

AI-DRIVEN SOLAR MOBILITY

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Abstract

This paper discusses integrating solar energy and artificial intelligence in electric vehicles to improve efficiency, sustainability, and overall performance. It then explores in detail how solar-powered EVs contribute to reducing GHG emissions through photovoltaic technology that converts sunlight into useful electricity. The paper also explains how AI optimizes energy management, predicts solar power generation, and enhances battery storage efficiency. Furthermore, a few words about the improvement of photovoltaic technology, among them the perovskite and multi-junction solar cells, are mentioned below to underline their significance in the increase of energy conversion efficiency. Another aspect is its role in the vehicle-to-grid (V2G) system, autonomous electric vehicles, and smart charging infrastructures. While some of the energy storage limitations, efficiency constraints, and high costs remain, this paper has brought out how continued advances in AI and solar energy can revolutionize transportation. Combining these technologies will make a future of cleaner, smarter, and more sustainable mobility increasingly possible.

Keywords: Solar energy, artificial intelligence (AI), electric vehicles (EVs), photovoltaic technology, GHG emissions reduction, energy management optimization, battery storage efficiency

1. Introduction**1.1 Background**

One of the greatest tackles in human history in terms of protection of our planet is Climate change and Global warming. Major participants are vehicles such as cars, trucks, ships, and planes that use fossil fuels. This leads to emissions of greenhouse gasses such as Carbon Dioxide. Transport is responsible for roughly 25% of the global Carbon Dioxide emissions. This leads to warming temperatures, critical health risks, increased droughts, etc. [1] Hence, to avoid such disasters, the demand for solar-powered vehicles has increased significantly in the past few years [2]. Solar-powered vehicles use solar panels, which are made up of many photovoltaic cells (PV cells). An individual PV cell generates around 1-2 Watts of power and is typically small. These cells are made of different semiconductor materials. g.g. Silicon) and are usually less thick than four human hairs [3]. To boost the power of PV cells, they are connected in long chains to form larger units known as modules or panels. Modules can be used individually, or many could be connected to form an array. One or more arrays are then connected to an electrical grid to form a complete PV system [3]. PV cells capture sunlight and produce electricity, hence making it the primary source of power. Solar vehicles are manufactured in several shapes and sizes and usually use an electric motor to drive. The electricity required by the motor is generated by the solar panels present on the vehicle [2].

1.2 Role of AI in Renewable Energy and Mobility

The integration of Artificial Intelligence (AI) can help enhance the performance of renewable energy

systems in numerous different ways: An improvement in the efficiency of the systems, reliability, and cost-effectiveness. AI has also proven to be effective in problem-solving situations; machine learning can be used to predict the amount of electricity generated by solar power plants with high accuracy. Moreover, AI can also be utilized in bettering prognostic and health management techniques (PHM) for renewable energy systems; these advancements may push us closer to carbon neutrality.

Furthermore, AI plays a crucial role in electric vehicles (EVs). It can be utilized to improve system efficiency and sustainability. AI can also be used to predict the optimization of charging schedules. It can predict when to charge EVs and how much to store for later use according to weather patterns, renewable energy availability, and real-time charging demand. In addition, AI can also manage energy storage systems, allowing the storage of excess energy when there is low demand and released when the energy generation is insufficient. [4]

AI also helps in the efficient management of charging stations, ensuring more desirable use and a reduction in energy wastage. AI would ensure when and where it is needed; this would also reduce waiting times for EV owners, avoiding vehicle logging at stations. AI-driven systems can predict when EV components are likely to fail; this would allow dynamic maintenance. Not only does this make it a lot safer, but it reduces the environmental impact of repairs, too. This prevents unexpected breakdowns and the need for extra parts. AI will also assist in the growth of next-generation batteries. By analyzing various materials

and structures, AI can help make stronger, more durable, and environmentally friendly batteries. This will reduce charging times and make EVs more competitive with everyday vehicles [4].

1.3 Photovoltaic Advancements and Energy Conversion

Photovoltaic technologies, also more commonly known as solar panels, generate power by absorbing energy and converting it into electrical energy. The conversion of light (photons) into electricity (voltage) is called photovoltaic effect. Usually, solar panels tend to have efficiencies ranging from 15% to 20%, with the highest being 23%, which is impressive considering the first solar modules only had an efficiency of 6% [5]. However, using anti-reflective coatings or light-trapping structures such as photonic crystals can increase the efficiency of a solar panel. Anti-reflective coatings minimize reflection losses; this increases the light absorbed and converted into electricity. Light-trapping structures extend the light path within the solar panel, this captures more light and increases the probability of absorption.

Each solar cell has a thin semiconductor wafer, which is made up of two layers of Silicon. One Silicon layer is positively charged and is known as P-type, and the other is negatively charged and known as N-type. N-type gives away electrons easily while on the other side, P-type receives extra electrons in the electric field. This positive and negative layer hence compliments the formation of an electric field on the solar panel. When sunlight strikes these PV cells, which have already formed an electric field, the photons of the sunlight startle the electrons inside these cells, activating them to start flowing. These loose electrons that flow in the electric field further create the electric current.

However, the electrical energy produced from these photovoltaic cells is DC. Direct Current (DC) electricity cannot be used to power homes and buildings, so it needs to be converted to Alternating Current (AC) electricity. To do so, special solar inverters are installed. Once DC is converted to AC, the current then runs through the electrical panel installed in your system and supplies power to the appliances being used [6].

2. Overview of Solar Mobility and Photovoltaic Technology

2.1 Solar Mobility: Concept and Applications

Solar power is a promising option for reducing Greenhouse Gas (GHG) emissions worldwide. In 2020, the U.S. Department of Energy (DOE) estimated that the transportation sector accounted for 27% of the GHG emissions. Although solar power is becoming more popular worldwide, it is

still in its infancy. Some countries leading the transition to solar transportation include the U.S., Japan, China, Germany, and India. [7] Let's explore some of the potential solar-powered modes of transportation that could make these much-needed changes possible.

Solar Cars - Solar cars depend on PV cells to convert sunlight into electricity. Thermal energy is also formed in the process of the photovoltaic effect, which converts to heat for either household purposes or industrial purposes. PV cells directly convert sunlight into electricity. A solar car gets the energy it requires to move from sunlight. If you look at the solar car below, you can observe that the majority of its surface is black. This helps it to absorb the sunlight as black objects are the best absorbers of light. Usually, black objects just get hot in the sun. But in a solar car, some of the light is converted to electricity by a device called a "solar cell." Each of the dark panels that you can see in the photograph contains many such solar cells. The electricity is used to drive the car's electric motor. Excess electricity is stored in a battery for cloudy periods.

Solar Arrays - Solar arrays collect energy from the sun and convert it into usable electrical energy. Firstly, solar arrays collect all the sunlight together, then immediately change it to electricity and send it to the power tracker. Power tracker converts the solar array voltage to system voltage; it converts it into energy that the car can utilize. This energy is then sent to the battery. The batteries store energy from the power tracker and make them available for the motor's use. After the power tracker converts the energy to the energy that is usable for the car, it sends it to the battery, and then the battery stores the energy. This energy is sent to the motor and the controller. The motor controller adjusts the amount of energy that flows to the motor to correspond to the throttle, and it uses that energy to drive the wheels.

To enhance energy efficiency and extended range, solar vehicles are often constructed with lightweight materials such as carbon fiber composites and aluminum alloys. These materials reduce the weight of the car, minimize energy requirements, and improve acceleration and handling. Efficient aerodynamic design is crucial for reducing drag force and optimizing solar vehicle performance. Streamlined body shapes, smooth contours, and optimized airflow help minimize resistance, allowing solar vehicles to glide through the air with minimal energy loss. Integrating solar panels flawlessly is essential for maximum energy capture. Solar panels are carefully positioned and aligned to ensure

maximum exposure to sunlight while maintaining the vehicle's aesthetics and aerodynamic profile [8].

Solar Trains - The UK has recently unveiled the world's first solar railway track. Solar-powered trains typically operate by installing photovoltaic panels near or directly on the rail lines, generating enough electricity to create a traction current that feeds into the grid. These systems could offer significant financial advantages to networks that currently depend heavily on traditional grids. The 'Riding Sunbeams' report, which shares its name with the project, indicated that harnessing solar power from DC traction power systems could greatly reduce grid dependence and save around £4.5 million annually. The report suggested that this model could soon be effectively adopted in urban metro systems like the London Underground, where solar energy could meet 6% of the energy demand.

However, while solar PV technology may soon be integrated into underground networks globally, its application in large-scale railways may still take some time. This isn't the only model in existence. In India, for instance, trains are equipped with solar panels on their roofs, and in 2017, Guwahati became home to the first fully solar-powered station in the country. The local government is also planning to implement solar PV at 8,500 stations in the coming years.

Similar projects have recently begun in Australia and Argentina, although they are currently limited to smaller locations [9].

2.2 Advances in Photovoltaic Technology and Challenges

2.2.1 Improvements in Solar Cell Efficiency

Perovskites are a class of materials that have displayed high performance, at potentially lower production costs, in solar cells. The term "perovskite" is derived from their crystal structure. The same materials used in other energy-related fields are fuel cells and catalysis. The type of perovskites that can be commonly used in photovoltaic (PV) solar cells is more precisely known as "metal-halide perovskites" because they are made from a combination of organic ions, metals, and halogens. Other applications of perovskites may use oxygen instead of halogens and usually are entirely inorganic.

Metal-halide perovskites are the primary light-absorbing material, or "active layer," in a perovskite solar cell. In this potentially cheaper technology, a thin layer of perovskite absorbs light, exciting charged particles called electrons. When these excited electrons are pulled out, they create electric power. Perovskite cells are referred to as

thin-film because they require much thinner active layers in comparison to crystalline silicon PV.

That may be because perovskite is very good at absorbing certain colors of light. Stacks of layers of perovskite absorbers can even be placed on top of another absorber layer to harvest light colors that didn't get absorbed in the perovskite, the result being a cell able to be much more efficient, theoretically, compared to cells based on either one alone. When two layers are stacked in such a way, it's called a tandem solar cell. Perovskite solar cells have taken tremendous strides over the past few years, with efficiency rapidly rising from around 3% in 2009 to over 26% today on small-area devices (roughly 0.1 cm²). Perovskite-silicon tandem cells have reached efficiencies of nearly 34%. While perovskite solar cells have become highly efficient in a very short time, perovskite PV is not yet manufactured at scale, and several challenges must be addressed before perovskites can become a competitive commercial PV technology [11].

However, there is another type of solar cell that is known to have a higher efficiency than the typical photovoltaic cell. Multi-junction solar cells are an exciting technology that may provide increased efficiencies in the solar panels of the future.

Because of different wavelengths, the top and bottom layers absorb different components of incoming sunlight. Multi-junction solar cells have been demonstrated to be considerably more efficient in the conversion of sunlight into electrical power than a single-junction device. That's many times more efficient than regular solar cells; however, the high production cost and ongoing research and development mean that it's not commercially available or even economically feasible for general use at the moment.

A multi-junction solar cell is a type of tandem solar cell having more than one p-n junction. In the practical world, this implies having multiple layers made from diverse semiconductor materials; each layer in these devices responds differently to varying wavelengths of light and, therefore, can also generate electrical currents. This would mean, theoretically, that multi-junction solar cells have the capability of converting more sunlight that reaches them into electricity as opposed to single-junction solar cells.

Like normal silicon solar cells, multi-junction solar cells convert light into electricity using the photovoltaic effect. The photovoltaic effect is a rather complex chemical and mechanical process that can be summed up in three major steps:

1. Light is absorbed by solar cells, and electrons in the semiconducting material are knocked loose.
2. Loose electrons flow through the p-n junction between semiconductor layers, creating an electrical current.
3. The current is captured and transferred to wires.

Those multi-junction solar cells with three junctions have theoretical efficiencies of over 45 percent, while the top-end single-junction cells max out at about 33.5 percent. Adding more junctions—up to 5 or 6 junctions—could see efficiency boosted by over 70 percent. To put that into perspective, the most efficient solar panels on the market today have efficiencies of about 22 percent. Multi-junction solar cells are a very exciting and promising technology that may help increase the efficiency of solar panels. They are still in the test and research stages and, therefore, cannot be bought for solar panel installation. [12]

3. Role of AI in Solar Energy Conversion and Management

3.1 AI-Driven Energy Conversion

In the last few years, attention given to artificial intelligence techniques, including machine learning and deep learning, has increased. This boosted their application in solving different problems in a variety of fields. Some applications of AI techniques in solar energy systems, which include both photovoltaic and thermal systems, have already been available. In the area of photovoltaics, AI techniques have been utilized and applied to solve the following problems:

Solar cells: Thin-film degradations, perovskite technology stability, optimization of efficiency, modeling, and prediction of the current-voltage (I–V) curves.

PV module/array: Power optimization by tracking the maximum power point under normal and abnormal conditions, fault detection, identification, diagnosis, and forecasting of the power produced.

PV systems (standalone, grid-connected, and hybrid PV systems): Control, optimal energy management, power sharing, and performance prediction [16].

In addition, ANNs have shown great potential in predictive modeling. Previous studies have proved that they can be effective in the estimation of PV system output using weather data, system characteristics, and historical performance data. It provides proactive maintenance and fault detection, hence reducing downtimes and increasing the quantity of energy generated by ML techniques. Furthermore, machine learning—especially deep learning—has been adopted to improve the

accuracy of PV power prediction; hybrid models that incorporate weather data and historical performance data show great potential in enhancing the reliability of forecasting. Lastly, there have been a large number of novel applications in the integration and optimization of PV systems in recent years. For example, ML algorithms have been applied in optimizing PV system design and layout, improving the estimation of energy yield, and enhancing system reliability by developing advanced control strategies.

Generally, the integration of ML techniques into PV systems has a huge potential to optimize performance, improve efficiency, and, most importantly, reliability. Hence, it is one avenue toward sustainable energy solutions.

3.1.2 AI's role in enhancing energy conversion efficiency

Looking across the board at the impact of AI in different fields, especially in the energy sector, helps us realize its potential to make big changes. Bringing AI into the energy field marks the beginning of a new era where better efficiency and sustainability are possible. The bonding of AI and Energy presents opportunities exciting for major improvement. This is especially important to the innovators in the energy sector because change in the energy systems can occur through them. AI has a great influence on energy production because it uses vast data, including real-time information and environmental conditions, to adjust power generation. This adjustment makes energy production not only more efficient but also reduces wear and tear on equipment, extending its life and reducing environmental impact.

In the operation of energy, AI can save significant costs. It helps reduce operating costs and increases profits by improving processes and reducing waste. Besides, AI supports sustainability because it reduces carbon emissions, enhances energy efficiency, and maximizes the use of renewable sources of energy, which is very critical in the global fight against climate change [17]. Moreover, AI's ability to forecast energy demand accurately is a significant improvement. It allows energy providers to better align supply with actual consumption, which reduces waste and improves the reliability of the grid. As

As we move toward renewable energy, such forecasting becomes essential to ensure that these resources are used effectively and support a sustainable energy transition [18].

3.2 AI-Enabled Energy Storage and Distribution

AI has become very relevant for effective use in solar power through the application of energy storage systems. Artificial intelligence algorithms

enable the prediction of when energy will be produced and consumed, hence allowing efficient utilization of energy storage. The excess energy from solar power, when it is in abundance, is stored in the batteries, and when at a lower amount, AI keeps the grid stable and increases the usage of renewable energy by using the stored energy in the batteries.

AI strongly affects demand forecasting and load balancing, which are critical for stability in the grid. Through analyzing past consumption data and variables at the moment, such as weather and economic activity, AI correctly predicts the energy demand. The forecast allows grid operators to manage demand and supply properly, lessening the need for fossil fuel-based power plants during peak load times [19].

EVs have replaced fossil fuel-based vehicles and offered better performance in simplicity, precision, and reliability. However, EVs have some disadvantages in limited travel distance and long charging time, with degraded battery performance under various uncertainties. In this way, an advanced and intelligent BMS is required to overcome those critical problems related to thermal runaway, cell unbalancing, overcharging, over-discharging, overheating, and fire risks.

The BMS is the brain in managing and optimizing EV performance. A BMS is the most important sub-system of an EV; it assures safety, longevity, and performance of the battery pack, guaranteeing an overall smooth driving experience for the end users. The development of an effective and intelligent BMS is essential to estimating the remaining useful life (RUL) state of energy.

(SOE), state of charge (SOC) and state of health (SOH), as well as to perform charge balancing, temperature management, and fault diagnostics. It uses different circuit devices, power electronics components, algorithms, and techniques to implement the different functionalities, including SOC management, overvoltage, and Under voltage protection, temperature control, battery cell balancing, energy efficiency, and expansion of battery life.

Inefficient algorithms for BMS in EVs can cause all sorts of problems: poor performance of the battery, safety issues, and a shorter life span for the battery. The development and implementation of proper BMS algorithms, in consideration of data accuracy, advanced modeling techniques, sensor quality, real-time monitoring, and adaptability in a variety of driving conditions and user behaviors.

Artificial intelligence approaches can enhance the functionality and performance of BMS in EVs. Some of the key benefits of AI-driven BMS in EVs

include better performance, safety features, energy efficiency, and user experience, which are also helping to prolong the life of the battery. Various state-of-the-art research articles have proved the importance of the AI approach in examining the effectiveness of the EV application. Some of the helpful characteristics of AI approaches over conventional ones: AI techniques require less knowledge taking less development time in designing complex battery systems compared to traditional model-based frameworks. Further, AI algorithms and optimization schemes do not necessarily require deep domain knowledge of physics, chemistry, and chemical reactions inside a battery but rather an abundance of data and high computational power. Also, they perform very well under the presence of sufficient data and are effective for managing uncertainties like noise, temperature variations, and aging effects.

Also, the self-learning operations allow these devices to realize the configurations quickly online, thus reaching excellent performance.

Conclusion

The merger of artificial intelligence and solar power in electric vehicles embraces a new and necessary step toward reducing the carbon footprint. Since transportation is the biggest emitter of greenhouse gases, a change to renewable sources is essential. Solar-powered EVs could be an alternative, lessening the use of fossil fuels and revoking the damage to the environment. While it is still early days for the technology, the possible advantages of integrating AI with solar mobility far outweigh the current challenges.

AI increases the efficiency of Solar-Powered EVs in numerous different ways. It optimizes energy conversion, anticipates energy storage needs, and ensures that the vehicles are charged at the most pocket-friendly and environmentally friendly-times. Moreover, it uses AI-driven battery management systems for improved longevity and predictive analytics to lower costs and assure vehicle reliability. Further, with autonomous electric vehicles in the works, AI opens up the possibility for a safer, more efficient way of transportation with reduced human intervention.

Advancements in PV technology, such as perovskite solar cells and multi-junction solar panels, are increasing the efficiency of solar energy conversion. Current solar panel efficiencies are still low, but with ongoing research and development, improvements are expected to be enormous. Further integrated with AI and V2G technology, EVs can supply surplus energy back to the grid, creating a dynamic and sustainable energy ecosystem.

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