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Opportunities and Challenges of Fuel Cell Electric Vehicle-to-Grid (V2G) Integration

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Abstract: This paper presents an overview of the status and prospects of fuel cell electric vehicles (FC-EVs) for grid integration. In recent years, renewable energy has been explored on every front to extend the use of fossil fuels. Advanced technologies involving wind and solar energy, electric vehicles, and vehicle-to-everything (V2X) are becoming more popular for grid support. With recent developments in solid oxide fuel cell electric vehicles (SOFC-EVs), a more flexible fuel option than traditional proton-exchange membrane fuel cell electric vehicles (PEMFC-EVs), the potential for vehicle-to-grid (V2G)'s implementation is promising. Specifically, SOFC-EVs can utilize renewable biofuels or natural gas and, thus, they are not limited to pure hydrogen fuel only. This opens the opportunity for V2G's implementation by using biofuels or readily piped natural gas at home or at charging stations. This review paper will discuss current V2G technologies and, importantly, compare battery electric vehicles (BEVs) to SOFC-EVs for V2G's implementation and their impacts.

Keywords: fuel cell vehicles; SOFC-EVs; electric vehicles; alternative fuel; clean energy; vehicle-to-grid (V2G); transportation; sustainability; fuel cell technology; fuel cell vehicle architecture

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1. Introduction

The use of alternative and carbon-emissions-free energy has gained more attention with increased public awareness and published laws for environmental protection [1–3]. In recent years, the EV market's growth has placed additional stress on the grid because charging EVs requires large power draws from the electrical grid, especially when fast-charging [4], for which battery energy storage at the charging station itself may be necessary [5]. Energy storage capabilities are crucial during peak energy demand times, when they discharge stored energy back to the grid to relieve pressure on the grid, reducing the strain, which is reflected in grid frequency stabilization, and promoting sustainability.

In addition to battery electric vehicles, which can store and release energy back to the grid, fuel cell electric vehicles configured as plug-in EVs are also set to play a significant role in bidirectional charging through V2X. The feasibility of proton-exchange membrane EVs (PEM-EVs) for grid integration has been tested at The Green Village, Netherlands, with promising results, with a 100 kW fuel cell stack powering multiple dwellings [6,7]. This suggests a hopeful future for integrating solid oxide fuel cell EVs (SOFC-EVs) into the grid, which offers increased flexibility over PEM-EVs, as SOFCs are not limited to pure hydrogen fuel only. SOFC-EVs can convert natural gas into electricity and heat through a highly efficient electrochemical process. This process enables fuel cell electric vehicles to provide both electricity and heat to buildings. Unlike battery EVs (BEVs), FC-EVs use piped natural gas at home and can function as mobile, decentralized power plants and offer backup generation to families. FC-EVs include a smaller onboard battery than BEVs, as the batteries in FC-EVs are primarily used to capture regenerative braking and boost acceleration [8,9]. The Li-ion battery used in BEVs has an energy density of 200 Wh/kg [9].

To avoid battery degradation, the actual usable state of charge (SOC) is between 20 and 90% [9,10]; this would limit useful specific energy to 140 Wh/kg [9]. Specific energy could be reduced further when taking into account the onboard thermal and electrical management system for the Li-ion battery [9]. For FC-EVs, hydrogen fuel has an energy density of 30,000 Wh/kg [11]; even after including the weight of the hydrogen tank, small onboard battery, and fuel cell system, the useful specific energy is still twice that of the Li-ion battery shown in Figure 1a [9]. When considering the useful energy density in volume for hydrogen, it is the same as the lithium battery when hydrogen is compressed to 35 MPa. However, while the energy density can be increased with a higher-pressure tank, as shown in Figure 1b, the added mass from the extra fiber wrap needed to allow for the higher pressure actually decreases the fraction of the mass of the system that is hydrogen fuel [9]. Since the main energy source in these vehicles is the fuel cell, with the battery used for regenerative braking and to act as a reserve when more power is needed than can be supplied by the fuel cell, the battery chemistry used in these vehicles could be a highly robust low-degradation battery like a lithium titanium oxide (LTO) and/or lithium iron phosphate (LFP) battery [12], which would also increase the financial feasibility of participation in V2X activities.

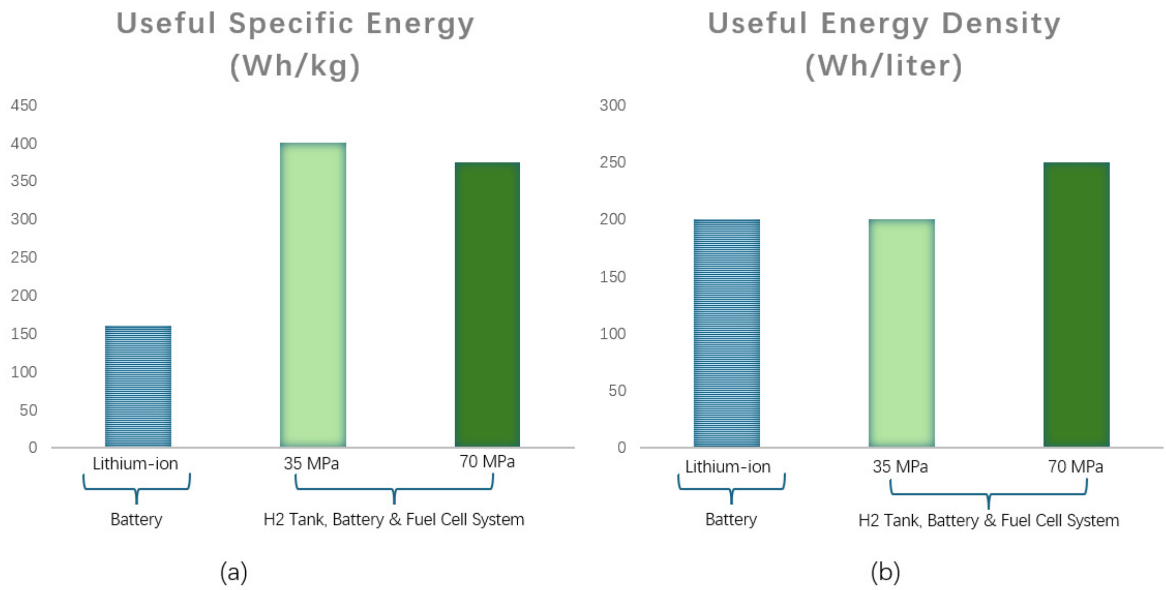


Figure 1. (**a**) The useful specific energy (energy per unit mass), adapted from [9]. (**b**) The useful energy densities (energy per unit volume), adapted from [9].

1.1. Introduction to V2X, V2I, V2V, V2B

The Internet of Things (IoT) became popular and possible after the deployment of the fifth-generation cellular network (5G) [13], which opened opportunities for smart technology, including vehicle-to-everything (V2X) [14,15]. V2X utilizes transformative communication technology that allows vehicles to interact with the surrounding environment and to be connected to infrastructure to enable safe and efficient energy transfer, reduce environmental impact, and support autonomous driving. This technology primarily relies on dedicated short-range communication (DSRC) or cellular vehicle-to-everything (C-V2X) [16,17]. However, V2X also plays an increasingly vital role in integrating energy systems, extending beyond transportation to enable seamless energy transfer between vehicles, buildings, and the electrical grid.

Vehicle-to-infrastructure (V2I) connects vehicles to communicate with traffic signals, road signs, and other infrastructural elements [18]. When these interact with vehicles, they can improve road safety and the flow of traffic. For example, smart traffic lights in a V2I system can adjust their timing based on real-time traffic flow. Drivers can also receive notifications on road maintenance and hazardous conditions. Beyond improving traffic management, V2I can also support energy integration through V2X systems, in which vehicles charge from the grid and supply energy back to buildings or infrastructure when demand peaks [19–21].

Vehicle-to-vehicle (V2V) utilizes vehicle communication that shares real-time data, including speed, position, direction, braking status, etc. [22]. Road safety and traffic efficiency depend on these data; this system uses both DSRC and C-V2X. For example, obtaining braking feedback and identifying obstacles can avoid collisions caused by platooning, giving drivers more time to react [23]. It also enables lane change assistance by informing drivers of other drivers' intentions, reducing sideswipe accidents, and enabling platooning vehicles to travel closely behind each other at high speed to improve fuel and traffic efficiency. V2V technology is also integrated into the V2X energy infrastructure, allowing moving vehicles to share energy data and respond to charging needs, enhancing the energy network's efficiency [24].

V2X also has the potential for vehicles to interact with the grid and buildings through vehicle-to-grid (V2G) and vehicle-to-building (V2B) technology. This will allow battery electric vehicles (EVs) to be used as energy storage systems [25,26].

The progress of V2X technology is not a solitary endeavor. It is a collaborative effort that is expected to enhance safety, improve traffic efficiency, reduce environmental impact, and contribute to sustainability. However, it is crucial to acknowledge that challenges remain for infrastructure development and the establishment of global standards, underscoring the importance of collective action and cooperation in this journey [27]. As these vehicles could be used for both transportation and energy storage systems, they will define the next phase of a smart, sustainable ecosystem.

1.2. Contribution and Organization of This Paper

This paper discusses the importance of sustainable energy use in fuel cell electric vehicles and the opportunities available for solid oxide fuel cell electric vehicles in relation to home electricity and energy integration. This paper also discusses V2X and energy integration, focusing on the technology available and future advancements.

Therefore, Sections 1 and 2 briefly summarize V2X technology. Section 3 will focus on integrating electrical vehicles with the grid and will propose the opportunities for using solid oxide fuel cell electric vehicles as both electricity and heat energy sources. Section 4 will examine the current and future infrastructure implementation.

2. Grid Integration

2.1. Grid Integration of Renewables

Integrating renewable energy sources into the power grid is a critical step in the transition toward a more sustainable and low-carbon energy system. Renewable energy sources, such as wind, solar, and hydropower, offer alternatives to fossil fuels and reduce greenhouse gas emissions [28–30].

One of the most significant challenges associated with renewable energy sources, particularly wind and solar, is their intermittent and variable nature. Unlike fossil-fuel-based power plants, which can generate electricity continuously, wind and solar power depend on environmental conditions. Even when nuclear energy is used to supply base power, the variability of renewables can lead to fluctuations in power generation, making it challenging to match supply with demand in real time, and energy storage systems such as batteries can provide leveling support [31]. Managing these fluctuations requires advanced grid management systems and the development of energy storage solutions that can store excess energy during periods of high generation and release it when generation is low [32,33].

2.2. *Vehicle-to-Everything (V2X) Technology*

2.2.1. Vehicle-to-Grid (V2G)

V2G technology integrates electric vehicles with the power grid, with the goal of enabling plug-in electric vehicles to sell demand response services to the grid. These demand services include delivering electrical power to the grid or, alternatively, reducing the demand from the grid by interrupting charging. In this manner, demand services reduce the demand peaks and reduce the likelihood of grid disruptions due to load variations. This revolutionary approach requires communication between the EV and the grid to modulate EV power draw and supply back to the grid [34]. The primary function of V2G is grid stabilization [35]. The electricity grid experiences fluctuating demand throughout the day; V2G can normalize peak demand as a mobile energy storage unit, which can help balance supply and demand, reducing the need for extra power plants.

A significant benefit of V2G technology is its potential to support renewable energy integration, which includes intermittent renewable energy sources such as solar and wind [36]. V2G can store the excess energy generated during high production and discharge it when production is low. For example, during sunny days, solar panels may produce substantially more energy compared to cloudy days or nights. Having energy storage capabilities not only helps to stabilize the grid but also contributes to a more sustainable and eco-friendly energy system.

Accurately assessing the number of EVs participating in the V2G network in the reserve and coordination between distribution networks could ensure the reliability and sustainability of the system [37–40]. Incentive payments could draw more participants into V2G contracts, and trading carbon emissions in the system to balance the energy demand could reduce carbon emissions [41,42]. However, a study by Zheng et al. also showed that BEVs participating in V2G for revenue generation at current rates do not cover the cost of battery degradation [43]. Further cost reductions in the battery, decreases in battery degradation per cycle, and increased feed in tariffs or net metering credit are all needed to draw more BEV participants; this also opens up opportunities for using FC-EVs for V2G's implementation.

V2G can also provide emergency power to homes and critical infrastructure [44,45]. This is crucial for disaster-prone areas as a stable power supply for emergency response and recovery operations [44,45].

2.2.2. Vehicle-to-Building (V2B)

Vehicle-to-building (V2B) technology is similar to V2G but without the intention of supplying demand response services to the grid. Rather, its focus is on using EVs directly to supply electricity to a building or as a backup power source, although this may export energy to the grid like a residential photovoltaics (PV) installation. Therefore, V2B is controlled at the house–building scale and much easier to implement [46]. This concept can be considered more viable and practical and can increase the electricity market share to let customers immediately take the opportunity to participate in peak shaving. V2B technologies can also preclude the need for additional investment to build new power generation facilities, taking great advantage of flexibility and mobility, especially for cities with a high level of electric vehicle penetration [46–48].

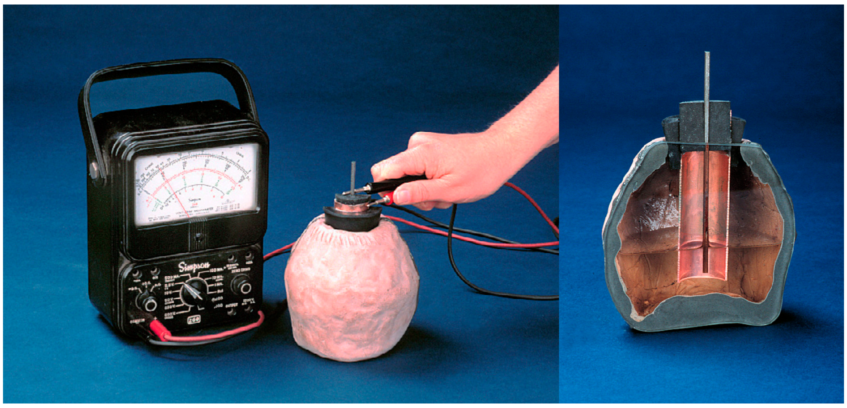
The V2B nanogrid is compact and cost-effective and does not require an external central controller and extensive communication links [49]. There are two architectures involved: AC and DC systems. The AC system has a broad market and more mature technology. As for the DC system, the standards for distribution are lacking, resulting in an immature market [50].

3. Vehicle-to-Grid

3.1. Battery Electric Vehicle-to-Grid

3.1.1. Battery Background

The history of the battery dates back to 2000 years ago, with the discovery of the Baghdad Battery, believed to be the first battery [28]. It consists of an iron rod inserted into asphalt and encased by a copper cylinder. When filled with vinegar, the jar can produce 1.1 volts (see Figure 2a) [51]. However, the first true battery was invented by the Italian physicist Alessandro Volta in the early 1800s and was called the voltaic pile (see Figure 2b). It consists of pairs of copper and zinc discs stacked on top of each other with a cloth serving as the electrolyte, filled with salt water [52].



(**a**)

(**b**)

Figure 2. (**a**) Baghdad Battery [51]. (**b**) Voltaic pile [53].

Batteries are electrochemical devices that can both store or release energy in a rechargable fashion. They consist of five main components: two electrodes (anode and cathode) with negative and positive charges, separated by an electrolyte and a separator, and enclosed by a current collector, as shown in Figure 3 [54]. When the battery discharges, electrons flow between electrodes, generating electric currents. The most commonly used battery in automobiles is the lead–acid battery. Lead–acid batteries were the first rechargeable batteries, invented by Gaston Plante in 1859 [55]. To this day, they are still the most commonly used batteries for starting, lighting, and ignition systems in automobiles. Although they are heavy and have low energy density, they are known for their reliability and cost-effectiveness.

Lithium-ion batteries have revolutionized the battery market because they are lighter and have higher energy densities [56]. They became popular through their use in modern portable electronic devices, electric vehicles, renewable energy storage systems, and in many other applications. Lithium-ion batteries were commercially introduced in the early 1990s and quickly dominated the market, which was previously occupied by lead–acid and nickel–cadmium batteries [57].

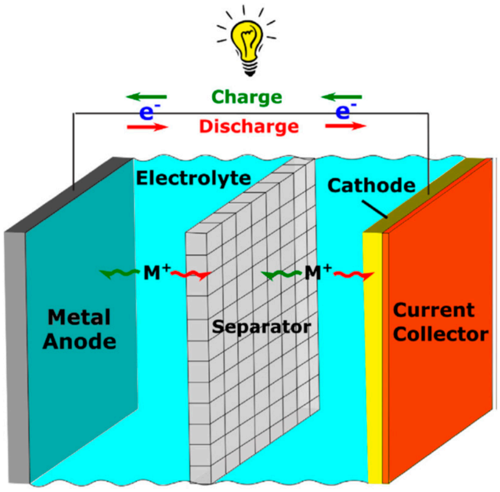


Figure 3. Typical battery components [54].

3.1.2. Battery Efficiency

To determine the overall performance and longevity of a battery energy storage system, it is critical to study the battery efficiency. There are three commonly used terms when referring to battery efficiency: Coulombic efficiency, energy efficiency, and round-trip efficiency.

Coulombic efficiency is the measure of the effectiveness of a battery in retaining and returning its charge during the charging process, which is measured in Coulombs or Ampere-hours (Ah). During the charging process, a specific amount of charge is stored in the form of chemical energy. Energy can be lost due to electrolyte decomposition or internal chemical changes. During the discharging process, it releases the stored charge to power a device or system. Coulombic efficiency can be expressed as shown in Equation (1) [58–60]:

$$Coulombic\ Efficiency\ (\%) = \left(\frac{Q_{Out}}{Q_{in}}\right) \times 100\% \tag{1}$$

where Q_{in} is the total charge stored during the charging phase and Q_{out} is the total charge delivered during discharging.

The battery efficiency can be misleading if only expressed in terms of Coulombic efficiency, which can be as high as 99% for lithium ion batteries, because it does not include the effects of required overvoltages on the ability of the battery to power a system.

When both Ampere-hours and voltage are considered, the term energy efficiency is used, and it measures the charge/discharge efficiency in units of energy (i.e., Watt-hours or Joules). It accounts for energy losses caused by internal resistance, usually in the form of heat generation, and other inefficiencies. During the charging process, electrical energy in Joules or Watt-hours is supplied to the battery. Due to internal resistance changes such as the battery's state of charge, temperature, cycle life and aging, charging and discharging rates, etc., some overvoltage is required to drive the processes involved in battery charging, and some energy is lost as heat [61,62]. When the battery is discharged, the discharging voltage will also be lower than the battery's nominal operating voltage due to various losses, including internal resistance, resulting in the energy delivered during discharge being less than the energy used during charging. The energy used for battery charging, E_{in}, can be expressed as shown in Equation (2), and if the applied current and/or applied voltage change as a function of time, such as in a modern constant current–constant voltage (CC-CV) profile, this can be generalized as shown in Equation (3) [63–68].

$$E_{in} = Q_{in} \times V_{in} \tag{2}$$

$$E_{in} = \int_{t=start\ of\ charging}^{t=end\ of\ charging} i(t)V(t)dt \tag{3}$$

Similarly, the energy extracted from the battery, E_{out}, which must include any losses incurred as self-discharge, can be written as in Equation (4). Since the voltage at which current is supplied by the battery is strongly dependent on the instantaneous power requirement and on the battery's state of charge, temperature, and other factors, the calculation of the total energy extracted can be generalized as in Equation (5).

$$E_{out} = Q_{out}V_{out} \tag{4}$$

$$E_{out} = \int_{t=start\ of\ discharging}^{t=end\ of\ discharging} i(t)V(t)dt \tag{5}$$

Therefore, a round-trip energy efficiency can then be written as in Equation (6).

$$Energy\ Efficiency\ (\%) = \left(\frac{E_{Out}}{E_{in}}\right) \times 100\% = \left(\frac{\int_{t=start\ of\ discharging}^{t=end\ of\ discharging} i(t)V(t)dt}{\int_{t=start\ of\ charging}^{t=end\ of\ charging} i(t)V(t)dt}\right) \times 100\% \tag{6}$$

E_{in} is the energy added to the battery;
V_{in} is the voltage at the time when the energy was added to the battery;
E_{out} is the energy withdrawn from the battery during discharge;
V_{out} is the voltage at the time when the energy was withdrawn from the battery during discharge.

In summary, while a high Coulombic efficiency is necessary to have a high energy efficiency, the battery charge and discharge profiles so affect the charging and discharging overvoltages that it is not sufficient to ensure high energy efficiency.

3.1.3. Batteries in Electric Vehicles

Lithium-ion batteries offer the benefit of high energy density, allowing them to store more energy per unit volume than other types of batteries. They can endure 500–3000 charge cycles before their capacity drops to 80% [69–71]. Additionally, they exhibit low self-discharge (they can retain their charge for long periods) and have high specific energy (they are relatively lightweight for the quantity of energy carried). With these advantages, they are currently the most suitable batteries for use in electric vehicles [72]. However, lithium-ion batteries are prone to overheating and thermal runaway, which can lead to fires and explosions. To constantly monitor the condition of the cells, it is necessary to incorporate a cooling system and a battery management system [73], which could add extra weight to the system if used in an electric vehicle. Additionally, lithium is limited in resources, and mining lithium could lead to environmental concerns, adding further costs to electric vehicles [74].

The price of lithium-ion batteries per kilowatt-hour (kWh) has dropped by 97% since 1991, when they were introduced above USD 7500 per kWh [75]. By 2018, prices fell to USD 181 per kWh [75]. However, from 2021 to 2022, a price rise of 5–10% was reported due to the pandemic and the Russia–Ukraine crisis [76]. Currently, at the pack level, the price is approximately USD 132 per kWh [76]. The development and progress in lithium-ion batteries and their composition, such as reducing the thickness of the separators and current collectors, could further reduce the material cost [76,77]. Lithium-ion batteries have to achieve USD 75 per kWh to stay competitive with the costs of internal combustion engines. Investors are aiming to reach this threshold price by the year 2030 [77].

The efficiency of lithium-ion batteries in electric vehicles is more complex than just the battery by itself, as it can be affected by various factors such as environmental temperature, pack design, internal resistance, charge current, and the age of the battery [64,78–80]. To simplify the analysis, we can use Equations (7)–(9), below, with the definitions of the charging efficiency ($\eta_{charging}$), discharging efficiency ($\eta_{discharging}$), energy pulled from the power source (ΔE_{in}), net battery energy ($\Delta E_{battery}$), battery discharge energy (ΔE_{out}), and charging and discharging efficiency ($\eta_{battery}$) [64,79]:

$$\eta_{charging} = \frac{\Delta E_{battery}}{\Delta E_{in}} \tag{7}$$

$$\eta_{discharging} = \frac{\Delta E_{out}}{\Delta E_{battery}} \tag{8}$$

$$\eta_{battery} = \frac{\Delta E_{out}}{\Delta E_{in}} \tag{9}$$

A single lithium-ion battery can achieve a charging and discharging energy efficiency of up to 92% under optimal conditions [64,79]. However, in most applications, battery packs consist of multiple cells, as illustrated in Figure 4a. When these batteries are connected in a pack, there will be energy loss between the connections, cell imbalances (as shown in Figure 4b,c), and uneven heat distribution (as shown in Figure 4d). Consequently, due to these inefficiencies, the optimal energy efficiency is reported to be in the order of 88% [64,79,81].

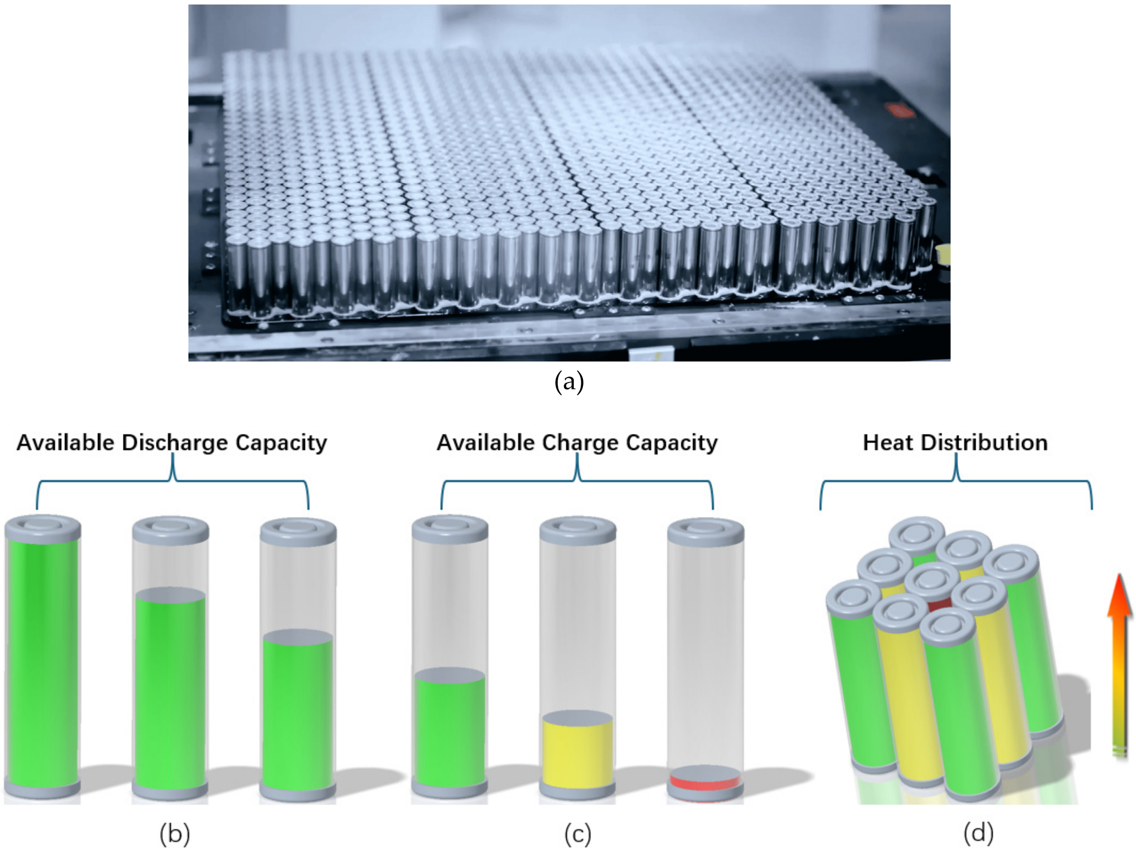
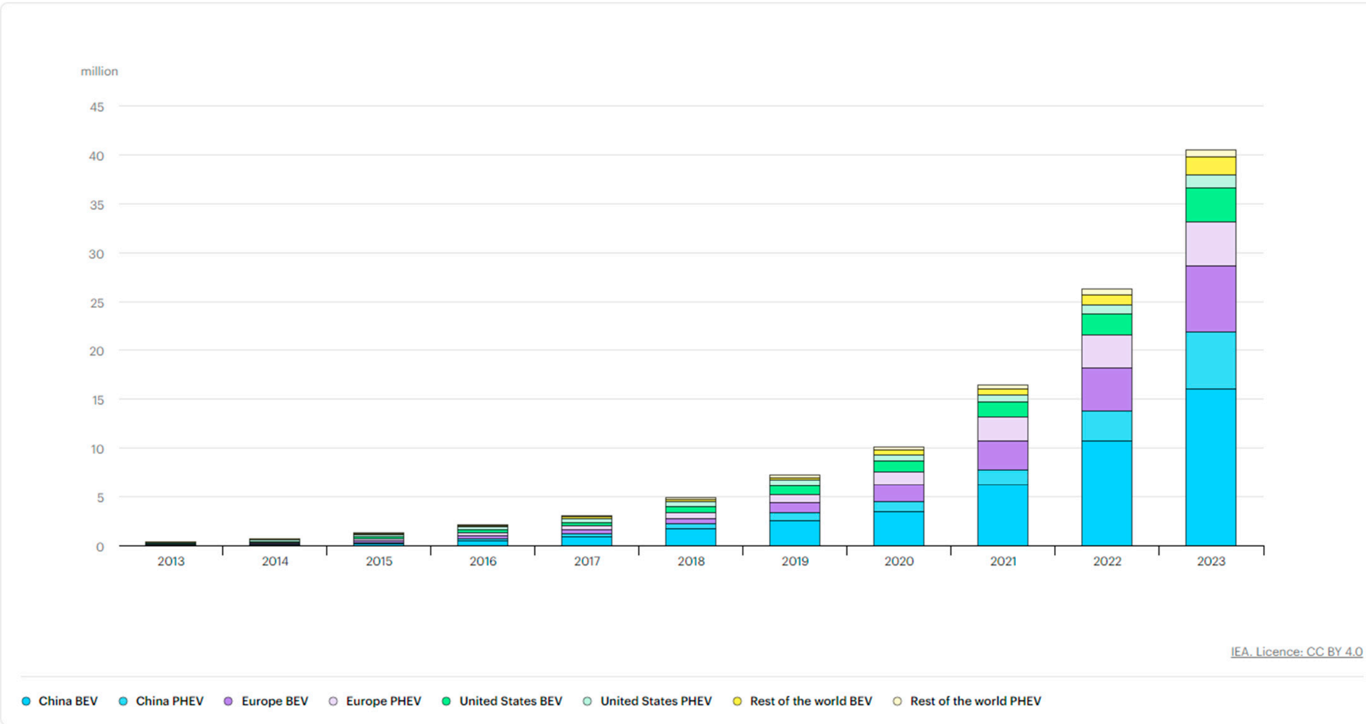


Figure 4. (**a**) Tesla batteries [82]. (**b**) Discharging of battery pack with inconsistent capacity, adapted from [81]. (**c**) Charging of battery pack with inconsistent capacity, adapted from [81]. (**d**) Uneven heat distribution in battery pack, adapted from [81].

3.1.4. Battery Electric Vehicles to Grid

The study of using electric vehicles for grid power, known as vehicle-to-grid (V2G) technology, is gaining in popularity as electric vehicle sales increase. In 2023, nearly 14 million electric vehicles were registered, and there are currently about 40 million electric vehicles on the road worldwide [83]. Figure 5a displays the global distribution of electric vehicles on the road. V2G technology involves integrating electric vehicle batteries into the power grid by allowing bidirectional energy flow. The integration system can be broken down into four major configurations, as shown in Figure 5b.



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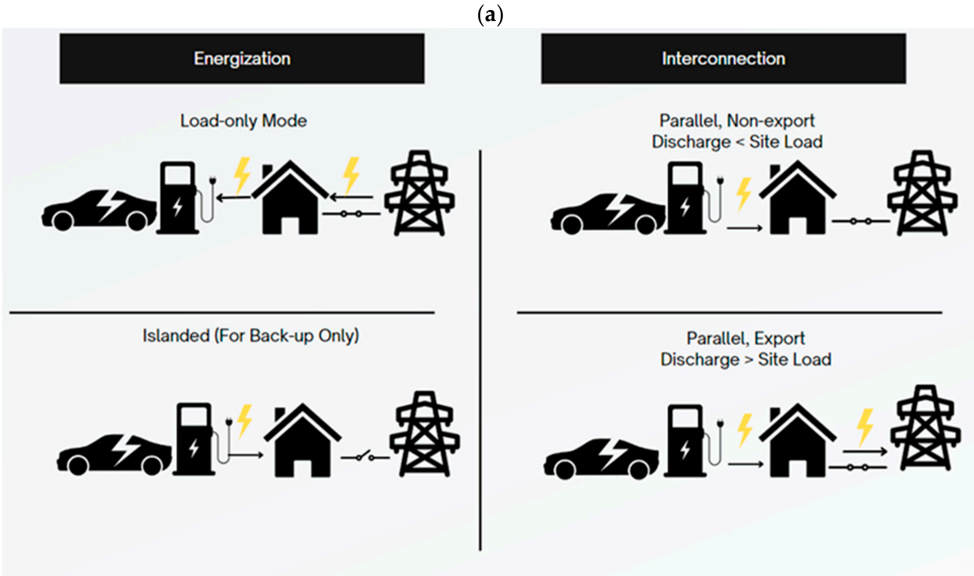


(**b**)

Figure 5. (**a**) Global electric car stock [83]. (**b**) Common V2X bidirectional charging system configurations [84].

V2G technology implementation has raised concerns about potential acceleration in battery degradation. In a V2G configuration, frequent charging and discharging cycles can speed up wear and tear on the battery, leading to a shorter overall lifespan and reduced capacity. This degradation poses a financial risk to owners, as battery replacement is the most significant cost associated with battery electric vehicles. The cost of battery degradation can be estimated as follows [84–86]:

$$Battery\ Degradation\ Cost = \sum_{t=1}^{EndofLife} \left(C_{battery} \times \frac{Deg_{cycle}}{Cap_{useful}} + Deg_{calendar} \right) \quad (10)$$

$C_{battery}$ = cost of the battery + replacement labor cost;
Deg_{cycle} = degradation per cycle of charge and discharge;
Cap_{useful} = capacity of the battery;
$Deg_{calendar}$ = degradation per unit of calendar time.

A New York case study shows that using BEVs for V2G integration is highly likely to operate at a loss with the current battery cost and feed offered in tariffs [87]. Advancements in battery management systems to optimize the charging and discharging process, as well as in heating and cooling systems for thermal management to decrease battery stress, along with the development of more robust chemistry, could further reduce battery degradation costs and make V2G systems more viable.

3.2. Fuel Cell Electric Vehicle-to-Grid

3.2.1. FCEV Overview

Fuel cells are electrochemical devices that convert chemical energy into electrical energy [88]. Unlike solar or wind energy, fuel cells are not restricted by geographic and space limitations and can be used at any time of day or night, and in any location [89,90]. There are six main types of fuel cells, which are classified by the types of electrolytes used, and each type is designed for specific applications and conditions.

Two types of fuel cell technology used in consumer vehicles are proton-exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs). While PEMFC electric vehicles were previously the only options available (see Figure 6 for milestones related to fuel cell vehicles) [91], in 2016, Nissan introduced the first SOFC concept electric vehicle, which opened up opportunities for using flexible fuels, including natural gas. Natural gas is readily piped into most American homes and can easily be attached to SOFC electric vehicles for continuous running to generate electricity from SOFC. They can be integrated into the grid like electric vehicles, with bidirectional charging technology.

The Hyundai Nexo and Toyota Mirai are two popular fuel cell electric vehicles currently available on the US market. Both models are based on PEM-EV technology. They can achieve up to 60% efficiency when generating electricity alone. If the generated heat is used, such as for heating, as described in Section 3.2.3, below, the models can reach up to 90% combined efficiency [92–94].

Currently, pure hydrogen is the only fuel that PEM-EVs can use. Impurities in the fuel could poison the cells [95], and the limited fuel tank size restricts continuous operation. While it is possible to steam-reform natural gas to hydrogen [96,97], this adds complexity and extra cost to the system.

In 2016, Nissan demonstrated the feasibility of using solid oxide fuel cells (SOFC) for electric vehicles, a technology previously considered unsuitable for this application [91]. This breakthrough has expanded the possibilities for using various types of fuel, including natural gas. Tanaka et al. proposed a SOFC co-generation system to be integrated with an electric vehicle charging station for apartments [98]. With co-generation incorporated, the efficiency reaches about 77% [98] (see Figure 7 for a diagram illustration of the SOFC co-generation). For example, if there is a spike in energy usage, the difference can be purchased from the electric grid.

Figure 8a depicts a designated docking station where a SOFC-EV is parked. In the US, most homes are already equipped with natural gas piping, which will supply the docking station to ensure continuous operation of the SOFC stack. In Figure 8b, the generated electricity is directed to a DC/DC converter to charge the vehicle's battery and connect to an AC inverter to supply electricity to the house. Any excess electricity or deficiency will be either fed into or sourced from the utility grid using vehicle-to-grid (V2G) technology. The waste heat produced by the SOFC stack is utilized for heating the hot water tank or for heating the house.

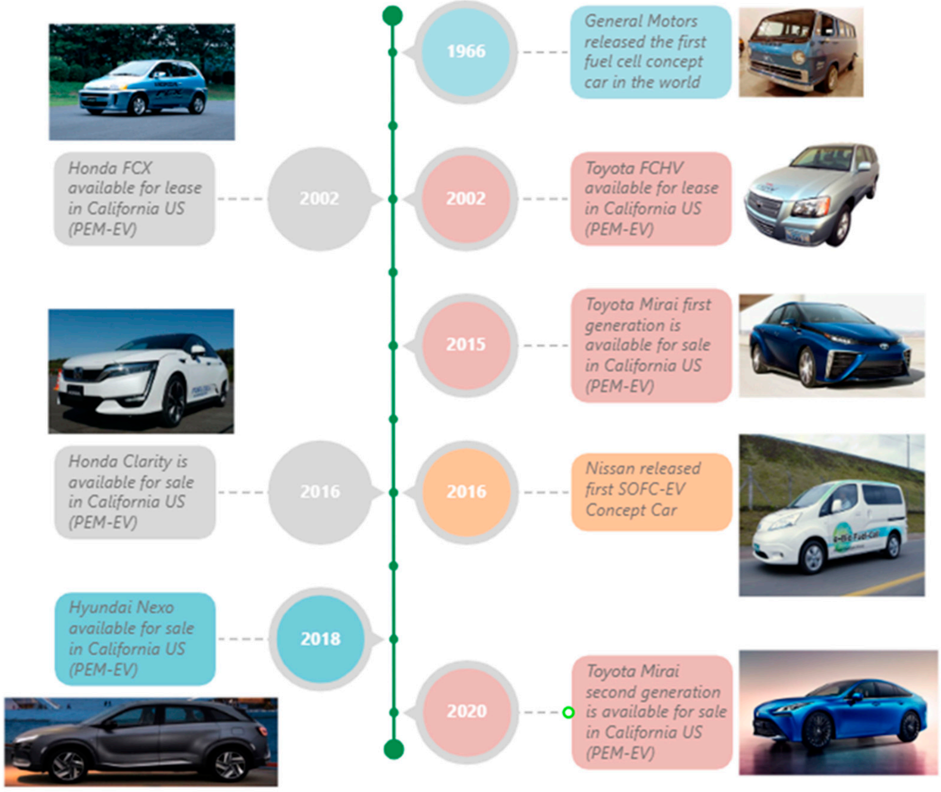


Figure 6. Fuel cell vehicle key milestones up to year 2024 [91].

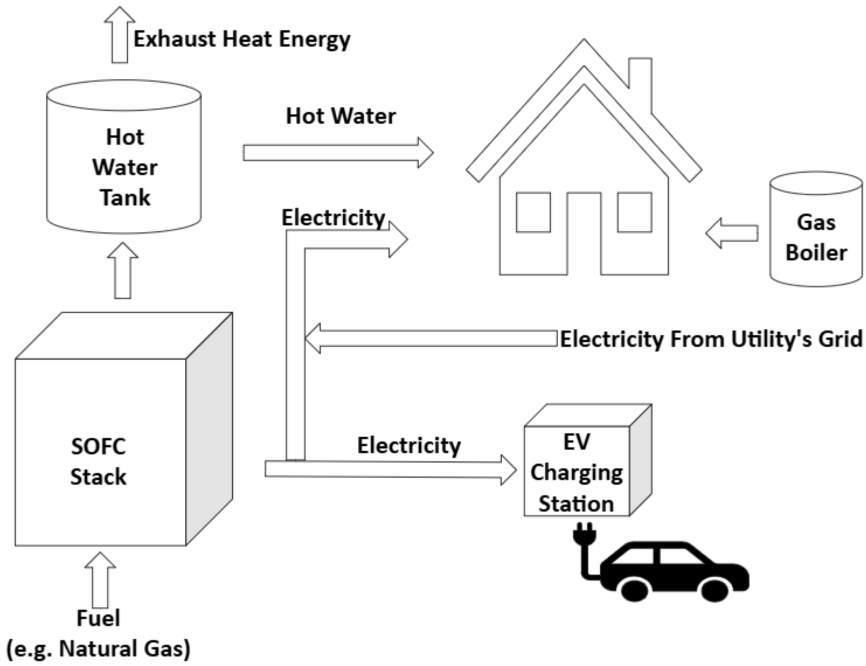
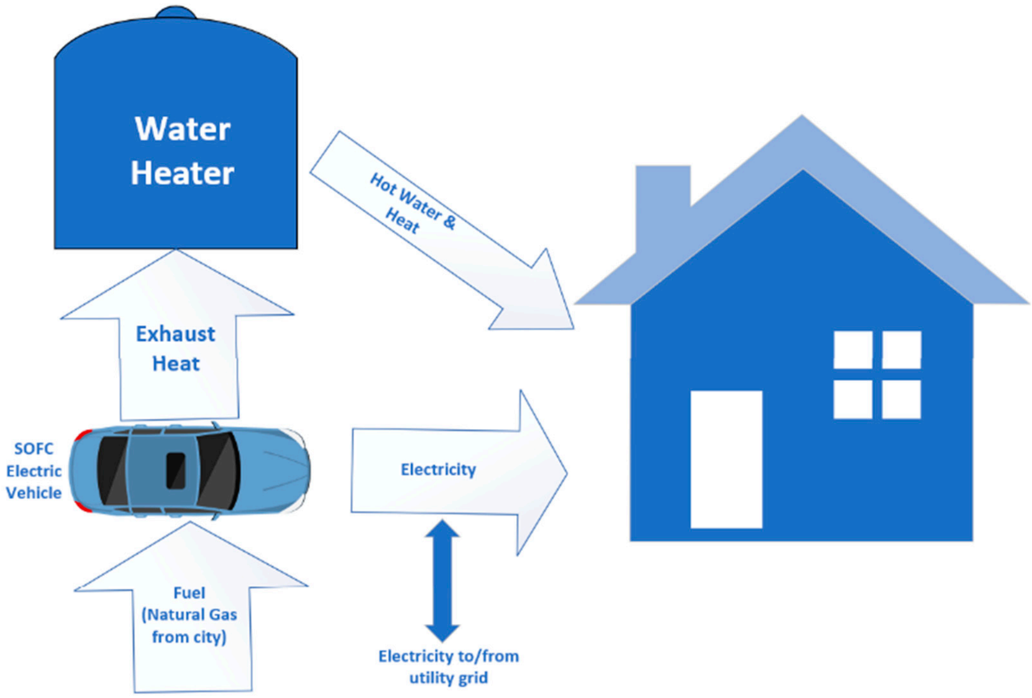
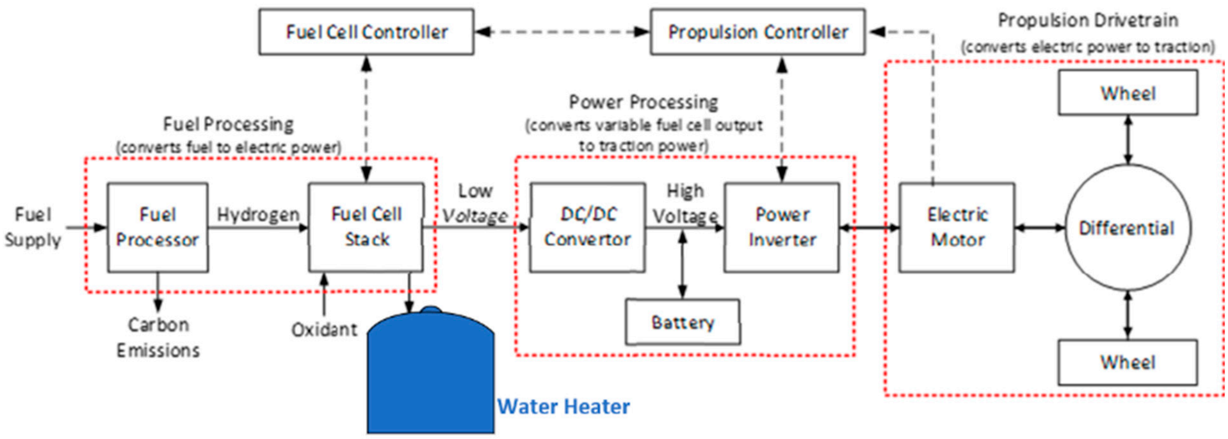


Figure 7. SOFC co-generation system), adapted from [98].



(a)



(b)

Figure 8. (**a**) SOFC electric vehicle co-generation sytem. (**b**) SOFC electric vehicle block diagram [91].

3.2.2. Fuel Cell Efficiency and Life Expectancy

Because fuel cells do not rely on converting heat into mechanical work, but rather use electrochemical reactions, the Carnot efficiency limit does not apply to fuel cells. Rather, a simple first law energy analysis of the maximum theoretical efficiency can be expressed as in Equation (11), below:

$$\eta_{electrical} = \frac{\Delta G}{\Delta H} = \frac{\Delta H - T\Delta S}{\Delta H} = 1 - \frac{T\Delta S}{\Delta H} = 1 - \frac{\Delta Q}{\Delta H} \quad (11)$$

where the following apply:

ΔG is the maximum work output from the chemical reaction;
ΔH is the total energy content of the fuel;
ΔS is the entropy generated by the fuel conversion;
T is the thermodynamic temperature of the system.

The $T\Delta S$ term can be combined and replaced by ΔQ, signifying that the generated entropy appears in the form of heat.

This means that, in principle, a hydrogen fuel cell operating under standard conditions can achieve an electrical efficiency of up to 83%, with the remaining 17% as heat loss. In practice, losses can be much higher due to other factors, including activation and Ohmic losses, and they are usually close to 60%. The heat generated is proportional to the electricity consumed but grows at a greater-than-linear rate when higher electrical power is demanded, because the losses from fuel cell overvoltage become larger at higher current through the fuel cell. In addition, if no electricity is generated, there will be no heat generated.

If the heat losses can be captured and used for practical purposes, rather than dissipated to the environment, then the total utilization of the energy present in the fuel can be much higher than implied by the electrical efficiency. This can be accomplished in combined heat and power (CHP) systems. A diagram illustrating the conceptual fuel cell CHP system is shown in Figure 9. The combined energy efficiency of the CHP system can be expressed as in Equation (12), below:

$$\eta_{comb,max} = \frac{\Delta G + \Delta Q}{\Delta H} \quad (12)$$

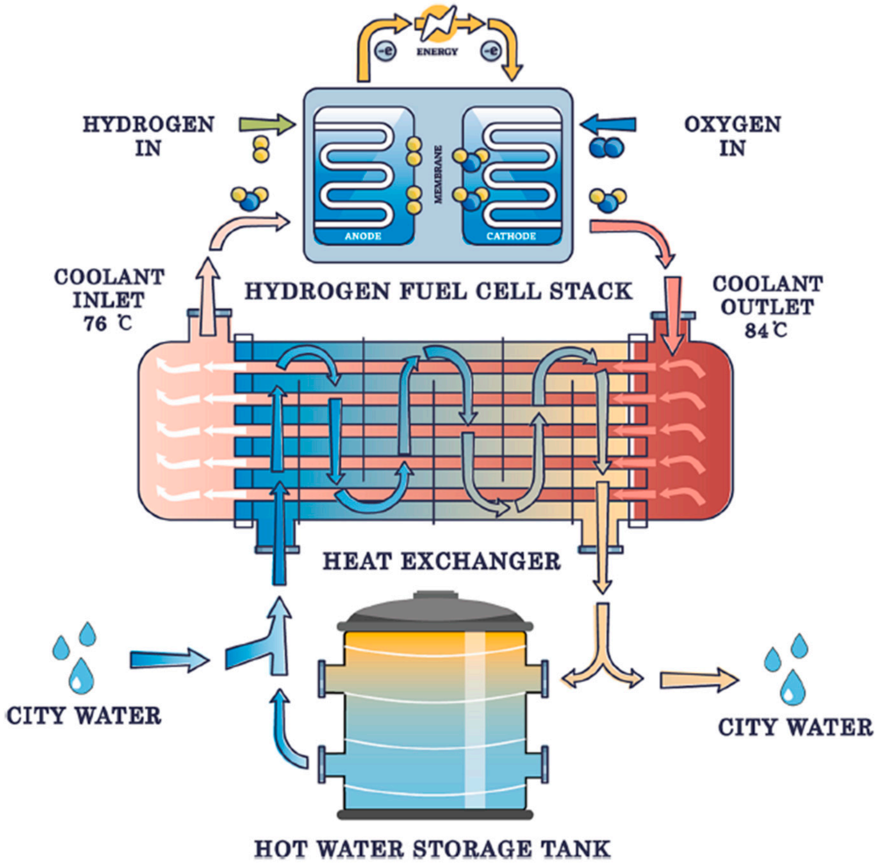


Figure 9. Fuel cell CHP conceptual process [92].

It should be evident that the maximal combined energy efficiency could then be as high as 100%, although due to various other equipment limitations, such as limited heat exchanger efficiency due to the need for a minimal approach to temperature in a practical heat exchanger, or if the heat generated cannot be exported for other uses, it will naturally be lower.

As fuel cell efficiencies differ, so do life expectancies for each type. While the PEM-FCs used in EVs have been shown to last up to 5000 h [99], when including the crucial road condition (e.g., vibration) [100], the expected life is reduced to 3700 h with 10% voltage degradation [101]. On the other hand, SOFCs have an average projection degradation rate of 0.2–0.5% per 1000 h of usage [102], and a potential service life of 40,000–80,000 h [103]. The cost equation can be derived as (13), where the PEM-FC reaches its end of service much faster than the SOFC. When considering FC-EV V2G integration, the SOFC is a better candidate as it can continuously operate for up to 10 years.

$$Fuel\ Cell\ Degradation\ Cost = C_{fuel\ cell} \times \frac{V_{drop}}{V_{initial} \times 10\%} 100\% \quad (13)$$

$C_{fuel\ cell}$ = cost of the fuel cell + replacement labor cost;
V_{drop} = voltage drops due to degradation;
$V_{initial}$ = initial fuel cell voltage as new

Note: Drops in voltage of 10% are considered end of service.

3.2.3. SOFC-EV CHP Processes

The combination of maximizing the use of both electrical generation and the associated heat generated results in the two optimization strategies illustrated in Figure 10: an electricity-led strategy and a thermal-led strategy. Since the battery's optimal charging current changes based on the state of charge, the electricity generated by the fuel cell battery pack will initially be used to charge the battery. Subsequently, as the electrical requirement of the battery decreases, eventually reaching zero as it reaches its fully charged capacity, any excess generated electricity will be directed towards the building. Since the building's electricity usage also varies throughout the day, to optimize efficiency, surplus electricity should be sent back to the grid.

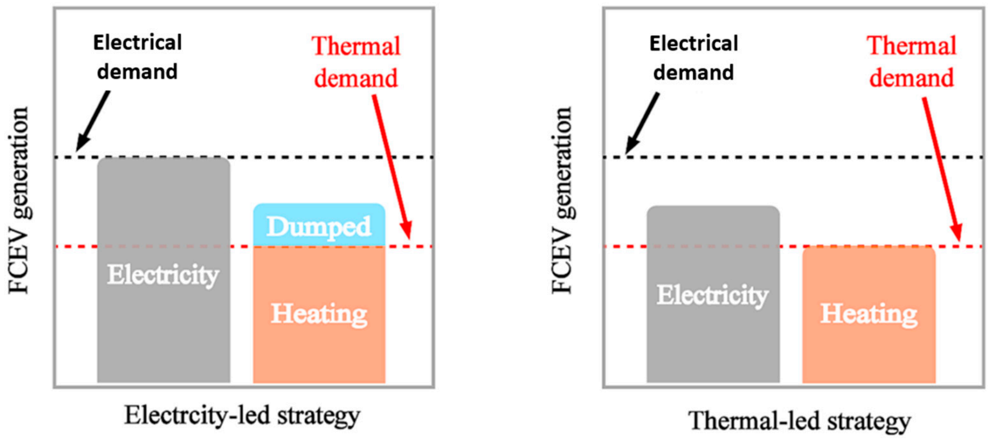


Figure 10. The difference between the electricity-led strategy and the thermal-led strategy [92].

In the electricity-led strategy, since excess electricity can be directed to the grid, the fuel cell may be operated continuously at maximum electrical efficiency. Since the heat generated by the fuel cell may exceed the maximum heating requirements of the building, excess heat that is not utilized will be dissipated into the environment.

Conversely, in the heat-led strategy, at maximal heat demand, the fuel cell provides the highest combined efficiency, with minimal energy waste. In this case, the electricity generated by the fuel cell is directed to the vehicle battery and building, with the remainder directed to the grid and, therefore, not lost to the environment. Furthermore, if the combined vehicle/building demand exceeds the limited required heat generation output of the fuel cell, the electricity deficit can be supplemented using the utility grid. Figure 10 demonstrates the process of thermal heat recovery for PEM-EVs.

The benefit of using PEM-EVs with cogeneration through a V2X model, eventually feeding the electrical grid, is that they fully utilize alternative energy generation. This is because consumer car usage accounts for less than 20% of driving time daily [94]. With PEM-

EV V2G technology, the PEM-EV could be utilized closer to 100% of the time. Implementing V2X energy integration with the CHP system further extends this advantage by using the fuel cell heat for useful processes, displacing the need for energy consumption from other sources for building heat applications. This could significantly help decrease carbon emissions from transportation and the built environment.

4. Infrastructure Implementation

Infrastructure implementation for SOFC-EVs is different from that for BEVs and similar to that for PEM-EVs; Table 1 shows the comparison. For BEVs, the V2G connection is much simpler than for FC-EVs, as a docking station, hydrogen reformer, drainage, and exhaust fan may be required during implementation, depending on the location used.

Table 1. Comparison between BEVs, PEM-EVs, and SOFC-EVs [91].

Parameters	BEVs	PEMFC-EVs	SOFC-EVs
Fuel Type	Electricity	H_2	H_2, BioFuel, Natural Gas [1]
Fueling Time	Slow	Fast	Fast
Tailpipe Emissions	No	Water	Water/CO_2
V2G Continuous Operation	Limited	Yes [2]	Yes
V2G Infrastructure Upgrade Cost	Low	High	High
V2G Cost Return [3]	Low	Medium	High
Vehicle Purchase Cost	High	High	High
Vehicle Maintenance Cost	Low	Low	Low
Vehicle Collision Repair Cost	High	High	High
Vehicle Operation Noise	Low	Low	Low

[1] Natural gas is available to most US residents. [2] A hydrogen reformer is needed to operate with natural gas. Impurities in the natural gas may poison the PEM fuel cell, leading to faster degradation. [3] BEVs' low cost return due to battery degradation, PEM-FCs' due to carbon poisoning degradation.

The successful integration of SOFC-EVs into V2G systems requires several key infrastructure developments. First and foremost, homes must be equipped with bidirectional charging stations compatible with SOFC-EVs. These stations charge the vehicle's battery and facilitate the flow of electricity from the vehicle back into the home or grid (Figure 11). Advanced smart meters and grid management systems are also essential to monitor and control the energy exchange, ensuring that electricity is dispatched efficiently and in response to grid demand [104].

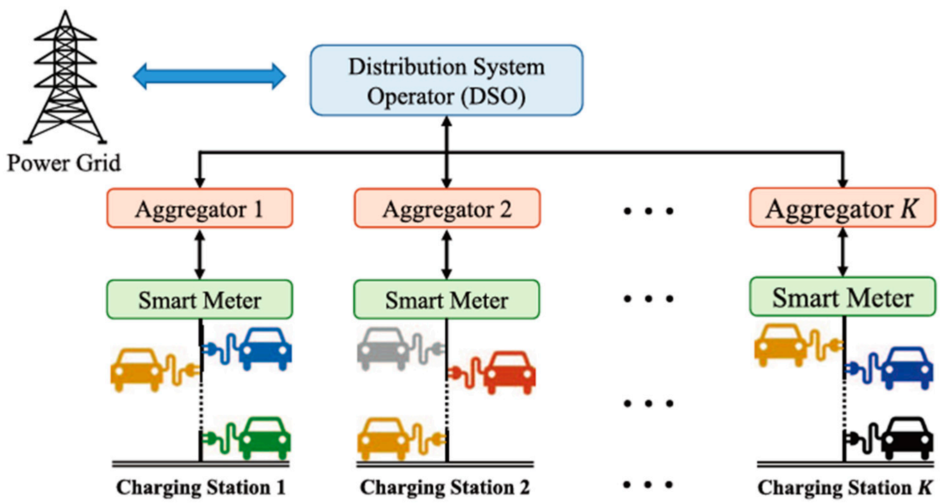


Figure 11. Electric vehicle integration into smart grid with bidirectional charging [105].

Furthermore, the natural gas infrastructure must be able to support this new application. While many homes already have natural gas piped into them, the delivery systems need to ensure a consistent and high-quality supply to power SOFC-EVs effectively. This might involve upgrading pipelines or installing pressure regulators and filtration systems to maintain the purity and pressure of the fuel used in the fuel cells. In addition, integrating SOFC-EVs with home energy management systems is crucial to optimizing energy use, balancing the demands of home consumption, vehicle charging, and grid services.

Installing home-based SOFC-EV systems also requires the development of user-friendly interfaces that allow homeowners to manage and monitor their energy usage easily. This includes setting preferences for when and how their vehicle participates in V2G programs, such as prioritizing home backup power during grid outages or maximizing financial returns by discharging electricity during peak demand periods.

5. Conclusions

The Green Village FC-EV-to-grid study provided a hopeful future for integrating SOFC-EVs into the grid. Using natural gas piped into the home, the integration of SOFC-EVs offers more fuel flexibility and less complexity than PEM-EVs. SOFC-EVs offer energy storage, as do battery EVs, they generate electricity for traction propulsion, and they can also supply electricity to buildings or the grid. One key advantage of the SOFC-EVs in the V2G systems is their ability to provide electricity and heat simultaneously; this adds value to waste heat, which can heat hot water and buildings.

FC-EV-to-grid can help to balance the grid's load without the need to build new power generation facilities. Unlike solar and wind energy, which are intermittent in their availability to generate power, SOFCs can generate power continuously without interruption as long as a natural gas supply and reformer are available. In recent years, the battery EV market's growth has significantly increased demands on the grid, and integrating SOFC-EVs into the grid could significantly reduce this pressure. However, challenges lie ahead in the advancement of regulation and the implementation of smart grids.

This paper also concluded that using SOFC-EVs to contribute to powering buildings improves efficiencies over using batteries alone as storage mediums. Many factors could impact battery efficiency, such as environmental temperatures, pack design, internal resistance, charge/discharge current, battery degradation, etc. Using SOFCs could prolong the battery's life, with fewer greenhouse gas emissions and a lower carbon footprint. BEVs' participation in V2X activities is limited by battery capacity. However, FC-EVs' participation in V2X activities is unlimited when combined with a natural gas line in residential homes, provided there is a continuous fuel supply. Considering that the life expectancy of SOFCs is 40,000–80,000 h of service, which is ten times more than that of PEM-FCs, the authors conclude that SOFC-EVs can significantly reduce costs and increase the opportunities of using FC-EVs for V2G and V2X applications.

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