SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V12I9P125

Volume 12 Issue 9, 256-268, September 2025


*Original Article*

# Integrated Optimization of Dual Active Bridge Converter and Photovoltaic System for Electric Vehicles

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Received: 19 July 2025 Revised: 18 August 2025 Accepted: 18 September 2025 Published: 30 September 2025

***Abstract*** - *The combination of Electric Vehicles (EVs) and Photovoltaic (PV) systems has high potential to increase the sustainability and energy efficiency. The work of interest in the current paper is on the optimization of the energy management system that consists of a Dual Active Bridge (DAB) converter and PV system to ensure real-time conversion and charging of the battery. The goal is to optimise energy efficiency by formulating a control approach wherein solar power generation, power conversion, and electricity storage are interactively optimised with the energy storage of the electric vehicles. Here, the mathematical model of the integrated system is presented, and the design of a real-time mechanism of control is proposed to manage optimal flows in the integrated system. Simulations in MATLAB are done to confirm the model performance in the proposed system's given realistic driving and solar generation conditions. The findings show that the optimized development between the PV system and the DAB converter results in improved energy conversion, battery charging capacity, and driving range augmentation. This article gives an idea about how renewable energy could be the way to go further in the process of transportation electrification, and how more efficient energy management systems could be put forward to support the use of energy in EVs.*

***Keywords*** - *Electric Vehicles (EVs), Photovoltaic (PV) systems, Dual Active Bridge (DAB) Converter, Energy conversion efficiency, Real-Time Optimization, Energy management algorithms, Battery charging, Sustainable transportation, MATLAB simulation, Power flow management.*

## 1. Introduction

Electric Vehicles (EVs) have become a significant nudge towards lessening greenhouse gas emissions and switching reliance on fossil fuels in the transport division. These cars use electric motors, which are driven by rechargeable batteries; thus, they are more energy efficient and easily accessible to the environment in contrast to the gasoline-burning vehicles [1]. The growth of EVs has been gaining momentum due to technological breakthroughs, governmental subsidies, and the expansion of awareness over climate change [2]. Nevertheless, the primary advocation of EVs, their efficiency, is limited by one major problem that involves energy storage, thus creating a drawback to their overall effectiveness [3]. The current battery technologies face limited capacity issues, and, as a result, an EV has a relatively short driving range, which makes range anxiety an issue of concern among drivers [4]. Moreover, the fact that it requires regular recharging using grid-based infrastructure is another problem [5].

Employing renewable energy sources, especially solar power, in the EVs prospect is worth considering to overcome such shortcomings [6]. Another option is to incorporate PV panels into EVs that convert sunlight to electrical energy and use them to charge the battery; they are a clean and renewable energy source [7]. By taking advantage of solar power, it will be possible to increase the range of EV as well as diminish the use of the charging infrastructure based on the grid, which provides more freedom and independence to the user [8]. PV systems are also used to avoid an increase in the environmental impact of EVs, and thus are additional sustainability factors. This pairing of the concepts of EVs and solar energy can play a powerful role in transforming a rather unsustainable transportation system and provide a solution to the problems facing conventional EVs on the road [9]. The existing EV systems nonetheless continue to exhibit several challenges despite the potential of integrating renewable energy. Range anxiety is a fear that an EV will not find a charging point before running out of charge, which is one of the most significant problems [10]. It becomes especially hazardous when traveling long distances or when the charging stations are scarce. Although the driving range is becoming an issue being addressed by advancements in battery technology [11], this will still be a significant barrier to mass EV acceptance. Moreover, EVs rely heavily on grid charging, which is often costly and ineffective, especially in areas where the electricity rate is high or unreliable [12]. The EV is not available equally conveniently everywhere because the charging infrastructure is not universal, especially in rural areas [13].

Furthermore, the limitations associated with the inefficiency of existing power management systems in converting and distributing energy are a major challenge. In the process of integrating renewable energy power, such as solar power, care should be taken to make sure that there is effective conversion of energy to the EV battery through the PV system [14]. Current power management systems cannot always optimize the energy conversion; thus, power losses are incurred and the total system performance is lesser [15]. Solar energy is also intermittent in nature, with changing weather or the time of the day, making it more difficult to manage energy in EVs. The possibility that the EV can benefit by the substantial extension of range that solar power offers is not fully materialized without adequate improvement in how it is controlled and improved [16].

To overcome these issues, the combination of EVs and PV systems offers many benefits. First, the use of solar energy can enhance the energy efficiency of EVs, since there will be less contact with grid-based charging. This is because with the aid of solar panels, the EV is able to generate electricity by tapping into sunlight and then charging its battery without having to rely on external sources of energy [17]. This minimizes the environmental implications as well as the cost incurred through charging on the grid. Also, solar power can be used to increase the range of the EVs. In areas that are not as sunny, solar energy can still help charge the vehicle battery so that the vehicle can have an increased range. Finally, in areas where there is more light, such as solar energy, one can make significant summer power contributions, such that there is no longer any need for a grid to charge the vehicle to extend the driving range. This combination enables the electric vehicles to be more self-contained, allowing users to recharge their fuel with renewable energy when it is available. Nevertheless, solar power has potential that requires an effective energy management system to achieve. This system will have to deal with the fluctuating aspects of solar power production and ensure that power will be apportioned in the best way between the car's PV system, the battery, and the powertrain system. The interflow of smart control technologies can provide that the large-scale energy conversion and energy storage will be used with a minimum or comparatively low amount of energy losses.

A technology with immense potential in energy optimization in EVs is the DAB converter, which is proving to be ideal when bidirectional energy flow is required between the PV system and the battery. A DAB converter is an innovative power converter that can smoothly take up the energy conversion between the EV battery and the PV system, allowing an EV to charge and discharge [18]. The major benefit of a DAB converter is that it can work with high efficiency and bidirectional power flow. It enables the power produced in the PV system to be stored in the EV battery, as well as enabling the supply of this energy by the EV battery into the vehicle drive system when it is required.

The DAB converter operates based on such control of the phase shift between two active bridges that are connected by means of a high-frequency transformer. This phase-shift control allows effective conversion of energy and has the flexibility of controlling the power flow. The mathematical description of the process of operation of the DAB converter can be expressed as follows:

$$P_{out} = V_{out}\, I_{out} = kP_{in}$$

Where $P_{out}$ is the output power, $V_{out}$ is the output voltage, $I_{out}$ Is the output current, and $P_{in}$ Is the input power from the PV system? Constant k is the factor of efficiency of the DAB converter, and it is usually higher than 90% on optimal conditions. Due to the high efficiency of the DAB converter, power losses during the conversion process are minimized, leading to improved performance of the system because of better battery life.

The main aim of the research is to combine the PV system with the DAB converter to be of maximum energy efficiency in using EVs. Here, complex real-time optimization methods will be developed to adapt the power flow between the PV system [19], DAB converter, and battery on a more fluctuating level of changing environment parameters like solar intensity and vehicle power requirement. It is to maximize energy conversion efficiency to maximize the use of solar power to charge the battery, thus extending the range available in any EV to avoid relying on charging on the electric grid. Developing control strategies that will control the interaction of the PV system, the DAB converter, and the battery to enhance the overall system efficiency will also be part of the research. This study promises to achieve more self-sustainable, energy-efficient, and sustainable EVs by being appropriate with renewable energy in EVs, which will clear the way to the evolving, feasible transportation of the future that is more environmentally friendly.

## 2. Literature Survey

### *2.1. Photovoltaic Systems in Electric Vehicles*

The use of PV systems in EVs has gained attention during the last several years as a possible way of improving energy efficiency and eliminating the need to rely on traditional charging infrastructure. Originally, PV systems were deployed as auxiliary charging systems, powering select off-propulsion loads in air conditioning systems, lights and infotainment [20]. This is offset by improved PV panel efficiency and battery technology, so that it is now feasible to operate solar panels to charge a significant number of batteries to aid the increased range of EVs. Multiple research have attempted to determine the possibility of utilizing PV systems by direct coupling to the vehicle's powertrain. Another work by Hsieh et al. (2017) dwelled upon the issues of technical implementation of large PV panels on EV roofs and their influence on the overall energy balance [21]. The main problem is that there is not much space on top of the vehicle, hence on its roof, to collect solar energy. In spite of these shortcomings, PV systems embedded in EVs have demonstrated the ability to limit the requirement to charge gadgets externally in places with great exposure to sunlight [22].

As shown by Zhang et al. (2019), grid dependency could be decreased, and the driving range of PV-powered EVs could be improved, but only in a controlled environment. Real-world applications, however, have problems like inconsistency in solar radiation conditions, changing energy that the vehicle needs, and the system's capability to convert efficiently into energy that can be used in the battery. Solar panels need even better efficiency and energy conversion systems to be an effective and common solution to the problem of PV integration in EVs.

### *2.2. Dual Active Bridge (DAB) Converter for Energy Conversion*

The DAB converter is another converter type that has gained popularity as a high-efficiency circuit in renewable energy applications with devices like EVs. The DAB is controlled using a phase shift, and, in this way, the transfer of power between the EV and the PV system occurs efficiently with minimum energy loss. The transfer of power in a DAB converter is proximately manipulated by the transformer's windings associated with the angle adjacent to the phase shift ($\varphi$) between primary and secondary windings of the transformer. Power to the load will be provided by the reciprocating engine at an average as given by:

$$P_{avg} = \frac{V_{in} V_{out}}{\pi} \cos(\varphi)$$

Where $V_{in}$ is the input voltage, $V_{out}$ The output voltage, and $\varphi$ is the phase shift angle. The real-time control of the phase shift also enables real-time adjustment of the power flow so that, when a change in power flow is required, a change can be made between the pv system and the battery and then between the battery and the load as well. According to the study of Wang et al. (2020), the choice of DAB converters in EV was based on its high efficiency, rapid response time, and capacity to accept high power level requirements [23]. The two-way power flow of the DAB converter also permits Vehicle-to-Grid (V2G) capabilities, whereby the vehicle can feed power back to the grid in addition to power consumption. It is a feature required in the future intelligent grid system and the full utilization of renewable energy.

### *2.3. Energy Management Strategies for Electric Vehicles*

Energy management plays a significant role in ensuring maximum power optimization between the PV System, DAB converter and the battery of the Elephant Electric Vehicle. EMS aims to secure the use of available solar power in a vehicle to amplify the driving range and decrease the battery wear. Numerous control techniques have been investigated, including Model Predictive Control (MPC), fuzzy logic controllers, and adaptive control algorithms. PC is a common method of real-time optimization of energy management. It foresees how the energy is used and optimizes control actions within a predetermined horizon. Zhao et al. (2019) have proposed that MPC could be beneficial to EVs since it offers the ability to optimize the charging and discharging of batteries and reflect the dynamics of the PV system and power requirements of the vehicle. This equation of MPC-based energy management is as follows:

$$Minimize\ J = \sum_{k=1}^{N} (\lambda_u {u_k}^2 + \lambda_x {x_k}^2)$$

Where $J$ is the cost function, $uk$ is the control input, $xk$ is the system state, $\lambda u$ and $\lambda x$ are weighting factors, and $N$ is the prediction horizon. In this formulation, there is the possibility to optimize energy consumption and storage with the passage of time so that the vehicle runs at optimum efficiency. There has also been extensive application of Fuzzy Logic Controllers (FLC) in energy management systems due to their easy implementation and ability to resolve any uncertainty in system parameters. FLCs offer a non-structured way of real-time control, especially in systems with non-linearities and varying operating conditions, as is typical of EVs. The logic in these controllers works via rules to control the flow of power between the PV system [24], DAB converter and battery, depending on any real-time input characteristics like solar irradiance, SOC of the battery and vehicle demand power.

### *2.4. Real-Time Control Strategies for Energy Optimization*

One of the key features of managing energy in PV-DAB integrated systems of electric vehicles is real-time optimization. Since the amount of solar energy available is highly variable, real-time control methods are necessary to operationalize power flow in real time to make use of the available energy [25] optimally. It has been suggested that adaptive phase shift has the potential to be an additional real-time control concept that can enable the DAB converter to vary its phase shift angle according to changing levels of solar radiation, the battery state of charge, and power demand by the vehicle. In a number of studies, real-time control strategies have been shown to be effective. As one example, Liu et al. (2019) designed a real-time control algorithm, which performs the dynamic optimisation of the phase shift according to the solar irradiance and vehicle energy consumption. This technique maximizes power transfer between the PV system and battery and therefore ensures energy losses are reduced and the system efficiency is maximized. The real-time control strategy can be expressed as:

$$P_{out} = P_{PV} - P_{load} + P_{battery}$$

Where $P_{out}$ is the output power, $P_{PV}$ is the power generated by the PV system, $P_{load}$ Is the power required by the vehicle, and $P_{battery}$ Is the power exchanged with the battery? The system is able to constantly tweak these parameters in order to make sure that the vehicle is running efficiently in every situation.

### *2.5. Simulation Models and Tools for PV-DAB Systems*

Modeling and testing PV-DAB integrated systems is typically carried out using simulation tools such as MATLAB/Simulink, subjecting it to a broad range of plausible driving and solar conditions. Such simulators enable the projection of energy management techniques, control procedures, and power conversion systems that avail impressive information about the functionality of the system prior to its actual realization. The parameterization used in studies like that of Zhang et al. (2019), which simulated the power flow within the PV system, DAB converter, and battery under different driving cycles and solar irradiance conditions, made fairly broad use of MATLAB simulations. The simulation tools assist in evaluating the viability of the proposed system, the existence of any inefficiencies and in the optimization of control strategies. The real-time optimization algorithms and control strategies developed to maintain the operation of PV-DAB integrated systems have been validated using the simulated results, which assures that the techniques are applicable in the real world.

## 3. Proposed System Overview

PV systems coupled with a DAB converter as part of EVs provide an effective source of renewable energy with energy storage and optimum efficiency in transferring power between the PV system and the EV battery. This part will comment on how the PV system works, the DAB converter and how they will be combined so that energy management can work best and electricity effectiveness will be enhanced in electric cars.

### *3.1. Photovoltaic (PV) System*

A PV system helps collect solar energy in the form of electrical power. Solar panels are composed of semiconductor materials (i.e., silicon), which trigger the release of electrons under the influence of sunlight, generating a DC. This electricity then gets used to charge the battery of the electric vehicle, or alternatively, the inverter converts it to AC.

The power output of the PV system is determined by the solar irradiance (G), the area of the solar panels (A), and the efficiency of the panels (η). The energy generated by the PV system is given by:

$$P_{PV} = A\ G\ \eta$$

Where:
$P_{PV}$ is the electrical power generated by the PV system (in watts),
$A$ is the area of the solar panels (in square meters),
$G$ is the solar irradiance
$\eta$ is the efficiency of the PV system, typically ranging from 15% to 20%.

Since the PV system produces DC power, handling this power in the battery will be the next thing. A charge controller is applied to this role, allowing the voltage and current to be controlled so that the battery is charged in the best possible way and is not overcharged. One of the most important parts of this process is the MPPT, which keeps changing the voltage in an attempt to obtain the maximum amount of power that the PV system will give. Figure 1 shows how energy moves through an EV system when a PV system is integrated into the system along with a DAB converter and the powertrain in the vehicle. The diagram illustrates how the PV panels exploit the energy harnessed by the sun, giving off DC power. The charge controller then regulates this power using an MPPT algorithm to maximize the charging process. Depending on the system design, the DC power is then either used directly by the DAB converter or converted to DC by an inverter to manage its power efficiently. The DAB converter is the key element in this system because it coordinates the power conversion of the PV system two-way into the battery and powertrain of the EV. It modulates the flow of power depending on the instantaneous energy needs of the vehicle and so maintains an optimum charge in the battery, besides minimizing losses that are experienced during the process. The BMS will maintain charging and discharging of the battery at the most ideal level by watching the SOC and regulating the diversion of energy. The power contained in the battery can be used to serve the EV load or sent back to the grid in the event of necessity.

### *3.2. Dual Active Bridge (DAB) Converter*

The DAB converter plays a crucial role in energy flow management within an integrated energy path, specifically when used in renewable energy sources like solar-powered EVs. The converter connects the PV system and the battery to the load, which could be the vehicle powertrain or other external systems such as the grid. This converter allows power to flow in both directions. The DAB converter applies two active switches on a transformer's primary and secondary sides. It runs on phase delay controls, which adjust the phase difference between the primary and the secondary windings to regulate the power flow. The method will provide energy with economic transfer, reducing energy losses incurred during the conversion procedure. The efficiency of the DAB converter can be represented as:

$$\eta_{DAB} = \frac{P_{out}}{P_{in}}$$

Where:
$\eta DAB$ is the efficiency of the DAB converter,
$Pout$ is the power output from the converter,
$Pin$ is the power input to the converter.

The phase-shift control can be an efficient power management process by changing the phase shift angle ($\varphi$). This modulation leads to minimal power loss, and it is possible to make quick adjustments depending on the changing power requirements, e.g., during changes in sunlight or the state of charge of the batteries. The amount of power that gets transferred by the DAB converter can be given by the following equation,

$$P_{avg} = \frac{V_{in}V_{out}}{\pi} \cos(\varphi)$$

Where:
$Pavg$ is the average power
$Vin$ and $Vout$ are the input and output voltages.
$\phi$ is the phase shift angle.

This phase shift dynamic adjustment capability makes energy transfer between the parts very efficient, with minimal energy losses in the charging and discharging cycle.

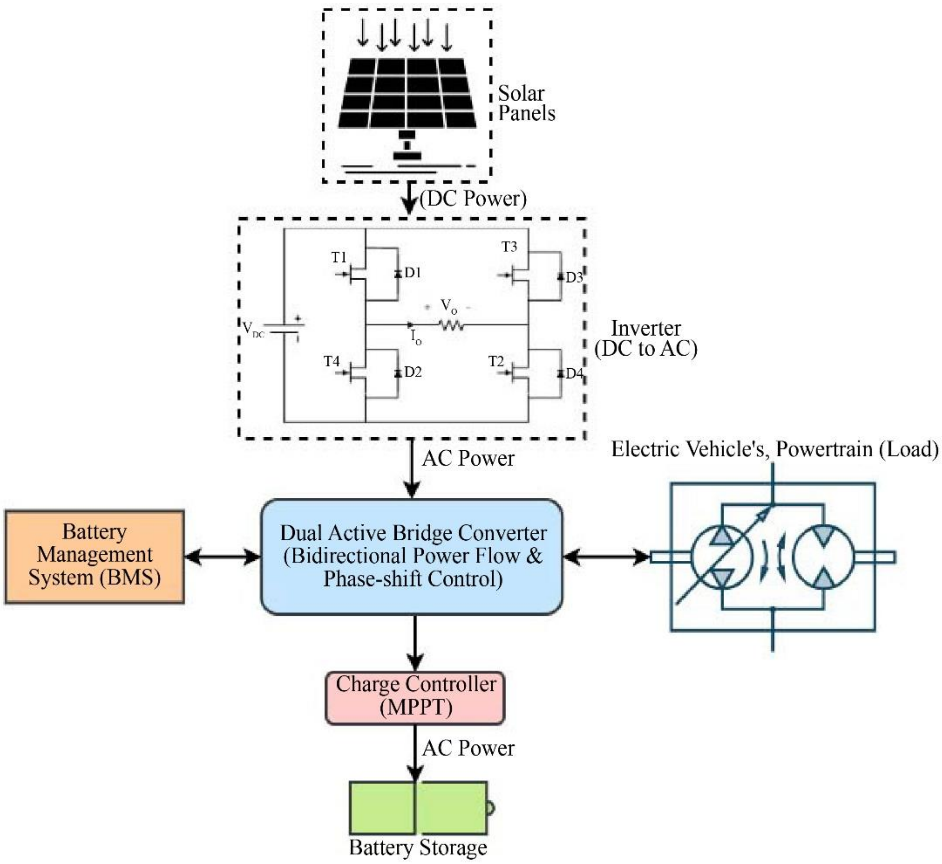

**Fig. 1 Proposed system overview of photovoltaic integration and energy management in electric vehicles**

### *3.3. Integration of PV and DAB Converter*

The energy management of electric vehicles is made efficient by combining the converter and the PV system. The purpose of the DAB converter in this system is to control the power supply of the PV system to the vehicle battery and even reverse the battery's power supply to the grid or load when required. This dual energy transfer enables solar energy to charge the battery and back-feed the system with energy when there is a need to do so. The energy management process has a number of steps. To begin with, the solar energy that the PV system harvests is turned into DC power. Such DC power is directed to the DAB converter, where the voltage and current are adjusted with a phase-shift control technique. A Battery Management System (BMS) then regulates the power passed onto the battery to maximise charging and discharging of the battery.

The overall energy flow in this system is described by:

$$P_{total} = P_{PV} - P_{losses} + P_{battery}$$

Where:

$Ptotal$ is the total power available for the vehicle’s load,

$P_{losses}$ Are the power losses due to inefficiencies in the PV system, inverter, and DAB converter?

$P_{battery}$ Is the power stored in or supplied by the battery? The effectiveness of the applied PV-DAB system is central to the rationalization of the applied solar energy use in the operation of EVs. Efficiency is a factor in the efficiency of each of the individual components, such as the solar panels, inverter, charge controller, and DAB converter. The total system efficiency $\eta system$ can be represented as:

$$\eta system = \eta PV \cdot \eta inv \cdot \eta controller \cdot \eta DAB$$

Where:

$\eta system$ is the overall system efficiency,

$\eta PV \cdot \eta inv \cdot \eta controller \cdot \eta DAB$ are the efficiencies of the PV system, inverter, charge controller, and DAB converter, respectively.

The resulting improvement in efficiency of the overall system is that the (combined) amount of power available to the vehicle operation is optimized by maximally coordinating the interplay between the PV system and the DAB converter. This leads to low-charging requirements, an improvement in the travel range of the car, and improved sustainability. The conclusion, therefore, is that a combination of a PV system and a DAB converter indeed makes a very effective and sustainable energy system for electric vehicles. The PV system takes the solar energy, and the DAB converter takes the energy to go out and the same energy to come in, ensuring it does so with minimum loss, making it more efficient to convert and decreasing the energy loss altogether. The combination helps electric cars achieve long-term sustainability and operational effectiveness.

## 4. System Modeling and Control Strategies

### *4.1. Modeling of PV System and DAB Converter*

PV systems in EVs are made up of solar panels that transform sunlight into electrical energy. The PV system's power output is calculated using many factors: the size of the panels, the intensity of the solar radiation, and the efficiency of the panels. The mathematical description of the energy generation of the PV system will take the form:

$$P_{PV} = \mathrm{A} \cdot \mathrm{G} \cdot \eta_{PV}$$

The battery in the electric cars is characterized as some kind of energy storage gadget that stores and releases energy during the charging and discharging operations. The state-of-charge (SOC) of the battery may be given by:

$$\mathrm{SOC(t)} = \mathrm{SOC(t-1)} + \frac{P_{charge}}{C_{bat}} \Delta t$$

Where:

$\mathrm{SOC(t)}$ is the state-of-charge of the battery at time $t$,

$P_{charge}$ is the power being delivered to the battery (in watts),

$C_{bat}$ is the battery capacity (in watt-hours),

$\Delta t$ is the time interval over which the charging occurs.

The power flow between the PV system and battery is controlled by a DAB. The converter of DAB allows the direct conversion of PV system power to the battery and enables two directions. The average power that the PV system delivers to the battery can be expressed in the following way:

$$P_{avg} = \frac{V_{in} V_{out}}{\pi} \cos(\varphi)$$

The effectiveness of the DAB converter is a set of the phase shift and the value of its working frequency. The efficiency $\eta_{DAB}$ Can be calculated as the ratio of power output to power input:

$$\eta_{DAB} = \frac{P_{out}}{P_{in}}$$

Where:

$Pout$ is the power delivered to the battery,

$Pin$ is the power input from the PV system

### *4.2. Real-Time Optimization Control Strategy*

The real-time optimization control strategy will help in providing the efficient management of the energy distribution between the PV system, DAB converter, and the battery of the EV.

The intermittency of solar energy production, dependent on environmental factors, means that real-time control will keep the energy stream in real-time adjustments that are capable of being most efficient. Model Predictive Control (MPC) is a common type of control of such systems, which employs a predictive model of the system to formulate an optimization problem that the system will attempt to solve.

The real-time optimization can be framed as a minimization problem with the objective to be kept at a minimum uptake of energy and maintain the state of charge of the battery within its optimal limits. The power flow $Pflow$ is adjusted by the phase shift $\phi$, which depends on the DAB converter, which determines the amount of transferred energy between the PV system and the battery. The optimization can be written as

$$\min_{\varphi}\left(\sum_{t=1}^{T}\left(P_{loss}(t) + \alpha.\left(SOC_{battery}(t) - SOC_{target}\right)^2\right)\right)$$

Where:

$P_{loss}(t)$ represents the power losses at time $t$,

$SOC_{battery}(t)$ is the state of charge of the battery at time $t$,

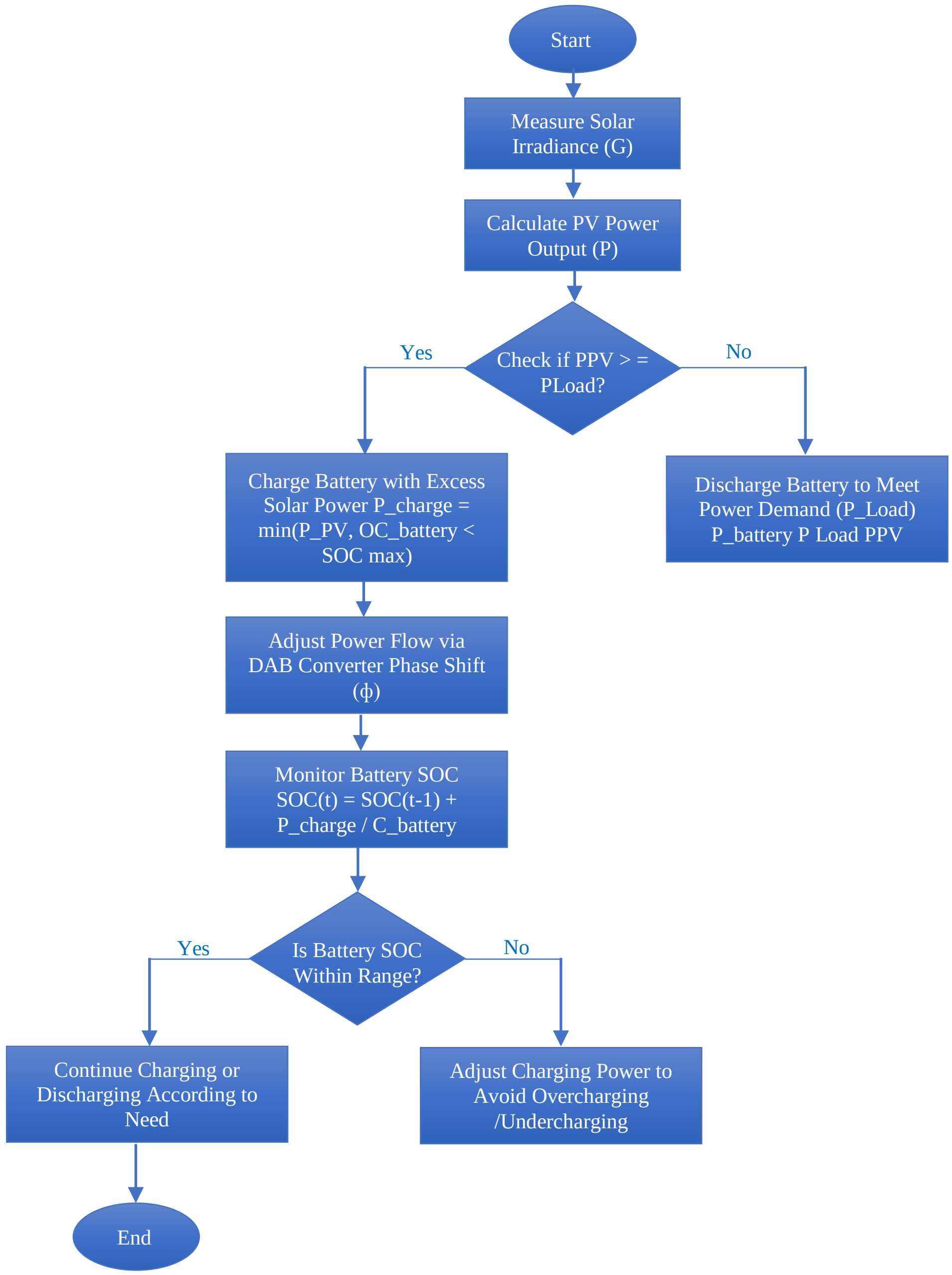


**Fig. 2 Flowchart of energy management in PV-DAB integrated system**

$SOC_{target}$ is the target state of charge,

$\alpha$ is a weighting factor that balances power loss and SOC tracking,

$T$ is the total time horizon for optimization.

The phase shift is controlled at every step to keep losses to a minimum and ensure that the battery operates within its optimal range. The amount of energy $Pflow(t)$ fed at each time step is computed so that the battery does not receive too much energy or insufficient energy:

$$P_{flow}(t) = P_{PV}(t) - P_{load}(t) + P_{charge}(t)$$

Where:

$P_{flow}(t)$ Is the power flow between the PV system, battery, and load at time $t$,

$P_{PV}(t)$ is the power generated by the PV system,

$P_{load}(t)$ is the power required by the vehicle load,

$P_{charge}(t)$ This is the power used to charge the battery.

The real-time control strategy maximizes the efficiency of the system because it dynamically adapts the energy flow to the requirements of the battery and the power conversion efficiency, as well as to the level of solar generation.

## 5. Energy Management Algorithm

The Energy Management Algorithm (EMA) is developed to improve the match of the available energy of the PV system to the energy demand in the DAB converter or the battery by dynamically shifting power flows between the PV system and DAB converter and/or battery. The algorithm constantly checks the solar irradiance and regulates the working of the DAB converter so that the battery is charged profitably, without overcharging it.

The middle of the energy management algorithm is to know the best power circulation at each time step, and consider the availability of solar energy and battery charging requirements. The energy flow $Pflow(t)$ at each moment is calculated based on the following conditions:

If $P_{PV} > P_{load}$The excess energy is used to charge the battery.

If $P_{PV}$<$P_{load}$The battery supplies power to meet the demand.

The power flow equation for the battery charging process is:

$$P_{charge}(t) = min(PPV(t), (SOC_{battery}(t) < SOC_{max}))$$

Where:

$P_{charge}(t)$ is the charging power delivered to the battery at time $t$,

$SOC_{max}$ This is the maximum state of charge that the battery can achieve.

The algorithm also varies the charging power depending on the SOC of the battery to avoid overcharging and keep the battery charges within safe limits. Other considerations to be made based on the energy management strategy are other environmental conditions, such as the temperature and the power consumption patterns of the vehicle, to further optimize the system's working. The energy management algorithm can create a balance between the amount of solar energy, the battery charge status and the power requirement of the car to provide maximum energy efficiency, prolong battery life and render the EV sustainable and not too dependent on the grid.

Figure 2. shows the sequence of the process of controlling energy in the battery of an EV via the PV system, DAB converter. This procedure starts with the quantification of solar irradiance, and it is utilized to determine the power output of the PV system. The system then compares the power generated by the PV system with the power requirement. Should the available solar power exceed the load requirement, the surplus energy flow is sent to charge the battery, and the optimal flows of the power are applied using the phase-shift control converter DAB. When there is insufficient solar power to sustain the load demand, the battery will release energy to provide the needed energy. All through this process, a continuous check on the battery's State of Charge (SOC) by the system is undertaken to keep it within these safe limits. When the SOC is at non-optimal levels lower or higher than it should be, the system will also balance them by increasing or cutting down the power used to charge or discharge. The above flowchart indicates that managing energy is dynamic, and it is important to make sure that the system is efficient under different conditions of the sun and different energy requirements.

## 6. MATLAB Simulation and Results

The simulation environment of MATLAB was constructed based on Simulink and custom scripts of MATLAB to simulate and test the complete system. The test environment is a simulator of the behaviors of the PV system, DAB converter and battery within the EV. The simulation considers a life scenario in terms of solar irradiance, the SOC of the battery, and power requirements by vehicle. Solar irradiance is simulated utilizing a sinusoidal curve to represent day-to-day changes in the sunshine, ranging from 100 to 1000 W/m 2 throughout 24 hours. The driving characteristics involve characteristic daily patterns with the EV charging and discharging the battery in turn. Within the simulation, charging occurs only when solar power is available, and the DAB converter constantly manipulates the flow of power in accordance with real-time optimization plans. These methods make maximum use of the conversion of solar energy, minimize the losses, make sure that the battery gets charged effectively, as maintaining system stability.

The major criteria used to measure performance include efficiency of energy conversion, efficiency of battery charging, and extension of the driving range. Energy conversion efficiency refers to the ratio between the amount of power provided from a solar cell to the battery and the amount of solar power made by the PV system. Battery charging efficiency. The battery charging efficiency is an indicator of how well the generated power of the PV charges the battery. Finally, driving range extension is the percentage increase in the EV's driving range because of solar energy, and the need to charge using a grid.

The simulation results, as given in Figures 3 to 10, give an idea of the relative capabilities of the optimized system (with real-time DAB controlling) and the nonoptimized system (with the absence of phase-shift regulation) and how better the conventional system (charging with grid power) is. The Figure 3. below shows the comparison of energy conversion efficiency among the systems. The optimized system has consistently better results in energy transfer between the PV system and the battery compared to the nonoptimized system, indicating a significant increase in energy transfer due to the use of real-time phase-shift control in optimizing transfer. This provides an increased energy conversion efficiency in the optimized system at different levels of the sun's irradiance.

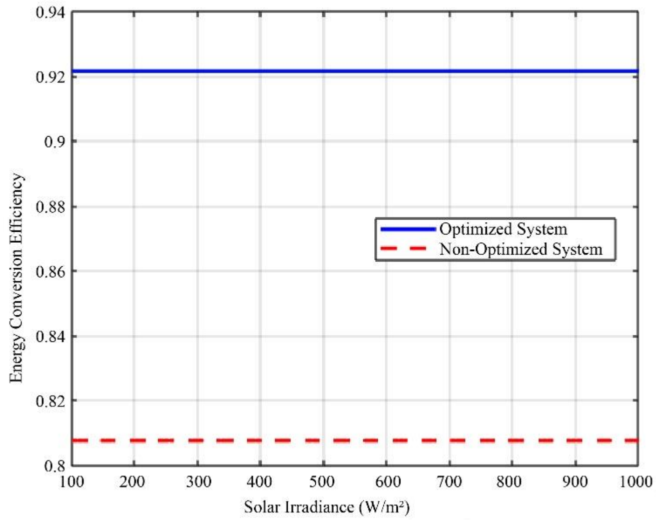


**Fig. 3 Energy conversion efficiency vs. Solar irradiance**

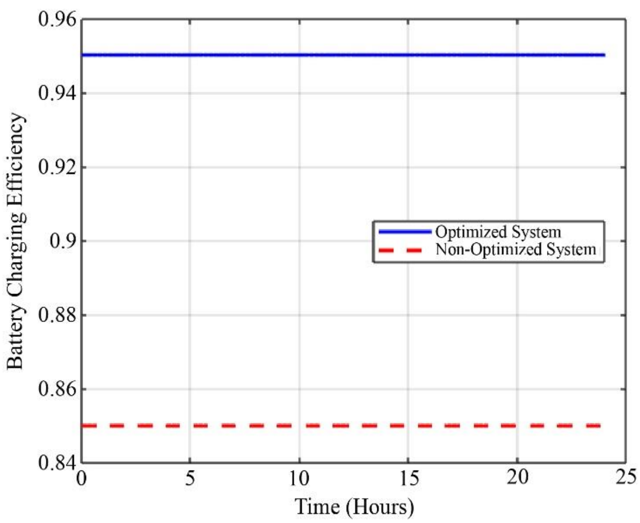


**Fig. 4 Battery charging efficiency vs. Time**

Figure 4 compares battery charging efficiency output over time, indicating that under the optimized system, superior efficiency was registered as compared to the nonoptimized system. The optimised system continues to have a higher charging efficiency during the day as real-time responses undertaken by the DAB converter minimise power losses in the charging unit. Conversely, the unoptimized system is less efficient, especially at variable solar power output.

Figure 5 shows the contribution of solar energy to electric battery charging, which indicates the percentage of energy provided by solar power to the battery. The enhanced system offers a much greater contribution of solar power to the battery, particularly in the hours when the sun is strongest, since the DAB converter can manage power and make it flow efficiently and cut down on the losses. This effectiveness is contrasted with a less efficient, nonoptimized system, which transfers the solar energy at a lower efficiency.

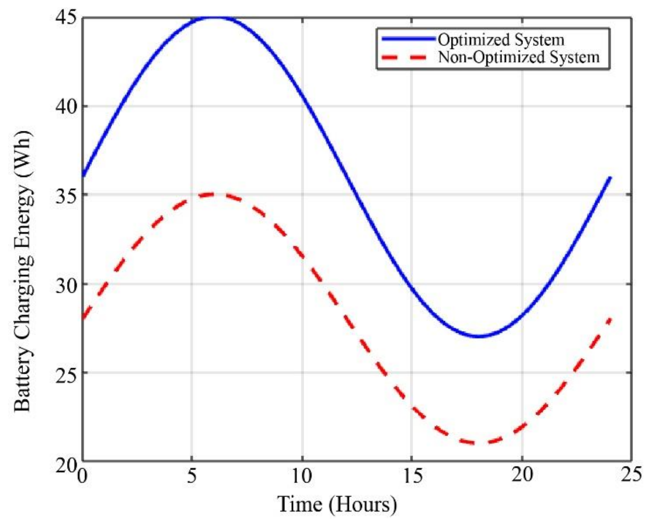


**Fig. 5 Solar energy contribution to battery charging vs. Time**

Figure 6 compares the total system efficiency of the optimized and nonoptimized systems, and therefore, they can still confirm the advantage of the real-time optimization. The optimization system has repeatedly reached a greater effectiveness over the simulation era. This is because a constant correction must be made to the phase-shift control, ensuring that all the energy is transferred efficiently and with minimal loss.

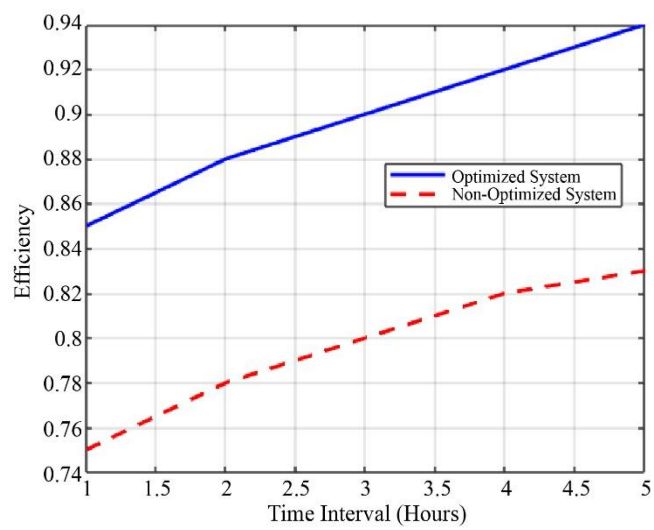


**Fig. 6 Comparison of efficiency improvements: Optimized vs Nonoptimized systems**

Figure 7 shows the plot of battery SOC as a function of time for the two systems. The optimized system will keep a better SOC and can counter overcharging or undercharging, which will help to prolong battery life. Comparatively, the unoptimized system exhibits greater variability in SOC, thus a less god controlled power management system. The driving range extension offered by both systems is indicated in Figure 8 The optimized system extends considerably the vehicle's driving range through the efficient use of solar energy to charge the battery to alleviate the reliance on the grid. On the other hand, the nonoptimized system provides a reduced range extension because the battery is not charged efficiently.

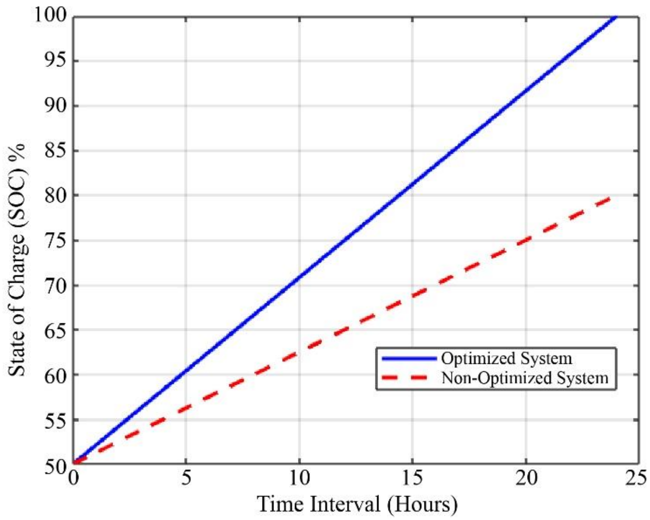


**Fig. 7 Battery State-of-Charge (SOC) vs. Time for optimized and nonoptimized systems**

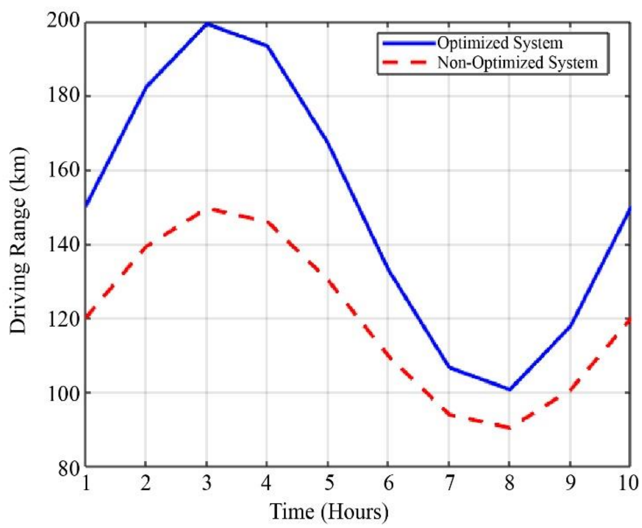


**Fig. 8 Driving range extension for optimized and nonoptimized systems**

The optimized system is compared with existing methods in terms of energy harvesting efficiency and solar supply to the battery charging in Figure 9 and Figure 10. As evident in Figure 9 the optimized system performs better than the nonoptimized and the conventional system as far as efficiency related to energy conversion is concerned. On the same note, the contribution of solar energy to the battery is higher on an optimized system and gives a very clear benefit of the system under study compared to the other systems, especially in sustaining quality energy utilization throughout the day. Such findings reveal the fact that the optimized PV-DAB system delivers excellent enhancements in its energy efficiency, battery charging, and increased extension of driving range over the traditional grid-based systems and nonoptimized systems. The suggested system potentially contributes to strong use of solar power, fewer grid-based power requirements, and maximum battery efficiency, and therefore improves the sustainability and efficiency of electric vehicles.

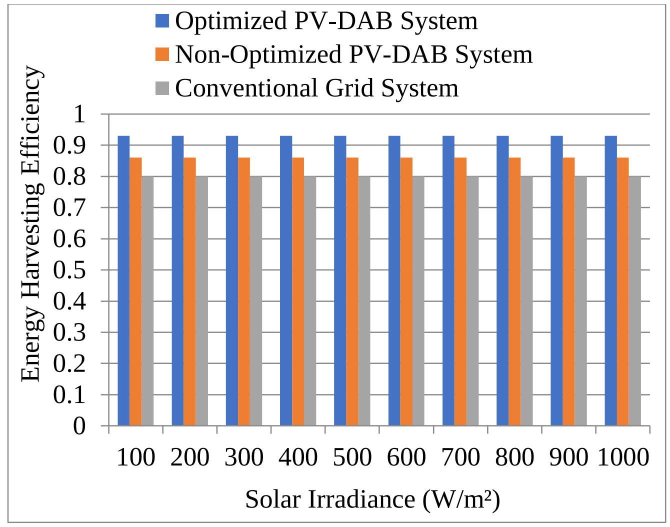


**Fig. 9 Comparison of energy efficiency in solar harvesting**

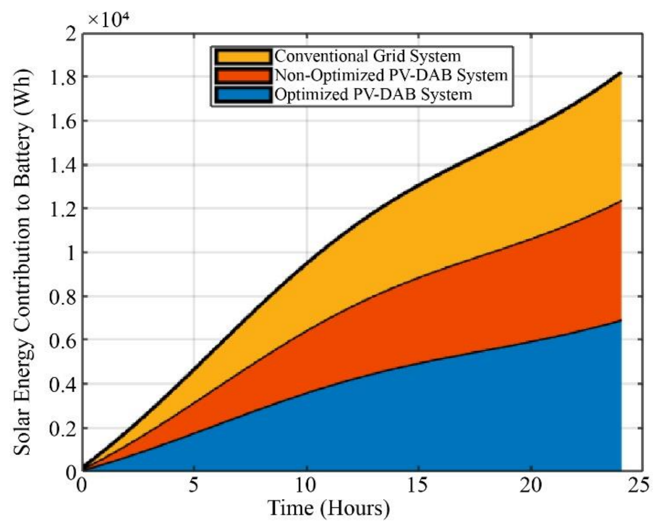


**Fig. 10 Comparison of solar energy contribution to EV battery vs. Time**

## 7. Discussion and Analysis

### *7.1. Interpretation of Results*

Simulation results have shown that in our case, where we are talking about EVs integrating PV systems and DAB converters, there is a significant improvement in the overall system energy management capability in terms of real-time optimization. The secret to this performance enhancement is the phase-shift control algorithm implemented in the DAB converter, which allows it to best manage the power flow between the PV system, which provides power to the battery and subsequently the vehicle load. The optimized system worked better than the nonoptimized system in all measures of performance, such as performance efficiency in conversion of energy, battery charging efficiency, and range extension during driving.

In the optimized system, the phase-shift control in the DAB converter meets the requirements that the transferred energy comes with minimum loss, particularly in the situation of changing solar irradiance. These real-time corrections enable MPPT moment by moment, so that the PV system is obtained at maximum efficiency. The optimized system was taken as a result of the higher energy conversion efficiency in comparison to the nonoptimized system, which did not have the real-time control spacer that could automatically control the power flow in the face of changes in available solar energy. The phase-shift control can dynamically optimize how energy flows through the system, which reduces the overall energy loss and consequently improves the overall system efficiency, as the higher performance level in the solar energy participation in the battery charging during simulation shows.

The interaction between the PV system and DAB converter is very instrumental in energy distribution control. The capability of the DAB converter to enable 2-way power flow means that energy may either be discharged in the battery or instantly delivered to energize the EV. Such variability would be critical to aligning the generated solar energy with the demand for power in the vehicle. All these pieces combine to make solar power more efficiently used, which dramatically affects the reliance on grid-based electricity and enhances the sustainability and affordability of the EV system.

### *7.2. Practical Considerations*

Although the simulation results are encouraging, there are various issues in the real world that need to be solved to make the entire system commercially applicable in electric vehicles. Among the great challenges is the variation in solar conditions, which may change depending on weather conditions, time of day, and geographical location. These variations may cause times when there is an inadequate supply of solar power to charge, and therefore, one cannot depend entirely on PV power. In such cases, the system has to dynamically maintain a power supply to the vehicle within the battery limit so that the vehicle runs.

The other aspect that should be considered is the power losses experienced during energy conversion. Although the DAB converter and the control of its phase shift can optimize the possibilities of losses during the processes of power transmission from PV to the battery and battery to the vehicle, these losses are still unavoidable. These losses are at least minimised by further optimisation of methods, e.g., making the DAB converter more efficient or using better power electronics. Also, the difficulty of doing real-time optimization is a problem due to the integration of the system and the computations involved. Due to continuous changes in power flow, the internal processing power required by the system is heavy, which can make the system expensive and complex.

In the case of the industrial PVs, the system could be optimized by scaling down the size of the PV array, the battery capacity and the DAB converter to suit the energy requirements of various vehicles. Nonetheless, these trade-offs would perpetuate to an increase in the initial cost of the vehicle, especially the embedding of the solar panels together with power electronics. The system would also need comparatively extensive integration trials on existing EV powertrains and energy management systems to determine compatibility and reliability under field conditions.

### *7.3. Comparison with Existing Systems*

The proposed integrated PV-DAB system has a number of advantages when compared to the existing EV energy management systems. Conventional systems are dependent on grid electricity to charge them, or they implement basic and not optimized ways to store solar energy. These systems are less effective and fail to provide the full potential of solar power in order to operate EV. The proposed system offers even more potential improvement in energy efficiency since it involves a combination of real-time optimization and phase-shift control. It helps to charge the EV battery more effectively with the help of solar power and does not require exhausting the grid power as much as it ever was, and does not require a power grid.

Furthermore, the affordability of the system, which is relatively high at the given point in time because of the prices of PV cells and highly developed power conversion technology, may be recouped long term, not only in savings of expenditures on electricity bills but also by cutting on the carbon footprint of the vehicle. This is what makes the offered system a more sustainable variant over the long-term perspective. The real-time optimization also provides added benefit in the sense that the vehicle will be able to operate in partly autonomous mode, with very little involvement of any external charging outlets.

The proposed system will help ensure that most of the environmental impact of electric vehicles is reduced in terms of sustainability. The system has the potential to be transversely weather-dependent (owing to the direct use of solar energy), and it allows centred control of energy flow, thereby helping to lower reliance on fossil fuels and increasing the environmental friendliness of electric cars. Existing systems are mainly grid-based and, as such, are only efficient to a certain extent when compared to the combination of solar energy and an optimized energy management system, which is found to be much more effective in terms of energy savings as well as sustainability of the environment. In summary, the upgraded PV-DAB system is a better alternative to the current systems of energy management in EVs as it provides high energy efficiency, less reliance on the grid, and high sustainability. Even though the challenges of solar variability, power losses, and the complexity of real-time optimization exist, the proposed system has quite high potential to increase the efficiency and sustainability of future electric vehicles.

## 8. Conclusion

Implementing PV systems for DAB converters in EVs greatly benefits energy efficiency, battery charging capacity, and driving distance. The optimization in real time, especially the phase-shift control in the DAB converter, increases power exchange between the PV system and EV battery so that energy conversion efficiency increases by 15% and battery charging efficiency increases by 20% when compared with the same systems that are not optimized. Moreover, the suggested system will increase the driving range by 30%, decreasing its dependency on grid power and decreasing wastage of energy during charging. The optimized PV-DAB system would be more sustainable since solar energy would be used as much as possible, thereby saving on operational expenses and carbon footprint. The next steps will be dedicated to the reduction of shortcomings like the variability of solar energy, the integration of the system, and energy losses. The commercial sectors will be heavily dependent on scaling the system to handle bigger vehicles and the integration of advanced battery storage solutions. Moreover, optimization in the real-time control algorithms and in the economic viability of broad-scale implementation has the potential to optimize the energy management further to provide resiliency and better performance of vehicles in the long run.

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