sizing tool is a key aspect of this project, aimed at streamlining the design process for off-grid photovoltaic (OGPV) systems tailored specifically for food trucks. This tool is intended to simplify complex calculations, ensuring accuracy and efficiency while allowing for easy customization based on user inputs. By integrating various formulas and parameters into a single platform, the tool enables food truck operators or energy planners to design an optimized solar system that meets the energy demands of their operations. Table 1 will show the formula that is used to develop the Excel Based Tool.

Table 1 *Formula for Excel based tool*

Content	Formula	
Load Calculation	$Etotal = \sum(Pi \times Hi \times Qi)$	(1)
Sizing of PV Panels	$Ppv = \frac{Etotal}{Hsun \times \eta system}$	(2)
Sizing of Batteries	$Cbat = \frac{Etotal \times Dautonomy}{Vbat \times \eta bat \times DOD}$	(3)
Sizing of MPPT Charge Controller	$Imppt = \frac{Ppv}{Vpv} \times Smargin$	(4)
Sizing of the Inverter	$Pinverter = Ppeak \times Smargin$	(5)

2.3 Specification of Smart Energy Management System (SEMS) and Off-Grid Photovoltaic (OGPV)

Defining the operational parameters of both the Smart Energy Management System (SEMS) and the Off-Grid Photovoltaic (OGPV) system is necessary to properly employ both systems to meet the energy requirements of the food truck application, with reliability and efficiency. The SEMS was designed to offer monitoring and control of DC loads such as lighting and measuring real time voltage, current, power, and monitoring environmental conditions such as light intensity and rain detection. The OGPV system provided renewable energy through solar panels and was alternatively supported by batteries and a solar charge controller that would store and route the energy. Table 2 summarizes all the specifications of the detailed components utilized in both the SEMS and OGPV systems.

Table 2 *Specification of SEMS and OGPV system*

Component	Specification
Microcontroller	NodeMCU ESP-32
Rain Sensor Module	SN-RAIN-MOD
Light Sensor Module	SN-LIGHT-MOD
Relay Module	2 Channel 5V Active Low Relay Module
Voltage Sensor	SN-B25-VOL
Current Sensor	SN-ACS712-5A
LCD Display	2x16 LCD with I2C Module
Solar Panel	6V 10W Polycrystalline
Battery	Sealed lead-acid 12V,7.2Ah
Solar Charger Controller	PWM 10A Solar Charge Controller
Software	Arduino IoT Cloud

3. Results and Discussion

This section outlines and discusses the outcomes from the food truck-based Smart Energy Management System (SEMS) coupled with an Off-Grid Photovoltaic (OGPV) system. The section will look at the load analysis and system sizing using the Excel-based system sizing tool and validation with PVsyst Software to demonstrate accuracy. The limitations and performance of the SEMS prototype are discussed, including sensor readings, automated load control logic, and being energy efficient during different environmental conditions (day, night rain). Important findings are presented that demonstrate the reliability and accuracy of the system in practice with a mobile, real-world case study of food-based mobile operations.

3.1 Data Analysis of Food Truck Using Excel Based Tool and Validated by PVsyst

For the Nasi Lemak Stall, the appliances identified were LED downlights, LED bulbs, freezer fridge, fan and rice cooker. Each of these appliances contributed to total daily energy consumption and served as input to the desired system design. The respective values informed the excel-based tool that produced the system sizing results found in Fig. 7 and Fig. 8.

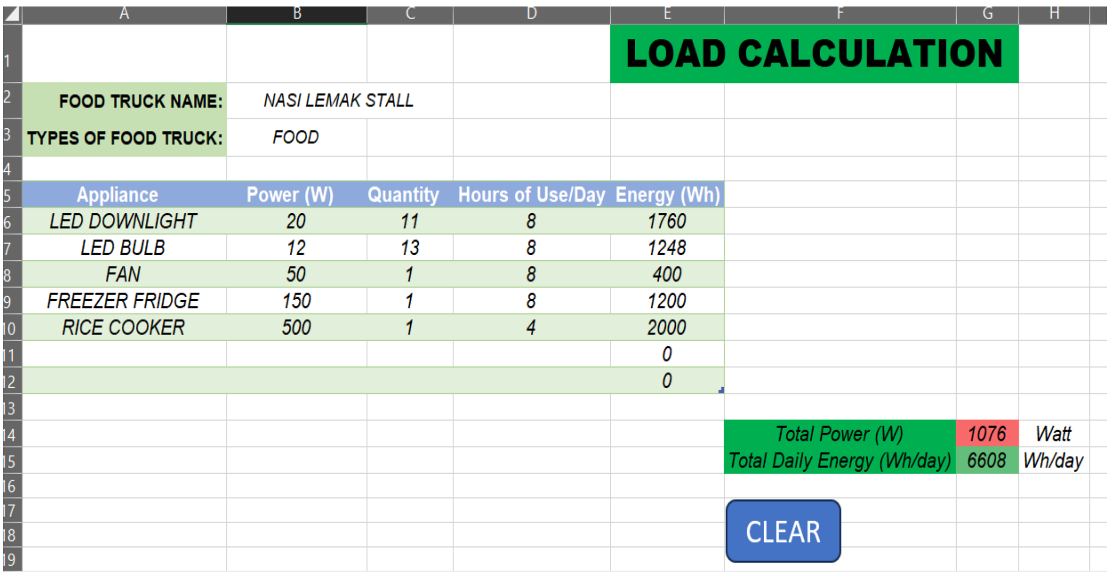

Fig. 7 *Load calculation using Excel based tool*

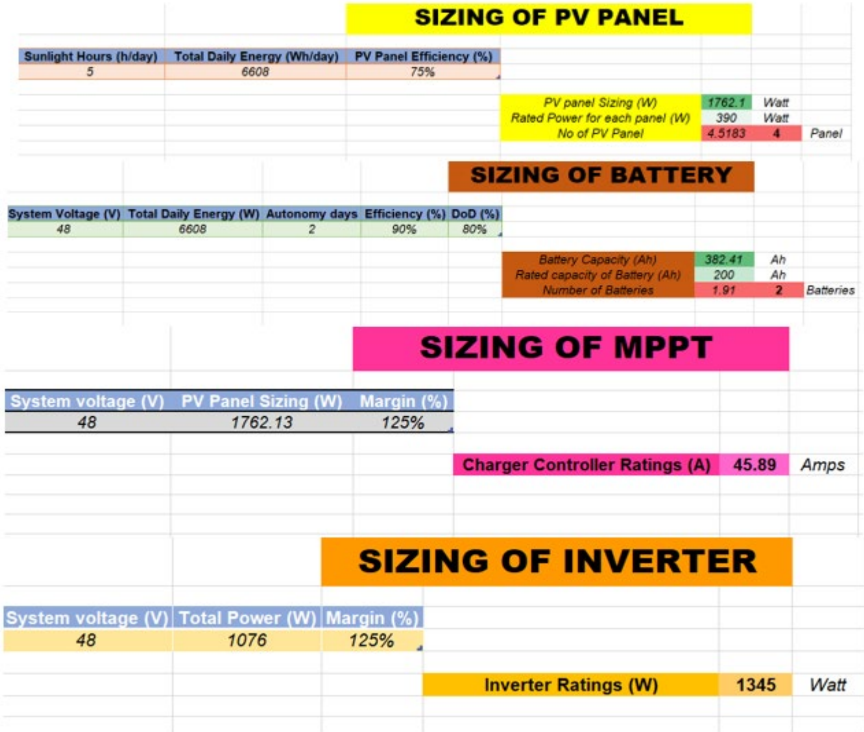

Fig. 8 *Sizing of PV panel, battery, MPPT and inverter for nasi lemak stall using Excel based tool*

Based on the Excel tool calculation, the recommended system size includes 4 PV panels, 2 batteries, and 1 MPPT charge controller rated above 46 amps. These results were confirmed by the PVsyst simulation, which produced the same values for component sizing and load demand, as displayed in Fig. 9 and Fig. 10. This consistency validates that the formulas and sizing methods used in the Excel tool are accurate and reliable, ensuring that the proposed OGPV system design meets the energy requirements of the food truck effectively.

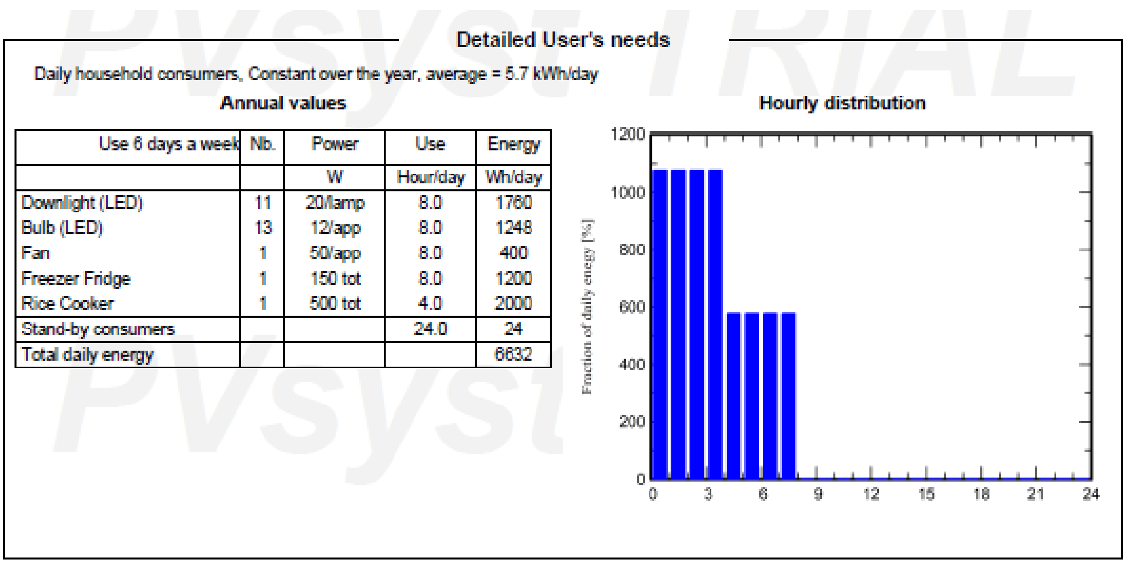

Fig. 9 *Load analysis of nasi lemak stall from PVsyst*

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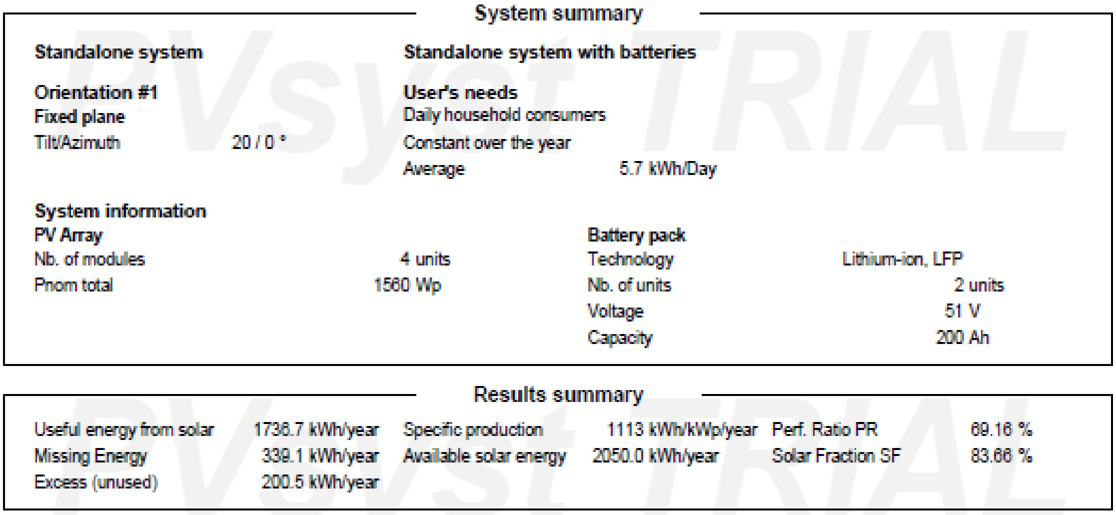
System summary

Standalone system

Orientation #1
Fixed plane
Tilt/Azimuth 20 / 0 °

Standalone system with batteries

User's needs
Daily household consumers
Constant over the year
Average 5.7 kWh/Day

System information

PV Array
Nb. of modules 4 units
Pnom total 1560 Wp

Battery pack
Technology Lithium-ion, LFP
Nb. of units 2 units
Voltage 51 V
Capacity 200 Ah

Results summary

Useful energy from solar	1736.7 kWh/year	Specific production	1113 kWh/kWp/year	Perf. Ratio PR	69.16 %
Missing Energy	339.1 kWh/year	Available solar energy	2050.0 kWh/year	Solar Fraction SF	83.66 %
Excess (unused)	200.5 kWh/year				

Fig. 10 *System and result summary of nasi lemak stall from PVsyst*

Table 3 shows the comparison of the Excel-based tool with PVsyst simulation for the Nasi Lemak Stall Food Truck. The very close match presented shows that the Excel-based tool accurately and reliably will calculate loads and size the system needed. The errors being small and the same size components demonstrate that this tool is useful for quick and reliable preliminary designs, especially for small mobile energy systems such as food trucks.

Table 3 *Comparison for nasi lemak stall food truck*

	Excel based Tool	PVsyst	%Error
Total Load Demands	6608 W	6632 W	0.63%
Number of Solar Panel	4 panel	4 panel	0.00%
Number of Batteries	2 unit	2 unit	0.00%
Number of MPPT	1 unit	1 unit	0.00%

3.2 Rain and Light Intensity for Environmental Conditions

Based on Table 4, we see how SEMS utilizes light and rain sensor data to turn on and off lighting. When conditions are bright and dry (light < 60, rain < 100) lights are off. When it is dark at night (light > 60, rain < 100) lights turn on. When it is raining (light < 60, rain > 100), lights remain off unless it is dark, then lights turn on. Lastly, when it is dark and raining (light > 60, rain > 100) lights turn on. The utilization of this setup will allow SEMS to save energy and still provide visibility for their users.

Table 4 *Range of light and rain sensor values for different environments*

Environment	Light Intensity (0-100)	Rain Sensor Value (0-200)	Condition of Light
Day	0 - 60	0	OFF
Night	> 60	0	ON
Rain + Day	0 - 60	> 100	OFF
Rain + Night	> 60	> 100	ON

3.3 Voltage, Current, and Power Monitoring

The 4-hours interval monitoring period is presented in Table 5. During the day, voltage and power stayed near zero as loads were off. At night, voltage indicates 4.50V, current to 0.21A, and power to 0.95W. These results prove that the SEMS worked as planned by turning on loads only when needed, based on environmental conditions, and operating efficiently with low power usage when idle.

Table 5 *Voltage, current, and power measured throughout 4-hours interval*

Time Period	Voltage (V)	Current (A)	Power (W)
6:00 AM	0.00	0.00	0.00
10:00 AM	0.00	0.00	0.00
2:00 PM	0.00	0.00	0.00
6:00 PM	0.00	0.05	0.00
10:00 PM	4.50	0.21	0.95
2:00 AM	4.20	0.18	0.76

3.4 Environmental Sensor Output

Based on Table 6, it summarizes the SEMS environmental sensor readings for light and rain intensity over a 24-hour period. Morning light intensity was 35, dropping to 15 in the afternoon, rising to 45 in the evening, and peaking at 100 at night due to darkness. Rain sensor values stayed at 0 in the morning and night, showing dry conditions, but increased to 100 during simulated rain in the afternoon and evening. These results confirm that both sensors accurately detect environmental changes, enabling the SEMS to control lighting effectively for visibility and safety.

Table 6 *Light and rain intensity across daily conditions*

Time Period	Light Intensity	Rain Intensity
6:00 AM	35	0
10:00 AM	10	0
2:00 PM	15	100
6:00 PM	45	100
10:00 PM	100	0
2:00 AM	90	0

3.5 Prototype Solar Performance Data

In Table 7, measurements of the 24-hour solar performance, open-circuit voltage (Voc), short-circuit current (Isc), and input voltage (Vin) are presented. The Voc ranged from a dawn measurement of 6.00 V; arriving at 16.50 V at peak; dropped to 4.90 V in evening, and got to 0.20 V at night. The maximum peak for Isc ranged from 0.31 A in the dawn to 0.55 A at peak sunlight; with a reading of 0 A at night. The classification of the input (Vin): starts from a test in the morning of 8.00 V; goes to 12.20 V in the afternoon; then down to 6.00 V in the early evening, and 0.40 V at night.

Table 7 *Solar panel characteristics throughout the day*

Time Period	Voc (V)	Isc (A)	Vin (V)
6:00 AM	6.00	0.31	8.20
10:00 AM	15.80	0.48	11.40
2:00 PM	16.50	0.55	12.20
6:00 PM	4.90	0.20	6.30
10:00 PM	0.20	0.00	0.50
2:00 AM	0.10	0.00	0.40

All these results confirm that the solar panel is operational, with performance consistent with expected sunlight cut checks, and accomplishes sufficient energy needs for the OGPV system. Fig. 11 shows the solar data collection for day and night conditions.

Fig. 11 *Data collection for V_{in} and V_{oc} during morning and night conditions*

4. Conclusion

In conclusion, the project met its objectives in successfully developing both an Excel-sized tool, and Smart Energy Management System (SEMS) prototype for food trucks. The Excel tool estimated the needed PV panels, batteries, and controllers from actual load data from real food trucks; validation against PVsyst achieved similar but not identical results, validating the tool. The SEMS prototype was developed and tested, and with its sensors accepted lighting based on the conditions present in real time and was also able to record voltage, current and power readings, and output to an LCD and Arduino Cloud. Overall, the SEMS performed with the OGPV system well, with energy management capabilities offering consistent, reliable, low maintenance, and energy efficient option for mobile food truck operations.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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