

The Role of Electronics Engineering in Driving the Renewable Energy Revolution toward a Sustainable Future

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ABSTRACT

This research investigates the integral role of electronics engineering in the advancement and efficiency of renewable energy systems. As the world grapples with the pressing challenge of climate change, the transition to renewable energy sources—such as solar, wind, and hydropower—has become imperative for reducing greenhouse gas emissions. This research highlights how electronics engineers are pioneering innovations in power electronics, embedded control systems, and smart grid technologies, enabling the effective management and integration of decentralized energy sources. Additionally, the study examines energy storage solutions, including batteries and super capacitors, that address the intermittency of renewable energy generation. Challenges such as energy storage limitations, supply variability, and grid stability are discussed, supported by case studies that illustrate real-world applications of these technologies. The paper concludes with a forward-looking perspective on emerging trends in renewable energy technologies, including advancements in photovoltaics, smart grids, and AI-driven optimization, reinforcing the critical role of electronics engineering in driving a sustainable energy future.

Keywords: Electronics Engineering, Renewable Energy, Power Electronics, Smart Grids, Energy Storage, Climate Change, Photovoltaics, Wind Energy, Hydropower, AI-driven Optimization, Multi Benefits, Solar, Environmentally Friendly, Green



INTRODUCTION

Electronics engineering plays a crucial role in the efficient operation of renewable energy systems. Engineers develop the power electronics that convert and manage energy from renewable sources, as well as the embedded control

systems that regulate power flows in wind turbines, solar panels, and hydroelectric systems. Smart grids, enabled by advanced electronics, allow for the integration of decentralized renewable energy sources into the power grid, providing a more flexible and resilient energy system. The development of energy storage solutions, such as batteries and super capacitors, is also driven by electronics innovation, enabling renewable energy to be stored and used when the sun isn't shining, or the wind isn't blowing. This research will explore these contributions in detail, focusing on how electronics engineers are at the forefront of renewable energy technologies. Climate change is one of the most significant global challenges of the 21st century. Renewable energy has emerged as a vital solution for mitigating climate change by reducing greenhouse gas emissions, and the role of electronics and electrical engineering in this domain is paramount. Electronics engineers are at the forefront of improving energy efficiency, optimizing renewable energy systems, and integrating them into existing energy grids. This paper explores the relationship between renewable energy technologies—such as solar, wind, and hydropower—and climate change. Furthermore, it examines the critical contributions of power electronics, smart grids, energy storage, and other electronic innovations to the widespread adoption and effectiveness of renewable energy systems. Challenges like energy storage limitations, variability in energy supply, and grid stability are discussed, alongside case studies that illustrate the real-world implementation of these technologies. The paper concludes with insights into future trends and innovations, particularly in areas such as advanced photovoltaics, smart grids, and AI-driven energy optimization. This study serves as an in-depth look at the role of electronics engineering in driving the renewable energy revolution toward a sustainable future. Using renewable energy instead of traditional electricity generated from fossil fuels offers numerous benefits across environmental, economic, and social dimensions. Here are some advantages:

First, Environmental Benefits

Reduced Greenhouse Gas Emissions: Renewable energy sources, such as solar, wind, hydroelectric, and geothermal, produce little to no greenhouse gas emissions during operation. This helps mitigate climate change by reducing the overall carbon footprint associated with energy production. **Moreover, Lower Air Pollution:** Unlike fossil fuel power plants, which emit pollutants like sulfur dioxide, nitrogen oxides, and particulate matter, renewable energy sources contribute significantly less to air pollution. This leads to improved air quality and better health outcomes for communities. In addition to that, **Sustainable Resource Use:** Renewable energy sources are abundant and inexhaustible over human timescales. Unlike fossil fuels, which are finite and deplete with extraction, renewables like solar and wind can be harnessed indefinitely, promoting sustainability.

Secondly, Economic Benefits

Job Creation: The renewable energy sector is labor-intensive, requiring a wide range of skills for installation, maintenance, and operation. Transitioning to renewables can create jobs in manufacturing, installation, and maintenance of renewable energy systems, contributing to local economies. **Furthermore, Energy Independence:** By investing in renewable energy, countries can reduce their reliance on imported fossil fuels, enhancing energy security and reducing vulnerability to price fluctuations and supply disruptions. Also, **Stable Energy Prices:** Renewable energy sources often have lower operational costs compared to fossil fuels, which can lead to more stable energy prices over time. Once installed, renewable energy systems, such as solar panels, have minimal ongoing costs.

Thirdly, Energy Reliability and Security

Decentralized Energy Generation: Renewable energy technologies can be deployed at various scales, from large solar farms to small residential systems. This decentralization can enhance energy resilience by reducing reliance on centralized power plants and transmission lines. In addition, **Diverse Energy Portfolio:** Incorporating a mix of renewable energy sources can enhance the reliability of the energy supply, reducing dependence on any single energy source and improving overall energy security.

Forth, Health Benefits

Improved Public Health: By reducing air and water pollution, renewable energy contributes to better health outcomes. Fewer respiratory illnesses, cardiovascular diseases, and other pollution-related health issues can result from cleaner air, leading to reduced healthcare costs. More importantly, **Access to Clean Water:** Some fossil fuel extraction processes can contaminate local water supplies. By using renewable energy, the risks of water pollution associated with fossil fuels are minimized, contributing to cleaner water resources.

Fifth, Technological Innovation and Development

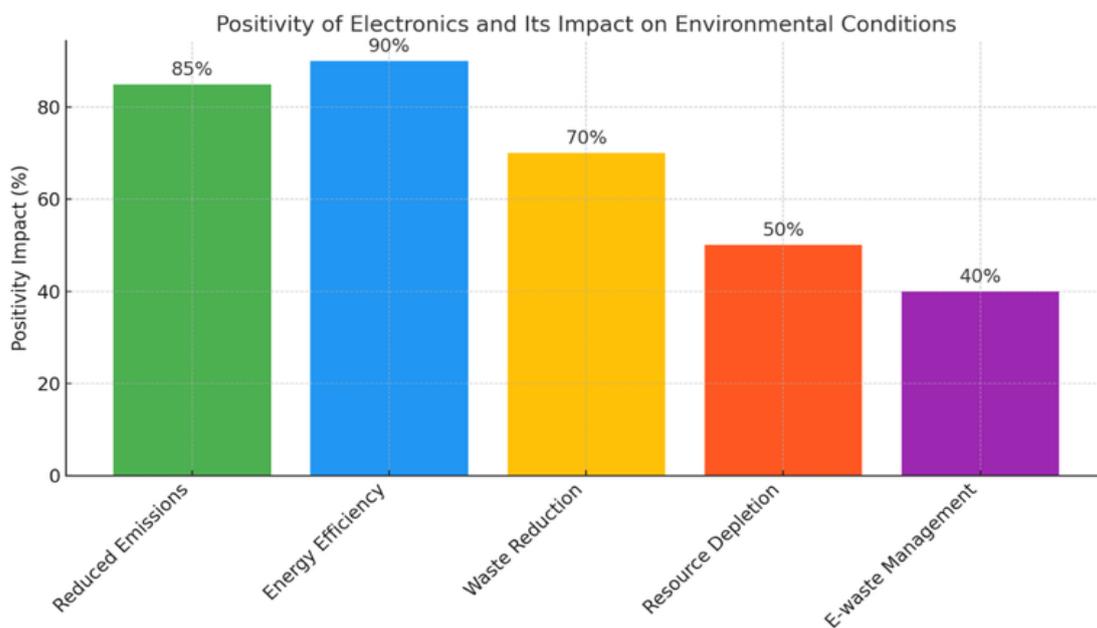
Advancements in Technology: The growth of the renewable energy sector drives innovation in energy technology, leading to improved efficiency and reduced costs.

Research and development in storage technologies (like batteries) and smart grid technologies are essential for enhancing the integration of renewables into the energy mix. Additionally, **Sustainable Infrastructure:** Investing in renewable energy encourages the development of smart infrastructure that can adapt to changing energy demands and integrate various energy sources more efficiently.

Sixth, Climate Change Mitigation

Resilience to Climate Impacts: Renewable energy sources can help mitigate the impacts of climate change, such as extreme weather events, by reducing greenhouse gas emissions. They also often have a smaller environmental footprint, contributing to more resilient ecosystems. Besides that, Global Cooperation: The transition to renewable energy promotes international cooperation and agreements aimed at combating climate change, fostering collaboration among nations to share technologies, best practices, and financial resources. Lastly, Renewable energy refers to energy derived from natural processes that are continuously replenished, such as solar, wind, hydro, geothermal, and biomass. Unlike fossil fuels, renewable energy technologies produce little to no greenhouse gas emissions during operation. For instance, replacing coal-based electricity generation with wind or solar power can reduce emissions by up to 90% (IEA, 2020). Transitioning to renewable energy is therefore essential in reducing humanity's carbon footprint and keeping global warming below 2°C, as outlined in the Paris Agreement. The global adoption of renewable energy has accelerated, but it requires further innovation, particularly in electronics and electrical engineering, to meet future energy demands.

This bar chart illustrates the positive impacts of electronics on various environmental conditions. Here is a breakdown of the percentages:



- 1. Reduced Emissions (85%):** Electronics contribute significantly to reducing emissions, particularly by improving energy systems and enhancing renewable energy deployment.
- 2. Energy Efficiency (90%):** Advances in electronics lead to better energy management and efficiency, lowering overall energy consumption.
- 3. Waste Reduction (70%):** Through automation, recycling technologies, and smart systems, electronics play a role in reducing waste.
- 4. Resource Depletion (50%):** While electronics help optimize resource use, challenges like reliance on rare minerals still affect their overall positive impact.
- 5. E-waste Management (40%):** Electronics can generate e-waste, and although improvements are being made, managing electronic waste remains a significant environmental concern.

Climate Change and Its Global Impact

Climate change refers to long-term shifts in temperatures and weather patterns, primarily caused by human activities, such as the burning of fossil fuels. These activities release carbon dioxide (CO₂) and other greenhouse gases (GHGs) into the atmosphere, trapping heat and causing global temperatures to rise. According to the Intergovernmental Panel on Climate Change (IPCC), the planet's average temperature has already risen by about 1.1°C since the late 19th century, with devastating effects including rising sea levels, increased frequency of extreme weather events, and disrupted ecosystems (IPCC, 2021). Combating climate change is one of the most critical challenges facing humanity today.

Electronics and Electrical Engineering: Catalysts for Renewable Energy

Electronics engineering plays a crucial role in the efficient operation of renewable energy systems. Engineers develop the power electronics that convert and manage energy from renewable sources, as well as the embedded control systems that regulate power flows in wind turbines, solar panels, and hydroelectric systems. Smart grids, enabled by

advanced electronics, allow for the integration of decentralized renewable energy sources into the power grid, providing a more flexible and resilient energy system. The development of energy storage solutions, such as batteries and supercapacitors, is also driven by electronics innovation, enabling renewable energy to be stored and used when the sun isn't shining, or the wind isn't blowing. This paper will explore these contributions in detail, focusing on how electronics engineers are at the forefront of renewable energy technologies.

Renewable Energy Technologies and Their Impact on Climate Change:



Solar Energy

Solar energy harnesses the power of the sun to generate electricity using photovoltaic (PV) cells or concentrated solar power (CSP) systems. PV cells convert sunlight directly into electricity through semiconductors, while CSP systems use mirrors to focus sunlight onto a receiver that heats a fluid to produce steam, driving a turbine that generates electricity. Solar energy is one of the cleanest energy sources available, with no emissions during operation, and it has the potential to meet the world's electricity demands multiple times over (Jacobson & Delucchi, 2011).

Electronics engineers are critical in the development of solar technologies, particularly in improving the efficiency of PV cells and power inverters. Inverters are essential for converting the direct current (DC) generated by PV panels into alternating current (AC) used by most electrical grids.

Modern inverters also perform Maximum Power Point Tracking (MPPT), ensuring that the solar system operates at its highest possible efficiency even under varying weather conditions. Additionally, engineers are working on enhancing energy storage solutions to store excess solar energy generated during the day for use at night or during cloudy periods.

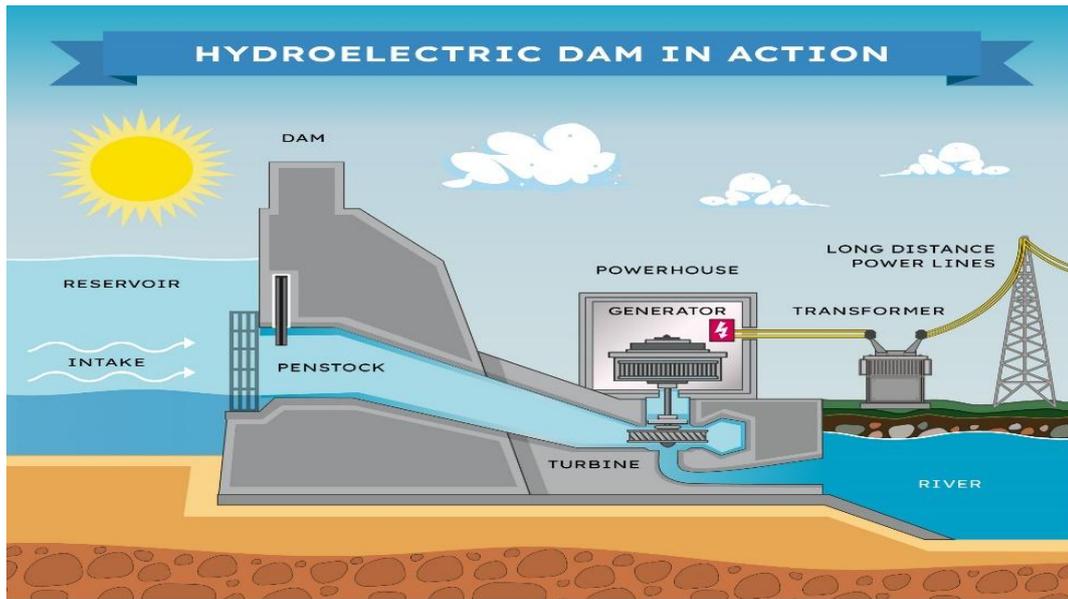
Wind Energy

Wind energy captures the kinetic energy of wind through turbines, which convert it into electrical power. Like solar energy, wind energy is a key renewable technology with enormous potential to reduce global carbon emissions. Wind turbines have a significant advantage in that they can operate both onshore and offshore, providing flexibility in location and scalability.

From an electronics engineering perspective, wind energy systems rely heavily on power electronics to control the turbine's generator and ensure stable energy output despite fluctuations in wind speed. Power converters manage the flow of electricity between the turbine and the grid, and control systems optimize turbine performance by adjusting blade pitch and yaw to capture the maximum amount of wind energy.

Furthermore, electronics engineers are developing better energy storage systems to address the intermittency of wind power, ensuring a stable supply of electricity even when wind speeds are low.

Hydroelectric Power



Hydropower is one of the oldest and most widely used renewable energy technologies. It generates electricity by capturing the energy of flowing water, typically using a dam to create a reservoir. While hydropower does not produce direct emissions, the construction of large dams can disrupt ecosystems and displace communities, leading to environmental concerns.

Electronics engineers contribute to hydropower systems by developing advanced control systems that regulate water flow through turbines, maximizing energy production while minimizing environmental impact. Power electronics are also used to integrate hydropower plants with the electrical grid, ensuring that the fluctuating energy supply from water flow changes is managed efficiently. Additionally, small-scale hydropower systems, such as micro-hydro projects, are becoming more popular in remote areas, and electronics engineers play a role in making these systems affordable and reliable.

Geothermal and Biomass Energy

Geothermal energy exploits the heat from beneath the Earth's surface to generate electricity or provide direct heating. Biomass energy, on the other hand, is produced by burning organic materials such as wood, agricultural waste, or dedicated energy crops.

Both technologies have a lower carbon footprint than fossil fuels, though biomass can still produce emissions depending on the feedstock and combustion process. In geothermal systems, electronics engineers develop the control systems that manage the flow of heat and electricity, optimizing the efficiency of energy conversion. For biomass energy, engineers focus on improving combustion processes and developing sensors to monitor emissions, ensuring that biomass plants operate as cleanly as possible.

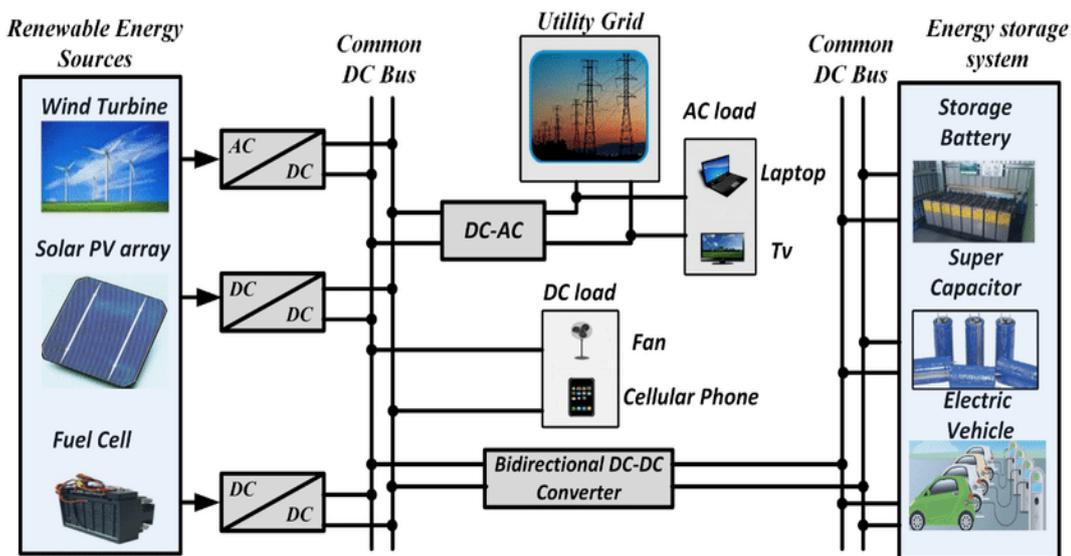
Energy Storage Systems

Energy storage is a critical component of renewable energy systems, as it allows for the storage of excess energy generated by intermittent sources like solar and wind power. The most common form of energy storage today is the lithium-ion battery, but other technologies, such as flow batteries, supercapacitors, and even hydrogen storage, are gaining traction.

Electronics engineers are at the forefront of developing energy storage technologies, from improving battery management systems (BMS) that optimize charge and discharge cycles to designing power electronics that efficiently integrate storage systems with renewable energy sources and the grid. Energy storage allows renewable energy to be used when generation is low, providing grid stability and reducing the need for fossil fuel-based backup power.

The Role of Electronics in Renewable Energy Systems

Power Electronics and Renewable Energy

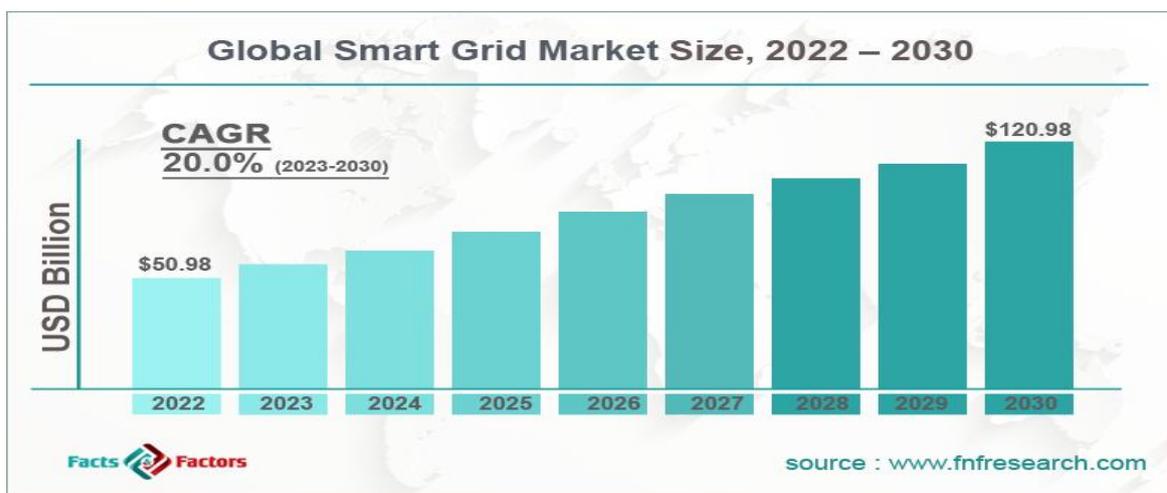


Power electronics is a crucial field within electronics engineering that deals with the conversion, control, and conditioning of electric power. In renewable energy systems, power electronics manage the flow of electricity from renewable sources, ensuring efficient energy conversion and grid integration. For example, in solar energy systems, inverters convert the DC power generated by PV cells into AC power that can be used by homes and businesses or fed into the electrical grid.

The relationship between renewable energy and electronics technology is deeply interconnected, with advances in each field driving progress in the other.

1. Renewable Energy Generation:

Electronics for Solar Panels: The efficiency and performance of solar energy systems depend heavily on advanced electronics, such as photovoltaic (PV) cells, which convert sunlight into electricity. Improvements in semiconductor materials and manufacturing processes have significantly increased the efficiency of solar cells. **Moreover, Wind Energy:** Wind turbines rely on electronic control systems to optimize their performance. Sophisticated electronics control the blades' angle, turbine speed, and energy output, maximizing efficiency and reducing wear. **Also, Hydroelectric and Geothermal:** These renewable sources also depend on power electronics to regulate electricity output, manage fluctuations, and connect to the electrical grid seamlessly.



2. Energy Storage Technologies:

Battery Technology: One of the biggest challenges with renewable energy is its intermittent nature (e.g., the sun does not always shine, and the wind does not always blow). Advances in battery technology, especially lithium-ion batteries, and emerging technologies like solid-state batteries, are crucial for storing energy from renewables so it can be used when needed. **Importantly, Energy Management Systems (EMS):** Electronics play a central role in managing how stored energy is distributed and used, ensuring that energy from renewables is efficiently stored and drawn when demand is high.

3. Smart Grids:

The integration of renewable energy sources into the grid requires the development of smart grids—advanced electricity networks that use electronics and communication technologies to monitor, control, and optimize the generation, distribution, and consumption of electricity.

Also, grids rely on sensors, data analytics, and electronics to balance the load between renewable energy and traditional power sources, ensuring grid stability and preventing blackouts.

4. Power Electronics:

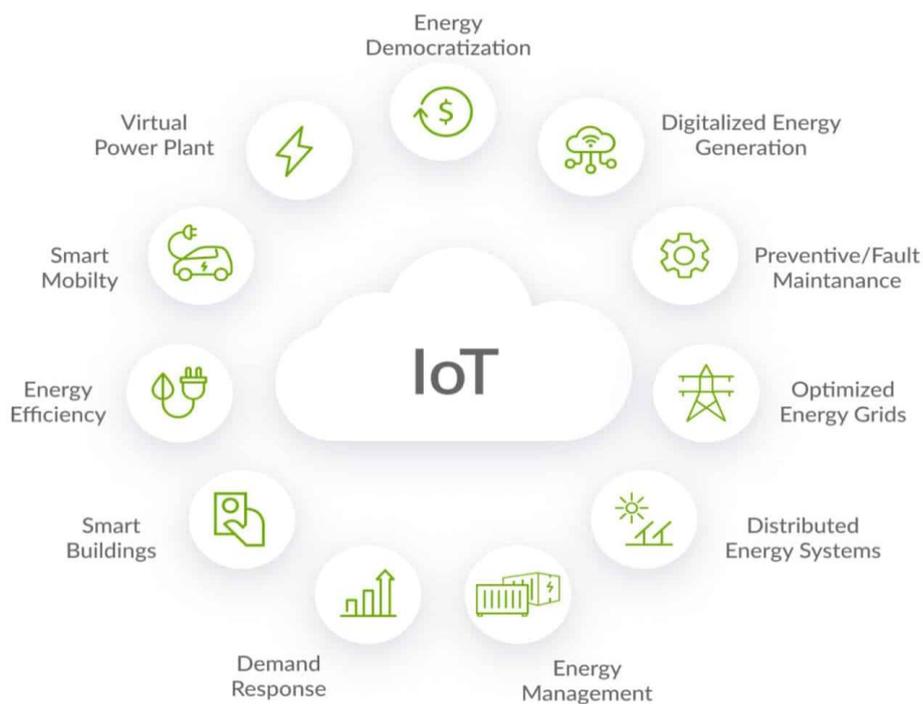
Inverters and Converters: Power electronics convert energy from renewables (such as the direct current (DC) from solar panels) into alternating current (AC) that can be used by the grid or within homes. Advanced inverters, with better efficiency and reliability, are essential for connecting renewable energy systems to the grid. In addition, Voltage

Regulation and Stability: Electronics technology enables better voltage regulation and frequency control, which is critical for integrating fluctuating renewable energy into a stable power supply.

5. IoT and Energy Efficiency:

The Internet of Things (IoT) plays a significant role in optimizing renewable energy use. Smart devices connected to the grid can adjust energy consumption based on real-time availability of renewable energy, enhancing efficiency and reducing waste.

Moreover, Home automation and smart appliances are examples where electronics technology can help manage energy consumption, using renewable energy when it's available and conserving power during peak hours.

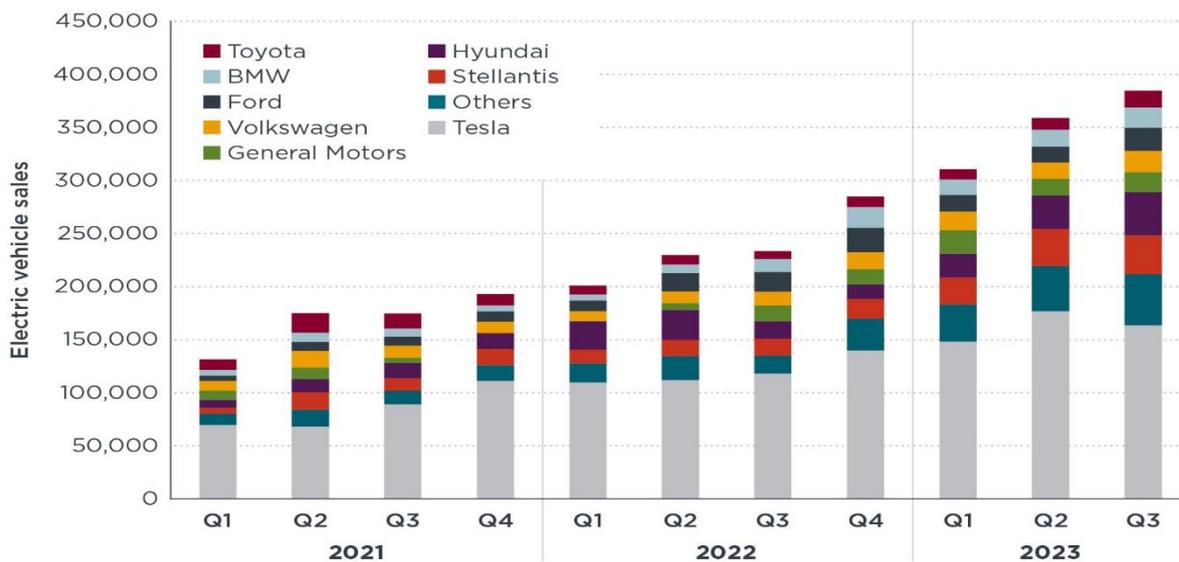
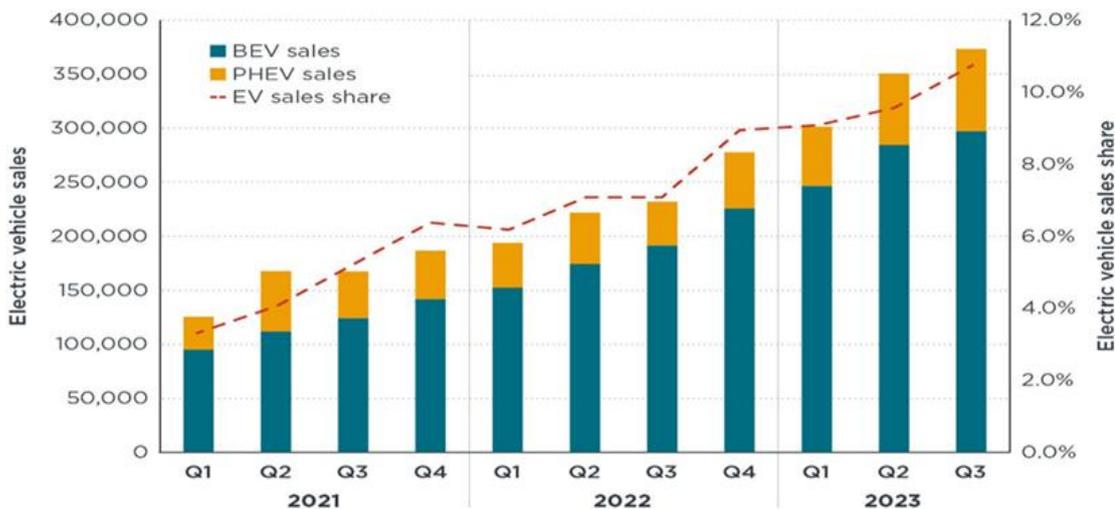


6. Manufacturing and Efficiency Gains:

Advances in electronics manufacturing, such as nanotechnology, have led to smaller, more efficient devices that can be integrated into renewable energy systems. For example, nano-electronics are being used to create more efficient solar cells and improve battery storage. Furthermore, Efficient power management circuits in renewable energy devices help reduce losses and maximize energy utilization.

7. Electric Vehicles (EVs): The relationship between renewable energy and EVs is vital. As the global shift toward electric vehicles continues, there is a growing need for renewable energy to charge these vehicles sustainably. Many EV owners are installing home solar systems to charge their cars using clean energy. Moreover, electronics technology improves EV battery life, charging efficiency, and integration with renewable energy systems (such as vehicle-to-grid

technologies). As it is clear that the sales of EV cars has been increasing in the past three years which shows that the environmental awareness



Although this research has focused on the relationship between electronics and renewable energy, renewable energy is primarily related to other several majors, including:

1. Environmental Science: Focuses on the study of environmental issues and the role of renewable energy in mitigating climate change and preserving ecosystems.
2. Energy Engineering: Centers on the design and implementation of renewable energy systems, including solar, wind, hydro, and geothermal technologies.
3. Mechanical Engineering: Involves the design and maintenance of machinery and systems used in renewable energy generation, such as wind turbines and solar panels.
4. Electrical Engineering: Focuses on electrical systems and technologies related to renewable energy generation, distribution, and storage.
5. Sustainable Development: Emphasizes the integration of economic growth, environmental stewardship, and social equity, often incorporating renewable energy solutions.
6. Chemical Engineering: Involves the development of processes for converting renewable resources into energy, such as biofuels and hydrogen production.
7. Public Policy or Environmental Policy: Focuses on the regulatory and policy frameworks that support renewable energy development and implementation.

CONCLUSION

Renewable energy and electronics technology are mutually reinforcing. As electronics evolve, they make renewable energy systems more efficient, reliable, and adaptable to the grid. Conversely, the growing demand for renewable energy drives innovations in electronics, especially in areas like energy storage, smart grids, and power management, fostering a more sustainable energy future. Switching to renewable energy from traditional fossil fuel-generated electricity provides significant environmental, economic, and health benefits. By reducing greenhouse gas emissions, improving air quality, and fostering economic development, renewable energy represents a crucial step toward a sustainable and resilient energy future. The continued investment in and adoption of renewable energy technologies is essential for addressing global energy challenges and achieving climate goals. This research has clarified that there is a multifaceted benefits of renewable energy and the pivotal role of electronics engineering in advancing these technologies. Renewable energy sources such as solar, wind, hydroelectric, and geothermal significantly reduce greenhouse gas emissions, leading to lower carbon footprints and improved air quality while promoting sustainable resource use, as these energy sources are abundant and inexhaustible. The transition to renewables creates jobs, enhances energy independence, and stabilizes energy prices due to lower operational costs compared to fossil fuels. Decentralized energy generation from renewables enhances resilience against supply disruptions, while a diverse energy portfolio improves overall energy security.

Additionally, renewable energy contributes to better public health by reducing air and water pollution, resulting in fewer pollution-related illnesses and decreased healthcare costs. The growth of renewable energy drives advancements in energy technology, particularly in storage and smart grid solutions, fostering sustainable infrastructure and aiding climate change mitigation by reducing emissions and promoting global cooperation. Electronics engineers are crucial in developing power electronics, embedded control systems, and smart grids that facilitate the efficient operation of renewable energy systems, with innovations in energy storage—such as batteries and super capacitors—being essential for managing the intermittent nature of these resources. Specific technologies like solar energy utilize photovoltaic cells and concentrated solar power, while wind energy captures kinetic energy through turbines; both rely on power electronics for optimization. Hydropower harnesses flowing water, with engineers improving control systems for better integration, and geothermal and biomass energies focus on efficiency and emission monitoring. Overall, the document underscores the urgent need for continued innovation in electronics and electrical engineering to support the widespread adoption of renewable energy, aiming for a sustainable future.

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