A Solar Powered Tent for Comfortable Outdoor Living, Emergency and Flexible Activities

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Abstract – Solar PV systems have become increasingly popular as viable power sources for utilities, commercial and residential areas, thanks to its decreasing cost and configuration flexibility. These factors also make the solar PV technology promising for variety of other stand-alone and mobile applications. However, these potential applications require research and development to be realized. This study develops one of such solar-PV-based applications via designing a solar powered tent with essential appliances that can be used for diverse purposes. Some of the purposes are sheltering military personnel during training, serving emergency workers during their missions, sheltering homeless people, as well as for camping and other outdoor activities. The tent is designed to minimize power usage while providing functions decidedly crucial to the well-being of users. A novel method of assigning power to loads on the basis of night and day needs is created to satisfy user needs while preserving the equipment life span. The tent is safe where its electrical system is DC with low voltage ratings (24V or less). The study also provides comprehensive understanding of this mobile application to facilitate its adoption by users and support their ability to reproduce the tent by themselves. For this goal, detailed tent design, sizing of solar PV panel and battery, other relevant component specifications, and control system coding are provided. Testing has shown that the tent functions properly and provides user comfort. Via the tent design, this study provides a model for developing similar solar-based systems or applications for general public. Wide public usage promotes solar PV adoption, which helps lower carbon emissions and protect the environments.

Keywords – Battery, camping, emergency usage, homeless, microcontroller, outdoor living, stand-alone power source, solar PV, solar tent, shelter.

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1. Introduction

Photovoltaic (PV) energy which may be harnessed by solar panels has been used in various applications in emerging and established areas, including but not limited to, utility power supply, residential power supply, contingency electrical power generation, municipal energy systems, transportation, healthcare, agriculture, and so on [1], [2], [3]. Various other examples indicate that the prevalence of solar energy is highly affected by a strong trend towards renewable energy usage aiming to reduce carbon emissions. While the perception that solar energy can be an approachable solution for numerous applications is certainly promising and hopeful, there are nonetheless realistic barriers to implementation that forbid or discourage many consumer products or popular processes from going full solar. There may be logistical concerns where factors like the price of a full-scale installation may be too expensive to commit to a partial or complete transition to solar means for many industries. Furthermore, a more realistic estimate of the actual energy generated by a small system may be disappointing or insufficient such that unless a series connection of modules is maximized by way of large panel arrays that entail much heft, space, and storage, there is little incentive to convert energy schemes [4]. As a result, contrary to popular perception, only a select number of products or industries can occupy the niche required to use solar energy without logistical challenges.

In other words, the solar PV technology could be applicable in variety of applications. However, these potential applications require research and development to be realized. This is a major motivation of this study where one of such solar-based applications is investigated via designing a solar powered tent with essential appliances that can be used for diverse purposes.

Another motivation for developing the solar powered tent involves the recognition of the conventional tent being a relatively low-consumption object where low-cost and low-power appliances may be powered by solar powered energy to fulfill the needs of users who require necessary, but not overly luxurious accommodations such as warmth, cooling, illumination, or sanitation.

In present situations, a need for modest amounts of energy in remote locations often require excessively high-capacity electrical generators powered by fossil fuels like diesel that release toxic byproducts such as carbon monoxide which is known to be a deadly gas. Apart from being dangerous to humans, these current offerings also significantly impact the environment in a negative way by exposing surrounding animals and plants to these byproducts [5]. Furthermore, since an electrical generator is fairly expensive and the prospect of purchase is inconducive to the need to supply only small, modest amounts of energy, many users may be torn between choosing to invest in a pricey diesel generator to fulfill minor needs or simply forgoing reliable electricity. As a result of these concerns, we anticipate that a variation of the traditional tent that provides valuable functions with little additional cost will be appreciated.

The tent can serve diverse purposes, such as sheltering military personnel during training, serving emergency workers during their missions, sheltering homeless people and people affected by natural disasters, as well as for camping and other outdoor activities. The tent can be very useful, considering homeless situation in the U.S. alone. In 2022 [6] over half a million people experienced homelessness where 30% of the homeless people were living in California. The solar powered tent can provide these unfortunate people with a temporary shelter that is far more comfortable than what is offered by most regular tents currently existing on the market.

Embedded in the consideration of designing the solar powered tent was the research team's agreement that it should be user-friendly. By configuring the system to work and provide benefits for the general public, we sought to create a closed-box system that would be convenient enough for general purposes all while preserving a backdoor option to allow those with electrical expertise to access and troubleshoot more technical aspects of the system in the rare event of system malfunction. Our insistence on a closed-box approach that would prevent unwanted changes in functionality and longevity was driven by a desire to extend usage of the product to the homeless community who may hope to benefit from the tent without much worry or thought to reliable operation.

While one may suppose that a backpack or entire mobile charging station could theoretically provide users with power, we sought a balance in terms of necessity. For example, a recent project has shown that solar powered backpacks are mostly effective for smaller portable electronics in the milliwatt range, whereas a stationary charging station for a local school could provide up to a thousand watts per hour [7], [8]. In contrast, a solar powered tent would service power needs in the middle range while providing an area of rest and shelter.

The following sections present details of the solar powered tent design, along with its component specifications and testing results showing its satisfactory performance.

The usefulness of this study in practical applicability is that, via the tent design, it provides a model for developing similar solar-based systems or applications for general public. Wide public usage promotes solar PV adoption, which helps lower carbon emissions and protect the environments.

2. Solar powered tent design

We deemed that a viable power capacity required to fulfill the tent purposes would be in tens of watts range. It should not require generation anywhere near the consumption of household AC appliances (hundreds of watts). The decision to limit the total energy consumption was in the interest of potential consumers. Since a project goal is to develop a low-cost product that would appeal to the general public, great emphasis was placed on optimizing all facets of the design to reduce costs of materials and assembly that would pass on to the consumer.

Our priority of minimizing costs sought to make the product financially attractive to potential users or organizations interested in helping the homeless people. Since total cost was dependent on per unit cost of tent appliances, rather than a direct correlation with wattage, we had some flexibility in choosing which items to include based on affordability and functions. This selection of specific appliances and their total wattage, however, would make a significant impact on the size of solar panel we would need for the entire system. Solar panels, while environmentally friendly, are not extremely energy efficient for their price. Fortunately, since a proportional decrease in appliances results in less energy usage, we were able to make a price-optimized determination of panel power specifications upon a consensus of amenities to include with the tent.

Overall, the design composes of a two-person tent powered by a 20-W solar panel with an energy storage component of a 12-volt lithium-ion battery configuration for night-time usage when the sun is absent. A hybrid configuration of relay and manual switches which interface the solar panel with a charge controller and loads (appliances) is managed by an ESP-32 microcontroller with an option for manual control by the user. The loads provide various functions deemed helpful to the user such as illumination, temperature control, and communication.

2.1 Tent selection

Market studies conducted by the authors have shown that it is common for consumers to camp either alone or with a partner with the majority of people opting for a 1-to-2-person tent [9]. Similar studies also indicate that people prefer tents that can provide resistance to weather in the event of precipitation or windy conditions [9]. Furthermore, from the perspective of the homeless situation, it may prove beneficial to have more space than usual to store personal belongings within a person arm’s reach. As a result, we determined that the waterproof and sturdy FORCEATT tent which could accommodate two people seemed like an economical choice. The dimensions of the tent, being at 7.3 x 4.11 x 3.10 ft, seemed to provide ample floor space for not only a homeless person or a typical camper, but also for the appliances. Furthermore, when folded up, the dimensions collapsed to 16.5 x 5.9 in. This compact size, along with a total weight of 5.4 lbs., is very conducive to the prospect of relocation or transportation if necessary. The tent, being made of 210T Polyester with PU5000 coding for flooring of the tent, is suitable for all four seasons and ideal for our weatherproof intentions [10].

2.2 Description of tent appliances

2.2.1 LED lighting

We anticipated that providing interior illumination would be greatly appreciated by users of the tent. As such, the system includes RGB LED lighting which uses low-power diodes to provide needed visibility after dark. We believe that this serves as a useful feature for the average camper and especially potential homeless users who may be more nocturnal than usual. We felt that a reliable and sensible choice was the KOPMHYE LED strip. The full length of the LED strip, being at 10 ft, would provide complete illumination within the tent. Also, with a weight of only 5.9 ounces and a translucent insulation that renders it IP65 waterproof, it seemed like a useful asset [11].

2.2.2 DC fan

We felt that it was prudent to provide a means of cooling to the user in the event that high temperatures inside the tent could bring discomfort to the user. The DC fan unit thus serves as a temperature control system for the user that may be powered directly by the solar panels during the day and the battery at night. The fan's size, being 10 x 12 x 7 in., is small enough to not occupy much floor space [12].

2.2.3 DC radio

A rechargeable and hand-carried radio may function as a source of both communication and entertainment. This may prove useful for campers without cellular data in the wilderness as well as homeless users who may not have a cell phone to make calls or receive information. Like the DC fan, the radio of size 4.7 x 1.2 x 2.75 in. is quite compact [13][14].

2.2.4 USB outlets

We chose to include USB outlets with the tent to provide users the option of charging any external devices they might need. This also seemed to be very beneficial for the potential homeless user, as those with the tent would no longer have to rely on public places to power their personal cell phones and other devices. The regular 5-V Dual USB 2.1A socket mount charger can charge up to two devices at once, highlighting it as a good accessory to the system.

2.2.5 UV water sanitizer

Since our design was potentially catered to the homeless people, we believed that it would be valuable to provide a way for them to sanitize water from otherwise suspect sources. Without a means to quickly boil water, most homeless people are prone to illness from drinking suspect water contaminated with pathogens. As a result, providing a small UV sanitizer (1.5x1x4.9 in.) to quickly disinfect water seemed like a worthwhile addition [15].

2.2.6 ESP-32 microcontroller

This component, which draws relatively miniscule current and subsequent power, performs significant functions crucial to operation of the tent system and its description will be discussed in a later section. Its 5-V input indicates that it may draw power directly from the charge controller's special port.

2.2.7 LCD screen

We provided an LCD screen to serve as a convenient user interface to display the date, as well as the time in military format based on the RTC clock. Furthermore, the LCD screen displays the percent state of charge (SoC) to indicate to the user of the battery available energy.

Table 1 shows the power consumption of each device during both expected day and night operation as the number of hours allocated for active use varies [16], [17], [18], [19]. Notably, the ESP-32 microcontroller and LCD are the only components that requires 24/7 power consumption to control and monitor the usage of the other loads.

2.3 Solar panel sizing

The solar panel provides energy to the appliances during the day and use any residual

Table 1 Power and energy of appliances

Appliance	Volts [V]	Amps [A]	Power [W]	Day Hours [h]	Day Energy [Wh]	Night Hours [h]	Night Energy [Wh]	Night Amp-Hours [Ah]
LED Lights	5	1	5	0	0	4	20	4
Radio	5	0.5	2.5	0.75	1.875	0.75	1.875	0.375
DC Fan	12	0.5	6	2	12	2	12	1
USB Outlets	5	0.5	2.5	2	5	2	5	1
UV Sanitizer	6	0.857	7	0.5	5	0	0	0
ESP-32 & LCD	5	0.21	1.05	12	12.6	12	12.6	2.52
Total		**2.877**	**19.05**		**34.98**		**51.48**	**8.89**

energy to charge the battery. Therefore, the total energy the solar panel must produce in a 24-hour day is the sum of the total Day Energy and Night Energy in Table 1, which is 86.46 Wh. Other critical factors, such as the average sun hours in California as well as the panel's performance ratio, are included to reach a more accurate calculation of the solar panel's proper size in Watts. The average sun hours in California are 5.38 hours [20]. The performance ratio (PR) measures the effective energy output of a solar panel relative to its nominal output (nameplate rating). A new solar panel's PR ranges from 0.9 to 0.6 [21]. The average PR

$$\eta = \frac{0.9+0.6}{2} = 0.75$$

is used in the solar panel calculation. The solar panel size determined by Equation 1:

$$S_P = \frac{E_T}{\eta \ x \ H_P} \quad (1)$$

where S_P is nominal panel size, η is the previously obtained performance ratio coefficient, E_T is the total energy usage for the entire 24-hour day, and H_P is average peak sun hours in California. The solar system based in California is calculated as

$$S_p = \frac{86.46 \, Wh}{0.75 \ x \ 5.38h} = 21.4 \, W$$

The online calculator PVWatts (provided by U.S. National Renewable Energy Laboratory) was used to verify if a 20-W solar panel could meet the energy demands of the appliances for each day throughout the year [22]. Under the Appendix section, the calculation goes into more detail and verifies that a 20-W panel is indeed suitable for the system. Therefore, a 20-W solar panel was selected.

2.4 Battery sizing

Conventional electrical processes typically use a lead-acid battery to store energy. However, as the project sought to emphasize an environmentally conscious approach, we instead opted for lithium-ion. Unlike lead-acid, Lithium Ion contains relatively safer chemicals that will not seep into the environment. Furthermore, Lithium batteries are typically lighter by a factor of 30 percent and allow for stable voltage throughout battery-life compared to lead-acid batteries.

To determine the size of the battery with the desire to have its nominal output voltage of 12V to be compatible with standard charge controller and solar panel voltages, several variables were taken into consideration. This includes the operating range of the battery capacity, the average losses when charging and discharging Lithium-ion type, and also the total amp-hours of the appliances at night. The operating range of the battery depends on the depth of discharge (DoD), as the battery will be charged up to 100% during the day. At 75% DoD there is a linear relationship between percent full capacity and number of cycles of charging/discharging [23]. This allows for an extended life of a Lithium-Ion battery to reach over 2000 cycles, making the battery life extend to a similar, if not longer, lifetime of the average tent life of 5 years [24]. The efficiency for charging and discharging the lithium-ion is between 90% - 80% [25]. Therefore, the average efficiency

$$\eta_c = \frac{0.9 + 0.8}{2} = 0.85$$

was used in the calculation of the battery capacity.

The capacity of the battery is estimated by

$$S_B = \frac{E_N}{\eta_C \ x \ D_R} \quad (2)$$

where S_B is the nominal capacity of the battery in Wh, E_N is the total energy in Wh used by appliances at night only, D_R is a constant representing the depth range of the charging and discharging cycle, and the previously derived η_C is a constant representing the average round trip efficiency of charging and discharging a lithium-ion. The battery capacity was calculated as

$$S_B = \frac{51.48 \, Wh}{0.85 \ x \ 0.75} = 80.75 \, Wh$$

Further, to accommodate the total amp-hours of the appliances at night of 8.89 Ah, a battery of capacity 120 Wh (12V and 10Ah) was selected.

2.5 Charge controller considerations

It was necessary to ensure that the physical durability of the lithium-ion battery, and hence system lifetime, would not be compromised. The charge controller would ideally serve as a guard between the storage element and solar power output that could potentially damage the battery. Since the specifications of the charge controller should reflect that of the entire system, our device was suited for approximately 12-V 5-A operation. The functions that the charge controller should manage are as follows.

2.5.1 Panel voltage limitation

It should attempt to limit and regulate the voltage from the solar panel to avoid overcharging the battery [26]. However, a pre-existing design flaw embedded in the device was an obstacle since it did not seem to regulate overcharging of the battery for our particular system. In order to overcome this issue, we implemented an alternative bypass connection to instead draw power directly from the solar panel whenever the battery was fully charged.

2.5.2 Reverse polarity protection

It should prevent the solar panel from passing some current in the reverse direction [26].

2.5.3 Over-discharging protection

It should regulate the battery to prevent it from excessive discharge by automatically disconnecting it from the loads if battery voltage falls to a certain threshold [27].

Selection of the charge controller for our design narrowed down to two types: PWM (Pulse Width Modulation) and MPPT (Maximum Power Point Tracking). While a MPPT type would be more energy efficient, this configuration is better suited for large systems where high energy production is critical. Since our design focused instead on relatively low power needs and an emphasis on minimizing costs and low-maintenance longevity, we chose to implement the PWM type, which is conventionally used for smaller scale projects, has a better lifespan estimate due to less components, and is comparatively cheaper than the MPPT type.

2.6 Electrical compatibility conditions

Our selection of DC appliances for use within the tent all have a voltage specification of 5 V, with the only exception being the fan which runs on 12 V. We thus anticipate connecting the latter directly to the solar panel system. However, all other devices have to be integrated with a 12-to-5 V buck converter which step down the voltage for feasible operation. This arrangement, in turn, is followed by a relay that is controlled by the ESP-32 microcontroller, which manages appliance power flow via programmed logic.

3. Electrical system characteristics

The tent electrical circuit diagram is shown in Fig. 1. The system and hardware schematic diagram is shown in Fig. 2. We implemented the design that sought to maximize functionality, power, and safety for all appliances. The overall system was composed of the following items:

(1) ESP-32 Microcontroller
(2) Buck Converters
(2) USB Outlets
(1) DC Cigarette Charger
(1) 8-Channel Relay Switch
(1) 390kΩ Resistor
(1) 100kΩ Resistor
(1) 2.2kΩ Resistor
(3) Manual Switches
(1) DS3231 RTC Module
(1) 16x2 Character LCD
(1) 0.1uF Capacitor

As previously mentioned, since the charge controller could only power on when connected the battery and the controller could not regulate power to prevent the battery from over- charging, we had to create a bypass for the battery.

To determine whether the ESP-32 should bypass or not bypass the battery, it must refer to logic which entails measuring the SoC of the battery and knowing the time of day (ToD). To determine the time of day we implemented a DS3231 RTC module which was programmed to display the correct time and date onto the LCD. This was done by accessing an RTC library that provides a general-purpose date/time class to access the year, month, day, hour, minute, and second parameters. Therefore, we could then decipher whether the system was operating in day or night by hard coding the peak sun hours from 9 AM to 4 PM. Nighttime would then be designated as the hours from 4 PM to 9 AM.

The hardware used to determine the SoC consisted of a voltage divider and a capacitor to stabilize voltage readings which fed into the ADC of the ESP-32. A voltage divider was necessary to step the voltage down from the 12-V LiFePO4 battery voltage since the maximum voltage the ESP-32 ADC could handle was 3.3 V. Since the ESP-32 ADC was non-linear, a 4^{th} order polynomial was used to linearize the voltage readings to within 1% accuracy [28]. This level of precision was necessary as the LiFePO4 batteries have flat discharge curves and small changes in voltage will yield large changes in SoC [29]. The software process regarding how a voltage reading is translated into a SOC is discussed in more detail later under the State of Charge Testing section.

Once the ESP-32 is able to determine the time of day and the battery SoC, the ESP-32 controls the 8-channel relay switch to either have the appliances run on the battery, or to switch to the bypass to run on the solar panel instead.

Each device (appliance) can be connected and powered through a USB connection with a maximum of 5 volts. Therefore, we had two USB outlets, one having two USB connections, and the other with one USB and one USB-C connector. Each of these outlets takes voltage input of 12 V and outputs 5 V.

In Fig. 1 and Fig. 2, the bypass path starts from the solar panel that outputs a voltage of 24 V. Therefore, a buck converter was required to step the voltage down to 12 V for the USB outlets. When not bypassing, the path taken flows power to the 8-channel relay instead. The diagram also displays three manual switches that are only meant to be used for maintenance purposes only.

3.1 Microcontroller and State Machine Logic

As said, the tent electrical system (Fig. 1) utilizes an ESP32 microcontroller to both manage logic and power delivery to the individual load components. It also protects the battery life by preventing over-discharging. The ESP-32 is programmed to follow a logic command which determines whether connected devices consume power from either the solar panel or the battery, depending on inputs such as time of day and state of charge (SoC) of the battery.

Due to design constraints from the manufacturer with regards to power source switching, the ESP-32 microcontroller must draw power from the battery at all times and is unable to switch sources between either the battery or solar panel. The microcontroller pulls only 160-210mA. Hence, in comparison to the current which the battery can typically supply, it is a very small amount. It follows that the potential problem of the ESP-32 drawing too much power is not a concern.

The load appliances are controlled by the ESP-32 GPIO pins and relays and, after the voltages are reduced to their respective nominal input voltages, the ESP-32 supplies power to the relay board and then allow power to flow from the battery to the individual loads.

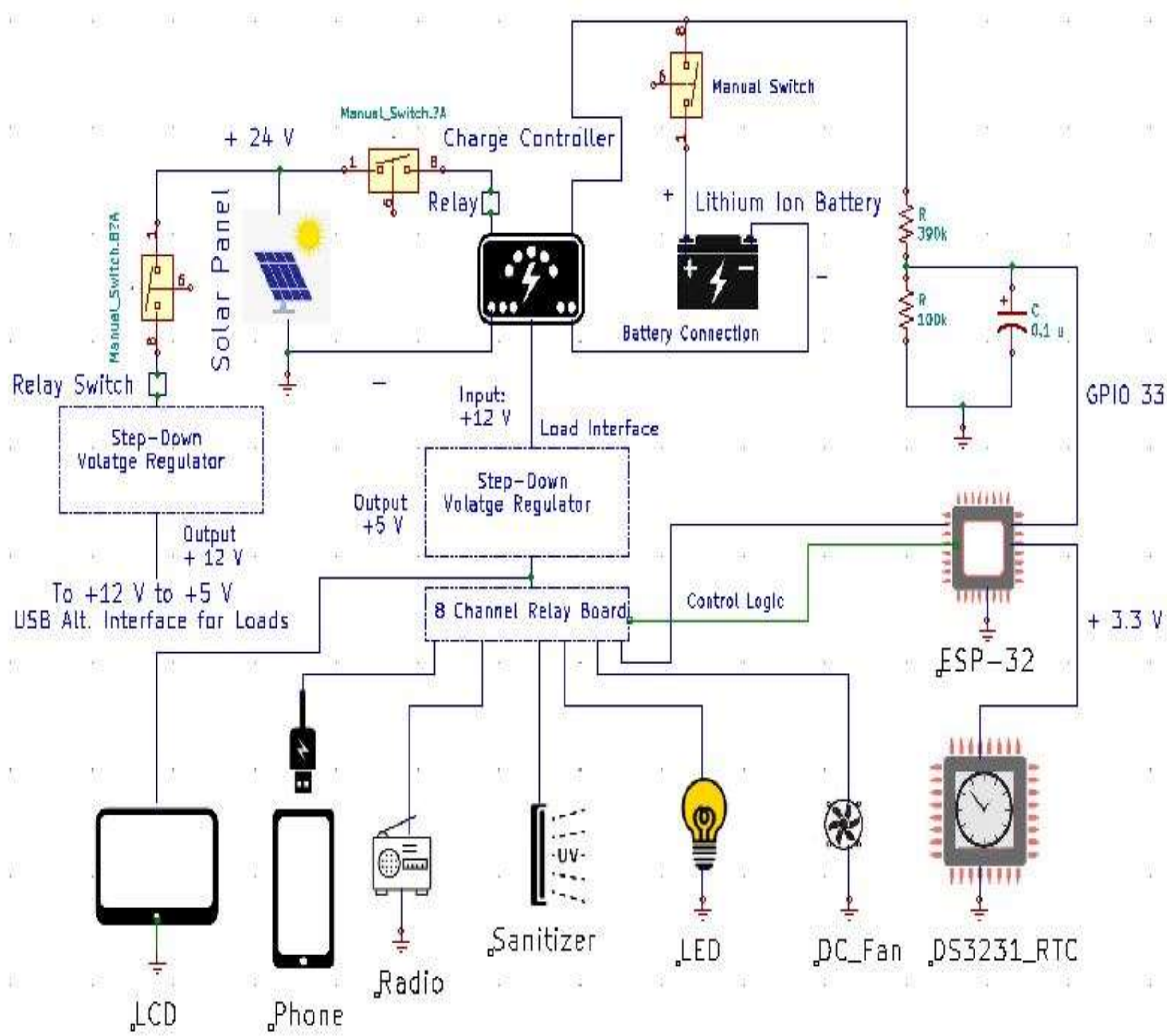

Fig. 1 Tent electrical circuit diagram

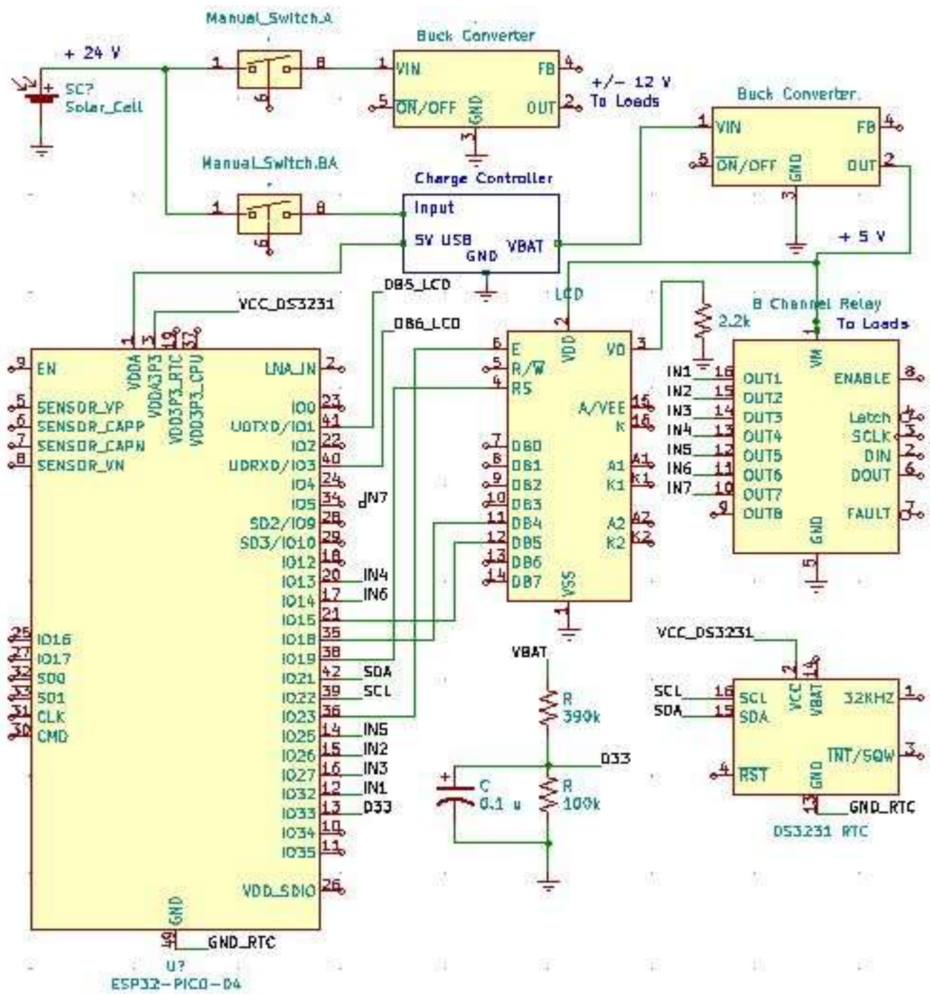

Fig. 2 System and hardware schematic diagram

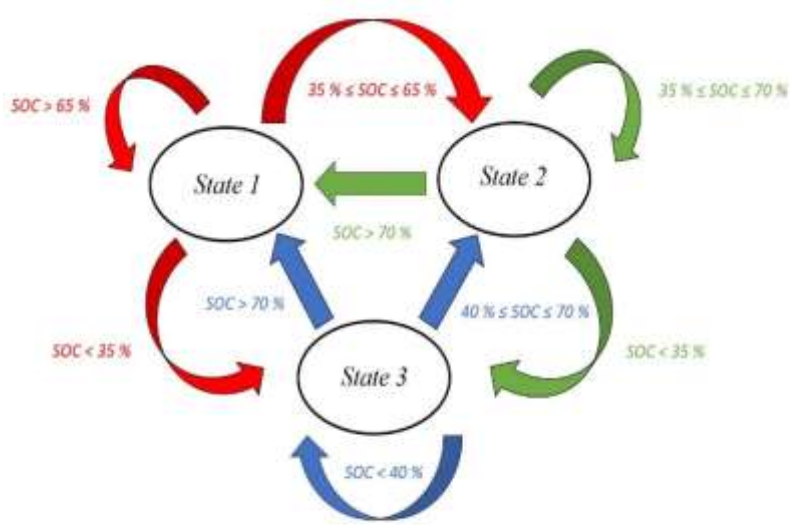

Fig. 3 State machine diagram

State machine operation

The state machine diagram of the ESP-32 microcontroller is shown in Fig. 3, and primarily revolves around constantly checking both the battery SoC and time of day. The ESP-32 verifies if the system is operating at a ToD (time of day) within peak sun hours and, if so, the solar panel then delivers power to the loads and charge the battery if extra power is available. However, once the system is observed to be operating outside of typical peak sun hours then the system instead switches to using the battery as the main source of power. Once the system switches to night-mode configuration operation, where power consumption is sourced from the battery, then the system follows one of three states, as follows.

State One: If the SoC is at 70% and above, then all appliances and the system are allowed to run at full power.

State Two: If the SoC is in between 70% and 30 %, then the DC fan is shut off since it consumes the most power.

State Three: If the SoC is below 30%, then all appliances are shut off to avoid total power depletion of the system.

The complete code for the state machine logic is provided in Appendix.

3.2 Voltage regulator

The charge controller (Figures 1 and 2) has an output of 12V and 10A. To ensure compatibility with the entire system, the 12-V output should be stepped down to 5 V. Furthermore, with regards to current, it was anticipated that in a full-load situation where the tent user desires to run all devices simultaneously, the system must also be prepared to supply a total of 2.87 A.

Therefore, the system requires a 12-V to 5-V, 3A converter. Initially, the team intended to use a simple voltage divider to reach the system specification. However, preliminary testing alerted us to the possibility that the voltage divider could get too hot for its enclosed environment (most electrical components are placed in a small junction box). This posed a danger as excessive heat could permanently damage other components of the system such as adjacent wires or logic flow if the microcontroller were to be adversely affected. As a result, we instead opted to implement a buck converter which would output 5V and a current maximum of 6A as a precautionary measure. Although only 3A would be required in full-load operation, the buck converter current rating of 6A was chosen such that we could operate it well below its maximum rated amperage. This helps prevents it, and the entire system, from heating up.

3.3 Relay board

A relay board is used for on-off switching of loads under the microcontroller control command so as to selectively provide power to the tent appliances. In essence, the relay board functions by taking dual inputs of ToD and SoC from the microcontroller and chooses whether the DC fan and USB devices are to source their power from either the solar panel or the battery. This is accomplished via switching of the plus (+) and minus (-) of a load port in common to either normally-open pin (designates battery as source) or normally-closed pin (designates solar panel as source) of the relay.

4. System testing and calibration

4.1 Preliminary hardware code test

Prior to full integration of the microcontroller code into the tent electrical system, the team performed preliminary testing of the intended code logic on a breadboard test circuit. As shown in Fig. 4, the test setup consisted of the microcontroller which would send logic commands to the relay switch for us to simulate and verify that the relay performed correctly by supplying power to the outlets. To avoid active draining of the battery to reach desired SoC levels for state machine states, a separate test code where we could manually input the ToD and SoC values was used instead. Furthermore, we used light-emitting diodes to uniquely determine which power state our system was currently in. In our arrangement, three LEDs were white to keep track of the state during the day while three other LEDs were red to designate their purpose as monitoring states at night. The three LEDs each for day and night status were used to visually represent the three levels of load power flow by hard coding the following hardware responses:

If System in State One, then 1 LED lights up.

If System in State Two, then 2 LEDs light up.

If System in State Three, then all 3 light up.

To verify the day logic, for instance, we specified the ToD to match a time within prime peak sun hours such that we could simulate the system as operating purely from the solar panel. As expected in this case, the test treated all inputs of battery SoC as logical “don’t care terms” and the relay responded appropriately by exhibiting the State One response or only one white LED being lit up.

On the other hand, it was imperative to verify that the system logic was able to distinguish and jump between states correctly for nighttime operation. Therefore, after inputting the ToD as a value in the prior designated nighttime span (8 PM), we proceeded to conduct tests to ensure that the State Machine Diagram of Fig. 3 was being correctly followed. For example, to mimic conditions when the system should be in State One, we inputted a SoC value of 90. With this value being greater than or equal to 70, the relay correctly allowed for full use of all outlets and loads and indicated that the system was indeed in State One by lighting up only 1 red LED. To verify that the system could also simulate and jump to State Two, we changed the SoC parameter to a value of 50. With this parameter now being between 30 and 70, we verified that the fan outlet no longer worked while all other USB outlets were still actively powered. We received visual

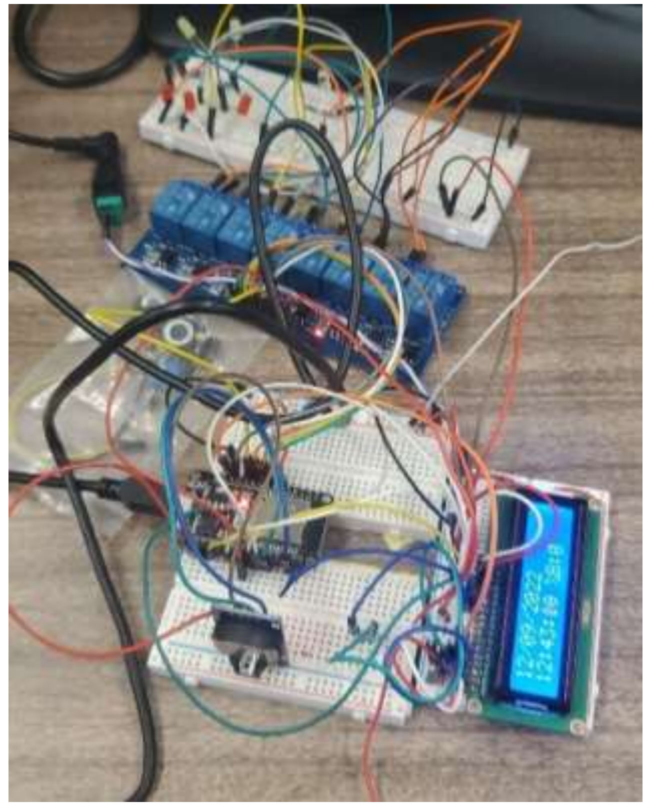

Fig. 4 Breadboard circuit for testing microcontroller code and logic

confirmation of the system being in State 2 when two red diodes lit up as expected. Finally, to verify that the system could reach State Three, we changed the SoC field to a value of 10. As this field was now below 30, we observed that none of the outlets were actively powered which seemed to validate that the hardware logic was properly responding to a situation of low battery. Furthermore, visual feedback of the system then being in State Three was received by observing that all three red diodes were lit up.

4.2 State of charge sensing

The SoC of the battery was approximated by using the voltage method, where the ESP-32 takes a voltage measurement of the battery and maps the value to a SoC. Since LiFePO4 batteries have a flat discharge curve, as shown in Fig. 5, and because the battery will be exposed to C-rates from 0-1, the discharge curves for 0.5C and 1C from approximately 95% to 15% SoC were placed on a grid for better estimations [29]. An equation of the line was derived for each curve that provided data for voltage and corresponding SoC. Since the 0.5C and 1C curve can be approximated by the same equation, just shifted down/up, then a correction factor was found that depends on the C rate (C) to shift the respective linear equation up or down as C-rates will not be exactly 0.5C and 1C. For the unique case when the battery is at rest (no appliances are used), Table 2, which relates specific voltages to SoC was used to formulate a series of linear equations to find specific values of SOC across small and precise ranges of voltages [30].

Additionally, to ensure that our system would be capable of charging the battery, we conducted a test. On a particularly sunny day, we brought our system outside where we observed the lithium-ion battery's state of charge after 5-minute intervals. The recorded SoC over time data is detailed in Table 3.

5. Implementation of tent system and evaluation

The orientation of the solar panel is quite important when it comes to optimizing solar energy gain. At the time of the experiment, winter was approaching, and the sun was much lower in the sky. Therefore, to maximize solar energy, we required a greater tilt angle than usual [28].

The location of our experiment had a year-round tilt angle of 28.8° [31]. However, to adjust it to the season, we calculated an optimal array tilt angle of

$$Array\ Tilt\ Angle = 28.8° + 15° = 43.8°$$

and rounded it up to 45° as shown in Fig. 6.

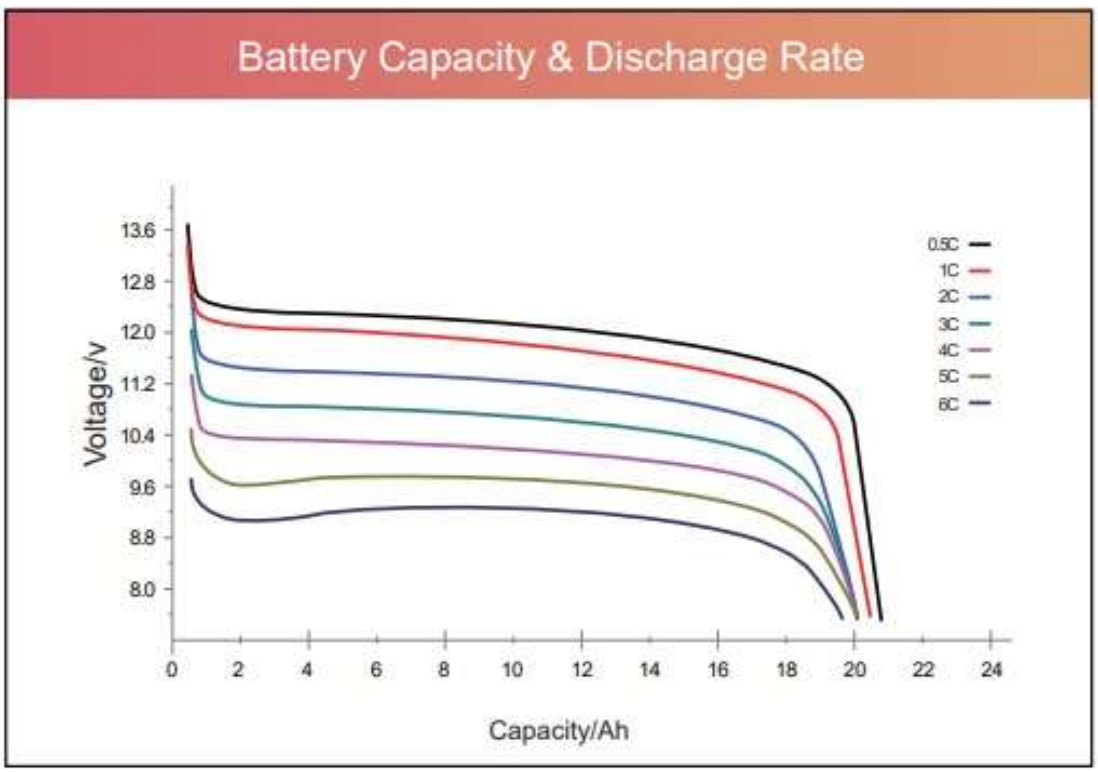

Fig. 5 Capacity and discharge rate of Eco-Worthy LiFePO4 battery

Table 2 Voltage to SOC conversion

$C-rate\ (C)$	$SOC\ (\%)$
$> 0.5\ and \le 1$	$100 + \frac{Voltage - [12.413 + 0.695(1-C)]}{0.01174}$
$> 0\ and \le 0.5$	$100 + \frac{Voltage - [12.7 + 0.695(0.5-C)]}{0.0113}$

$C-rate\ (C)$	$Voltage\ (V)$	$SOC\ (\%)$
0	$14.6 - 13.4$	100
0	$13.4 - 13.3$	$100 + \frac{Voltage - 13.31}{0.0111}$
0	$13.3 - 13.2$	$100 + \frac{Voltage - 13.35}{0.005}$
0	$13.2 - 13.1$	$100 + \frac{Voltage - 13.30}{0.00333}$
0	$13.1 - 12.9$	$100 + \frac{Voltage - 13.70}{0.01}$
0	$12.9 - 12.5$	$100 + \frac{Voltage - 18.23}{0.0667}$
0	< 12.5	$100 + \frac{Voltage - 27.86}{0.1785}$

Table 3 Battery state of charge data from testing

Tilt Angle	Time of Day	Time Interval, min	SOC, %
45 degrees	11:50	0	51
	11:55	5	51
	12:00	10	52
	12:05	15	55
	12:10	20	55
	12:15	25	56
	12:20	30	57
	12:25	35	57
	12:30	40	58
	12:35	45	58
	12:40	50	57
	12:45	55	58
	12:50	60	58
	12:55	65	58
	1:00	70	59
	1:05	75	60
	1:10	80	59
	1:15	85	60
	1:20	90	60
	1:25	95	60
	1:30	100	60
	1:35	105	60
	1:40	110	59
	1:45	115	59
	1:50	120	60

5.1 Tent layout and wiring arrangement

The consensus was that the appliances should be presented in a safe and tidy manner to the user. Since the thought of having unsightly and potentially dangerous bundles of wires as well as sensitive electronic components scattered throughout the tent seemed problematic, a junction box arrangement where everything could be kept electrically insulated and organized was implemented, as shown in Fig. 7.

The above arrangement makes it simple to transfer power from the solar panel to the appliances, since all necessary components such as the voltage regulator, relay board, and microcontroller are contained within the box. Furthermore, since the design of our tent anticipated a permanent connection of appliances to the relay, it was rarely in the interest of the user to have access to the wires during normal operation following initial soldering and connection. However, if maintenance was required, the junction box was also designed to be accessible to the user via screwdrivers. Since it was desired for users to place appliances wherever within the tent rather than having limited reach, fitting the appliances with longer wires which could be folded via zip ties was preferred.

5.2 Junction box

The junction box from the user's perspective consists of just the LCD display, a DC cigarette charger outlet, USB outlets and the three manual switches. The manual switches are located on the side above the LCD display and the appliance outlet ports are on the left side, as shown in Fig. 8. We keep all interface outlet ports on the same side to make it convenient for the user to locate them.

5.3 Appliance arrangement

The interior layout of the tent consists of appliances directly connected to the output channels of the relay board via the junction box interface. While the user certainly has free choice over where to place appliances according to personal preference, the recommendation of the team was to place all appliances relatively close to the junction box ideally such that the entire arrangement of appliances is on the same side of the tent as the box itself. This is a avoid having long wires (insulated) hanging around.

5.4 Wire gauge selection

Selection of the correct wire sizes for each device follows Table A1 in Appendix (the American Wire Gauge Chart), adhering to the International Electrotechnical Commission Code IP65 [32] [33]. This guideline detailed the insulation requirements for outdoor electrical wires for ensuring user safety.

5.5 Solar panel stand and tilt angle selection

Another design consideration entailed the positioning of the solar panel itself. While it was initially desired to physically attach the panel to the tent, the team ultimately decided that it would be better if the user could have the tent in the shade while the panel was actively generating the necessary energy in the sun. As a result, the team decided on having a solar panel stand separate from the tent.

With regards to calibrating the tilt angle to obtain best-possible sun light (solar irradiation), the solar panel can be easily adjusted to five angles: 0 degrees, 15 degrees, 30 degrees, 45 degrees, and 60 degrees. The stand has a screw on the left side which can be unscrewed to adjust the panel to the desired angle. Theoretically, the optimal angle varies based on the tent location of expected usage. If used during the Spring and Summer, the angle may not have to be adjusted from the location's optimal angle. However, if the tent is used in the Autumn and Winter, as was in our case, then it would be helpful to add an additional 15 degrees to the location's optimal angle. These small but impactful adjustments will help maximize the power generated by the solar panel.

Fig. 6 Side-view of solar panel stand with title angle selection (45° selected)

Fig. 7 Interior of junction box

Fig. 8 Junction box with LCD Display, DC Cigarette outlet, USB outlets and manual switches

Fig. 9 Two-person tent with solar panel connected to junction box

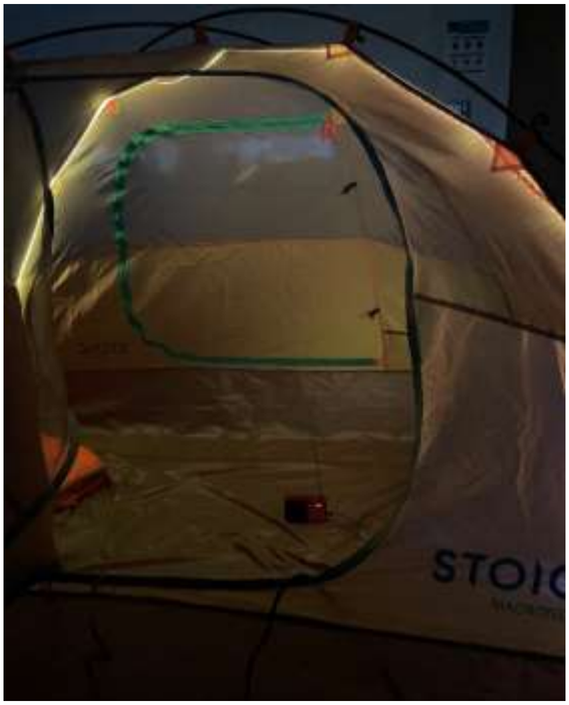

Fig. 10 Tent lit up by LED light strip

Fig. 11 Junction box with appliances
(Junction box size: 10" x 7.9" x 4.7")

5.6 Tent assembly and user guideline

The startup operation of the tent has been simplified for the user to avoid any complications. It is recommended to store the tent, appliances, and panel in the same travel bag for more effective organization.

To set up the tent the user should first start by sliding the fiberglass poles into the loops located along the outside of the tent to provide it structure to stand as in Fig. 9. The only appliance that is already attached to the tent is the LED strip, as shown in Fig. 10. Once the tent is set up, the user is instructed to place the junction box inside the tent to the side closest to the solar panel.

On the junction box there are three switches: the bypass, non-bypass, and the battery. Upon start-up of the system, both the bypass and non-bypass switches along with the battery switch should be ON in order for the entire solar tent system to be operational. The switches should not be flipped to the off-setting unless maintenance is required. Once the solar panel is connected to the junction box (plug-in) and the system is stable, the LED indicators on the USB ports will be lit to indicate that they are operational. The user then has the choice to connect any appliance they choose to the USB ports. Fig. 11 indicates an example set-up of appliances connected to the outlet ports.

5.7 Weather and electrical safety

For withstanding weather and ensuring electrical safety, except for interfacing devices (e.g. USB ports), all the electrical components needed to power the tent are enclosed in the junction box. From the user's perspective, the junction box only has the appliance outlets and the manual switches which eliminates user interface with any of the circuitry inside. Furthermore, to ensure maximum weather protection, we verified that the junction box follows the IP65 code which is mandatory according to the IEC by utilizing water-resistant sealant around all areas where there could be any possible water access [33]. The LED strip was chosen to IP65 waterproof.

It should be noted that the tent electrical system is DC with voltage ratings of 24V and below. All appliances are also DC. This system is much safer than AC systems.

5.8 Troubleshooting and lessons learned

Throughout the implementation of the solar tent, we faced several difficulties and challenges. One of the biggest challenges was ensuring that the system would be able to power all loads regardless of the charge controller. As mentioned previously, the manufacture's design of the solar charge controller is that the circuit will not be complete if the battery is not connected. Therefore, we implemented the circuit block seen in Fig. 1 where we were able to bypass the charge controller during certain situations. For example, during the day once the SoC reaches 100%, the switch between the solar panel and the charge controller will open and stop the panel from overcharging the battery. On the other hand, the connection from panel to loads will still be present.

Another issue we solved is what the team encountered when testing the microcontroller code. While the battery was charging via the solar panel, we observed that the LCD screen displayed random data whenever the state updated. We initially tried to remedy the issue by adding a delay in the code but the problem nonetheless persisted. Then, by soldering additional decoupling capacitors, the LCD could display correct data.

5.9 Final evaluation of completed system

Final evaluation of the tent completed system shows that it performs as expected. All the components including the LCD display and the outlets work properly. The tent is cozy where the user can listen to the radio while being cooled by the DC fan and the tent is lit by the LED strip at night (Figures 9, 10, 11). It should also be noted that the junction box containing the tent electrical system is small (longest dimension is 10 inches) so it does not take much space inside the tent.

6. Conclusion

In this study, a solar powered tent was designed for diverse users such as campers, homeless individuals, and emergency workers. A prototype of the tent was implemented and tested to evaluate its functionality and performance. The key design components are as follows: a 20-W 24-V solar panel, a 120-Wh Lithium-Ion battery, a charge controller, 5 outlets (3 USB-A, 1 USB-C, 1 Cigarette socket), a relay board, and appliances (DC fan, radio, UV water sanitizer, clock, LED lighting) for user comfort.

Based on the test results, the following conclusions were made:

1) The entire system correctly operates according to the electrical circuit design and control logic.
2) The microcontroller is able to switch the power source between the solar panel and charge controller, as well as switching the loads appropriately based on battery state of charge.
3) During the day, the solar panel supplies some power to the loads and charges the battery. Once the battery is fully charged it is disconnected, allowing the power from the panel to flow to the loads. During the night, the battery becomes the main power source for the loads.
4) The tent provides the user with a comfortable shelter. It offers coziness where the user can listen to the radio while being cooled by the DC fan. The tent is lit by the LED strip at night. The user can charge their devices, such as a phone, using the USB outlets. In addition, the user can use the UV sanitizer to clean unsanitary water (such as lake or pond water) for safe drinking. The LCD display shows a clock and the battery state of charge that keep the user informed of the energy available for use.
5) The tent electrical system is DC where the voltage ratings is 24V and below and all appliances are also DC. This system is much safer than AC systems.

Overall, the results satisfy the project goals to create a solar powered tent that is useful for diverse purposes, such as providing a cozy shelter for homeless people and emergency workers. Via the tent design, this study provides a model for developing similar solar-based systems or applications for general public. Wide public usage promotes solar PV adoption, which helps lower carbon emissions and protect the environments.

Appendix

Table A1 American wire-gauge parameters and sizes

AWG #	Diameter		Cross Section Area			Resistance in Ω		Current in Amps	
	Mm	Inch	mm2	inch2	Kcmil	Ω/ kft	Ω/ km	Chassis Wiring	Power Transfer
14	1.6277	0.0641	2.0809	0.0032	4.1067	2.525	8.285	32	5.9
15	1.4495	0.0571	1.6502	0.0026	3.2568	3.184	10.448	28	4.7
16	1.2908	0.0508	1.3087	0.002	2.5827	4.015	13.174	22	3.7
17	1.1495	0.0453	1.0378	0.0016	2.0482	5.063	16.612	19	2.9
18	1.0237	0.403	0.823	0.0013	1.6243	6.385	20.948	16	2.3
19	0.9116	0.0359	0.6527	0.001	1.2881	8.051	26.415	14	1.8
20	0.8118	0.032	0.5176	0.0008	1.0215	10.152	33.308	11	1.5

Table A2 Components and costs of tent prototype

Component	Cost
Tent	$80.00
Solar panel and Battery	$120.00
Solar panel stand	$40.00
Splitter wire	$8.00
Rechargeable batteries	$14.00
LED Lights	$14.00
DC Radio	$15.00
DC Fan	$24.00
UV Sanitizer	$60.00
USB Outlet (2)	$45.00
ESP-32 Microcontroller	$11.00
DS3231 RTC	$22.00
Junction Box	$23.00
Buck Converters (2)	$29.00
DC Cigarette Charger	$7.00
8-Channel Relay	$10.00
Manual Switch (3)	$10.00
16x2 Character LCD	$10.00
Water-resistant sealant	$10.00
Total	**$552.00**

A. Calculations

Solar panel size verification using PVWatts

When filling out the required information for PVWatts, the location is set to Pomona, CA and system information: a DC system size of 0.05 kW, tilt of 34 degrees, and default values for system losses (14.08 %), module type (standard), array type (fixed open rack), and azimuth (180 degrees). The average annual energy production for these parameters and location is 83.5 kW/y.

E_{year} = energy production of 50 W solar panel per year = 83500 W/y
E_{day} = energy production of 20 W solar panel per day

$$E_{day} = E_{year}\, x \left(\frac{2}{5}\right) x\ \frac{1\,y}{365\,days}$$
$$= 83500 \frac{W}{y}\, x \left(\frac{1y}{365\,days}\right) x \left(\frac{2}{5}\right)$$
$$E_{day} = 91.5\,W$$

Since the total energy demand for appliances in a 24-hour day is only 86.5 W and E_{day} exceeds this value, a 20-W solar panel is sufficient for the solar tent.

B. ESP-32 microcontroller code

```
#include <SPI.h>
#include <RTClib.h>
#include <Wire.h>
#include <LiquidCrystal.h>

RTC_DS3231 rtc;
LiquidCrystal lcd(19, 23, 18, 17, 16,
15);

int   state = 1;              //
Initial state: day time and battery is
FULLY charged.
int   prevState = 3;
int   timeState     = 0;
int   prevtimeState = 1;
float R1 = 390000.0f;
float R2 = 100000.0f;
float totalCurrent = 0.0f;
float maxCurrent = 4.8f;
float ESP32Current = 0.21f;
float voltage = 0.0f;
float sum = 0.0f;
int   SOC;
float Crating = 0.0f;

byte  RelayloadPin[3]  = {32, 26, 27};
// (+) Connection of Load1, Load2,
Load3
byte  GroundloadPin[2] = {13, 25};
// (-) Connection of Load1, {Load2,
Load3}
byte  PVtoSystemPin[2] = {14, 5};
// [0]: connects PV to C.C., [1]:
connects PV to loads
float loadCurrent[3]   = {0.6f, 2.1f,
2.1f};          //     Current of
Worst-Case Scenario

float ReadBatteryVoltage(byte pin);
// Function Prototypes
int   getSOC(float V, float
batteryCurrent);
void  printToLCD(const DateTime
currentTime, const int SOC);
void  resetLCD();

void setup(){
  Serial.begin(115200);
  lcd.begin(16, 2);

  if (! rtc.begin()) {
  Serial.println("Couldn't find RTC");
  while (1);
  }

  //rtc.adjust(DateTime(__DATE__,
__TIME__));       // When first
compile, uncomment. Otherwise, keep
commented.

  for(int i = 0; i < 3; i++){
    pinMode(RelayloadPin[i], OUTPUT);
// Set relays connected to (+) Load as
Output
    digitalWrite(RelayloadPin[i],
HIGH);            // Initially loads
connected to Solar Panel
  }

  for(int k = 0; k < 2;
k++){                       // Set
relays connected to (-) Load as Output
    pinMode(PVtoSystemPin[k], OUTPUT);
// Set relays connecting PV to C.C. and
loads
    pinMode(GroundloadPin[k], OUTPUT);
    digitalWrite(GroundloadPin[k],
HIGH);           // Initially loads
connected to Solar Panel
```

```
  }

  digitalWrite(PVtoSystemPin[0], HIGH);
// Initially PV disconnect from C.C. to
charge battery
  digitalWrite(PVtoSystemPin[1], LOW);
// Initially PV connected to loads
  pinMode(33, INPUT);
// Set ADC as input
} // void setup()

void loop(){

  resetLCD();
  DateTime now = rtc.now();
  printToLCD(now, SOC);

  switch(timeState)
  {
    case 0:   // Day time: Solar panel
is source (9 am to 4 pm)
      prevtimeState = timeState;
      timeState = (now.hour() >= 9 &&
now.hour() < 16) ? 0 : 1;
      break;
    case 1:   // Night time: Battery is
source (4pm to 9 am)
      prevtimeState = timeState;
      timeState = (now.hour() >= 16 ||
now.hour() < 9) ? 1 : 0;
      break;
    default: { // This will never
execute
      break;
    }
  } // case(timeState)

  switch(state)
  {
    case 1: {   // Turn ON all loads
      if(prevState !=
state){                              //
Update totalcurrent and new load states
        if(timeState == 1)
          totalCurrent = maxCurrent +
0.29f;             // All loads are ON
        else
          totalCurrent = 0.29f;
// ESP32/relays/LCD powered by battery
during day
        digitalWrite(PVtoSystemPin[1],
LOW);              // Connect PV to
loads

        for(int i = 0; i < 3; i++){
          if(timeState == 0)

digitalWrite(RelayloadPin[i], HIGH);
// Switch to +12V buck during day
          else

digitalWrite(RelayloadPin[i], LOW);
// Switch to +Bat during night
        }

        for(int i = 0; i < 2; i++){
          if(timeState == 0)

digitalWrite(GroundloadPin[i], HIGH);
// Switch to -12V buck during day
          else

digitalWrite(GroundloadPin[i], LOW);
// Switch to -Bat during night
        }
      }

      /* Update next state by voltage
translation */
      sum = 0;
      for(int i = 0; i < 256; i++)
        sum +=
ReadBatteryVoltage(33)*(1.0f+R1/R2);
      voltage = sum/256.0;
      SOC = getSOC(voltage,
totalCurrent);
      prevState = state;
      state = (SOC > 65) ? 1 : ((SOC >=
35 && SOC <= 65) ? 2 : 3);

      if(SOC == 100)
// Disconnect PV from C.C. if SOC is
fully charged
        digitalWrite(PVtoSystemPin[0],
HIGH);
      else if(SOC < 90)
// Connect PV to C.C. if battery needs
to be charged
        digitalWrite(PVtoSystemPin[0],
LOW);
      break;
    }
    case 2: {   // Turn OFF fan, turn
ON USBs
      if(prevState !=
state){
// Update totalcurrent and load states
        if(timeState == 1)
// totalCurrent during night
          totalCurrent =
maxCurrent+0.23f-(float)loadCurrent[0];
```

```
        else
// Only ESP32/relays/LCD powered by
battery during day
          totalCurrent = 0.23f;
        digitalWrite(PVtoSystemPin[1],
LOW);          // Connect PV to loads

        // Fan will recieve solar power
during day (ON) and night (OFF)
        digitalWrite(RelayloadPin[0],
HIGH);
        digitalWrite(GroundloadPin[0],
HIGH);

        for(int i = 1; i < 3; i++){
          if(timeState == 0)

digitalWrite(RelayloadPin[i], HIGH);
// Switch to +12V buck during day
          else

digitalWrite(RelayloadPin[i], LOW);
// Switch to +Bat during night
        }

        if(timeState == 0)

digitalWrite(GroundloadPin[1], HIGH);
// Switch to -12V buck during day
        else

digitalWrite(GroundloadPin[1], LOW);
// Switch to -Bat during night
      }

      /* Update next state by voltage
translation */
      sum = 0;
      for(int i = 0; i < 256; i++)
        sum +=
ReadBatteryVoltage(33)*(1.0f+R1/R2);
      voltage = sum/256.0;
      SOC = getSOC(voltage,
totalCurrent);
      prevState = state;
      state = (SOC > 70) ? 1 : ((SOC >=
35 && SOC <= 70) ? 2 : 3);
      break;
    }
    case 3: {   // Turn OFF all loads
      if(prevState !=
state){                       // Update
totalcurrent and load states

      totalCurrent = 0.085f;
// Only ESP32/relays/LCD  is powered by
battery
      digitalWrite(PVtoSystemPin[1],
HIGH);         // Disconnect PV from
loads

      for(int k = 0; k < 3; k++)
        digitalWrite(RelayloadPin[k],
HIGH);        // Switch to +12V buck

      for(int k = 0; k < 2; k++)
        digitalWrite(GroundloadPin[k],
HIGH);       // Switch to -12V buck
      }

      /* Update next state by voltage
translation */
      sum = 0;
      for(int i = 0; i < 256; i++)
        sum +=
ReadBatteryVoltage(33)*(1.0f+R1/R2);
      voltage = sum/256.0;
      SOC = getSOC(voltage,
totalCurrent);
      prevState = state;
      state = (SOC > 70) ? 1 : ((SOC >=
40 && SOC <= 70) ? 2 : 3);
      break;
    }
    default: {  // This will never be
executed
      break;
    }
  } // switch(state)

} // void loop()

float ReadBatteryVoltage(byte pin){
  float reading = analogRead(pin);
  if(reading < 1 || reading > 4095)
return 0;
  return (-0.000000000000016 *
pow(reading,4) + 0.000000000118171 *
pow(reading,3)
    - 0.000000301211691 *
pow(reading,2)+ 0.001109019271794 *
reading + 0.034143524634089);
}

int getSOC(float V, float batCurrent){
  int S = 0;
  float correctionFactor = 0.0f;
  Crating = batCurrent/10.0f;
  if(Crating >= 0)
  {
    correctionFactor = 2*0.695*(1.0f-
Crating);              // Shift the y-
intercept up if C > 0
```

```
    S = 100 + (V - (12.413 +
correctionFactor))/0.01174;
  }
  else
// Use look-up table when battery at
rest (C = 0)
  {
    if(V >= 14.595)
      S = 100;
    else if(V >= 13.35)
// SOC: 99 - 90
      S = 100 + (V - 13.31)/0.0111;
    else if(V >= 13.2)
// SOC: 90 - 70
      S = 100 + (V - 13.35)/0.005;
    else if(V >= 13.14)
// SOC: 70 - 40
      S = 100 + (V - 13.30)/0.00333;
    else if(V >= 12.95)
// SOC: 40 - 20
      S = 100 + (V - 13.70)/0.01;
    else if(V >= 12.65)
// SOC: 20 - 14
      S = 100 + (V - 18.23)/0.0667;
    else
      S = 100 + (V - 27.86)/0.1785;
  }
  if(S > 100)
    return 100;
  else if(S < 0)
    return 0;
  else
    return S;
}

void printToLCD(const DateTime
currentTime, const int SOC)
{
  if(currentTime.month() < 10)
    lcd.print("0");
  lcd.print(currentTime.month());
  lcd.print("/");
  if(currentTime.day() < 10)
    lcd.print("0");
  lcd.print(currentTime.day());
  lcd.print("/");
  lcd.print(currentTime.year());
  lcd.print("     ");
// Blank Space to remove junk char on
power-up reset

  lcd.setCursor(0,1);
  if(currentTime.hour() < 10)
    lcd.print("0");
  lcd.print(currentTime.hour());
  lcd.print(":");
  if(currentTime.minute() < 10)
    lcd.print("0");
  lcd.print(currentTime.minute());
  lcd.print(":");
  if(currentTime.second() < 10)
    lcd.print("0");
  lcd.print(currentTime.second());
  lcd.print(" %B:");

  if(SOC < 100)
{                      // Blank Space
to remove junk char on power-up reset
    lcd.setCursor(13,1);
    lcd.print("  ");
    lcd.setCursor(12,1);
  }
  else {
    lcd.setCursor(15,1);
    lcd.print(" ");
    lcd.setCursor(12,1);
  }
  lcd.print(SOC);
  lcd.home();
  delayMicroseconds(949928);         //
Set delay such that the instruction
time to execute entire loop program is
1 second.
}

void resetLCD(){
  lcd.home();
  lcd.print("                ");
  lcd.setCursor(0,1);
  lcd.print("                ");
  lcd.home();
  delay(50);
}
```

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