Driving the Energy Transition: Large-Scale Electric Vehicle Use for Renewable Power Integration

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Abstract: The global energy shift towards sustainability and renewable power sources is pressing. Large-scale electric vehicles (EVs) play a pivotal role in accelerating this transition. They significantly curb carbon emissions, especially when charged with renewable energy like solar or wind, resulting in near-zero carbon footprints. EVs also enhance grid flexibility, acting as mobile energy storage, stabilizing power supply. Integrating EVs into renewable systems offers demand response programs, optimizing energy use. However, extensive infrastructure development, particularly charging networks, is a significant challenge. Collaboration among governments, utility companies, and private sectors is crucial to ensure a smooth transition to electric mobility.

Keywords: electric vehicles; vehicle-to-grid technology; V2G; renewable energy; carbon footprint; greenhouse gases; grid energy; power system infrastructure; smart grid; energy storage; battery; accumulators

1. Introduction

Renewable energy integration is fundamentally the establishment of a system that is continuously able to convert energy into a useful form (i.e., electricity), from sources which do not harm or deplete the natural resources available in the ecosystem in which such a system and its energy output utilisation persists. Research, development, and usage of renewable energy has taken place since the early 20th century, until when “fossil fuels”, i.e., sources which rely on the natural resources of the planet, were solely used. Therefore, “fossil fuels” have been termed as conventional energy sources (see Figure 1), while renewable energy, being a recent advancement in power generation, has been termed as a non-conventional energy source.

The 2021 United Nations Climate Change Conference, commonly referred to as COP26, held from 31 October to 13 November 2021 at the SEC Centre, Glasgow, Scotland, United Kingdom, culminated into the Glasgow Climate Pact (the latest agreement to restrain global climate change) which pledges to restrict Global Warming to “well-below 2 °C” per year and not let it exceed 1.5 °C per year. In order to achieve this, it advocates the reduction in carbon dioxide emissions by 45% (with respect to emission levels in 2010) till 2030 and accomplishing “net zero” greenhouse gas emissions by 2050. Thus, with humanity aiming at achieving complete “carbon-neutrality” by the mid-21st century, it becomes essential to undertake large-scale energy transition from conventional to non-conventional energy, that is, from “fossil fuels” to renewable energy.

Keeping in step with the same ethos, this research aims at one of the ways of achieving this goal—integrating large-scale usage of electric vehicles into electricity grids powered completely by renewable energy [2–5].
2. Global Climate Issues That Renewable Energy Integration Aims to Solve

2.1. Greenhouse Gases

The Earth’s atmosphere now is composed of various gases, both naturally occurring and man-made. Many of these gases are greenhouse gases. Insolation on the Earth’s surface produces infrared radiation, which is absorbed by greenhouse gases, trapping heat inside the Earth. This leads to the greenhouse effect, causing climate change and global warming, and causing the Earth’s surface to become hotter.

Greenhouse gases, in their natural trace amounts, are essential for life on Earth, as they trap heat and maintain the Earth’s average temperature of around 14 °C (57 °F) even
during nighttime. Without the greenhouse effect, nighttime temperatures could drop to $-18\, ^\circ C$, making it too cold for life to exist.

Carbon dioxide is a major contributor to the greenhouse effect, discharged by natural processes like volcano eruptions and aerobic respiration. The Industrial Revolution in the 1800s increased CO$_2$ levels by 50% (see Figure 2) due to forest clearing and the burning of “fossil fuels”. This has led to catastrophic climate change, as carbon dioxide is now present in large amounts in the atmosphere.

![Cumulative CO$_2$ emissions (1850-2021)](image)

Figure 2. Cumulative carbon footprints of various nations (1850–2021) [13].

Natural greenhouse gases include methane, nitrogen oxide, and water vapour, which is abundant in the Earth’s atmosphere. Water vapour remains in the atmosphere for a few days, while CO$_2$ remains for centuries. Other man-made greenhouse gases, like hydrofluorocarbons (HFC), perfluorocarbons (PFC), and sulphur hexafluoride (SF6), are released during industrial processes and are not naturally present in the environment. These gases have a significant potential for the greenhouse effect, with SF6 gas being over 23,000 times more potent than CO$_2$. To reduce greenhouse gas emissions, it is essential to reduce the use of “fossil fuel” powered energy sources and replace them with non-conventional renewable energy sources like wind and solar energy. Small daily changes, such as reusing and recycling, can help reduce pollution and save the planet’s, and thus humanity’s, future.

2.2. Carbon Footprint

The term “carbon footprint” describes all greenhouse gas emissions from various sources, such as individuals, products, events, or organisations. The carbon footprint on the atmosphere is the sum of all greenhouse gas emissions during a product’s lifetime. As humanity advances, it increasingly relies on energy to sustain a better life and reduce human labour. This dependence on “fossil fuels”, which are burned to generate energy, leads to pollution and increased greenhouse gas emissions. Fossil fuels, such as coal, petroleum, and natural gas, contribute to the carbon footprint by producing harmful gases such as carbon dioxide, methane, and nitrous oxide (see Figure 3).

![Cumulative CO$_2$ emissions (1850-2021)](image)

Renewable energy sources have a very low (“net Zero”) carbon footprint compared to fossil fuels, producing minimal greenhouse gas emissions. However, their intermittent nature poses challenges in deploying them for global energy needs. To ensure the safe and healthy future growth of humanity, efficient and effective energy management systems must be developed to meet the ever-growing demand for clean energy.
2.3. Other Environmental Effects

The previously described shortcomings of conventional “fossil fuels” are culminating into global environmental crises, if not energy crises. While the energy crises linked to extensive use and eventual depletion of “fossil fuels” are complex and politically manipulated, the environmental crises are evident, straightforward, and are posing an immediate existential threat to life on Earth.

1. **Climate change mitigation**—renewable energy is crucial for mitigating climate change and reducing greenhouse gas emissions with minimal environmental impact.

2. **Air pollution reduction**—renewable energy sources do not release harmful pollutants, improving air quality and public health, unlike fossil fuel combustion, which cause acid rains and damage to flora and fauna due to adverse pH levels.

3. **Water conservation**—fossil fuel power plants require significant water for cooling, burdening local water supplies in areas facing water shortages. Many renewable technologies require significantly less or no water at all.

4. **Resource conservation**—fossil fuel reserves will run out, leading to scarcity and higher costs. Transitioning to abundant, sustainable renewable energy will conserve valuable natural resources for future generations.

5. **Biodiversity preservation**—extracting fossil fuels often involves destructive practices such as deforestation or habitat destruction, leading to loss of biodiversity in ecosystems. Utilising renewable energy minimises these negative impacts and helps preserve biodiversity.

Thus, this paper aims to propose pure renewable energy dependence of the future power grids by means of large-scale integration of electric vehicles as mobile energy storage devices for such power systems.

3. Efficient Energy Storage Systems

Electric vehicles (EVs) are becoming increasingly popular due to their lower emissions and reduced dependence on fossil fuels. With improved range and charging infrastructure, EVs can now travel over 300 miles on a single charge. Efficient electric storage systems are crucial for managing electricity from renewable sources like solar and wind power. These systems store excess electricity during low demand and supply it back to the grid during peak hours or low renewable energy generation. Advancements in battery storage technology have significantly increased the efficiency and capacity of these systems. [15,16]
Current and Future Trends in Energy Storage (Rechargeable Battery) Infrastructure

Due to their high energy density and prolonged cycle life, lithium-ion batteries are widely utilized in EVs and energy storage. However, future research is focusing on next-generation technologies with higher energy densities, faster charging times, and lower costs, like solid-state batteries.

Essentially, energy storage balances production and demand by storing energy for later use. A device that stores energy is referred to as an accumulator or a battery. Humans develop various energy storage devices using various technologies:

1. **Mechanical**—springs, compressed air energy storage (CAES), flywheels, solid mass gravitational, hydraulic accumulator, etc.
2. **Electrical or electromagnetic**—capacitor, supercapacitor or superconducting magnetic energy storage (SMES), etc.
3. **Electrochemical (battery energy storage system, BESS)**—flow battery, rechargeable battery, ultra-battery, etc.
4. **Thermal**—eutectic system, steam accumulator, phase-change material, etc.
5. **Chemical**—biofuels, hydrated salts, hydrogen peroxide, power-to-gas (methane, hydrogen storage, oxyhydrogen), etc.

Among these energy storage techniques, at present electrochemical battery energy storage systems (BESSs) are being used most extensively, being the most reliable, feasible and effective, with Lithium (Li) ion rechargeable batteries currently having the most widespread applications [17]. However, the available storage systems are still very bulky and not capable enough to enable complete reliance on electric vehicles and renewable energy-powered electricity grids. Thus, intensive research is being conducted with the following objectives in the field of efficient energy storage systems: [18,19].

1. **Increased energy density**—one of the most significant research objectives in battery storage technology is the improvement of energy density. Researchers are continuously probing for ways to store more energy in smaller and lighter battery cells, leading to increased energy storage capacity with a smaller physical footprint. Batteries are now also being optimised for utilisation in Nanoelectronics [20].
2. **Longer lifespan**—battery technology research is improving lifespan, retaining more capacity over more cycles, reducing replacement needs, and enhancing the economic viability of storage systems.
3. **Cost reduction**—battery storage costs are decreasing due to manufacturing advancements, economies of scale, and increased demand, making it more accessible, and economically competitive than fossil fuel alternatives.
4. **Grid-scale deployments**—battery storage systems are now being deployed at grid scale for energy storage, stabilising the grid, managing peak demand, and improving resilience.
5. **Hybrid systems**—combining battery storage with other energy storage technologies, such as pumped hydro, compressed air, or flywheels, has emerged as a promising approach to achieving better overall system efficiency and reliability.
6. **Vehicle-to-grid (V2G) technology**—as electric vehicle adoption increases, V2G technology allows bidirectional power flow between EV batteries and the grid allowing EVs to both take power from the grid and return power to the grid, contributing to grid stabilisation and load balancing. [16,18,19]
7. **Solid-state batteries**—they offer long-lasting, faster-charging, safer, and inexpensive technology with up to 500 watt-hours per kilogram of energy density. Many manufacturers and startups aim for commercialisation within a decade.
8. **Sodium-ion batteries**—sodium (Na)-ion batteries are gaining popularity as an alternative to Li-ion batteries due to their use of abundant resources, lower cost, and safety. Research is underway to produce Na-ion batteries with energy density comparable to Li-ion batteries.
4. Design of Electricity Grids with Dynamic Supply and Load Points

Conventional energy sources, such as “fossil fuels”, have been used for decades for electricity production. These non-renewable resources cannot be regenerated. To address this issue, renewable energy technology is continuously being developed, utilizing unlimited, non-exhaustive sources like solar, wind, and nuclear power. These renewable resources are becoming increasingly important in electricity grids.

The integration of purely renewable energy systems into the power system infrastructure requires careful planning and design to ensure reliability and stability, as it is a well-known challenge in pure renewable energy integration that the maximum power generation hours of renewable energy sources are mostly different from the peak load demand hours of the electricity grids to which they are connected, as is evident from the load demand and supply curve for a solar powered grid in Figure 4a,b.

Thus, the basic steps for integrating renewable energy sources into electricity grids are:

1. Analysis of resources plays an important role in renewable energy setup. Firstly, it is necessary to check the geographical conditions of the area where a particular renewable energy harnessing plant is going to be setup. For example, solar plants must be located in areas where the sun’s radiation intensity is high for a major part of the year.

Figure 4. Load curves of a solar powered grid. Notice the difference in durations and occurrences of maximum supply and maximum demand peaks, respectively [21]: (a) Load curve during summers; (b) load curve during winters.
(2) Energy storage is also crucial. For this, efficient batteries with large storage capacities and slower discharge rates are essential for efficient energy storage during non-peak load hours, to be used when power production decreases but demand increases.

(3) Management of grid demand is very crucial. To manage this, advanced algorithms and systems of grid management are being researched and gradually used, which perform real-time monitoring and forecasting of grid demand and available supply. This controls and manages the balanced supply and demand, stability and mitigates fluctuation.

Designing electricity grids with dynamic load points is crucial due to renewable energy’s variability, requiring control and balancing. Advanced forecasting tools, smart grid technology, monitoring, and infrastructure are essential for grid stability, and the international grid interconnections will maintain power balance.

4.1. The International Grid Interconnection

International grid interconnection is a crucial initiative connecting electric power networks across borders, enabling efficient renewable energy utilization. The “One Sun, One World, One Grid” (OSOWOG) project, proposed by Indian Prime Minister Narendra Modi, aims to create interconnected renewable energy networks. India and the UAE are working on an agreement to boost investments in solar and wind projects, promoting a sustainable, low-carbon future and reduced fossil fuel dependency.

International grid interconnections offer benefits like reduced fossil fuel dependency, enhanced energy security, and a sustainable, low-carbon future. They utilize advanced technologies like HVAC, HVDC, VSC (voltage source converters), LCC (line-commutated converters), and FASAL (flexible alternating current transmission system). Research focuses on ultra-high voltage transmission systems, smart grid solutions, and clean energy initiatives.

4.2. Advanced Smart Grid Control Algorithms for Vehicle-to-Grid Technology

Smart grid technologies allow real-time monitoring, control, and optimization of renewable energy systems, enabling efficient electricity generation, distribution, and consumption. Designing dynamic bidirectional grids considers factors like peak demand fluctuations, weather patterns, and geographical distribution. Integrating distributed energy resources (DERs) and grid control algorithms based on machine learning improves resilience and optimises power flow. Thus, its large-scale usage is the basic requirement for the application of V2G technology in renewable energy power grids [12].

In this regard, our research is based on the California Independent System Operator or CaISO’s Annual Summer Loads and Resources Assessment Reports for the solar powered grid in the state of California, USA.

The California Independent System Operator or CaISO [9,22–26]

The California Independent System Operator (CaISO) is a non-profit organisation responsible for operating and managing the high-voltage electricity grid in the state of California, USA. Established in 1998 and regulated by the Federal Energy Regulatory Commission (FERC) of 1992, CaISO is one of the largest independent system operators in the world, supplying over 300 MWh per annum, i.e., over 80% of California’s power demand. Its primary function is to ensure the reliable and efficient transmission of electricity across California and to facilitate the integration of renewable energy resources into the power grid.

CaISO has implemented two types of vehicle-grid interfaces (VGIs) to assess, monitor and research advanced smart grid algorithms for vehicle-to-everything (or V2X) technology. They are:

(1) Unidirectional power flow (V1G), unidirectional controlled charging services, unidirectional V2G, or smart charging

In V1G, the time/rate of electric vehicle charging is altered. Both adjusting the charge rate to provide frequency stability or load balancing services and charging during the day to capture solar energy that would otherwise be lost are examples of V1G techniques. CaISO
uses V1G as a mechanism where EVs act as passive loads, drawing power from the grid during ‘favourable’ charging periods. CaISO has been actively exploring the integration of V1G technology into its operations to enhance grid flexibility and accommodate the growing number of electric vehicles.

I. **V1G with aggregated resources** refers to the coordinated management of multiple electric vehicles connected to the grid as a collective resource. CaISO considers EVs as an aggregate to create a virtual power plant, harnessing combined battery capacity for flexible energy support, grid stability, and ancillary services.

II. **V1G with fragmented actor objectives** are challenges arising when stakeholders, i.e., EV owners, utilities, and grid operators, have conflicting objectives for EV battery usage. For instance, EV owners prioritise range, while grid operators seek to optimise battery usage for grid support. CaISO aims to address these fragmented objectives by developing coordinated strategies and policies that align stakeholder interests and ensure efficient EV battery utilisation within the grid.

(2) **Bidirectional power flow (V2G)**

Vehicle-to-grid (V2G) is a concept enabling electric vehicles to draw and feed power back into the grid during peak demand periods. CaISO is studying its potential to enhance grid flexibility, integrate renewable energy, and provide ancillary services. However, current analysis shows the process is high-loss, low-efficiency, and has the potential for battery life reduction. The Southern California Edison V2G pilot project’s economic benefits became diminished due to higher administration costs than revenues.

It is this form of implementation which has been found to be most reliable, effective, and resilient, thus has the best scope for future development and utilisation. CaISO has tested the following V2G systems:

I. **Bidirectional local V2G (V2H, V2B, V2X):** Vehicle-to-home (V2H), vehicle-to-building (V2B), or vehicle-to-everything (V2X) systems employ the electric automobile’s battery to supplement or replace grid electricity when there is a power outage. For instance, solar-powered vehicles charged during the daytime may power a home all night long without grid energy utilisation. Other than Japan, which has had commercial V2H operations since 2012, V2X had not yet reached market adoption as of 2022.

II. **Bidirectional (fast) DC charging** is often possible for electric vehicles by connecting the battery directly to the transformer within the charging station. Bidirectional DC charging technology is currently being developed. With this technology, the station has a DC-to-AC converter, and the automobile can either charge itself or supply power to the station. In theory, EVs lacking hardware support for vehicle-to-grid may achieve bidirectionality with a simple software upgrade, a major milestone objective.

In summary, CaISO’s efforts in managing electricity transmission, facilitating wholesale markets, and integrating renewable energy in California, make it an exemplar for achieving humanity’s ambitious but necessary “clean” energy goals, including the integration of a higher share of renewable energy, reducing greenhouse gas emissions, and enabling grid decarbonization, in pursuit of a greener and more resilient energy system.

5. **Conclusions**

In conclusion, the integration of large-scale electric vehicle (EV) use with renewable power systems represents a pivotal step towards a sustainable and cleaner energy future. EVs not only substantially reduce carbon emissions but also enhance grid flexibility and enable innovative demand response programs.

However, infrastructure development, particularly a charging network, is crucial for widespread EV adoption. Collaboration between governments, utilities, and private stakeholders is essential. Research should focus on optimizing EV integration into renewable energy systems, developing advanced grid management techniques, and exploring innovative financing models. The resolution of these challenges will accelerate the transition to a more sustainable and resilient energy ecosystem.
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References


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