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Design, Integration and Experimental Performance Evaluation of a Hybrid Solar–Battery Power System for a 12 V DC Tyre-Inflation Compressor

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Abstract

A standalone hybrid solar–battery power system was designed, assembled and experimentally evaluated as an alternative electrical supply for a 12 V DC tyre-inflation compressor. The prototype comprised a nominal 120 W DC reciprocating compressor, a 175 W monocrystalline photovoltaic (PV) module, a 12 V, 40 Ah deep-cycle battery and a 20 A maximum-power-point-tracking charge controller. The performance of the system was investigated under battery-only and solar-assisted operating conditions using three tyre sizes: 225/70R16, 185/70R14 and 175/65R14. The reported mean inflation times under battery-only operation were 288.3, 261.7 and 251.7 s, respectively, compared with 350.0, 301.7 and 285.0 s under solar-assisted operation. The maximum pressures attained were 35 psi and 30 psi for battery-only and solar-assisted operation, respectively. Battery endurance tests recorded operating durations of 30 and 25 min, corresponding to five and four tyre-inflation operations. The measured electrical input powers were reported as 91.46 W and 75.05 W for battery-only and solar-assisted operation, respectively. Compressor temperature increased from 29.4 °C to 41.3 °C during 15 min of continuous operation. The results demonstrate the practical integration of a photovoltaic charging system, battery storage and a small DC compressor. However, differences in attainable pressure and unresolved electrical measurement conditions highlight the need for further experimental validation before comparative energy-performance claims can be established.

Keywords: photovoltaic system; battery storage; DC air compressor; tyre inflation; hybrid power supply; experimental performance

1. Introduction

Tyre inflation is a routine automotive service that depends on the availability of a suitable compressed-air source[1, 2]. Small compressors used in workshops and roadside service settings are commonly powered from the electricity grid, while fuel-driven units may be used where grid electricity is unavailable[3]. Grid interruptions and voltage fluctuations can interrupt service, whereas fuel-powered alternatives introduce

fuel, maintenance, noise and exhaust-emission burdens[4, 5]. The transition towards sustainable transportation and mobility systems increasingly emphasises the adoption of renewable energy and electric propulsion technologies as strategies for reducing greenhouse gas emissions and environmental pollution [6]. These considerations motivate the evaluation of renewable-energy supplies for small, intermittent mechanical loads. In this regard, energy audits have been recognised as important tools for evaluating energy consumption, identifying opportunities for improved energy efficiency and assessing the economic and environmental implications of energy use in industrial applications [7].

Photovoltaic (PV) systems convert incident solar radiation into electrical energy. In standalone configurations, a charge controller regulates energy transfer from the PV module to an electrochemical battery, allowing the stored energy to supply a load when solar irradiance is insufficient or unavailable. PV-powered pumping, lighting and refrigeration systems are well established, but a compressor presents a different load profile: motor start-up can impose a substantial transient current, and the compressor must deliver a useful pressure within a practical time [8-11]. The design and fabrication of air-powered mechanical systems also demonstrate the importance of compressed air as an energy carrier for producing useful mechanical work. Such systems rely on the controlled expansion of compressed air to generate mechanical output, highlighting the importance of pneumatic technology in engineering applications [12].

Unlike resistive electrical loads, DC compressors constitute motor-driven loads whose electrical demand can vary considerably during operation[13]. At start-up, the compressor motor may draw a current higher than its nominal operating current, resulting in temporary voltage reduction across the battery and associated electrical connections. Under photovoltaic operation, variations in solar irradiance can further influence the electrical power available for charging and load support. These conditions make the integration of photovoltaic modules, battery storage and DC compressors an important design consideration. In particular, the battery must provide sufficient current to accommodate motor start-up and continuous operation, while the charge controller must regulate battery charging without introducing undesirable voltage limitations during compressor operation. Energy efficiency in compressor-driven systems has received considerable research attention, particularly regarding the optimisation of electrical consumption through improved component selection, system design and operational control strategies[14]. These considerations are equally important in small DC compressor applications, where the available electrical power and operating conditions can influence overall system performance.

Although photovoltaic systems have been widely investigated for domestic and small-scale electrical applications, the performance of hybrid PV–battery configurations under intermittent motor-driven loads requires further experimental attention. In particular, the interaction between battery voltage, compressor operating current, available photovoltaic power and the resulting tyre-inflation performance is important in determining the practical suitability of such systems. Evaluating only the installed PV capacity or battery rating does not adequately establish the ability of a system to maintain compressor performance under varying operating conditions. Therefore, experimental assessment should consider both the electrical characteristics of the supply system and the corresponding mechanical output of the compressor.

The present study addresses this engineering challenge through the development and experimental evaluation of a standalone hybrid solar–battery power supply for a 12 V DC tyre-inflation compressor. The investigation considers the relationship between the electrical supply characteristics and compressor performance by examining tyre-inflation time, maximum attainable pressure, battery endurance, photovoltaic charging behaviour and compressor temperature. Particular attention is given to the

differences between battery-only and solar-assisted operating conditions and the practical integration challenges associated with supplying a motor-driven load from a battery-supported photovoltaic system.

The present work investigates a compact hybrid PV–battery supply for a 12 V DC tyre-inflation compressor. The study focuses on the integration of the PV module, charge controller, battery and compressor, and compares the prototype's reported performance in battery-only and solar-assisted modes. The contribution is an experimental case study of a small compressor operated from a standalone renewable-energy supply, including observations on system integration and load-related voltage drop.

The specific objectives were to (i) design and assemble a PV–battery supply for a small DC compressor, (ii) integrate battery charging and energy storage with the compressor, and (iii) evaluate inflation time, attainable pressure, battery endurance, PV charging behaviour, electrical input and compressor temperature.

2. Materials and methods

2.1. Prototype components

The prototype used a single-stage, 12 V DC reciprocating air compressor as shown in Figure 1. A monocrystalline PV module, a deep-cycle battery and an MPPT charge controller as presented in Figure 2(a), (b) and (c) respectively. Measurement equipment listed in the project record comprised a DC voltmeter, DC ammeter, pressure gauge, stopwatch, multimeter, clamp meter and infrared temperature gun. Table 1 presents the specifications of the major components and measuring instruments used in this work.

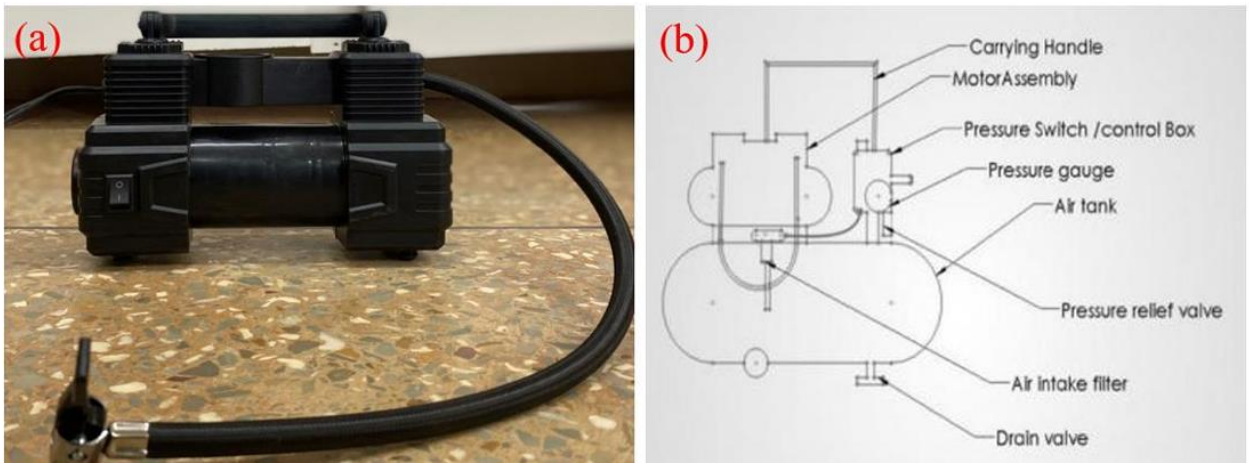


Figure 1 Compressor for tyre inflation (a) compressor used (b) schematic diagram of the air compressor

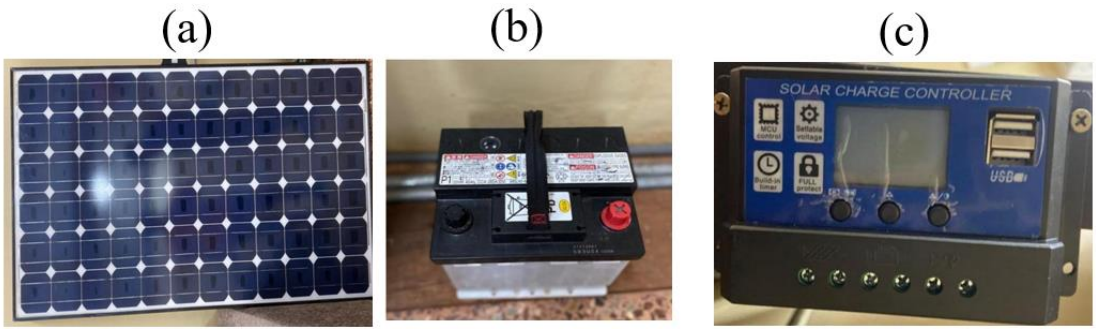


Figure 2. Prototype components (a)175W monocrystalline Solar panel (b) a 12V battery and an MPPT charge controller.

Table 1: Specifications of the Major Components and Measurement Instruments Used in the Prototype

Component	Reported specification	Quantity
DC air compressor	120 W; 12 V DC; 10 A rated; reciprocating	1
PV module	175 W; monocrystalline	1
Battery	12 V; 40 Ah; deep-cycle	1
Charge controller	20 A MPPT	1
Measurement instruments	Voltmeter, ammeter, pressure gauge, stopwatch, temperature gun	As required

2.2. System configuration and sizing

The PV module was connected to the PV input of the MPPT charge controller, which regulated charging of the 12 V battery. The compressor was supplied through a selector/changeover arrangement to permit battery-only and solar-assisted tests. An inline fuse was installed in the battery-positive circuit. During troubleshooting, the compressor was connected directly to the battery through the fuse, bypassing the controller's load output, while the controller remained in the PV-to-battery charging path. Figure 3 presents the system configuration and components-flow arrangement of the hybrid solar–battery compressor system.

The PV module was sized from the 120 W compressor rating using assumed battery and controller efficiencies of 0.90 and 0.95, respectively. The calculated requirement was $120/(0.90 \times 0.95) = 140.4$ W. Applying a 25% design margin gave 175.5 W, for which a nominal 175 W module was selected.

The nominal battery capacity was estimated from the expected daily electrical energy demand, the system voltage and the allowable depth of discharge. The battery capacity requirement was calculated using Equation 1.

$$C_b = \frac{E_d}{V_b \times DOD \times \eta_b} \quad (1)$$

Where, C_b= required battery capacity (Ah), E_d= daily energy demand (Wh), V_b= nominal battery voltage (V), DOD= allowable depth of discharge and η_b= battery efficiency

For a daily energy demand of 240 Wh, nominal battery voltage of 12 V, allowable depth of discharge of 0.50 and assumed battery efficiency of 0.90,

$$C_b = \frac{240}{12 \times 0.50 \times 0.90}$$

$$C_b = 44.44\ Ah$$

The PV current estimate was 175 W/12 V = 14.6 A, leading to selection of a 20 A MPPT controller.

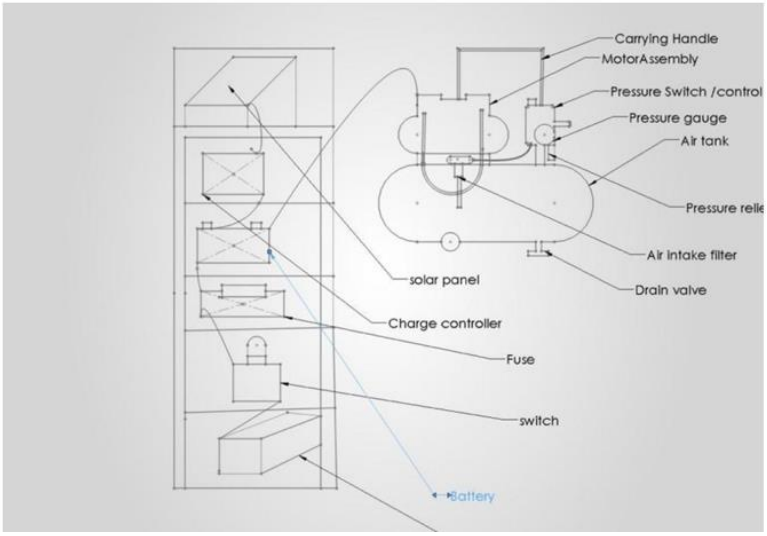


Figure 3. System configuration and components-flow arrangement of the hybrid solar–battery compressor system.

2.3. Experimental procedure

The prototype was evaluated in battery-only and solar-assisted modes. The reported tests included tyre inflation time, maximum pressure, battery endurance, PV charging, electrical input and compressor temperature. Three tyre sizes were reported as 225/70R16, 185/70R14 and 175/65R14.

For maximum-pressure testing, the compressor was operated until its pressure switch cut off, and the indicated pressure was recorded. For battery endurance, a fully charged battery was used until the system reached its minimum safe voltage; two trials were reported. PV voltage and charging current were recorded at 09:00 and 15:00. Compressor temperature was recorded at 0, 5, 10 and 15 min during continuous operation.

The experimental evaluation was conducted under two operating conditions: battery-only and solar-assisted operation. For each test, the tyre was initially adjusted to a predetermined starting pressure before the compressor was connected to the supply system. The compressor was then operated until the specified target pressure was attained, and the corresponding inflation time was recorded using a stopwatch. The

procedure was repeated for the three selected tyre sizes to assess the influence of tyre size on inflation performance.

To improve experimental repeatability, the initial tyre pressure, target pressure, battery state of charge and ambient conditions were maintained as consistently as possible. The voltage and current supplied to the compressor were recorded simultaneously during operation to establish the electrical input characteristics.

2.4. Electrical Performance Evaluation

The electrical performance of the hybrid power system was assessed by measuring the voltage and current supplied to the compressor under the two operating conditions. Electrical power was calculated from the measured voltage and current using Equation 2.

$$P = VI \quad (2)$$

where $P$is electrical power (W), $V$is the measured voltage (V) and $I$is the measured current (A).

The electrical energy consumed during compressor operation was estimated using Equation 3.

$$E = Pt \quad (3)$$

where $E$is electrical energy (Wh), $P$is electrical power (W) and $t$is the operating duration (h).

For improved accuracy, voltage and current measurements should be taken simultaneously at the compressor terminals during operation. Where the electrical input varies with time, the energy consumed should be determined by integrating the instantaneous electrical power over the operating period.

$$E = \int_0^t V\,(t)I(t)\,dt$$

This approach accounts for variations in voltage and current during compressor start-up and continuous operation. The measurement locations and instruments used for voltage and current monitoring should be clearly identified in the electrical circuit diagram.

2.5. Data processing

Electrical power was calculated as P = VI, and energy as E = Pt, with time expressed in hours. The work also calculated energy per tyre and a percentage energy difference between operating modes. Because the reported inflation endpoints and the electrical measurement points are not sufficiently documented, these derived values are presented as reported rather than interpreted as verified system efficiency.

3. Results

3.1. Tyre inflation time

The average inflation time varied across the three tyre sizes and power supply modes, as presented in Figure 4 and Table 2. Tyre A (225/70R16) recorded an average inflation time of 288.3 s in battery mode compared with 350.0 s in solar mode. Similarly, Tyre B (185/70R14) required 261.7 s and 301.7 s in

battery and solar modes, respectively, while Tyre C (175/65R14) recorded 251.7 s in battery mode and 285.0 s in solar mode.

The results indicate that solar mode consistently required longer inflation times than battery mode across all three tyre sizes. The difference ranged from 33.3 s for Tyre C to 61.7 s for Tyre A, representing an increase of approximately 13.2%–21.4% relative to battery operation. This trend is consistent with the lower average power output observed during solar operation. Furthermore, the difference in inflation time increased with tyre size, with the largest tyre (Tyre A) exhibiting the greatest time penalty, while the smallest tyre (Tyre C) showed the least. This suggests that larger-volume tyres are more sensitive to the reduced power availability under solar operation, resulting in longer inflation times.

Table 2: Mean Tyre Inflation Time for Battery-Only and Solar-Assisted Operating Modes

Tyre size	Battery-only (s)	Solar-assisted (s)	Difference (s)
225/70R16	288.3	350.0	61.7
185/70R14	261.7	301.7	40.0
175/65R14	251.7	285.0	33.3
Mean of three tyre-size means	267.2	312.2	45.0

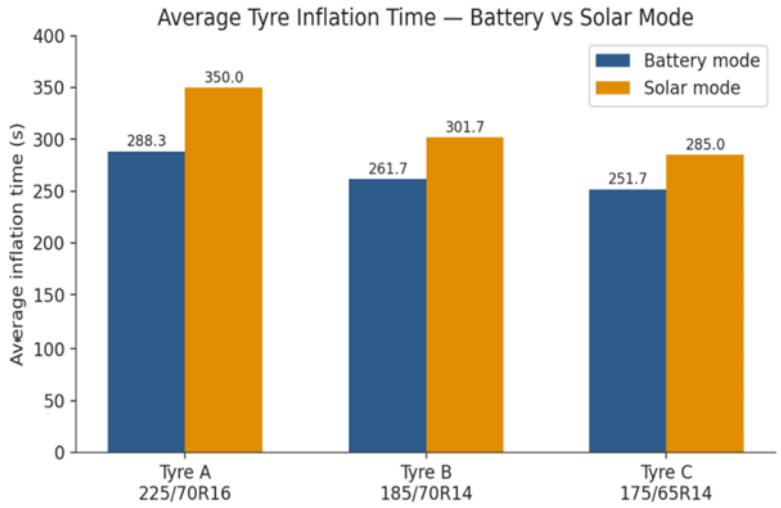


Figure 4. Reported mean inflation time for the three tyre sizes in the two operating modes.

As illustrated in Figure 4 and quantified in Table 2, solar-assisted operation required longer inflation times for all three tyre sizes compared with battery-only operation. The additional time ranged from 33.3 to 61.7

s, corresponding to approximately 13.2–21.4% relative to the battery-only times. The largest absolute difference was observed for the 225/70R16 tyre.

3.2. Maximum pressure

The maximum pressures attained by the compressor under battery-only and solar-assisted operating conditions are presented in Table 3, while their comparison is illustrated in Figure 5.

Table 3: Maximum Pressure Attained under the Two Operating Modes

Operating mode	Maximum pressure (psi)
Battery-only	35
Solar-assisted	30

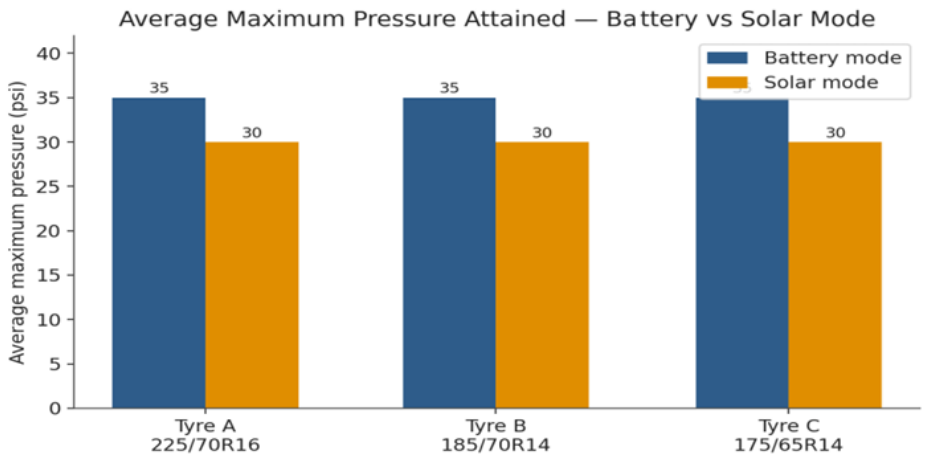


Figure 5. Reported maximum pressure attained in each operating mode.

The reported maximum pressure was 5 psi lower in solar-assisted mode than in battery-only mode. The difference in maximum attainable pressure suggests that the electrical supply conditions influenced the operating performance of the compressor. In a DC motor-driven compressor, a reduction in the voltage available at the motor terminals may affect motor speed and the resulting compression performance.

3.3. Battery endurance

The battery endurance results, including the operating duration and number of tyres inflated during each trial, are summarised in Table 4. The corresponding operating duration for the two trials is illustrated in Figure 6. The battery was fully charged, and tyres were inflated continuously until the battery reached its minimum safe voltage and the number of tyres and total operating time were inflated.

Table 4: Battery Endurance Performance during Battery-Only Operation

Trial	Operating time (min)	Tyres inflated
1	30	5
2	25	4

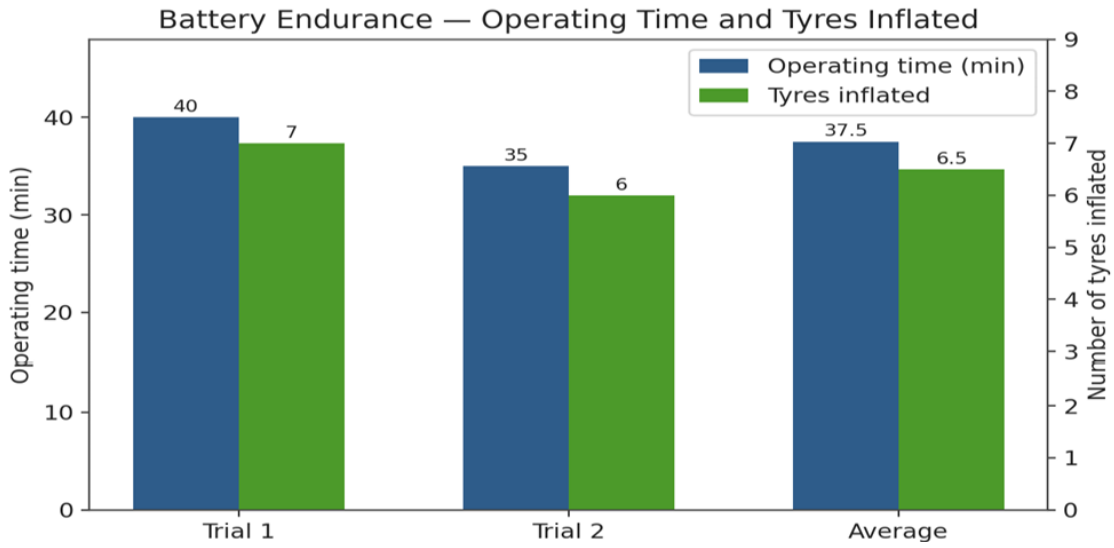


Figure 6. Battery-only operating duration in the two reported endurance trials.

3.4. PV charging behaviour

The recorded PV voltage and charging current at 09:00 and 15:00 are presented in Table 5. The variations in these electrical parameters between the two measurement periods are illustrated in Figure 7.

Table 5: Recorded PV Voltage and Charging Current at Different Times of the Day

Time	PV voltage (V)	Charging current (A)
09:00	12.6	2.35
15:00	15.8	3.34

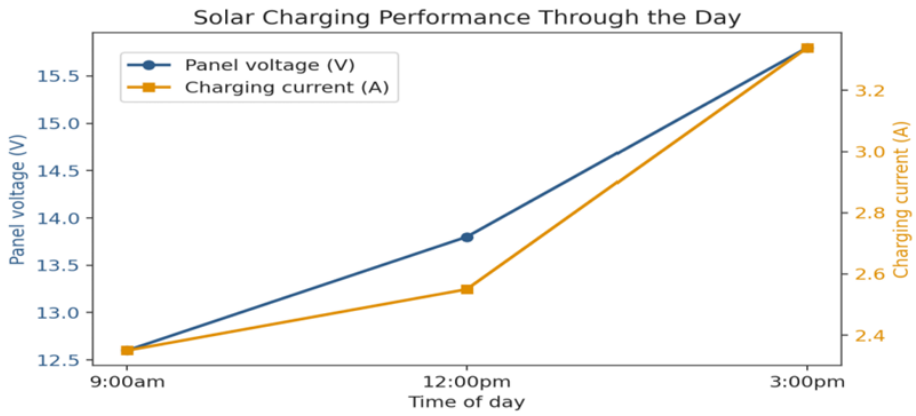


Figure 7. Reported PV voltage and charging current at the two measurement times.

The recorded PV voltage increased from 12.6 V at 09:00 to 15.8 V at 15:00, while charging current increased from 2.35 to 3.34 A. Irradiance, module temperature, tilt angle, weather conditions and battery state of charge were not reported, limiting interpretation of the two-point measurements.

3.5. Electrical input and temperature

The measured voltage, current, calculated electrical power and reported energy consumption for the two operating modes are summarized in Table 6.

Table 6: Electrical Input Parameters and Reported Energy Consumption for the Two Operating Modes

Parameter	Battery-only	Solar-assisted
Voltage (V)	12.9	15.8
Current (A)	7.09	4.75
Calculated power (W)	91.46	75.05
Reported energy per tyre (Wh)	7.11	6.74

The reported electrical input powers were 91.46 W in battery-only mode and 75.05 W in solar-assisted mode. The measurement location and whether the solar-assisted voltage/current values represent PV output, controller output or compressor-terminal input are not specified. The energy-per-tyre estimates (7.11 and 6.74 Wh) were calculated using different mean inflation durations elsewhere in the report; because the underlying test definitions are inconsistent, the stated 5.2% energy reduction should be treated as provisional.

The variation in compressor temperature during continuous operation is presented is illustrated in Figure 5. The temperature increased from 29.4 °C initially to 38.2 °C at 5 min, 39.4 °C at 10 min and 41.3 °C at 15 min, representing a total increase of 11.9 °C over the recorded period. The relatively rapid temperature increase during the initial 5 min was followed by a smaller increase during the subsequent measurement

intervals. However, the 15-minute observation period was insufficient to establish whether the compressor had attained thermal equilibrium. Further temperature monitoring over an extended operating period is required to determine its thermal behaviour under continuous loading.

The electrical operating characteristics provide useful information on the interaction between the power supply and the compressor during operation. However, the interpretation of the measured voltage and current depends on the measurement location within the electrical circuit. Measurements obtained at the PV module, charge controller and compressor terminals may differ because of charging regulation, cable resistance and voltage drop across electrical connections. For this reason, electrical comparisons between the two operating modes should be based on measurements taken at equivalent locations, preferably directly at the compressor terminals. Simultaneous voltage and current monitoring would also provide a more reliable estimate of the electrical energy consumed during each inflation cycle.

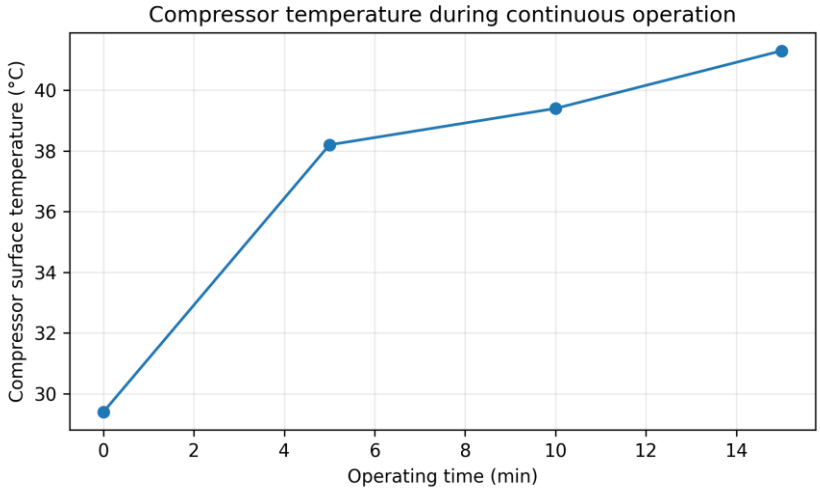


Figure 8. Reported compressor temperature during continuous operation.

4. Discussion

The prototype demonstrates that a small 12 V DC compressor can be integrated with a PV module, charge controller and battery to provide a portable tyre-inflation supply. The results indicate a clear performance difference between the two reported operating modes: battery-only operation was faster and attained a higher maximum pressure, whereas solar-assisted operation exhibited lower reported electrical power and longer inflation times. This behaviour is consistent with the possibility that the available electrical supply under the test irradiance was insufficient to operate the compressor at the same performance level as the battery supply.

The differences in inflation performance are evident in Table 2 and Figure 1, while the maximum pressure comparison in Table 3 and Figure 2 further demonstrates the lower pressure attained during solar-assisted operation.

The battery endurance results suggest that the prototype supported approximately four to five tyre-inflation operations per full charge under the particular test conditions. However, tyre starting pressures, target pressures, tyre volumes, ambient conditions and battery state-of-charge limits need to be controlled and documented before this endurance result can be generalized.

As shown in Table 4 and Figure 3, the two endurance trials produced operating durations of 30 and 25 min, corresponding to five and four tyres inflated, respectively.

A practical integration issue was observed when the compressor was initially supplied through the charge controller's load terminal. The reported voltage sag and subsequent low-voltage disconnect were resolved by connecting the compressor directly to the battery through an inline fuse. This observation is important for motor-driven loads, for which transient starting current can trigger protective circuitry even when the battery is not fully discharged. A robust design should specify the fuse rating, cable cross-section, switch current rating, battery discharge capability and measured motor starting current.

The two recorded PV voltage and charging-current measurements (Table 5 and Figure 4) indicate higher electrical readings at 15:00 than at 09:00. The reported electrical input parameters in Table 6 provide a comparison of the voltage, current and calculated power recorded under the two operating modes. The temperature trend presented in Table 7 and Figure 5 indicates a progressive increase in compressor temperature during the 15-minute observation period.

4.1. Influence of Electrical Supply on Compressor Performance

The performance difference between battery-only and solar-assisted operation indicates that the electrical supply configuration plays an important role in determining the operating characteristics of the compressor. The battery-only arrangement provided a shorter inflation duration and a higher maximum pressure than the solar-assisted arrangement under the reported test conditions. One possible explanation is the difference in the electrical conditions available at the compressor terminals during operation. The current demand of a DC motor-driven compressor may increase during start-up and under higher compression loads, making the system sensitive to voltage drop and limitations in the available current. In the solar-assisted configuration, the PV module, charge controller and battery operate as an integrated power supply, and the available power may be influenced by irradiance and battery charging conditions. Nevertheless, additional measurements of voltage, current and pressure variation with time are required to establish the exact relationship between electrical supply characteristics and compressor performance.

4.2. Implications for Practical Application

The results demonstrate the potential application of a hybrid PV–battery supply for small-scale tyre-inflation services, particularly in locations where access to grid electricity is limited or unreliable. The use of battery storage provides an opportunity to operate the compressor independently of instantaneous solar irradiance, while the PV module can support battery charging during periods of solar availability. However, the practical suitability of the prototype depends on its ability to maintain adequate compressor performance under different operating conditions. Battery capacity, PV module rating, charge-controller characteristics, electrical protection and compressor duty cycle should therefore be considered together during system design. The observed reduction in maximum attainable pressure under solar-assisted operation also indicates that the electrical configuration requires further optimisation before the system can be considered a reliable alternative to conventional compressor supplies.

Beyond the technical performance of the system, energy efficiency and environmental considerations are important in evaluating the sustainability of alternative power supplies. Energy audits provide a framework for assessing energy consumption, identifying potential efficiency improvements and evaluating the associated economic and environmental benefits of industrial energy-use practices [7]. Such

considerations are relevant when assessing the long-term sustainability of renewable-energy-powered equipment.

The adoption of renewable-energy technologies in automotive-related applications is consistent with broader efforts to promote sustainable mobility and reduce the environmental impacts associated with conventional transportation systems. Recent developments in intelligent mobility highlight the importance of renewable energy and electric propulsion in reducing greenhouse gas emissions and promoting environmentally sustainable transportation [6]. In this context, the integration of photovoltaic energy and battery storage into automotive service equipment represents a complementary approach towards improving the sustainability of vehicle maintenance operations.

5. Conclusions

The present study involved the design, assembly and experimental evaluation of a hybrid solar–battery power supply for a 12 V DC tyre-inflation compressor. The prototype incorporated a 175 W monocrystalline photovoltaic module, a nominal 12 V deep-cycle battery and a 20 A MPPT charge controller. The reported experimental results showed that battery-only operation provided shorter tyre-inflation durations and a higher maximum pressure than solar-assisted operation. The battery endurance tests recorded operating durations of 30 and 25 min, corresponding to five and four tyre-inflation operations, respectively. The compressor temperature increased by 11.9 °C during the 15-minute observation period.

The results demonstrate the practical possibility of integrating photovoltaic charging and battery storage with a small DC compressor. However, differences in attainable pressure, uncertainties in electrical measurement locations and inconsistencies in the reported energy calculations limit the extent to which the two operating modes can be compared quantitatively. Further experimental investigations involving controlled inflation pressures, verified component specifications, simultaneous voltage and current measurements, solar irradiance monitoring and repeated endurance tests are necessary to establish the overall electrical and mechanical performance of the system. The findings provide an initial basis for improving the design and performance of standalone renewable-energy-powered tyre-inflation systems.

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