Energy consumption of solar hybrid 48V operated mini mobile cold storage

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Abstract. A global shift headed for a greener and low emissions will necessitate notable advancement in the way in which the energy is being produced and used in all logistics and transportation sector. The solar hybrid electric vehicles (SHEV) are on the peak of the list of choices available for eco-friendly and clean vehicle technologies for smart city transportation. Current cold chain vehicle consumes too much energy and cannot guarantee the perfect quality of food, which is against to the sustainable development of environment. Solar energy used in mobile mini cold storage vehicle as an auxiliary power source of on-board fuel has not been extensively investigated. SHEV setup has been constructed, and experimental verifications are presented that explicitly demonstrate utilizing the PV module adds 15-25 km to the cruising range of a HEV with the weight of 450 kg in a normal operation of the SHEV during one sunny days, and provides higher power efficiency (90.2%) and speed (24.96 km/h). SHEV mini cold storage was energy consumed 104 Wh/day at 21°C ambient temperature and its energy consumption increased with increasing ambient temperature.

1. Introduction
Mainly road transport rates worldwide have been growing unprecedentedly in last few years. The pollutant gases emissions from transportation sector are higher than any other energy consuming sector [1]. Road transportation mainly contributes to air pollution in urban areas. This area is a major present source of environmental pollution and demands higher energy worldwide. More than 20% of the world’s energy is used for transportation, half of this in car and other private vehicles. The progress in transportation system introduces greenhouse toxic gasses [2]. These systems have important impacts on the environment as it accounts for 20–25% of the world energy utilization and CO$_2$ emissions as shown in figure 1. Data obtained by OPEC, the requirement for oil worldwide grows by 1.26 million barrels per day or 1.26% in last year 2017 from 1.38 million barrels per day in 2016 [11, 12]. Indian transport sector highly dependent on oil. Oil dependency is a major concern for India due to these three factors such as energy security, local environment and climate change. According to PPAC data 70% of diesel and 99.6% petrol are utilized in transportation. Energy problem and atmospheric change are compelling drivers to develop electric mobility in India [13]. Due to fuel shortage and continuously boost in fuel prices results in market shift towards more energy efficient transportation. In the past few years trends our main focus is only improving the efficiency of IC vehicles but not focus on other modes of transportation. Sustainable development is compulsory due to problems such as environmental pollution, random use of energy, damage to the environment. Sustainable development is possible in the transportation only through managing the energy systems [3, 4].
This paper draws attention to hybrid electric vehicle use for passenger and freight transport. As compared to conventional gasoline vehicles, electric vehicles are better alternative solutions because they are environmentally friendly. Due to environmental issues and economic considerations, there is an upward trend in developing the usage of electric vehicles rather than vehicles with internal combustion engines, so that there is an ascending interest for different types of EV charging stations in some countries. A SHEV utilizes its electric motor to offer the power needed for propulsion, and is more efficient compared to a traditional HEV that mainly uses an internal combustion engine. The V2G technology implemented in SHEVs is another benefit that makes them more beneficial and popular. In particular, the advantage of a PHEV is highlighted when it is linked to a micro grid or a smart grid to manage and balance load demand [5-9]. In 2015, almost 54% of the world’s population was living in cities and the normal electricity consumption was higher than 3.1MWh/person/year. Cities have become hot spots for electricity demand, which has to date been mostly covered by fossil fuel combustion in utility scale power plants. However, this form of supply directly contributes to global warming and should be avoided by an energy source that could be commissioned locally, with use of local assets and owned by the users. It has gradually been acknowledged that solar photovoltaic (PV) energy is the fittest candidate to tackle this challenge. Past research data represented higher growth of cumulative direct current production that has been boosted from 100 to 120,000 Mw from 1992 to 2015 respectively [10-13]. This study addresses this problem by presenting four novel batteries/PV hybrid power sources to be utilized in SHEV. In the proposed hybrid power source, the internal combustion engine has been replaced with four PV module located on the roof of the SHEV, and solar energy has been utilized as a clean and renewable energy to extend the cruising range of the SHEV.

1.1. Availability of solar energy
The solar radiation received by earth (area 127,400,000 km$^2$) is $1.740 \times 10^{17}$ W and it reflects 30% of power reverses back to space. Annually solar energy received by earth atmosphere is $5.5 \times 10^{24}$ J and only its 60% is gained by top earth surface. Earth surface obtained $3.3 \times 10^{24}$ J energy is more than 6800 times world’s annual energy consumption. If we can utilize only 0.5% of solar energy, it completes global energy demand. Solar energy received by earth surface is dependent on environmental conditions. Sunshine presents in India 300 days in a year (7 to 8 hours per day). Solar energy is 10,000 times more as compared to energy produced by fossil fuels and nuclear energy combined [7].
1.2. Electric vehicle production worldwide

Global electric vehicle stock in 2014 was 665000 vehicles and 113,000 EV sales in 2013. It is found that 70% EV sales in 2013 and 53% in 2014 worldwide. Sales of EV raise 49% in 2012, 54% in 2013 and 57% in 2014 globally. India uses few electric buses as compare to china (36,500 electric buses). Indian market for electric vehicles is still growing but due to lack charging infrastructure in big cities faces problem. It has been found that EV could close to 5% of the Indian car market in 2018. Where in global market could reach about 20 million cars by 2020 [4, 5].

1.3. Global refrigerated road transportation market

Global refrigerated vehicle by road transportation market will rose at a capital annual growth rate of more than 26% between 2017 and 2021. Food industries have higher losses about$750 billion worldwide. All Bio-pharma product sales $260 billion is highly depend on cold chain transportation annual. One third of food produced are wasted every year and Fruits and vegetables about 25% at its production level. Demand for refrigerated road transportation across worldwide is increasing due to growing awareness among farmers and harvesters about the benefits of cold chain. Manufacturers are increasingly refrigerated trucks for delivery process to offer high-quality products. Increasing demand for frozen foods has propelled suppliers to equip their refrigerated units with multi-temperature systems to keep the food at the adequate temperature during transportation. But most of refrigerated trucks operated with IC engine and give highly environmental pollution. One of the latest developments in the market is the rapid move towards sustainable refrigeration units to reduce environmental impact and carbon footprint refrigeration [4, 5].

2. Methodology use in design and development of SHEV

It includes modelling and optimization of photo voltaic module which is installation on SHEV roof. PV modelling and optimizing parameters used in this experiment work are shown in Figure 2.

2.1. Modelling of photovoltaic device with its circuit

Photovoltaic module converts solar radiation into direct current. We use 4 PV modules in series for charging battery bank of plug-in solar hybrid electric vehicles. Practical photovoltaic modules with its circuit are shown in Figure. $I_p$ depends on solar radiation intensity and $I_d$ is measured by Shockley diode equation. The circuit of photovoltaic module has resistances $R_i$ (internal resistances in the gridlines) and $R_{sh}$[6]. Both are garnet by manufacturing defects [8]. This PV module tested under standard test conditions such as irradiance of 1000 W/m² with cell temperature 25 °C. This photovoltaic module is modelled by using a single-diode model approach and measures its behaviours in terms of $V, P, \eta_{pv}$, and find different situations. Equations written blow are used for modelling [12-13]. The DC current ($I_{sc}$) received by photovoltaic module is directly depend on intensity of solar radiation. Maximum voltage comes from photovoltaic module represents by $V_{oc}$ when $I$ equals to zero.

\[
I = I_{pv} - I_d - \frac{V + R_S I}{R_p}
\]

\[
l_{pv}(T) = \frac{G}{G(nom)} \left[ l_{sc}(T_{1,nom}) + \left( l_{sc}(T_2) - l_{sc}(T_1) \right) \frac{T_2 - T_1}{T_2 - T_1} \right]
\]

\[
l_d = l_0 \left( e^{q(V_{oc}(T_1]} - 1 \right)
\]

\[
l_0 = l_{sc}(T_1) \left( e^{q(V_{oc}(T_1)} - 1 \right) \times \left( \frac{T}{T_1} \right)^{\frac{1}{n}} \times e^{\frac{q(V_{oc}(T_1)}{k(T - T_1)}}
\]

By substituting the value $l_{pv}$ and $l_0$ in the first equation, the Equation is derived (written blow) because it does not show direct result.
\[ I - f(G, T, V_g, n, R_s, R_{Sh}, I, V) = 0 \]

Here, \( f(G, T, \ldots, V) \) are means function of variables \((G, T, \ldots, V)\). The values of \( I \) are find after putting \( V \) values by minimizing the error \( I - f(I, V) \) equal to zero. Garneted model depends on four variables \((R_p = 0 \text{ or neglect})\). \( I_L \) and \( I_o \) are calculated by \( V_g = 1.1 \). Value of \( n \) and \( R_s \) are estimated through curve fitting method.

### Table 1 Technical specification and electric parameters measured for 150 W PV module

| Parameter name       | Value  |
|----------------------|--------|
| Capacity (W<sub>p</sub>) | 150 W  |
| Module volt (V)      | 12     |
| Width (W)            | 666 mm |
| Height (H)           | 1483 mm|
| Thickness (T)        | 35 mm  |
| Tolerance            | +/- 5% |
| Module weight        | 11 kg  |
| Cell in series       | (9x4) 36|
| \( V_{oc} \)         | 21.5 V |
| \( I_{sc} \)         | 8.75 A |
| \( P_{Max} \)        | 150 W  |
| \( V_{pm} \)         | 18 V   |
| \( I_{pm} \)         | 8.33   |
| FF                   | >0.70  |
| Efficiency (\( \eta_{pv} \)) | >15.0 % |
| Max. system voltage  | 1000 V |

#### 2.2. Solar radiation available on SHEV photovoltaic module

Maximum solar energy incident on photovoltaic module in a given area is derived by using equation written below [12]:

\[
S_{module} = S_{incident} \sin\left(90 - \varphi + \delta + \beta\right)
\]

Declination angle \( \delta \) finds by following equation

\[
\delta = 23.45 \times \sin\left[\frac{360}{365} \times (284 + d)\right]
\]

**Figure 2** Parameters of solar photovoltaic module used in SHEV and its equivalent circuit

#### 2.3. Height of center of gravity calculation for SHEV
Height of centre of gravity is an important parameter to find stability of SHEV by putting values of total self-weight of SHEV and wheelbase distance. It transfer loads between front and rear wheels. 

\[ h_{CG} = \frac{\text{wheelbase distance} \times \text{difference in vehicle weight}}{\text{total weight of vehicle} \times \tan \text{slope of trace}} = \frac{W_b (W_{FR} - W_F)}{m_v \tan \theta} \]

\( h_{CG} = 1453 \text{ mm} \) by putting \( m_v = 390 \text{ kg} \), \( W_b = 2105 \text{ mm} \), \( \theta = 2 \text{ degrees} \), \( W_{FR} - W_F = 9.4 \text{ kg} \). The location of centre of gravity is effected by weight present in the mini cold storage of SHEV.

2.4. Air resistance force for SHEV

The value of air resistance force is varying with SHEV speed change. Its value highly depends on structure design of SHEV. Air resistance force derived by following equation [12].

\[ F_{air} = 0.613 (A C_d V^2) \]

\( F_{air} \) is depends on aerodynamic drag coefficient \( C_d \). \( F_{air} = 6.84 \text{ kg} \), by putting \( C_d = 1.05, V = 30 \text{ m/s} \) and \( A = 1.18 \text{ sq. M} \).

2.5. Power requirement and selection of motor

Aerodynamics plays significant role during design of SHEV and its performance. Drag force becomes proportional to the square of speed. Its value increases gradually with increase vehicle speed. SHEV motor power derived by following equation [10-13]

\[ P_r \geq 0.5 \rho_a C_d A V^2 + W (C_r \cos \theta_s + \sin \theta_s) V. \]

2.6. SHEV battery bank capacity

Battery bank (charged by grid electricity) acts as a primary energy resource for SHEV and solar charging is secondary. During cloudy or rainy season mini cold storage operating by battery bank. Weight of battery bank is effects on travelling performance of SHEV. Batteries selection is important parameter during SHEV design [8]. Battery bank capacity is selected using the following relation

\[ P_b = \frac{\text{power required} \times \text{operating duration}}{\text{battery efficiency} \times \text{battery voltage} \times \text{maximum DOD} \times \text{days of autonomy}} = \frac{P_r t}{\eta_b V_b (DOD)n} \]

\( P_b \) is find 420 Ah for power required 3 kW when operating duration (t) = 8 hours/day and day of autonomy (n) = 1. Lead acid batteries are most popular in India due to robust usage in SHEV and economic range. Therefore, we selected lead acid batteries for experimental analysis.

**Table 2** Technical specification of battery bank and charge controller used in experimental setup

| Battery bank company | Exide Invaplus Tubular battery |
|----------------------|--------------------------------|
| Rated output         | 105 Ah, 12V (4 no. in series) |
| Depth of discharge   | 80% (First 1500 cycles)       |
| Overall efficiency   | 60%                            |
| MPPT controller company | Su-Kam                      |
| System voltage       | 24/48 auto recognition        |
| Max charge/load current | 45A                         |
| Efficiency           | 96%-98%                       |
2.7. Distance travelling by SHEV
The distance travelled by SHEV received by following formula [13]

\[ D_{\text{vehicle}} = \frac{\text{energy conversion efficiency} \times \text{energy from solar panels}}{\text{vehicle tractive force}} = \eta \frac{E_s}{T_f} \]

3. Principle and operation for experimental setup
The working principle of modelled SHEV is briefly described in Figure 3. Four photovoltaic modules are installed on the top of vehicle roof which converts solar power directly into electrical power. The maximum power point tracking (MPPT) controller is installed to get the maximum power output from solar panels for charging the four lead-acid automotive batteries (48V). The brushless direct current (BLDC) electric motor (1000W) is setup to convert battery bank power into mechanical energy for SHEV. BLDC type motors are highly efficient and safe to operate with minimum noise and less frictional losses. The motor controller of the motor senses the position of the stator and supplies the energy to the rotor by using Hall Effect sensor. Power from the motor (BLDC) is transmitted to wheels through differential gears. The photographic view of fabricated SHEV with PV modules is shown in figure 4. Experiments have been conducted in the months of April and May in the climatic conditions of NIT, Jalandhar. These type electric vehicle use more popular in transportation of poultry farm products, dairy products like ice cream or milk, fast food items, bakery, cold chain products and in enter city advertisement. Technical specification of SHEV as shown in table 3.

4. Specification of 12V/24V operated mini cold storage
This mini cold storage especially suited for solar power applications its technical specification as shown in table 4. It operates on very low energy and gives highly efficient cooling. Energy consumption of DC operated cold storage as shown in figure 5. It was found that energy consumption increasing with increasing of ambient temperature. This tested separately with battery bank and PV module.
| Parameter name         | Value                                      |
|------------------------|--------------------------------------------|
| Wheel base             | 2105 mm                                    |
| Overall length         | 2765 mm                                    |
| Overall width          | 990 mm                                     |
| Overall height         | 1190 mm                                    |
| Cargo box dimensions   | 1295 mm×945 mm×600 mm                      |
| Vehicle weight         | 390 Kg (without PV & cold storage unit)    |
| Seating capacity       | One driver                                 |
| Estimate range         | 100 km (without solar PV)                  |
| Maximum speed          | 25 km/hour                                 |
| Climbing ability       | 20 % grading                               |
| Rating output          | 1000 W DC motor                            |
| Battery                | 4 Lead acid (48V)                          |
| Single battery capacity| 12 V-105Ah                                 |
| Brake                  | Drum type                                  |
| Charging time          | 100 % in 8 hours                           |
| Tire size              | 3:0-12                                     |
| Wiring harness         | 1” heavy duty water proof                  |
| Charger                | 48V 15A SMPS charger                       |
| Body material used     | High grade steel                           |
| Load capacity          | 400-450 kg                                 |

**Table 4** Specification of 240 liters mini cold storage used in experimental Setup

| Parameter name         | Value                                      |
|------------------------|--------------------------------------------|
| Dimensions of outer cabinet | 1145 mm×850 mm×690 mm                        |
| Inner dimensions       | 900 mm×673 mm×440 mm                        |
| Operating voltage      | 12V or 24V DC (normal)                      |
| Temperature range      | -16 to +6 °C                                |
| Ambient temperature range | 10 to 43 °C                                |
| Refrigerant used       | R-134a (eco-friendly)                       |
| Door type              | Top opening                                 |
| weight                 | 58 Kg                                      |
| capacity               | 240 L                                      |
| Insulation             | Polyurethane (12 cm thick)                 |
| Compressor type        | DC compressor                              |

5. **Environmental impact on performance of SHEV**

India is situated in Asian region. Effect of seasonal change era on the performance of the solar hybrid electric vehicle is considerable due to profuse cloud cover and less solar intensity. The place (NIT Jalandhar playground) used for performing experimental work, particularly is influenced by northeast monsoon during November to half of March. This problem was solved in the fabricated vehicle by providing a DC electric port along with alternating current to direct current adapter (48V 15A SMPS charger) for charging battery bank using AC grid supply. It was estimated that standard speed of SHEV decreases by 5-12% in this time period of the year [13] due to lack of visibility problems. The power required to drive the vehicle would be 6-15% more during rainy season due to heavy traffic and broken down roads. When sunlight not available during monsoon season or cloudy day SHEV charged by grid electricity.
6. **Experimental performance test on SHEV**

The performance test is mainly executed to check battery behaviour (charging or discharging) of SHEV by product load varying in mini cold storage. Battery bank sited in SHEV was charged using solar energy by PV panels located on upper portion of SHEV. All performance tests were carried out to analyse the performance of SHEV on a typical sunlight day and check effect on speed of SHEV. Power output of PV modules was 4 units (4 KWh). Discharge rate of battery bank with vehicle speed relation for SHEV as shown in Figure 6. This experiment was conducted with a variable load ranging from without load (self-vehicle’s weight of SHEV) up to 310 kg which was the maximum weight SHEV can hold.

![Energy consumption](image)

**Figure 5** Energy consumption of DC operated mini cold storage

![Effect on battery discharge on SHEV speed by varying load of product](image)

**Figure 6** Effect on battery discharge on SHEV speed by varying load of product

7. **Conclusions**

In this paper, four novel batteries/PV hybrid power sources were proposed to be utilized in hybrid electric vehicle. In the hybrid power source, the gasoline powered internal combustion engine of a HEV has been replaced with four PV solar operated module positioned flat on top of the SHEV, and
solar energy has been utilized as a eco-friendly and non-convection energy resource to extend cruising range of hybrid electric vehicle. The power source has the capability of SHEV to grid, and utilizes four batteries (48 V) as the main energy storage device and four 150W PV modules as the auxiliary power source. SHEV has been built, and experimental verifications were presented. It was demonstrated that utilizing the PV module adds 15-25 km to the cruising range of a SHEV with the weight of 450 kg in a normal operation of it during one sunny day, and provides higher power efficiency (90.2%) and speed (24.96 km/h). SHEV mini cold storage energy consumed 104 Wh/day at 21°C ambient temperature and its energy consumption increasing with increasing ambient temperature as shown in figure 4. Energy consumption was 218 Wh/day at 32°C ambient temperature. It was also shown that the power source high accurately regulates the DC-link voltage, and produces suitable stator currents for the traction electric motor.

8. Nomenclature

- $S_{\text{module}}$: Solar radiation incident on PV module (W/m²)
- $S_{\text{incident}}$: Solar radiation measured perpendicular to the sun (W/m²)
- $h_{CG}$: Height of center of gravity in SHEV (mm)
- $I_0$: Current diode
- $G(\text{nom})$: Nominal irradiation (1000W/m²)
- $\Phi$: Latitude (degree)
- $\Delta$: Driving cycle time step
- $V_{\text{ao}}$: The velocity at time step i
- $C_d$: Dimensionless aerodynamic drag coefficient
- $C_r$: Rolling resistance coefficient
- $R_s$ or $R_{SH}$: Parallel resistance or shunt resistance
- $I_{sc}$: Current in short circuit
- $V_{oc}$: Voltage in Open circuit
- $I_{ph}$: Incident light current generated on PV
- $I, V$: Current and voltage in PV cell
- $K$: Boltzmann cont. (1.38066 x10^-23 J/k)
- $I_S$: Saturation current in reverse direction
- $\theta$: Angle of incidence (degree)
- $\omega$: Hour angle of PV module
- $V_{ch}$: Battery charging voltage (Volt)
- G, E, GHI: Solar irradiation (W/m²)
- OPEC: Organization of the petroleum exporting countries
- PPAC: Petroleum planning and analysis cell
- $W_F, W_R$: Weight of front tires while rear wheel in horizontal direction
- $\eta$: Energy conversion efficiency
- $P_b$: Capacity of battery
- DOD: Depth of discharge
- n: Day of autonomy
- $\theta_s$: Slope of track (degrees)
- $\delta$: Declination angle (degrees)
- $N_d$: No. of day in year
- $\eta_{\text{pv}}$: PV efficiency (%)
- $V_{p}$: Band gap of energy (eV)
- $T$: Cell temp. (°C)
- $P_r$: Motor power required (Watts)
- $T_{\text{ch}}$: Reference temp. (25°C)
- $\gamma$: Surface azimuth angle (in degree)
- $T_{\text{air}}$: PV module back surface temp. (°C)
- $F_{\text{air}}$: Air resistance force
- $\rho_{\text{a}}$: Ambient air density (kg/m³)
- $A_F$: Frontal area of SHEV
- $\beta$: Tilt angle in degree
- $\omega$: Hour angle of PV module
- $V_{ch}$: Battery charging voltage (Volt)
- G, E, GHI: Solar irradiation (W/m²)
- $\omega$: Hour angle of PV module
- $V_{ch}$: Battery charging voltage (Volt)
- G, E, GHI: Solar irradiation (W/m²)
- OPEC: Organization of the petroleum exporting countries
- PPAC: Petroleum planning and analysis cell
- d: Day of the year
- $m$: vehicle mass (kg)
- $W_b$: wheelbase distance (mm)
- A: Vehicle frontal area
- $E_{\text{fp}}$: Energy from solar panels
- $T_r$: Vehicle tractive force
- $\delta_t$: Battery efficiency
- $V_b$: Battery voltage

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