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Solar PV-Powered Switched Reluctance Motor Drive for Electric Vehicles with Adaptive Energy Management

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Abstract: ***Electric vehicles (EVs) are becoming popular as a green option compared to regular petrol or diesel vehicles. But, many EVs use electricity from the grid, which often comes from coal or gas, making them less eco-friendly. Adding solar photovoltaic (PV) systems to EVs can help by using sunlight to power the vehicle, cutting down on pollution and running costs. This paper looks at a solar PV-powered Switched Reluctance Motor (SRM) drive for EVs, with a smart energy management system to make it work better. SRMs are efficient, cheap, and strong because of their simple design [1]. The smart energy system handles changes in solar power, switching between solar, battery, and braking energy to keep the vehicle running smoothly. It also fixes SRM issues like shaking and noise for a better ride. This study shows that this setup works well, saves money, helps the environment, and points out some challenges. By using less grid power, this idea makes transport greener, and with better tech, solar-powered EVs can be the future.***

Keywords: Solar PV, SRM drive, electric vehicles, adaptive energy management, renewable energy, green transportation

I. INTRODUCTION

Electric vehicles (EVs) are very important for making transportation cleaner, as they produce much less pollution than regular vehicles that run on petrol or diesel. But, if EVs charge using grid electricity that comes from coal or gas, they're not as eco-friendly as they could be. Using renewable energy like solar power in EVs can make them even better by cutting down on pollution and saving money, while also making them less dependent on the grid [2].

Solar PV technology makes clean electricity from sunlight, which is perfect for running EV motors or charging their batteries without needing the grid. Solar panels can be put on the vehicle itself or at solar charging stations, which helps reduce the use of fossil fuels and lets the EV drive farther without needing to stop for charging so often. A key part of this system is the Switched Reluctance Motor (SRM), which is great for EVs because it's simple, strong, and doesn't need expensive rare-earth magnets [1].

There are some challenges in using solar PV with SRM drives because solar power changes with the weather and time of day. A smart energy management system helps by balancing solar power, battery power, and energy from braking to keep the EV running smoothly. This paper explores how this combination makes EVs more efficient, saves money, and helps the environment, showing why solar-powered EVs are a good choice for the future [1].

II. SOLAR PHOTOVOLTAIC (PV) SYSTEMS

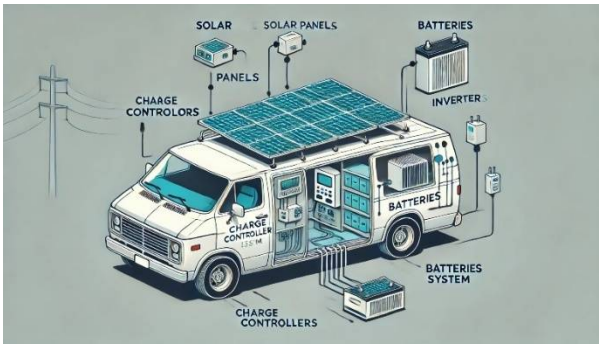
Solar PV systems turn sunlight into electricity using special materials, giving clean, renewable power with almost no harm to the environment [3]. Adding this to EVs means less need for grid power, lower costs, and less pollution.

A. Basics of Solar PV Technology

Solar PV works by using cells, usually made of silicon, to turn sunlight into electricity. When sunlight hits the cells, it makes electrons move, creating direct current (DC) electricity that can power systems, charge batteries, or be changed to alternating current (AC) using an inverter. The main parts are:

1) Solar Panels: Arrays of PV cells that catch sunlight [1].
2) Inverter: Changes DC to AC for the EV to use [3].
3) Battery Storage: Saves extra energy for when there's no sunlight [4].
4) Charge Controller: Makes sure the battery charges properly [1].

B. Solar PV in EVs

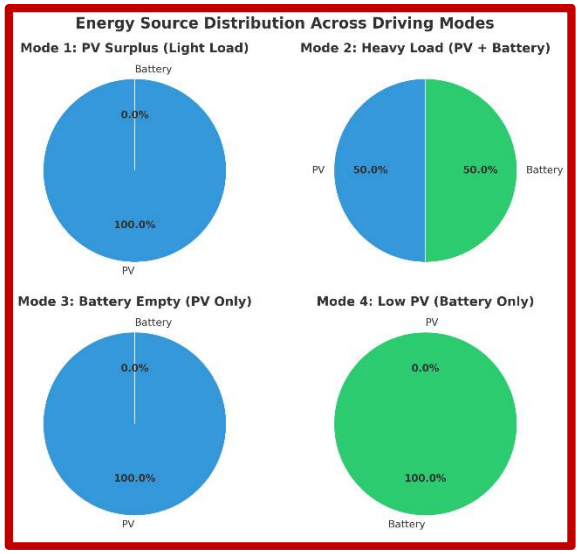


Adding solar photovoltaic (PV) systems to electric vehicles (EVs) has many benefits by letting them use sunlight for charging. Solar panels can be put on the vehicle, like on the roof, or connected to solar charging stations, so EVs can use clean solar energy. This reduces the need for grid electricity, making EVs more independent and cutting down on pollution by lowering carbon emissions.
The amount of energy a solar PV system makes depends on things like the size and efficiency of the panels, where the vehicle is (like sunny or cloudy areas), and how strong the sunlight is (called solar irradiance, which is how much solar energy hits a spot). In places with lots of sunlight, solar PV systems can really increase how far an EV can drive, so you don't need to stop and charge as often, making electric travel easier [5].
Also, solar-powered EVs can use hybrid energy setups, where solar power is mixed with other green sources like wind or biomass, along with grid power. These hybrid systems are more reliable and flexible, making sure the EV keeps running even when there's less sunlight, like on cloudy days or at night.

C. Driving Modes

The system works in four different ways to use power:

1) Mode 1: For light driving, extra solar PV power is used directly [1].
2) Mode 2: For heavy driving (like going uphill), it uses both solar and battery power [6].
3) Mode 3: If the battery is empty, it uses only solar PV power [1].
4) Mode 4: When there's little sunlight, it switches to battery power [1].



D. Benefits of Solar PV for EVs

1) Clean Energy: Solar power makes no pollution, helping fight climate change [7].
2) Self-Reliance: Less need for the grid, great for faraway places [9].
3) Cost Reduction: Free sunlight lowers running costs over time [7].
4) Extended Range: Charging on the go reduces worries about running out of power [5].

5) Challenges
6) Space Constraints: There's not much space on an EV for solar panels, so they can't make a lot of power [1].
7) Weather Dependence: Clouds or rain reduce solar power, so you need good batteries [8].
8) Efficiency Limits**:** Solar cells don't use all sunlight, so research is needed to make them better [8].

E. Future Outlook

New solar cells, lighter panels, and better batteries could make solar PV in EVs much better, giving more energy and reliability [8].

F. Benefits of Solar-Powered Electric Vehicles Over Normal EVs

Solar-powered electric vehicles (EVs) use solar panels to make electricity from sunlight, which gives them some big advantages over normal EVs that mostly charge from the power grid. Here are the main benefits in simple terms:

1) Longer Driving Distance: Solar-powered EVs can go farther because they get extra energy from the sun while driving. For example, on a sunny day, solar panels on the vehicle can add power to the battery, letting the EV travel more miles without stopping to charge. In places with lots of sunlight, this can add up to 20–30 extra miles per day, depending on the size of the solar panels and how efficient they are [5]. Normal EVs don't have this extra power from the sun, so they can only go as far as their battery allows, which might mean more stops for charging on long trips.
2) Less Time Spent Charging: With solar power, these EVs don't need to stop and charge as often. The solar panels can charge the battery while the vehicle is moving or parked in the sun, which means less time plugged into a charging station. For example, if a normal EV needs to stop for 30 minutes to charge on a long trip, a solar-powered EV might not need to stop at all because it's already getting power from the sun [7]. This makes trips faster and more convenient, especially in sunny areas.
3) Using More Solar Energy and Less Grid Power: Solar-powered EVs depend more on the sun for energy, which means they don't need to use as much electricity from the power grid. In places where the grid uses dirty energy like coal or gas, this is a big win because it cuts down on pollution. For example, using solar power can lower an EV's pollution by up to 70% compared to charging from a grid that uses fossil fuels [9]. Normal EVs mostly rely on the grid, so they might still cause more pollution if the grid isn't clean. Solar EVs can work more on their own, especially in sunny places or with solar charging stations.
4) Lower Cost to Run: Solar-powered EVs save money because sunlight is free. Once the solar panels are added to the vehicle, they make electricity without any extra cost, unlike grid charging, which can get expensive over time. For example, if a normal EV owner spends $500 a year on grid charging, a solar-powered EV owner might spend much less because they're using free solar energy for part of the time [7]. Even though adding solar panels costs money at first, the savings add up over the years, making solar EVs cheaper to run in the long term.

   In short, solar-powered EVs can drive farther, spend less time charging, use more clean solar energy, and cost less to run compared to normal EVs. These benefits make them a great choice for saving money and helping the environment, especially in sunny places [9].

III. SWITCHED RELUCTANCE MOTOR (SRM) TECHNOLOGY

SRMs are becoming popular for EV motors because they're strong, cheap, and efficient, and they don't need rare-earth magnets [1].

A. SRM Design and Function

The design of an SRM is very simple. It has a stator (the outer part) with windings and a rotor (the inner part) made of steel layers, with no magnets or wires on the rotor. The stator gets electric pulses one by one, making a magnetic field that pulls the rotor to line up with it. This happens because the motor works on the idea of reducing magnetic resistance (called reluctance). This pulling makes the motor turn, and by carefully timing the electric pulses with the rotor's position—using sensors or smart tech—the motor keeps spinning. Since there are no wires or magnets on the rotor, there's less energy loss, so SRMs work well, especially at high speeds [4].

SRMs can be made with different numbers of stator and rotor poles, like 6/4 (six stator poles, four rotor poles) or 8/6 setups, depending on what kind of power and speed you need. More poles can make the motor smoother but harder to control. The simple design also makes SRMs last longer because there are fewer parts that can break [5].

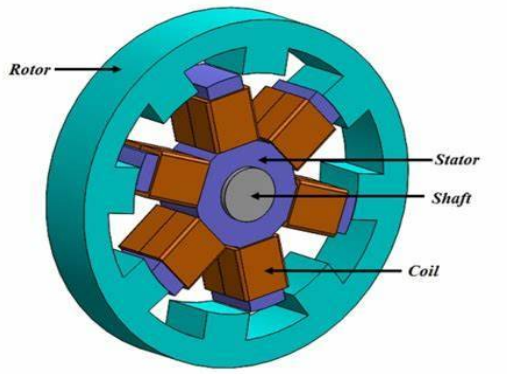
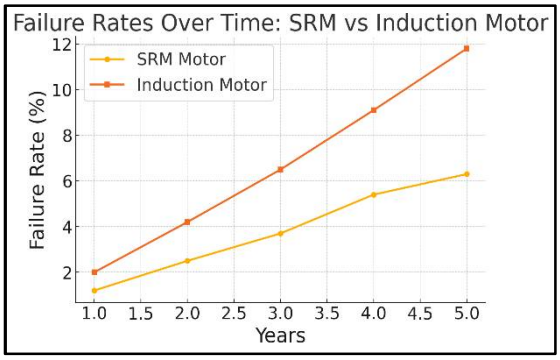


Figure 1 - 3D model of a switched reluctance motor

B. SRM Advantages for EVs

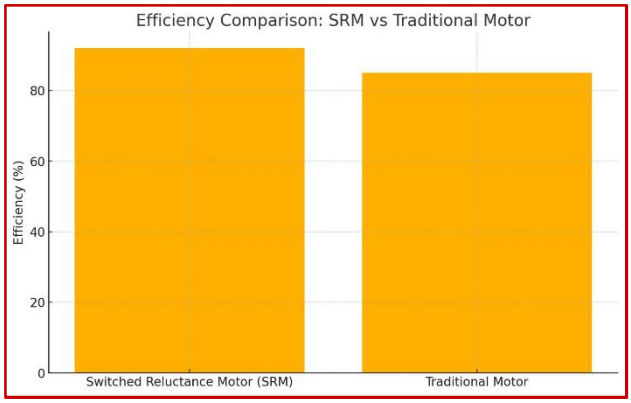
1) Simple Design and Long Life: SRMs don't have magnets or rotor wires, so there are fewer parts to make or break. This makes them cheaper to build and very strong, perfect for the tough conditions of EV driving [5].



2) Good Efficiency at All Speeds: SRMs work well at different speeds, which is important for EVs that need to change speed a lot—like in city traffic, on highways, or when speeding up. They're especially efficient at high speeds because the rotor doesn't lose much energy [10].

3) Low Cost: SRMs don't use rare-earth magnets, which are costly and hard to get. This makes SRMs cheaper to make and better for the environment since mining those magnets causes pollution [1].

4) Handles Heat Well: Since there are no wires on the rotor, it doesn't get too hot, making it easier to keep the motor cool. This is great for EVs where heat can be a problem [5].



5) Keeps Working if Something Breaks: SRMs have separate windings for each phase, so if one part fails, the motor can still run at lower power. This makes EVs safer and more reliable [1].

6) Works at High Speeds: SRMs can spin very fast without issues like magnet damage (a problem in other motors), making them good for powerful EV motors [6].

C. SRM Challenges

SRMs have some problems that need to be fixed to work well in EVs:

1) Shaking (Torque Ripple): When the SRM switches power on and off, the motor shakes because the power isn't steady. This shaking makes noise and vibrations, which can make the ride bumpy, especially at low speeds like in city traffic. It can also wear out parts faster over time [2], [15].
2) Noise: The way SRMs make power creates a lot of sound, especially when driving slowly. The quick changes in the magnetic field make the stator vibrate, which is louder than other motors like PMSMs. This can be annoying in EVs, where people expect a quiet ride [4].
3) Hard to Control: SRMs need smart tech to run smoothly because their magnetic behavior is tricky. The power needs to switch at the exact right time with the rotor's position, which requires complicated systems and fast electronics. This makes SRM systems harder and more expensive to design [1].

D. Fixes for SRM Issues

Here are some ways to solve SRM problems and make them better for EVs:

1) Smart Control Tech: Using advanced methods can reduce shaking by controlling the power better. For example, torque-sharing functions (TSF) spread the power across different parts of the motor to make it smoother, and pulse-width modulation (PWM) fine-tunes the power to lower shaking and noise. Smart systems like fuzzy logic or neural networks can also adjust the motor in real-time to handle its tricky behavior [2], [4]. This makes the ride more comfortable, especially at low speeds [15].
2) Better Design and Materials: Changing the shape of the stator and rotor—like making the poles slanted—can make the magnetic changes smoother, reducing shaking. Using high-quality materials like special silicon steel can improve efficiency and lower noise. Adding things like vibration-dampening mounts or soundproofing around the motor can also make it quieter for EVs [12], [15].
3) No-Sensor Control: To make control easier, we can use tech that guesses the rotor's position without physical sensors, which can break or add cost. By using voltage and current data, these methods simplify the system and make it more reliable, though they need strong computers to work well [14].
4) Using Energy Management Systems: A smart energy system can help by controlling the power going to the SRM. For example, in a solar-powered EV, it can adjust power based on how you're driving, reducing shaking at low speeds. By keeping the power steady from solar panels, batteries, and braking, it makes the SRM easier to control [1].

E. SRM with Solar PV

Combining SRMs with solar PV systems in EVs is a great idea because both work well together for green travel. SRMs are efficient, strong, and can handle changes in power, which is perfect for solar energy that changes with the weather and time of day [1].

A big plus of SRMs is that they can work with varying power. Solar PV makes electricity that changes depending on sunlight, clouds, or night. SRMs can handle this because they don't need steady power like some other motors that might get damaged. For example, when the sun is bright, solar PV can directly power the SRM, using clean energy and saving the battery. When it's cloudy or dark, the system switches to the battery, and the SRM's strong design keeps it running even if the power isn't perfect [1], [13].

The smart energy system helps a lot by balancing power from solar panels, the battery, and braking energy. For example, in city driving with lots of stops, braking energy can be saved in the battery and used later to power the SRM, making the EV more efficient. On a sunny highway drive, the system can use solar power first, saving the battery and letting you drive farther [1].

SRMs also save money because they're simple and don't use expensive magnets, which fits well with solar PV's goal of lowering costs with free sunlight. Plus, they're better for the environment by avoiding rare-earth mining, which causes pollution, while solar power cuts down on emissions [1], [9].

There are some challenges, though. Solar power changes can make SRM control harder because the motor needs precise power adjustments. Smart tech, like AI that predicts solar power, can help keep the SRM running smoothly [20]. Also, EVs don't have much space for solar panels, but SRMs are efficient, so they make the most of even small amounts of solar power [22].

In the future, this combo can get even better. New thin-film solar panels can capture more energy without adding weight [12], and AI can improve SRM control for changing solar power [20]. There's also a chance for vehicle-to-grid (V2G) systems, where EVs can send extra solar power back to the grid, helping use more renewable energy [17]. Overall, SRMs with solar PV make a strong, cheap, and green solution for EVs [1].

IV. FLEXIBLE ENERGY CONTROL SYSTEMS

Flexible energy control systems are very important for making solar PV-powered SRM drives in EVs work well. They handle different energy sources—like solar PV, battery, grid power, and braking energy—to keep the EV running efficiently and reliably, even when things change. By smartly sharing power, they fix issues like solar power changes and SRM control problems, making them a key part of modern EVs [1].

A. System Overview

These systems bring together different energy sources into one setup, adjusting to changes in energy and what the vehicle needs. They use sensors, small computers, and smart programs to control power flow between solar panels, batteries, the SRM, and other parts like AC or music systems. This flexibility makes sure the EV works well in all kinds of driving, like city traffic or long highway trips, while using as much renewable energy as possible [14].

B. Core Functions

1) Energy Sharing and Saving: The system decides where to get energy based on what's needed. For example, when the sun is strong, it uses solar PV to power the SRM and charges the battery with extra energy. When there's less sunlight, it switches to the battery or grid power, keeping everything running without wasting energy [1], [15].
2) Real-Time Checking and Fixing: Sensors keep an eye on things like solar panel power, battery level, and SRM needs. The system uses this info to make quick changes. For example, if clouds cover the sun while driving, it can use more battery power to keep the SRM going smoothly [1].
3) Focusing on Important Parts: The system gives power to the most important parts first, like the SRM, over less important ones like lights or music. During fast driving, it can lower power to extra systems to make sure the SRM has enough energy, helping the EV go farther, especially when solar power is low [6].
4) Using Braking Energy: The system saves energy when the EV slows down. The SRM acts like a generator, turning the slowing-down energy into electricity to store in the battery. This saved energy can be used later, reducing the need for outside charging and saving more energy [13].

C. Benefits

1) Better Energy Use: By using solar and battery power wisely, the system cuts energy waste and helps the EV go farther. This helps with worries about running out of power, as it makes sure energy is used well even when things change [1].
2) More Reliable System: The system can switch between energy sources easily, making the EV more dependable. For example, if solar power drops suddenly, it can use the battery or grid power, keeping the EV running without issues [14].
3) Longer Part Life: Smart energy use reduces stress on parts like the battery by avoiding overuse. For example, using solar power during the day means less battery use, making it last longer and saving money on replacements [11].
4) Helping the Environment: By using more solar power, the system lowers the EV's pollution, especially in places where grid power comes from coal or gas. This supports global goals for clean energy in transport [9].

D. Challenges

1) Complicated Programs: Making programs to handle different energy sources in real-time is hard. These programs need to deal with solar changes, battery behavior, and SRM needs, which takes a lot of skill in tech and system design [17].
2) Fitting with Old Systems: Adding these smart systems to older EVs can be tough because old parts might not work well with new tech. New EVs designed with these systems from the start work better [1].
3) Higher Starting Cost: Building these advanced systems costs more at first because of expensive computers, sensors, and software. But the money saved from better efficiency and lower running costs makes up for it over time [17].
4) Heat Problems: The system's heavy computing can make the electronics hot, so you need good cooling to stop overheating and keep things working well [21].

E. Future Prospects

The future looks bright for these smart energy systems in solar PV-powered SRM EVs, with lots of new ideas coming. Adding artificial intelligence (AI) and machine learning can make the system smarter, helping it predict solar power, battery wear, and driving habits better. For example, AI can guess if clouds are coming and adjust power use to keep things running well [20].

New battery tech, like solid-state batteries that hold more power and charge faster, will make these systems even better by giving more reliable energy storage [11]. Also, vehicle-to-grid (V2G) tech can let solar-powered EVs send extra solar energy back to the grid during busy times, opening new ways to manage energy [17].

Working together between car and renewable energy companies can bring new ideas, making standard systems that are cheaper and easier to use widely. Projects like Europe's "Solar Roads" show how teamwork can improve green transport [16]. As these technologies grow, smart energy systems will make solar PV-powered SRM EVs more efficient, reliable, and affordable, helping clean energy become a big part of cars [18].

V. BENEFITS OF SOLAR-POWERED ELECTRIC VEHICLES OVER NORMAL EVS

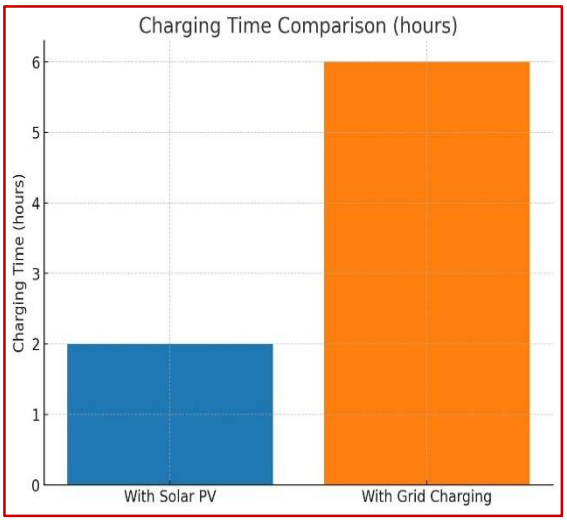
Solar-powered electric vehicles (EVs) use solar panels to make electricity from sunlight, which gives them some big advantages over normal EVs that mostly charge from the power grid. Here are the main benefits in simple terms:

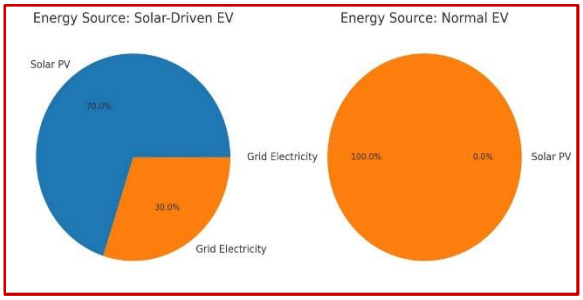
1) Longer Driving Distance: Solar-powered EVs can go farther because they get extra energy from the sun while driving. For example, on a sunny day, solar panels on the vehicle can add power to the battery, letting the EV travel more miles without stopping to charge. In places with lots of sunlight, this can add up to 20–30 extra miles per day, depending on the size of the solar panels and how efficient they are [5]. Normal EVs don't have this extra power from the sun, so they can only go as far as their battery allows, which might mean more stops for charging on long trips.

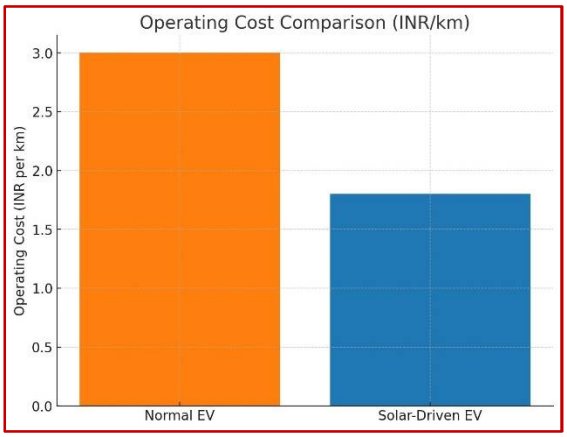
2) Less Time Spent Charging: With solar power, these EVs don't need to stop and charge as often. The solar panels can charge the battery while the vehicle is moving or parked in the sun, which means less time plugged into a charging station. For example, if a normal EV needs to stop for 30 minutes to charge on a long trip, a solar-powered EV might not need to stop at all because it's already getting power from the sun [7]. This makes trips faster and more convenient, especially in sunny areas.

3) Using More Solar Energy and Less Grid Power: Solar-powered EVs depend moreon the sun for energy, which means they don't need to use as much electricity from the power grid. In places where the grid uses dirty energy like coal or gas, this is a big win because it cuts down on pollution. For example, using solar power can lower an EV's pollution by up to 70% compared to charging from a grid that uses fossil fuels [9]. Normal EVs mostly rely on the grid, so they might still cause more pollution if the grid isn't clean. Solar EVs can work more on their own, especially in sunny places or with solar charging stations.

4) Lower Cost to Run: Solar-powered EVs save money because sunlight is free. Once the solar panels are added to the vehicle, they make electricity without any extra cost, unlike grid charging, which can get expensive over time. For example, if a normal EV owner spends $500 a year on grid charging, a solar-powered EV owner might spend much less because they're using free solar energy for part of the time [7]. Even though adding solar panels costs money at first, the savings add up over the years, making solar EVs cheaper to run in the long term.







In short, solar-powered EVs can drive farther, spend less time charging, use more clean solar energy, and cost less to run compared to normal EVs. These benefits make them a great choice for saving money and helping the environment, especially in sunny places [9]

VI. CHALLENGES AND SOLUTIONS

Solar-powered electric vehicles (EVs) are super V. Challenges and Solutions for Solar-Powered Electric Vehicles
Solar-powered electric vehicles (EVs) are super cool because they use sunlight to run, but they also have some problems. Let's look at the main challenges and how we can fix them, in simple words for college students like us.

A. Challenges

1) Not Enough Sunlight Sometimes: Solar EVs need sunlight to make electricity, but what if it's cloudy or raining? In India, during monsoon season, the sun might hide for days, so the solar panels can't make enough power. This means the EV might have to use the battery more, and if the battery runs out, you're stuck [3]. Also, at night, there's no sun at all, so you can't charge while driving.

2) Small Space for Solar Panels: An EV doesn't have a lot of space to put solar panels—only the roof, hood, or sides can be used. But these areas are small, so the panels can't make a lot of power. For example, a normal car roof might only give enough energy to drive 10-15 km per day, which isn't enough for long trips like going from Delhi to Jaipur [22].

3) Charging Takes Time: Even with solar panels, charging the battery fully can take time, especially if the sun isn't strong. If you're in a hurry and the battery is low, you might still need to stop at a charging station, which can take 30 minutes or more. This can be a problem if you're late for college or a family function [7].

4) High Starting Cost: Adding solar panels to an EV makes it more expensive at first. For example, a normal EV might cost ₹10 lakh, but a solar EV could cost ₹12 lakh because of the panels and extra tech. For many students' families, this extra cost is a big deal, even if it saves money later [23].

5) Battery Gets Old Fast: If the solar power isn't enough, the EV uses the battery a lot, which can make the battery wear out faster. Replacing a battery is costly—like ₹2-3 lakh—and it might need to be changed every 5-7 years if you use it too much [11].

B. Solutions

1) Mix Solar with Other Power: To fix the problem of not enough sunlight, we can use a mix of solar, battery, and grid power. For example, during the monsoon, the EV can use the battery or plug into a charging station. Some EVs can also use other green energy like wind power, so you're not stuck if the sun isn't shining [19]. This way, you can still drive to college even on a rainy day.
2) Better Solar Panels: Scientists are making new types of solar panels that are more powerful even in small spaces. For example, thin-film solar panels can be put on more parts of the EV, like the windows, and they can make more electricity—maybe enough to drive 30-40 km per day instead of just 10-15 km [12]. This means you can go farther without worrying, like from Mumbai to Pune.
3) Faster Charging Options: To reduce charging time, we can add fast-charging stations that work with solar power. These stations can charge your EV in just 15-20 minutes instead of 30 minutes or more. Also, solar panels can keep charging the battery while you're parked, like during college classes, so you don't need to stop as often [7].
4) Lower Costs with Government Help: The government can help make solar EVs cheaper by giving discounts or subsidies. For example, if the government gives a ₹1 lakh subsidy, the solar EV price drops from ₹12 lakh to ₹11 lakh, which is easier for families to afford. Also, when more companies make solar EVs, the price will come down because of competition [24]. So, soon, even students like us might be able to buy one!
5) Smarter Battery Use: To make the battery last longer, the EV can have a smart system that decides when to use solar power and when to use the battery. For example, on a sunny day, it can use solar power directly and save the battery for nighttime or cloudy days. This way, the battery doesn't get overused and can last 8-10 years instead of just 5-7 years [11]. It's like saving your phone battery by not playing games all the time!

In short, solar-powered EVs have some issues like less sunlight, small panel space, slow charging, high cost, and battery wear. But with solutions like mixing power sources, better panels, faster charging, government help, and smart battery use, these problems can be fixed, making solar EVs a great choice for students and families in India [9].

VII. CASE STUDIES

Let's look at some real-life examples of solar-powered electric vehicles (EVs) to see how they work in the real world. These case studies show how solar power can be used in different vehicles, what challenges come up, and what we can learn for making better EVs in India. We'll talk about a solar race car, solar buses, and a big solar EV project in Europe, in simple words for college students like us.

A. Sunswift Solar Car (UNSW, Australia)

The Sunswift solar car is a project by students at the University of New South Wales (UNSW) in Australia. They built a super cool solar-powered car called Sunswift to race in solar car challenges, like the World Solar Challenge, where cars drive across Australia using only solar power [18].

What They Did: The Sunswift car has solar panels all over its body—like the roof and sides—to catch as much sunlight as possible. It uses a smart system to manage the solar energy, deciding when to use it directly for driving or save it in the battery for later. The car is very light, made with special materials, so it doesn't need much power to move fast. In races, it has driven over 3,000 km across Australia, using mostly solar energy, which is like driving from Delhi to Mumbai and back without stopping for fuel [18].

Challenges: One big problem was that the car's solar panels couldn't make enough power on cloudy days, so they had to plan the race carefully, saving battery power for when the sun wasn't shining. Also, the car is small and built for racing, so it's not practical for everyday use—like you can't take your family in it to the market [18].

Lessons for Us: The Sunswift project shows that solar power can work really well for driving long distances if you design the vehicle smartly. For India, we can learn to make lightweight EVs with good solar panels to go farther on sunny days. Also, their smart energy system gives ideas for how to mix solar and battery power, which can help during our monsoon season when the sun hides [18].

B. Solar Buses (Shenzhen, China)

In Shenzhen, China, they've started using solar-powered buses for public transport, which is a big step for making cities greener. Shenzhen is a busy city with lots of people, and they wanted to cut down on pollution from regular diesel buses [19].

What They Did: These buses have solar panels on their roofs to make electricity while they drive or wait at stops. The solar power is used to help run the bus and charge its battery, so it doesn't need to plug into the grid as much. Shenzhen also has solar charging stations where the buses can get extra power if needed. In 2022, they had over 100 solar buses running, and each bus saved about 1,500 liters of diesel per year, which means less air pollution in the city **[19].**

Challenges: The solar panels on the buses are small, so they can't make all the power the bus needs—they still need to charge from the grid sometimes, especially at night or on rainy days. Also, putting solar panels on buses costs more money at first, and some people worried it might not be worth it if the panels don't make enough energy [19].

Lessons for Us: In India, we have big cities like Mumbai and Delhi with lots of buses and pollution. Shenzhen's solar buses show that we can use solar power for public transport to make our air cleaner. Even if the panels don't make all the power, they still save fuel and money over time. We can start with a few solar buses in sunny cities like Jaipur or Ahmedabad, and use solar charging stations to help when the sun isn't enough [19].

C. European Solar EVs (Solar Roads Initiative)

The Solar Roads initiative in Europe is a big project where they're testing how to mix solar power with EVs on a large scale. It's led by the European Research Council and involves many countries working together to make roads and vehicles that use solar energy [16].

What They Did: In this project, they're building special roads with solar panels inside them—called solar roads—that make electricity when the sun shines. EVs can charge while driving on these roads using wireless charging tech, so they don't need to stop as often. They're also testing solar-powered EVs with panels on the vehicle to add more power. In 2023, they set up a 1-km solar road in the Netherlands, and EVs driving on it could get enough energy to go 20-25 km extra per day without plugging in [16].

Challenges: Building solar roads is very expensive—like crores of rupees for just 1 km—so it's hard to do this everywhere. Also, the solar panels in the roads can get dirty or damaged by vehicles, which makes them less efficient. For the EVs, the same problem of small panel space came up, so they couldn't rely only on solar power for long trips [16].

Lessons for Us: The Solar Roads project shows a big idea for the future—roads that charge EVs while driving! In India, we can try this on small highways, like between Pune and Mumbai, where there's a lot of traffic and sunlight. Even if it's costly, starting with short stretches can help us learn how to make it cheaper. Also, their wireless charging idea is great for reducing charging time, which can make EVs more convenient for students like us [16].

D. What We Learned Overall

These case studies teach us some important things for solar-powered EVs in India:

1) Solar Power Works, But Needs Backup: All three examples show that solar power can help EVs go farther and save energy, but you need a battery or grid power for when the sun isn't there—like during monsoon or at night [18], [19], [16].

2) Design Matters: The Sunswift car shows that making vehicles light and using good solar panels can make a big difference in how far you can go. We can use this idea for Indian EVs to make them more efficient [18].

3) Start Small, Think Big: Shenzhen's buses and Europe's solar roads show that starting with small projects—like a few buses or a short road—can help us learn and grow the tech for bigger use later [19], [16].

4) Cost Is a Challenge, But Worth It: Adding solar power costs more at first, but it saves money and fuel in the long run, as seen in all three cases. In India, government help with subsidies can make this easier for companies and people [**19].** These examples give us hope that solar-powered EVs can work well in India, especially in sunny places, and help us build a cleaner future while saving money [9].

VIII. CONCLUSION

Solar-powered electric vehicles (EVs) are a great idea for making travel cleaner and cheaper, especially for students like us in India. This paper shows how using solar power with smart energy systems can make EVs even better. These systems help the vehicle use sunlight, battery, and braking energy in a clever way, so it works well no matter the weather or time of day [1].

We learned that solar EVs can go farther, like 20-30 extra km on a sunny day, because the solar panels keep charging the battery while driving. They also don't need to stop for charging as much—sometimes you can skip a 30-minute charging stop completely! Plus, they use more solar energy, which means less pollution (up to 70% less) compared to normal EVs that charge from the grid [9]. And over time, they save money because sunlight is free, unlike grid electricity that costs ₹500 or more per year [7].

But there are some problems too. For example, if it's cloudy or raining, like during the monsoon, the solar panels can't make enough power. The space for panels on the vehicle is also small, so they might only give enough energy for 10-15 km per day. Charging can still take time, the starting cost is high (like ₹12 lakh), and the battery might wear out faster if used too much [22], [23]. Don't worry, though—there are fixes! We can mix solar with battery and grid power, use better panels to get more energy, add fast-charging stations, get government discounts, and use smart systems to make the battery last longer [12], [24].

In the future, solar-powered EVs can become even better. New tech like AI can help the vehicle guess when the sun will shine and use power smarter [20]. Better batteries and more solar projects, like the ones in Europe, can make these EVs more popular [16]. For us students, this means we might soon have affordable, eco-friendly vehicles to drive to college or trips, helping the planet while saving money [9].

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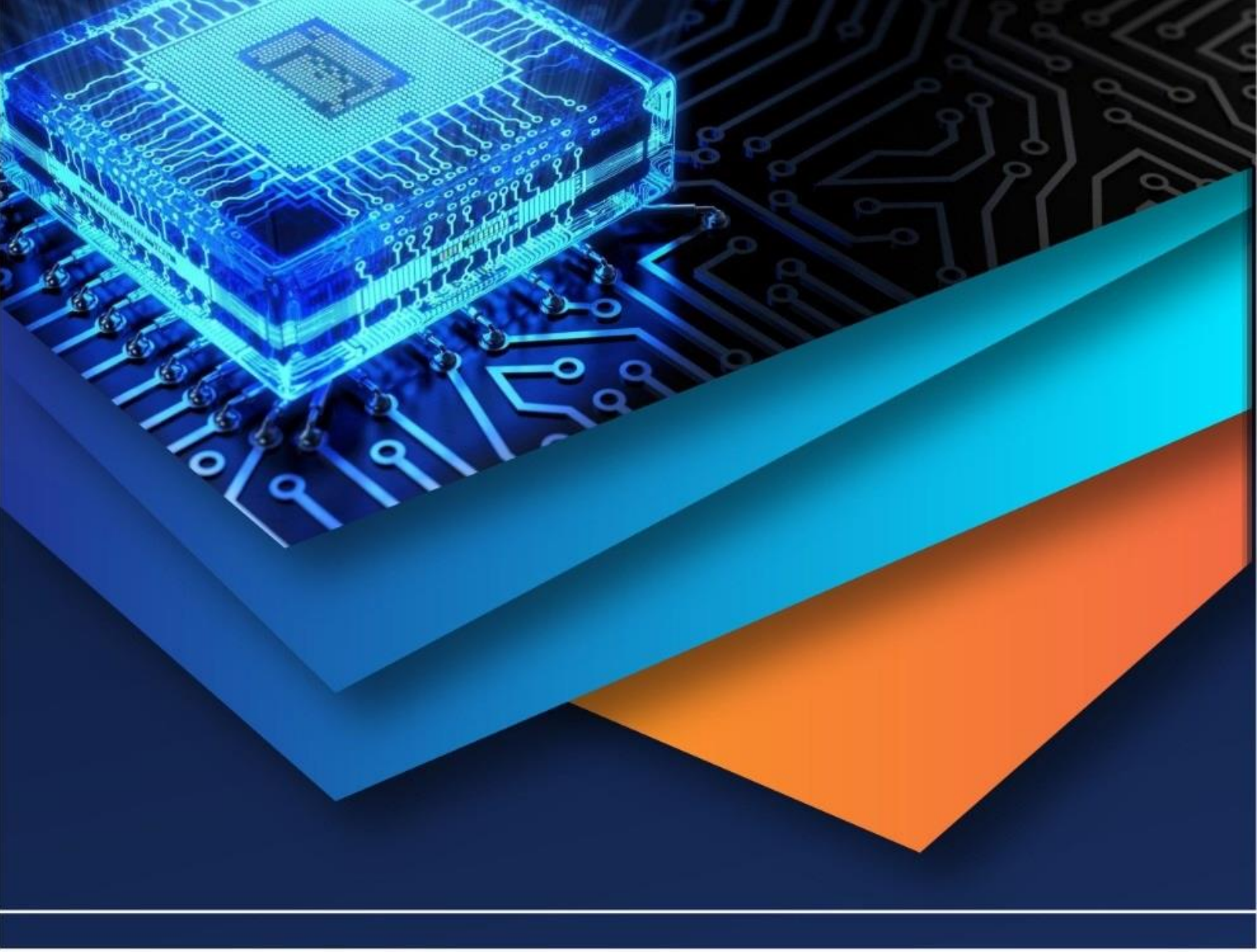

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