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Review

Rooftop Solar and Electric Vehicle Integration for Smart, Sustainable Homes: A Comprehensive Review

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Abstract: The rapid growth of the energy and transport sectors has led to an increase in fuel consumption, resulting in a significant rise in greenhouse gas emissions. Switching to renewable energy sources and replacing internal combustion engines with electric vehicles (EVs) can significantly reduce greenhouse gas emissions. In recent years, the electrification of the transportation sector has become a primary focus of research and development efforts. However, if EVs are charged using conventional energy sources, we are unable to fully capitalize on their potential to reduce emissions. Charging EVs using renewable energy sources is the optimal solution. Otherwise, the increased number of EVs on the roads can significantly impact the stability of existing electric grids. As a result, smart homes with EV charging stations are becoming increasingly popular worldwide. This review focuses on the concept of grid-connected rooftop solar photovoltaic (PV) smart homes integrated with EVs and energy management systems in Australia. Australia can reduce emissions in the building and transport sectors by electrifying a range of vehicles and ultimately powering them with 100% renewable energy sources. The benefits of EV integration alongside rooftop solar systems for smart homes with house-to-vehicle or vehicle-to-house, as well as vehicle-to-grid or grid-to-vehicle (bidirectional EV charging) capabilities are also explored in this article. By adopting these systems, these smart homes can provide energy schemes for commercial use, ultimately contributing to the owner's economic benefit.

Keywords: electric vehicle; greenhouse gas; home energy management system; renewable energy source; smart home

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1. Introduction

The utilization of fossil fuels for electricity generation in thermal power plants [1] and within the transportation sector [2], coupled with the surge in energy demand, leads to both environmental pollution and the depletion of fossil fuel resources [3]. Amidst the current crisis, it is imperative that researchers in the sustainable energy field take action to maximize the use of renewable energy resources, while also focusing on improving energy production, and reducing the negative impact on the environment [4]. The primary environmental challenge we are facing at present is the reduction in carbon emissions [5]. According to the "Annual Report from NOAA's Global Monitoring Lab 2023", the global average atmospheric carbon dioxide (CO_2) reached 417.06 parts per million in 2022, a 50% increase from pre-industrial levels [6]. Human activities, mainly fossil fuel burning, contribute roughly 4% to annual CO_2 levels, with fossil fuels (coal, oil, and gas) accounting for 85% of emissions. This adds nearly 1.4 metric tons of carbon per person per year on a global scale [7]. Australia boasts the world's highest per capita greenhouse gas (GHG) emissions [8]. Australia had per capita CO_2 emissions of 15.09 tons, totaling 391,187,420.00 tons annually. This accounted for about 1.05% of the world's CO_2 emissions in 2021 [9].

The global building sector has a major impact on CO_2 emissions, making up around 40% of the overall emissions. Additionally, it consumes a significant portion of primary energy, accounting for roughly 30 to 40% in developed countries and 15 to 20% in developing countries annually [10,11]. Similarly, the transportation sector is responsible for one-quarter of GHG emissions [12], with passenger cars being the primary culprit, contributing 39% of the total emissions [13]. In Australia, the transportation sector is the second-largest consumer of energy, while the residential sector ranks fifth in terms of energy utilization, as shown in Figure 1. The data used in Figure 1 were sourced from [14]. These statistics underscore the urgent need for action in both sectors to reduce the carbon footprint and promote sustainable practices. By implementing energy-efficient building designs and promoting sustainable transportation, we can effectively address the environmental challenges we face at present and pave the way for a more sustainable future.

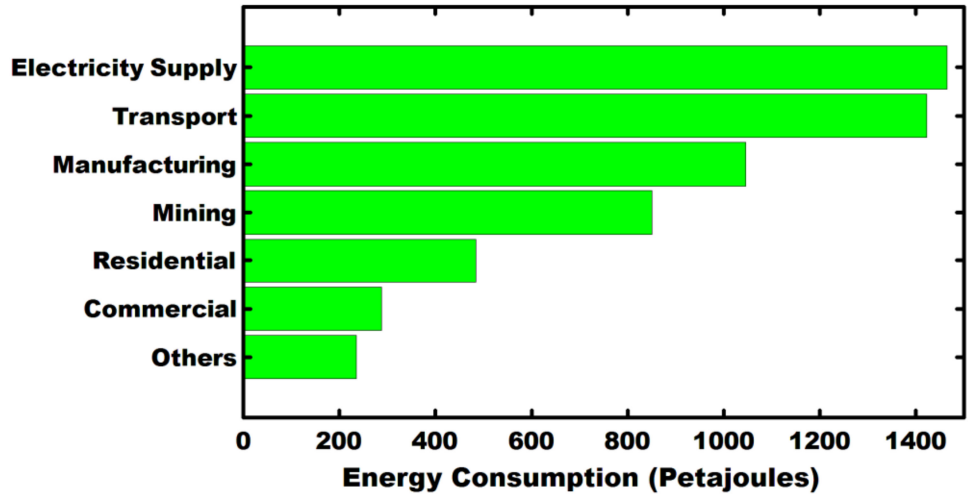


Figure 1. Australia's energy consumption, by sector 2021.

Renewable energy has made substantial progress as a global, viable alternative to counter fossil fuel depletion [15] and contribute to CO_2 emission reduction [16]. EVs can also play an essential role in cutting down on fossil fuel dependency and carbon emissions in the distribution network [17] to facilitate the decarbonization of the transportation sector [18]. Nevertheless, a large number of electrical appliances and EVs have appeared in the grids as electric loads, which are confirmed reasons for fluctuations during peak and off-peak demands. These fluctuations pose several challenges to grid stability, including harmonic distortion, reliability issues, reduced efficiency, appliance damage, increased utility bills, increased use of fossil fuels, and higher emissions. Researchers are actively exploring the integration of renewable energy sources (RESs) within power grids as a means to reduce energy consumption levels [19]. By leveraging renewable energy, it is possible to achieve both economic growth and low-carbon emissions. Additionally, the increased generation of renewable energy at low voltage levels provides end-users with green energy at low costs. In this way, the promising technology for prosumers is the installation of rooftop PV panels; however, they cannot provide continuous energy during the nighttime. Battery-based electrical energy storage systems (ESSs) are therefore recommended for night-time usage in combination with solar PV systems [20]. Notably, the utilization of EV batteries as ESSs is viable, particularly in conjunction with their primary application in transportation. However, the long charging time for EVs presents a significant challenge, as refueling for traditional vehicles occurs in minutes. The increased demand for charging places stress on power grids and can lead to energy imbalances. Additionally, a lack of developed charging infrastructures poses a barrier to widespread EV adoption. A promising solution is to generate and utilize energy from solar PV systems [21]. Consequently, the significant adoption of RES (solar PV systems) and the integration of

EVs have been remarkable developments in recent decades [22]. The combination of solar PV systems and EVs is an optimal solution for environmental pollution, energy generation, and energy savings. However, the widespread penetration of these technologies can result in overgeneration and overloading, which in turn can cause technical issues, such as system losses, fluctuation, frequency and voltage deviations, and component overloading. Fortunately, PV–EV matching can also help alleviate these problems while also providing economic benefits to customers [23]. Particularly, power balancing techniques are also of importance in regulating voltage profiles in grid-tied microgrids during periods of energy shortages or excessive production [24]. Furthermore, the energy management system is thus useful for domestic and industrial applications. The deployment of a home energy management system (HEMS) at the residential level is important to reduce the complications of energy management [25], especially in contexts involving the integration of solar PV systems and EVs with the grid. The HEMS system is responsible for monitoring, managing, and controlling the energy flow between the sources and the electric load [26], leading to energy savings and prioritizing the cheapest energy source.

The primary objective of this paper is to review the concept of rooftop solar PV smart homes integrated with EVs and HEMS in Australia. In addition, this research also highlights the significance of V2X or X2V (X = home, grid) technologies, enabling bidirectional EV charging. Overall, our research is structured as follows: Section 2 provides an overview of the solar energy potential in Australia. Section 3 focuses on the grid-connected rooftop solar PV smart home integrated with EVs in residential areas. In addition, Section 4 provides a comprehensive review of the relevant literature about solar PV smart homes integrated with EVs. Furthermore, Section 5 looks into discussions on the current advancements and near-future developments in this field, along with outlining a future roadmap. Finally, Section 6 concludes the paper, summarizing the key findings and highlighting the significance of the research.

2. The Potential of Solar Energy in Australia

The sun shines on the surface of the Earth with a considerable potential of 174 petawatts of power, which is about 10,000-times more than all other conventional power resources used by human beings on the Earth [27]. A mere 0.16% of the Earth's surface covered with solar systems operating at just a 10% efficiency can generate a staggering 20 terawatts of power. This amount is twice the power consumption level derived from fossil fuels used worldwide [28]. According to Australian Energy Update 2022, Australia generated the majority of its energy from fossil fuels (70.9%) and only 29.1% from RESs in 2021. Of that 29.1%, solar energy accounted for 11.7% of the energy mix [14], as shown in Figure 2.

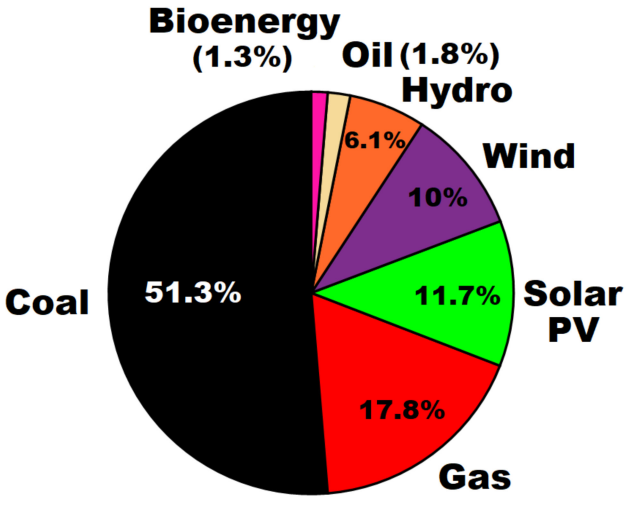


Figure 2. Australia electricity generation fuel mix, 2021.

Solar PV systems are a highly effective means of generating electricity from RESs for a sustainable future [29]. The adoption of solar PV energy into distribution networks can improve power quality, reliability, and efficiency while managing loads, supporting voltages, and reducing line losses [30]. However, solar PV systems contributed only 11.7% of energy generation in Australia in 2021 [14], despite the country's abundance of solar energy resources for power generation [31]. On average, Australia receives 58 million petajoules of solar radiation per year, which is approximately 10,000-times greater than the country's energy consumption [32]. The solar irradiance prediction for a whole year in Sydney, Australia, is shown in Figure 3, demonstrating that solar PV systems can meet the energy demand for the whole year due to the ample availability of solar radiation.

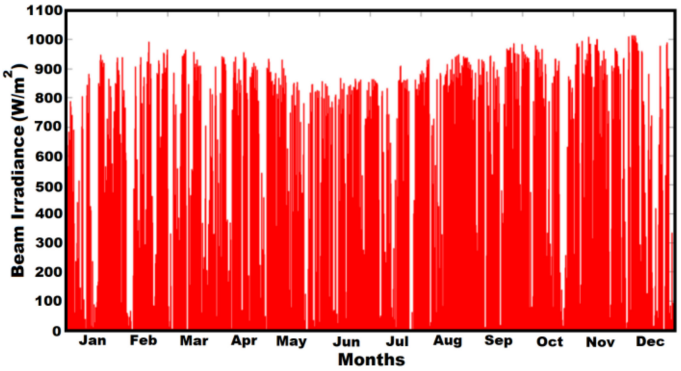


Figure 3. Solar beam irradiance prediction for a whole year in Sydney, Australia (the data are exported from the System Advisor Model software tool, U.S Department of Energy, operated by, Alliance for Sustainable Energy LLC).

According to the School of Photovoltaic and Renewable Energy Engineering at the University of New South Wales, Australia possesses a significant rooftop solar potential, estimated at 179 giga watts (GW) of power in each planning zone across the nation, as shown in Table 1 [33]. Rooftop solar panels have the ability to generate an annual energy output of 245 terawatt-hours, which exceeds the total energy demand on main grids. In the residential zone alone, the rooftop solar potential amounts to 96 GW, representing approximately half of the unused potential. The industrial and commercial sectors combined have a rooftop solar PV potential of 28 GW. Australia installed just over 8 GW of rooftop solar panels by the end of 2018 and used less than 5% of the country's rooftop solar PV generation potential capacity by the end of June 2019 [33]. To achieve net-zero emission targets, it has been projected that the solar PV capacity will increase to 20 and 72 GW by 2026 and 2050, respectively [34].

Table 1. Potential for rooftop solar energy in each planning zone.

S. No.	Zone	PV Potential (GW)	Annual Energy Output (GWh)
1	Water	0.0	0
2	Transport/Infrastructure	0.6	774
3	Recreational/Open space	1.7	2346
4	Conservation/National park	2.1	2884
5	Unknown	2.2	3052
6	Community use	3.9	5371
7	Mixed use	4.0	5584
8	Special use	6.7	9357
9	Commercial/Business	9.3	12,601
10	Industrial/Utilities	19.0	26,464
11	Rural/Primary production	33.9	46,680
12	Residential	96.0	130,153

3. Grid-Connected Rooftop Solar PV Smart Homes Integrated with Electric Vehicles

The residential sector, known for consuming a significant amount of energy and contributing to GHG emissions [35], is presently witnessing a growing interest in solar PV homes. These homes utilize renewable energy for electricity generation, leading to a reduction in fossil fuel consumption and CO_2 emissions within the sector on a global scale [36,37]. A smart home functioning as a residential microgrid incorporates various components, such as generation resources, controllable loads, and ESSs [38]. This setup enables the house to not only export surplus electricity to the grid stations [39], but also contribute to the grid through demand responses and active and reactive power insertions [38]. In the case of solar PV homes integrated with EVs, the EV batteries serve as energy storage, allowing these houses to stabilize the grid by minimizing the load regulations and voltage fluctuations. Additionally, this integration helps in reducing CO_2 emissions and lowering energy costs [38,40]. Figure 4 depicts a schematic diagram illustrating the complete concept of integrating a solar PV home with an EV. In solar PV smart homes, household appliances efficiently utilize solar energy and charge batteries, including those in EVs through an EMS, during daylight hours. Moreover, these batteries can also be charged from the grid during off-peak hours using a bidirectional converter, enabling them to supply power back to the grid during peak hours. In times when solar energy is unavailable, these charged batteries can serve as backup power sources. Homeowners can export excess energy to the grid and retrieve it as needed through the use of a smart meter (SM), while the energy import and export processes to and from the grid remain mostly unchanged. If an EV is utilized throughout the day, optimal charging options include home-to-vehicle (H2V) or grid-to-vehicle (G2V) techniques, as well as battery swapping methods. Additionally, these types of homes have the potential to generate revenue by allowing EV owners to charge their vehicles on-site. The main objectives of these types of houses are elaborated in Table 2.

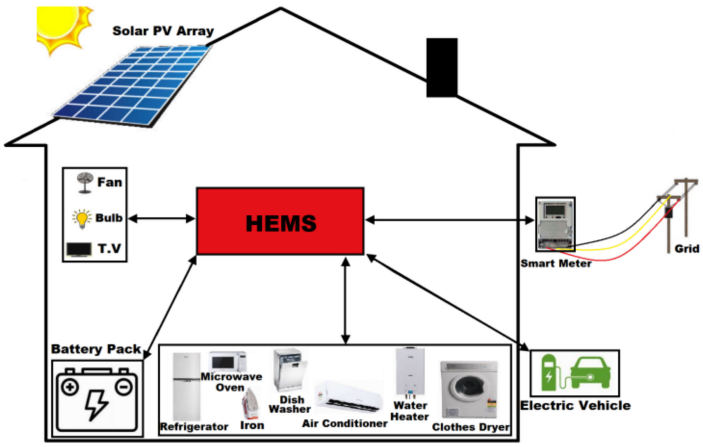


Figure 4. Schematic diagram of a grid-connected solar PV smart home integrated with EV.

Table 2. List of common objectives of grid-connected solar PV smart homes integrated with EVs.

The main objectives of these types of houses are:
• To reduce the reliance on fossil fuels and promote clean and sustainable energy generation. • To enhance energy independence by reducing dependence on the traditional electrical grid. • To maximize the utilization of solar energy, for both household energy consumption and EV charging. To optimize energy usage and increase overall energy efficiency. • To reduce energy costs for homeowners. • To enhance grid stability, especially during periods of high electricity demand. • To create an interconnected and intelligent energy ecosystem.

The details of each component involved in such types of homes are expressed below.

3.1. Rooftop Solar PV System

The PV module (or PV array) serves as the primary component responsible for converting solar energy into direct-current (DC) electricity. However, to fully harness and utilize this energy, additional components are necessary to form a complete solar PV system. These components enable the storage and distribution of the generated energy to end-users. A standard PV system consists of four essential components: a PV module or PV array, a charge controller, a battery, and an inverter as shown in Figure 5. These integral components work together to ensure efficient energy conversion, storage, and distribution outcomes. The batteries store the surplus energy for usage on cloudy or low-sunlight days or at night. The charge controller effectively prevents the batteries from experiencing overcharging or complete discharge, ensuring their longevity and optimal performance within the system. The inverter converts the DC power to alternating-current (AC) power [41]. This energy is used in powering AC household appliances, enabling the creation of an off-grid/stand-alone PV system. However, when this system is linked to the main utility grid, it is referred to as a grid-connected PV system.

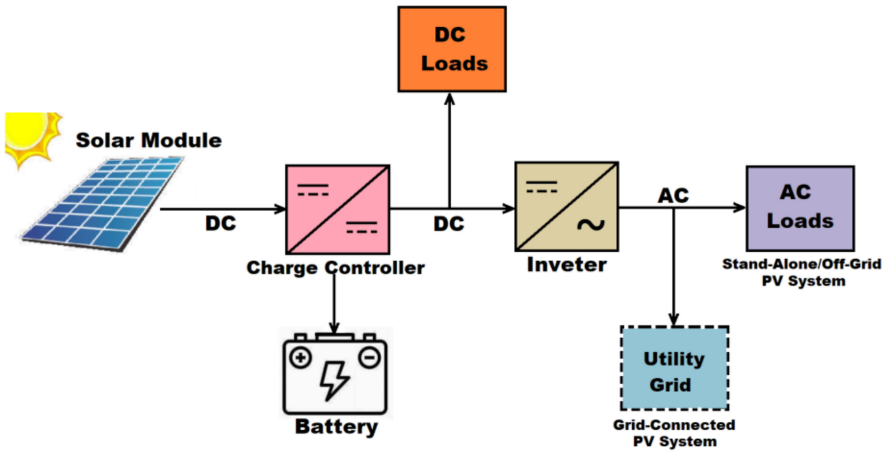


Figure 5. A standard solar PV system.

The generation of electrical energy from solar PV systems is considered one of the best choices for alternative energy in building a sustainable and green future [29]. PV power generation systems are highly admired for their affordability in terms of their low maintenance requirements, operational cost, and eco-friendliness. Table 3 outlines the key benefits of PV systems. The information presented in Table 3 was obtained from [41].

Table 3. Advantages of solar PV systems.

S. No.	Advantages
PV power generation systems offer numerous benefits that make them highly desirable.	
1	Free source of energy.
2	Clean, green, and environmentally friendly energy source.
3	Noiseless energy generation, an ideal solution for residential and urban areas.
4	During electricity generation, there are no harmful GHG emissions *.
5	The generation can be performed closer to the consumer.
6	The operational and maintenance costs are low, approximately negligible compared to other renewable energy systems.

* GHG emissions are linked to the manufacturing, transportation, installation, and dismantling of solar PV panels [42].

Despite the initial investment required for solar panels, PV systems, particularly those connected to the grid, have gained significant popularity in numerous countries due to their promising medium- and long-term economic advantages [43]. The amount of solar energy produced is contingent upon factors, such as sunlight availability, weather conditions,

and the geographical location of the region. As previously mentioned, Australia boasts tremendous energy potential, making it an ideal location for solar energy utilization. The visual representation of the predicted average solar PV generation for a typical Australian house can be seen in Figures 6 and 7. These graphs illustrate the expected power production levels throughout a day, providing a comprehensive overview for each month over the span of a year, as well as detailing the energy generation patterns for each month within the first year. Figures 6 and 7 are derived from simulations of a 4.5 kW solar system conducted using the system advisor model (SAM) software tool in the author's study.

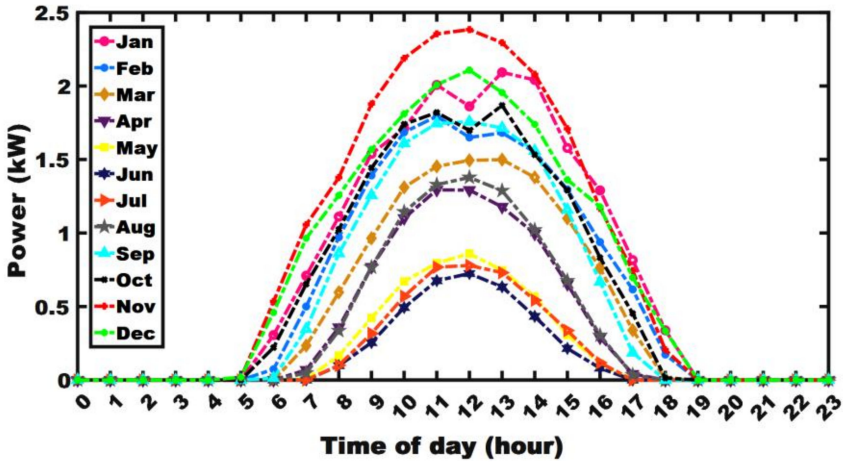


Figure 6. Solar PV power generation prediction over the course of a day for each month for a typical house situated in Sydney, Australia.

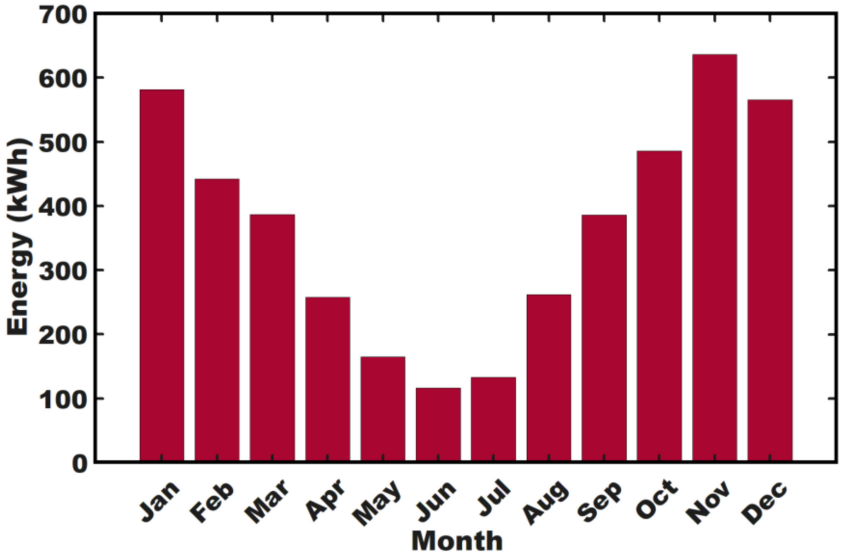


Figure 7. Solar PV energy generation prediction for each month of year 1 in a typical household in Sydney, Australia.

The PV industry has experienced a rapid expansion due to appealing financial schemes, like feed-in tariffs and renewable energy certificates implemented by various countries. The Australian government has also launched such initiatives [44], including subsidies for solar panel installations, incentivizing residents [45], and also introduced two incentive schemes for solar PV houses: net feed-in tariffs for extra energy sent to the grid and gross feed-in tariffs that compensate for all the generated electricity [39]. In Australia, the government has implemented a solar flagship program with a budget of AUD 1.6 billion over six years. This program supports residents by promoting solar technologies and facilitating

the development of four solar power projects with a total capacity of 1000 MW, equivalent to conventional coal-fired power stations. This highlights the significant contribution of solar energy to the country's power generation [46]. Additionally, the "Small-scale Renewable Energy Scheme" has been introduced to encourage the adoption of small-scale renewable energy systems, such as solar, wind, and hydropower, as well as solar hot-water systems, targeting households and small businesses nationwide [47]. The fall in capital costs of PV solar panels, coupled with rising electricity prices, has led to shorter payback periods for solar PV systems [48]. Payback periods for rooftop PVs in Australia vary from 11 to more than 25 years [49]. With declining costs, government subsidies, and utility incentives, residential customers at present have the opportunity to shift toward these technologies [50]. Australia's solar PV market is witnessing a remarkable growth, with a compound annual growth rate of 52.46%, positioning the country among the leaders in solar energy adoption. Projections from the Commonwealth Scientific and Industrial Research Organization (CSIRO) indicate that solar energy will contribute to approximately 30% of Australia's energy supply by 2050 [51,52].

3.2. Energy Storage System (ESS)

The integration of renewable RESs and ESSs on the demand side has propelled the concept of smart green homes and cities to the forefront [53]. ESSs offer an effective solution for managing and storing excess RES generation, especially during inclement weather conditions characterized by uncertainties [54]. Energy storage is a key element in improving the economy, security, and flexibility of a power system, and plays a vital role in promoting energy Internet, new energy deployment, and supporting power distribution. The development of dynamic EMSs has enabled the control of ESSs to accommodate real-time electricity costs and fluctuating renewable energy generation [55]. By optimizing the sizing, placement, and operation of ESSs, significant improvements can be achieved in the energy efficiency of distribution networks and overall network performance. This includes meeting the peak energy demand, managing power quality, curtailing distribution network expansion costs, and maximizing the benefits of RESs and distributed energy source integration [56]. Demand response programs (DRPs) and distributed energy resources (DERs), such as on-site solar PV generation and ESSs, offer opportunities to reduce energy consumption levels and mitigate peak demand emissions from the grid [57]. In residential buildings, two common methods for energy storage are EV batteries and on-site battery storage [58]. EV batteries offer the added advantage of dual utility by serving as a power source for vehicles as well as supplying energy to home appliances or grids.

A battery is an electrical energy storage device that converts chemical energy into electrical energy [59]. It serves as a means to store energy that can be utilized during periods of high energy tariffs [60]. Batteries are necessary in meeting load alteration requirements in ESSs [61]. They enable the storage of surplus power generated from sources, like PV systems, allowing for the better utilization of renewable energy that cannot be consumed immediately. The charging and discharging actions of batteries can be adjusted to purchase energy during low-demand periods or consume electricity during high-demand periods, thereby maximizing profits and reducing the regional loads [62]. Compared to other energy systems, batteries exhibit a high energy efficiency [63,64]. Power converters equipped with advanced metering infrastructure are used to control, regulate, and monitor a battery's capacity and state of charge (SOC) [65,66]. Chargers are utilized to ensure the smooth charging of batteries, enabling their efficient operation. Bidirectional DC/DC converters are employed [67] to regulate the charging and discharging processes of batteries and to facilitate power transfer in both directions [68]. The Australian government introduced Community Batteries Funding Round 1, 2023 [69]. The objective of this scheme was to facilitate the implementation of community batteries throughout Australia. This initiative aimed to achieve multiple benefits, including the reduction in energy costs, the mitigation of emissions, the alleviation of strain on the electricity grid, and the facilitation of expanded distributed solar installations.

Sustainable EV Battery Solutions

Lithium-ion batteries dominate the market [70] with an anticipated 22% annual growth in energy storage due to rising EV, electronics, and stationary ESS needs. However, meeting this surge solely with lithium-ion batteries poses challenges [71]. Hence, the search for innovative technologies curbing the traditional battery material demand and environmental impacts in their supply is crucial. Niobium has shown potential in enhancing battery component performance and can serve as a partial substitute for conventional battery materials [70]. Enter lithium–sulfur technology: a prospective solution for conversion and expansive energy storage. Its strengths include promising high-energy density and cost-effectiveness, attributed to sulfur's abundance and affordability. Positioned as a prime contender for the subsequent wave of energy storage solutions, from EVs and consumer electronics to grid-level storage, the lithium–sulfur innovation holds significant potential [71]. Hence, battery manufacturers have the choice to substitute the materials in their battery compositions.

The management of end of life is a pivotal stage in a product's lifecycle. End-of-life EV batteries find new life as second-life batteries for homes and utilities [72]. Second-life batteries reduce raw material use, global warming potential, energy demand, and environmental impact versus new battery production [73]. By incorporating recovery (reuse, repurposing, and recycling) to extend the product life and reduce material demand, and powering production with renewable energy to enhance the CO_2 footprint, these strategies drive circular battery production. Yet, risks, like supply chain disruption and technological shifts, challenge the shift from linear to sustainable circular production [74]. Lithium-ion batteries have fewer toxic materials and are sometimes disposed in landfills. In Australia, 98.3% of portable lithium-ion batteries end up in landfills due to the lack of recycling [75]. By implementing regulations, we can mandate proper recycling practices for batteries, ensuring that end-of-life batteries are properly managed.

To ensure battery sustainability and longevity, we utilized battery energy in ways that proved advantageous for us. However, conventional approaches lack precision in detailing factors, such as charging cycles, energy consumption, and the distinction between active and standby periods. The integration of advanced algorithms becomes essential to fulfill operational requirements and extend a battery's lifespan [76]. These advanced algorithms enhance our ability to better manage and optimize various battery functions, ensuring an efficient performance over extended periods of use. This integration is pivotal to maximizing battery utility and achieving sustainable, long-lasting energy solutions.

3.3. Home-Based Electric Vehicle Charging Infrastructure

EVs are typically categorized into several types, including battery-powered EVs (BEVs), hybrid EVs, plug-in hybrid EVs, and fuel cell EVs, as shown in Figure 8a. Among these, a BEV relies exclusively on a rechargeable battery for propulsion and does not incorporate an internal combustion engine [77]. Based on the charging power, the charging system can be categorized into various types, including residential, public, workplace, warehouse, private, and remote charging systems [78]. The charging infrastructure of EVs is shown in Figure 8b. Over the past four years, there has been a steady increase in investments in public charging infrastructures, even though the majority (up to 80%) of EV charging occurs at home [79]. Residential charging is a popular choice for EV owners who reside in rowhouses, detached houses, or apartment buildings where they have access to park and charge their EVs using a dedicated charging facility [80]. Therefore, home charging is typically adequate for the majority of EV users. By starting the day with a fully charged battery, they can complete their daily trips and conveniently recharge their EVs once they return home, ensuring readiness for the following day [81]. Charging at home is the most prevalent method for recharging EVs, and it typically involves the use of either level-1 or -2 chargers [82]. This cycle of home charging allows for a seamless and uninterrupted use of the vehicle without relying on an external charging infrastructure.

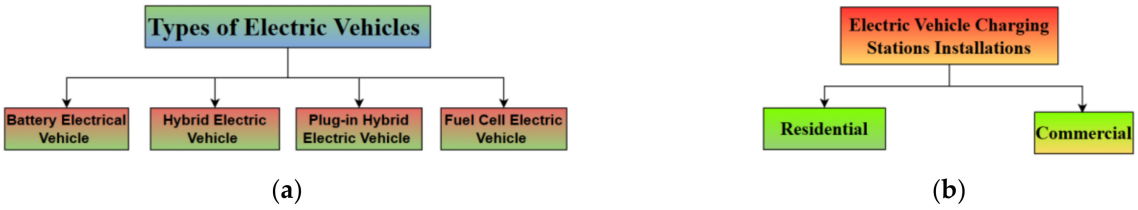


Figure 8. (**a**) Classifications of EVs; (**b**) EV charging infrastructure.

Charging EVs with solar energy requires less electricity from fossil fuels. Through the use of distributed solar PV panels, cleaner electricity is generated, and subsequently stored in EV batteries. This dual approach actively fosters sustainability by decreasing the reliance on fossil fuel-based electricity [83]. EVs commonly utilize lithium-ion batteries due to their reliability, lightweight, and high efficiency. However, it is expected that solid-state technology will replace conventional lithium-ion batteries in the near future [84]. Charging a battery and controlling the current flow involve various processes. Rectifiers are employed to convert AC to DC for EV battery charging [85–87]. EV batteries can be charged during extended parking periods. Communication between the EV and grid is scheduled to avoid charging during times of grid overload. Optimal charging involves the smart integration with solar PV systems during peak output hours, offering advantages, such as reduced grid constraints, tariff-based charging benefits, increased PV utilization, minimized overloading, enhanced profits for distributors and customers, and the maintenance of grid frequency and voltage [88]. To address power losses, power demand, harmonics, and to improve power quality, designing appropriate power converters for EV charging is an alternative approach [89].

The power converter operates as a buck converter during the charging mode and functions as a boost converter during discharging. Figure 9 illustrates an off-board charger, a grid-connected PV + EV battery charging system. In this setup, a grid-connected solar PV system charges the battery bank while simultaneously transferring excess power to the grid during sunny hours. During periods of low solar irradiation, the battery charges from the grid. To enable this dual functionality, a bidirectional converter is utilized. It acts as an inverter when power is transferred to the grid and operates as a rectifier during EV battery charging [90]. In the context of EVs, batteries serve as a vital link between electricity and EVs [91].

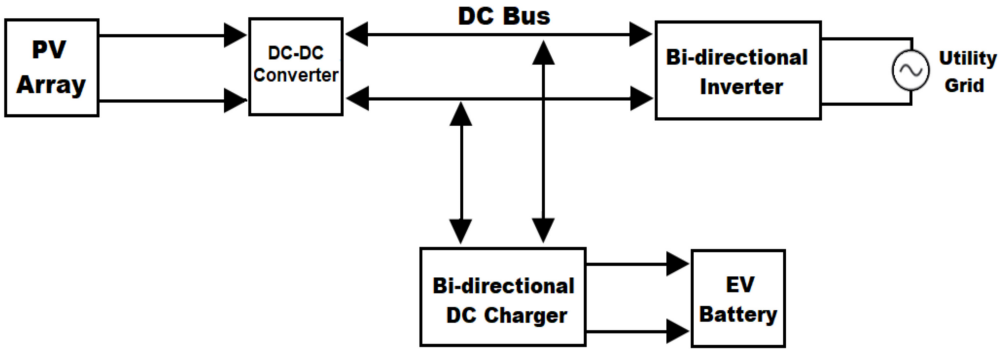


Figure 9. Charging system of EV with grid-tied solar PV arrays.

The number of EVs is increasing on Australian roads over time, as shown in Table 4. In only 2022, EVs accounted for 3.8% of all new car purchases, representing an impressive 86% increase compared to the previous year [92,93]. Moreover, there are at present +83,000 EVs actively driving on our roads. The average driving range of BEVs has experienced a remarkable evolution over the years. In 2011, the average driving range stood at 139 km, which increased to 233 km in 2016. By 2021, the average driving range further increased to 349 km, with some models capable of reaching up to 550 km. This represents a significant 50% growth in the average BEV driving range since 2016 [79].

Table 4. Total vehicles sold vs. EVs sold in Australia.

Years	Total Number of EVs Sold in Australia	% of Total Vehicles Sold in Australia
2015	1771	0.15%
2016	1369	0.12%
2017	2287	0.19%
2018	2216	0.3%
2019	6718	0.65%
2020	6900	0.78%
2021	8688	1.57%
2022	26,356	3.8%

According to the "Australian Electric Vehicle Industry Recap" report [92], Australia has a limited number of EV charging inlet points, with only 4943 available across the country. These charging stations include 1928 normal charger types, 365 fast charger types, and 99 ultra-fast charger types, covering the entire region. Given the potential for a surge in EV uptake, these public charging stations would be insufficient. Consequently, we need to consider alternative options. To address the challenges related to charging new EVs, a promising solution is to harness energy from solar PV systems. This approach offers a potential remedy to the charging problem by utilizing clean RESs for powering EVs [21]. According to the "Future Fuels And Vehicles Strategy 2021" report [94], the Australian government has introduced groundbreaking concepts and incentives related to EVs, fueling, and charging, paving the way for innovative home-based EV charging solutions. As part of these initiatives, new smart chargers, which are powered by rooftop solar systems, are being implemented. These chargers not only facilitate home-based EV charging, but also contribute to enhancing the grid reliability within households. Bidirectional chargers are expected to play a central role, with approximately 75% of EVs being charged at home. In this setup, BEVs serve as distributed energy resources, further strengthening the integration of EVs into the energy grid. Below are some practical techniques for charging/discharging EV batteries at the residential level.

3.3.1. X2V or V2X Technologies (X = Home, Grid)

Various modes of operation can meet the energy demand of EVs and home appliances. When there are peak hours of sunshine, power can be transferred from the house to both the vehicle and grid. Conversely, during nighttime or inclement weather, power is transferred from the vehicle or grid to power home appliances. In this discussion, we explore several technologies for power transfer in these scenarios.

1. Home-to-Vehicle (H2V) Technology

The H2V strategy involves harnessing solar PV generation to fulfill both home energy needs and charge EVs using excess energy. In this strategy, the EV battery functions as a load [95]. To optimize the synergy between PVs and EVs, an EMS is implemented [96]. By integrating solar PV systems, consumers can rely less on the grid, potentially eliminating electricity bills and reducing carbon footprints [97]. Homes that combine solar PVs and EVs represent a promising model for the future [48]. This approach is characterized by its cost-effectiveness, innovation, simplicity, and efficiency, making it the optimal choice for home EV battery charging. During daylight hours, the solar PV array converts sunlight into electricity, which is used to power home appliances and charge EVs. If an EV is unavailable for charging during the day, the battery swapping technique can be employed to fulfill the energy requirements of EVs.

2. Vehicle-to-Home (V2H) Technology

The concept of using the EV battery to supply electricity to the home instead of relying solely on the grid is known as V2H. V2H enables a bidirectional power flow between the EV battery and the home's electrical system, effectively utilizing the EV battery as a backup

for the ESS [98,99]. This innovative design allows for the optimization of energy benefits, such as reduced electricity costs, by effectively managing the charging and discharging process. The V2H mode proves particularly valuable when there are uncertainties in the operation of RESs and during peak hours, as the EV can discharge excess electricity to power the home [100,101]. Homes equipped with solar rooftop PV panels can locally store energy in the EV battery and utilize it within the home as needed [102]. This makes V2H technology intriguing, as it not only transforms vehicles into means of transportation, but also controllable power sources for the distribution grid [103]. Consequently, V2H represents an efficient and promising technique for HEMSs [104].

3. Grid-to-Vehicle (G2V) Technology

The process of charging an EV battery through the grid is known as the G2V mechanism [105]. When there is an energy demand that exceeds the generation capacity of RESs, the surplus energy can be efficiently managed by storing it in EV batteries via the grid [106]. EVs not only serve as a means of transportation, but also as electrical loads [107]. In G2V and V2G modes, EVs play an important role in ensuring short-term energy security while maintaining a balance in the energy demand [108]. Additionally, controlling the charging power in these modes improves power generation adequacy [109,110]. During the charging process, energy flows unidirectionally from the G2V, whereas during the discharging process, power flows bidirectionally from the vehicle back to the grid [111]. This technique proves particularly beneficial in situations when solar PV generation is unavailable and battery replacement is not a viable option. In such cases, the EV battery relies on the grid for charging, while during peak hours of solar irradiation, the surplus energy can be fed back to the grid through smart metering.

4. Vehicle-to-Grid (V2G) Technology

The strategy of using a vehicle to feed electricity to the grid is referred to as the V2G approach [98]. The adoption of EVs along with alternative energy sources also contributes to enhancing the reliability and efficiency of the grid [112]. However, the uptake of EVs, particularly V2G technology, has been slow in Australia. EVs can act as ESS by injecting power back into the grid, thereby assisting in grid stabilization. When idle, they can also aid in maintaining frequency and voltage regulations. Additionally, EV owners can generate revenue by utilizing RESs for charging, thus reducing the overall cost of vehicle ownership. This is made possible through the implementation of the bidirectional power flow enabled by smart grid networks [113–116]. The advancement of V2G technology has facilitated the integration of EMSs with the grid, allowing for the bidirectional control of charging and discharging [117]. Moreover, V2G technology can contribute to the reduction in carbon emissions [105].

3.3.2. EV Battery Charging and Discharging Challenges

Integrating EVs into the V2X/X2V primarily serves the purpose of recharging them for their subsequent journeys. However, through effective EV charge/discharge management, additional objectives beyond the primary goal can also be accomplished [118]. These vehicles serve as distributed energy storage sources, enhancing network efficiency and performance through well-managed charge/discharge control [119]. While EV batteries offer advantages in V2X/X2V scenarios, drawbacks do exist. Frequent EV battery usage, observed in discharging and recharging cycles throughout the day, accelerates the degradation of the EV battery lifespan [120]. However, researchers have established that batteries operating within the 20% to 80% SOC range exhibit a commendable cycling performance, with an essential capacity degradation reduction [121]. Despite the complexity of battery longevity being influenced by various other factors, like temperature, depth of discharge, and charging power parameters [122], controlling these factors is critical, but essential, for the smooth operation of EVs. To combat these challenges, EV manufacturers should implement battery management systems that limit discharging and charging between the 20% and 80% SOC range, facilitating the reuse of batteries in the second-life battery

industry [121]. Although, there are inherent limitations and challenges associated with repeatedly charging/discharging EV batteries. However, technology, infrastructure, and planning can counter these drawbacks. Collaborative efforts involving utilities, regulators, technology providers, and consumers are necessary to address these challenges. Strategies, such as optimizing charging behavior, integrating EVs into the broader energy ecosystem, and employing smart technologies, are key to a smooth transition toward a more sustainable and grid-friendly transportation future. Otherwise, vehicle mobility is restricted for acting solely as a battery.

3.4. Smart Metering

Smart meters (SMs) are advanced electric meters that have the capability to measure energy consumption levels and record the timing of utilization, often at intervals of an hour or less. They facilitate two-way communication between consumers and electricity utilities. In regions where electricity shortages and supply instabilities are prevalent, governments in the EU and US have mandated the deployment of SMs for demand-side management [123]. These meters capture real-time power consumption data, including voltage, frequency, and phase-angle measurements [124]. They can also transmit pricing information and real-time electricity consumption rates [125]. SMs come in various forms and serve different purposes; however, high-quality and high-resolution SMs provide sufficient data for load forecasting when combined with weather variables [126,127]. The data collected by SMs offer valuable insights into the load profiles and routine consumption patterns, leading to an improved accuracy in load forecasting, either on an individual or collective level [128]. Moreover, SM data aid utilities in identifying demand response operations and designing effective tariff structures [129,130]. SM data are also utilized in HEMSs and battery energy management systems [131]. With their ability to precisely record imported and exported electricity levels between the grid and a solar-powered house at regular intervals, SMs offer a reliable source of information regarding the energy dynamics of a household. This information can be leveraged to make informed decisions regarding energy storage for solar houses [48] and to determine optimal charging times for EVs.

3.5. Home Energy Management System (HEMS)

Solar PV generation, battery energy storage, heating ventilation air conditioning systems, and EVs are implemented in residential homes as part of demand response programs (DRPs). However, manually managing such devices is difficult for residential customers [132]. The addition of EV charging infrastructure increases the grid load demand, affecting other electricity consumers reliant on the grid. To handle the complexities arising from bidirectional power flow and high penetration levels, an advanced EMS is required [91]. Ensuring grid stability is of utmost importance in energy management [133], and HEMSs plays a vital role in supporting demand response initiatives and optimizing the operation of electrical appliances [132]. At present, HEMSs have gained significant research attention due to their relevance in the development of future smart grids [134]. The residential sector consumes over one-quarter of electricity worldwide as of 2021. The HEMS proves to be an effective tool in monitoring the power consumption levels of smart appliances, reducing peak loads, and saving energy costs [135]. An HEMS comprise various components, including distributed PV modules, smart appliances, user interaction terminals, ESSs, central control units, and SMs [62]. Serving as a bridge between home appliances and utilities, this automated device manages power consumption by transferring and eliminating demands [136].

The primary goal of an HEMS is to optimize the utilization of solar PV energy and minimize the reliance on the grid based on load profiles [137]. In addition, the system aims to achieve fuel economy, enhance system performance, prolong the lifespan of system components, extend battery life, increase consumers' comfort levels, and reduce electricity bills and carbon emissions [138–142]. HEMS research focuses on two major concerns: scheduling strategy and system modeling. Wireless communication facilitates an automatic

interaction between devices within the HEMS network [143]. An HEMS intelligently regulates the charging and discharging of ESSs and EVs, along with traditional home appliances, to further mitigate the uncertainties related to renewable energy generation, energy costs, and peak demands [140]. The HEMS monitors, manages, and controls the energy flow between sources and electric loads. Figure 10 illustrates the comprehensive functionality of HEMSs, consisting of five key objective modules. These key objective modules are discussed in Table 5 as follows [26].

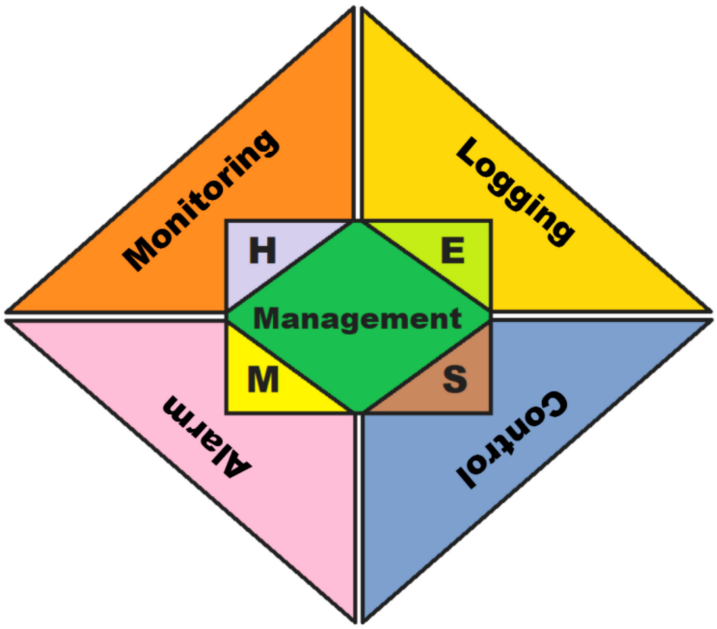


Figure 10. Home energy management system functionality.

Table 5. Key objective modules of the HEMS.

S. No.	Modules	Description
1	Monitoring	Monitoring capabilities, which involve tracking real-time data from smart appliances and displaying information related to the users' preferences, current energy utilization, and energy cost.
2	Logging	Logging functionality involves an authentication process that verifies and grants the user access to sensitive data, allowing them to read or modify the information securely.
3	Control	Control allows the direct control of both the end-user's control system and facilities, empowering users to manage and manipulate various smart devices. This direct control is attained through portable personal computers or smart phones, enabling the convenient monitoring and assessment of the user's consumption habits even from remote locations.
4	Management	The management component focuses on optimizing energy efficiency by effectively controlling renewable distributed energy resources, home energy storage systems, and smart appliances. This optimization is achieved through a demand response analysis, which involves the real-time adjustments of electricity prices.
5	Alarm	The alarm actively monitors and promptly alerts users in the event of any detected irregularities or anomalies.

Moreover, energy management should involve exchanging information with utility companies through the HEMS [144]. The HEMS also enables utilities to develop new business models based on real-time pricing [140]. Future research directions are divided into two categories: HEMSs and demand DRPs. Firstly, improving the smart grid infrastructure can lead to the efficient optimization of peak hours. The infrastructure includes smart appliances, communication technologies, smart metering, and control algorithms. Such improvements can decrease DRPs' reliance on customers' willingness to participate. Secondly, storage devices can significantly enhance the efficiency of DRPs by solving the issues of load scheduling and uncertainties in renewable energy resources' outputs. To ensure an optimal performance, DRPs must emphasize the use of control algorithms for storage devices [136]. The major role of DRPs is to send appropriate signals to energy consumers, influencing them to adjust their demand responses accordingly [145,146]. The DRPs provide utilities with new options to balance the demand and supply, thereby reducing utility bills [147]. Hence, an HEMS is a system that can determine whether to buy or sell electricity to the grid or store it in a battery bank [148].

4. Selected Literature on Solar PV Smart Homes Integrated with EVs

Within the existing literature, researchers have explored a wide array of techniques, scenarios, algorithms, and software to optimize energy management within households, particularly in conjunction with solar PVs and EVs. These studies propose a multitude of methods aimed at reducing energy consumption levels, lowering costs, and improving energy management, specifically in residential buildings. Thorvaldsen et al. [149] examined the effect of flexible assets on the long-term operation of a residential building under a measured-peak grid tariff, which incurred the highest single-hour peak cost import over the month. To do so, they utilized a mathematical model of an HEMS and stochastic dynamic programming to analyze the case of a Norwegian building with the smart control of a battery energy storage system, space heating, and EV charging. The analysis focused on each flexible asset individually and considered an energy-based grid tariff. The study found that EV charging had the greatest impact on peak power, reducing the total electricity costs by 14.6%. The model also demonstrated how the system optimized the timing and level of the peak demand by co-optimizing both real-time pricing and the measured-peak grid tariff, resulting in an optimal performance. This study investigated the use of EVs and their minimum SOCs over a week as a means of providing black start services while minimizing consumer electricity bills through V2H modes. The authors analyzed the impacts of different electricity tariffs and PV penetration rates using a machine learning model classifier for the prediction of real-world EV travel data locations in England across four weeks of the year, which were then employed in an optimization model to determine SOC percentages and consumer electricity costs for various scenarios. The results show that the model exhibits an accuracy of over 85.80% and both electricity tariffs and PV penetration rates have an effect on the SOC percentages that EVs can maintain during a week and the resulting total electricity costs. SOC percentages can remain above 40% for black start services throughout the week with a dynamic tariff aligned with the wholesale electricity market while maintaining total weekly electricity costs under GBP 30.00 [150]. We reviewed some studies related to solar PV smart homes integrated with EVs and battery storage systems (BSSs) located in different regions, summarized in Table 6.

Table 6. Selected literature on PV smart homes integrated with EVs.

Ref.	Year	Methods	Key Findings
[151]	2019	Four-Stage Optimization and Control Algorithm	An advanced four-stage intelligent technique developed to optimize energy management schedules for day-ahead and hour-ahead planning, provide timely EV price updates, and enable real-time control. The main objective of the control algorithm is to reduce the operational costs of the integrated smart charging station, while simultaneously enhancing customer satisfaction.
[48]	2019	Smart Meter Data/Intelligent Algorithm	An innovative and generic decision-making framework, incorporating an intelligent algorithm, utilized to develop an economic model and calculate electricity quantities for enabling EV charging through solar energy instead of grid power. The adoption of this approach resulted in a significant reduction in electricity costs (38%) for homes with solar PVs.
[152]	2020	Variable Step-Size MPPT	To facilitate the charging of plug-in hybrid EVs, the authors developed a self-contained charging station that incorporated a fuel cell system with RESs. With a high level of efficiency (99.6%) and a short payback period (16 months), the charging station also reduced the burden on the grid.
[153]	2020	Pyomo Framework and Gurobi Optimization Solver	The system model incorporates solar PV generation, two EVs equipped with V2H technology, an ESS, and two batteries. The proposed strategy yielded significant cost savings, reducing electricity tariffs by 30% when utilizing V2H technology, 50% when the battery was added, and up to 85% when utilizing a specific EV under the time-of-use tariff without the use of a battery.
[154]	2021	Markov Decision Process and Gradient Algorithm	The model considers solar PV generation, household demand, and the unpredictability of EV mobility with an objective of electricity cost minimization and network load alleviation during peak periods. The simulation results demonstrate that utilizing EVs for home energy management is an efficient and cost-effective technique.
[155]	2021	MATLAB	This research work presents a conceptual model for a pure PV–EV nationwide energy system. The surplus power generated by the solar PV system is stored in EV batteries, which can be used to meet the energy demand when solar energy is unavailable. This theoretical study assumes that the widespread adoption of EVs can be achieved, as EVs remain stationary 95% of the time, making them an ideal source of energy storage. Ultimately, the model showcases how solar PV systems have the potential to provide energy to the entire country.
[156]	2021	MATLAB/Simulink	By utilizing the optimal automation, controlling, and scheduling of appliances effectively, the approach is capable of countering unexpected fluctuations. The surplus power generated by the solar PV system is fed back into the grid and used to charge an EV. The stored energy in the EV battery can then be used to power the smart home during high-load periods, delivering a reliable 2.8–3 kW of power. The simulation results demonstrate the home-centralized PV with an HEMS's ability to deliver high-quality power, even during undesirable fluctuations, showcasing its reliability.
[157]	2021	Mixed-Integer Linear Programming.GAMS Software (GmbH, US and Germany) /CPLEX Solver	The use of an optimized strategy in a solar PV system and EV tied to a grid improves energy resilience and robustness. During the daytime, the solar PV system generates energy, while during the nighttime, the EV supplies power to the building. The load profiles consist of a base load of 16 kW, a critical load of 2.4 kW, and solar energy varying from 1–20 kW. In the absence of solar and grid energy, the system can cover 51.4% of critical loads. The proposed model is highly efficient, reducing critical loads by 10% and energy loss by approximately 15%.

Table 6. *Cont.*

Ref.	Year	Methods	Key Findings
[158]	2021	Energy Plus	Buildings equipped with solar panels can store energy to power appliances during blackouts, while an EV battery can expand the energy capacity of the ESS. The SOC of the battery is set to 20%, which is the typical SOC discharging limit. Different load percentages are considered in various scenarios, and the study results show that reducing the energy demand can enhance a building's resilience during blackouts.
[159]	2022	Rule-Based Intelligent EMS/Priority-Based Decision Algorithm	This article proposes an intelligent energy management system integrated with a small-scale home area power network that utilizes a cost-effective power schedule. The study analyzes residential power usage, EV driving behavior, and battery charging/discharging patterns using real-world data collected over the course of a year. The simulation results demonstrate that the combination of PV arrays, EV storage, and the grid serves as a source of clean and affordable energy.
[160]	2022	Extended Bellman–Ford–Moore Algorithm	This study implements a two-level laboratory hierarchical EMS to optimize the profiles of PV and battery storage as DC sources for day-ahead and real-time decisions. This smart charging tactic is designed for charging EVs in a home–energy–hub system, using data on solar irradiation, electricity tariffs, and power consumption. The proposed strategy provides a solution for the smart charging of EVs in domestic applications, with rapid real-time decision making for users to maximize profits. The simulation results show that the power grid and home–energy–hub system have a positive impact on the behavior of EVs.
[19]	2022	Particle Swarm Optimization Algorithm	This research proposes an EMS optimization with two hierarchical layers to achieve various goals in four different scenarios. The study aims to reduce electricity bills and provide free charging for plug-in electric vehicles in a smart home connected to a PV generator by managing the charging/discharging of PEVs to and from the smart home. The simulation results indicate that the proposed approach provides smooth energy profiles for the home, achieves almost free PEV charging, and reduces electricity bills by 26%, 15.57%, 31.68%, and 25% in autumn, winter, summer, and spring, respectively.
[132]	2022	Novel Demand Response Strategies	This study compares three novel strategies with the existing demand response mechanisms in an HEMS for managing uncertainties. The first scenario involves a BSS supplying energy when a PEV is not in a V2H capacity, while the second scenario involves a bidirectional charging system allowing the PEV to provide energy in a unique V2H capacity, without requiring battery storage deployment. The objective is to evaluate the electricity bills through a mathematical formulation. The study results indicate that demand response strategies are more effective than other programs, with the peak demand reduced by approximately 2 kW when the time-of-use tariff is applied.
[161]	2022	MATLAB Toolboxes/TRNSYS	The authors proposed an EMS for a house that included controllable loads, EV batteries, and grid-connected hybrid renewable energies. The system uses hourly based simulations of meteorological data to make decisions about connection architecture through switch control states and variation conditions for H2V, V2H, and G2V scenarios. The study concludes that, during the daytime, the H2V scenario is performed, and in the insufficiency of renewable energies, the EV cooperates with the home when the grid-to-home scenario is in progress.

Table 6. *Cont.*

Ref.	Year	Methods	Key Findings
[162]	2023	MATLAB Lyapunov Optimization Technique	This study focuses on the analysis of a smart home that incorporates inflexible loads, such as lighting, a computer, and a TV, as well as flexible EV loads, HVAC systems, water heaters, and RESs. The home operates in a grid-connected mode, allowing for energy trading, both purchasing and selling energy. The objective is to optimize the overall cost, minimize thermal discomfort, and efficiently manage the charging and discharging of batteries and EVs. The findings highlight the effectiveness and superiority of the proposed algorithm in achieving optimized energy consumption and management in a real-time scenario.
[163]	2023	MATLAB Type-2 Fuzzy logic Controller	This paper presents an EMS for a smart home that utilizes RESs along with EVs and an ESS. The EMS, based on a type-2 fuzzy logic controller and smart switches, connects various controllable and non-controllable household appliances to meet the electricity demand. To determine the optimal configuration of the controller, the number and distribution of membership functions are chosen based on real input data collected over a year in Tehran, Iran. The results show that the smart home system can reduce its reliance on grid electricity by 49.186 kWh on a daily basis, leading to a weekly reduction of approximately 343.95 kWh from the grid. Furthermore, the implementation of the proposed strategy leads to a 71.5% reduction in electricity costs and a 64.6% decrease in the peak-to-average ratio.

5. Discussion and Near to Future Advancements and Future Roadmap

Energy is vital for the sustenance of life on Earth, as it serves as the lifeblood that powers various activities [164]. However, our current reliance on fossil fuels for energy generation poses urgent concerns. It is essential to swiftly implement and enhance RESs to ensure energy security and foster a cleaner environment [165]. Multiple organizations are advising for a swift transition from fossil fuels to renewable energy [166] because the burning of fossil fuels is one of the reasons for air pollution [35]. Harnessing energy from RERs, particularly solar power, offers numerous advantages, as depicted in Figure 11. The information used in Figure 11 was extracted from [167]. Not only is the energy derived from these sources more cost-effective, but it also contributes significantly less to noise and air pollution. Importing coal and gasoline for electricity generation has adverse effects on a country's economy. Furthermore, petrol cars typically incur an average annual fuel cost of approximately AUD 2400, while the average EV requires only about AUD 400 in electricity expenses. Additionally, EVs tend to boast lower maintenance costs compared to petrol cars. The widespread adoption of EVs holds the potential to substantially reduce air pollution, leading to a broad range of health and environmental advantages. The transition to EVs not only brings about environmental benefits, but also presents a significant opportunity for job creation and industry growth from manufacturing to maintenance in Australia. Australia possesses abundant mineral resources, sufficient capital, and the necessary capabilities to fully take advantage of this opportunity [79]. However, by generating energy domestically and home-based charging from clean and environmentally friendly sources, the entire nation can foster economic growth while simultaneously promoting a greener future.

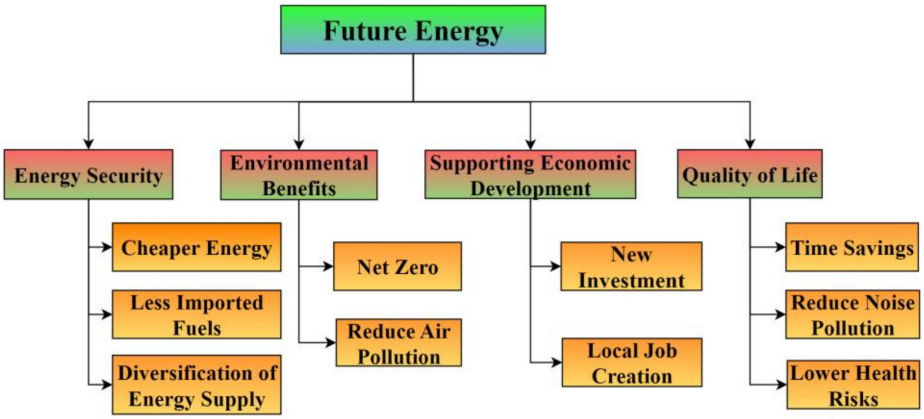


Figure 11. The benefits of future energy.

In recent times, the Australian government has recognized the potential barriers associated with the costs of installing solar PV systems and purchasing EVs. They have taken proactive measures to address these issues and promote the adoption of these technologies. By implementing incentives and subsidies, the government aims to make these technologies more affordable and accessible to the general public. These initiatives include financial support through rebates, grants, and tax credits, which help lower the barriers to entry and accelerate the transition toward cleaner and more sustainable energy solutions. Moreover, the government's focus extends beyond the adoption of EVs to the charging infrastructure itself. They propose innovative solutions, such as smart chargers powered by rooftop solar PV systems in households, which not only improve grid reliability but also tap into the potential of bidirectional chargers. These chargers allow BEVs to serve as distributed energy resources, enabling greater grid flexibility. Furthermore, the integration of grid-connected solar PV systems and EV fast charging stations can address power-quality challenges. Instead of solely relying on traditional charging stations, alternative solutions, like battery swapping and inductive charging stations, can be implemented in homes, enhancing the overall EV charging experience. Overall, these initiatives put forth by the Australian government aim to promote the widespread adoption of solar PV systems and EVs, stimulate the green economy, create job opportunities, and contribute to the reduction in GHG emissions. By focusing on both affordability and charging infrastructure, the government strives to accelerate the transition toward a sustainable transportation future. This paper discussed the most accurate and up-to-date information on the roadmap for solar PV homes integrated with EVs in Australia. Based on the discussion above, the literature suggests the following strategies for future developments in Australia:

- Increasing the Adoption of Solar PV Systems: solar PV systems will continue to gain popularity in Australia; the Australian government supports solar energy adoption [44] through subsidies [45] and incentive schemes [39]. Falling capital costs of solar PV panels, coupled with rising electricity prices, and government initiatives have led to shorter payback periods for solar PV systems [48]. Australia is experiencing a significant growth in the solar PV market and aims to have solar energy contribute 30% of its energy supply by 2050 [51,52], as discussed above in detail. This will result in more solar PV installations in residential properties, enabling homeowners to generate clean and green energy for powering their home appliances and selling the extra energy to the utility.
- Integration with the Energy Storage System: to maximize the utilization of solar energy, homeowners will increasingly incorporate ESSs, such as batteries, into their smart homes. This will allow them to store excess solar energy generated during the day for use during the night or periods of low sunlight. Moreover, with an ESS in place, households have the option to sell any excess energy back to the utility. According to the "State of the Energy Market 2022" report [168], households equipped with solar panels and batteries have the opportunity to sell surplus energy to their retailer or

neighbors, as well as participate in demand response programs. Home battery systems can contribute significantly to addressing the grid demand peaks, contingent upon the advancements in technology that result in lower installation costs.

- EV Integration: to reduce energy consumption levels, certain EVs can serve as energy storage for both households and the electricity grid. The advancements in bidirectional charging technology, which enables EVs to both receive and discharge energy, will expand the number of EV models that can provide electricity to power homes (V2H) and the grid (V2G). Furthermore, EVs have the potential to store surplus power generated by solar PVs and other renewable energy systems, offering assistance in electricity grid management [79]. According to the "Future Fuels and Vehicles Strategy 2021" report [94], the Australian government introduced pioneering concepts and incentives for EVs, fueling, and charging, which drive the development of innovative home-based EV charging solutions.
- Home Energy Management System: an HEMS is a technological platform that enables the monitoring and control of at least one residential customer's assets. These assets commonly integrated within an HEMS include solar PVs, batteries, EV chargers, as well as household appliances [169]. The Australian government encourages the implementation of HEMSs throughout the country according to the "Smarter Homes for Distributed Energy 2022" report. This study aims to develop HEMSs that can adapt to dynamic operating conditions and unleash the full potential of distributed energy resources. By providing real-time data on energy generation, usage, and storage, the HEMS empowers homeowners to make informed decisions, optimize energy management, and decrease grid dependency.
- Neighborhood/Community Storage and Shared Electricity: local energy communities are emerging as a collaborative approach for both consumers and prosumers to collectively invest in distributed RESs, community storage systems, and share electricity within their community. These communities, composed of various generation and storage units, hold significant potential as flexible assets that can be effectively utilized by the distribution system operator [170], where residents can share and exchange the excess electricity generated from RESs. The Australian government introduced "Community Batteries Funding Round 1" to implement community batteries nationwide, aiming for cost reductions, emission mitigation, grid relief, and increased distributed solar installations [69].
- Energy on Wheels/Mobile Energy Storage System: the system primarily consists of ESSs and vehicles, which play a vital role in meeting the emergency energy requirements following significant power outages/maintenance [171]. Mobile energy storage systems have garnered considerable attention in the research due to their inherent mobility and flexibility, offering distinct advantages over static resources. In recent years, these systems have been deployed within the existing energy systems to enhance their resilience [172]. Transportation carriers within the system are equipped to transport and distribute the stored energy to the necessary locations. These carriers serve as mobile power sources, delivering the stored energy to primary loads that require an uninterrupted operation.
- Virtual Power Plant: virtual power plant technology offers a powerful solution for aggregating distributed energy resources and user-side assets to actively engage in energy market activities. By integrating various energy sources, a virtual power plant can overcome the challenges associated with relying solely on a single resource and effectively cater to users' diverse energy requirements while ensuring system stability and security [173]. A virtual power plant is a collection of resources that are managed through software and communication technology to provide services typically offered by a traditional power plant. In Australia, grid-connected virtual power plants specifically aim to coordinate rooftop solar panels, battery storage, and controllable load devices [174].

- Smart Grid Technology: the increasing adoption of solar PV smart home integration with EVs poses challenges for the power grid, even with the installation of solar-powered charging stations. To address these challenges, the existing grid stations should incorporate smart grid technology. A smart grid is capable of managing bidirectional power flow, allowing EV owners to return electricity back to the grid. This bidirectional power flow enhances the efficiency and cost-effectiveness of EV charging, while facilitating the integration of RESs, like solar power [88]. A smart grid is sought after in Australia to address the rising electricity costs, aging infrastructure, and transition from coal-fired power. Investments in the smart grid enhance utility operations, ensure grid reliability, and prioritize robust and secure electricity supply for economic growth and technological innovation [175].
- Grid Integration and Demand Response: with a significant number of solar PV smart homes and EVs in the system, there is a need for grid integration and demand response mechanisms. These technologies enable the seamless communication between homes, EVs, and the electricity grid, allowing for an optimized energy flow, load management, and participation in grid-balancing programs. In October 2021, Australia introduced a wholesale demand response mechanism to enable consumers, either individually or through aggregators, to actively participate in reducing their electricity loads during peak periods. By voluntarily reducing their energy consumption, consumers have the opportunity to receive rewards. This demand response initiative not only benefits consumers, but also contributes to the stability of the power system during high-demand periods [168].
- SolarEV City Concept: cities considerably contribute (60–70%) to the pollution that causes climate change due to how much energy they use. With urban populations growing, it is vital to find affordable methods for enhancing cities' cleanliness and livability standards [176]. Using rooftop solar PVs and EVs proves to be highly efficient in reducing carbon emissions from urban energy systems in a cost-effective manner [177]. Kobashi et al. introduced a "SolarEV City" concept, which combined roof-top solar PVs and EVs to provide cheap and clean electricity to urban residents [176]. The Australian government actively encourages rooftop solar PV systems and EV adoption through incentives, while also prioritizing technologies, like HEMSs, community battery storage, shared electricity, and virtual power plants, all collaborating to create a SolarEV city. With its ample sunlight, extensive land area, and increasing focus on renewable energy and electric mobility, Australia is well-suited for such a development.

Affordable low-emissions technologies, as previously explained, play a pivotal role in enabling Australia to achieve its goal of reaching net-zero emissions by 2050 [52]. These technologies offer sustainable alternatives across various sectors, reducing GHG emissions while ensuring affordability and accessibility. Embracing and promoting these technologies is vital in the transition to a low-carbon economy. By investing in the research, development, and deployment of such technologies, Australia can effectively mitigate climate change and foster a cleaner and more sustainable future.

6. Conclusions

The integration of grid-connected rooftop solar PV smart homes with EVs has experienced a significant surge in popularity in recent years. Solar PV homes offer households the significant advantage of accessing free energy generated by the sun. These systems utilize solar panels to convert sunlight into electricity, allowing homeowners to power their homes without relying solely on grid electricity. By harnessing the power of the sun, solar PV smart homes empower homeowners to take control of their energy consumption habits. In addition, EVs, powered by electric motors, require minimal maintenance, generate lower levels of noise pollution, and are highly efficient in terms of energy consumption and storage. These factors contribute to their overall appeal. This paper reviewed the concept of grid-connected rooftop solar PV homes, encompassing home energy management systems, BSSs, bidirectional EV charging, and various smart metering technologies, with a focus

on the Australian context, and provided the future roadmap to adopt these technologies. The depletion of fossil fuels and the escalating GHG emissions emphasized the urgency of adopting this integrated approach at the residential level.

Despite the growing number of electrified vehicles on the road, the availability of charging infrastructure remains limited, posing challenges for EV owners, particularly for long-distance journeys. In such scenarios, solar houses can offer valuable services to EV owners. In addition, solar PV smart homes provide households with free energy and surplus electricity can be sold back to the grid, offering a potential revenue stream for owners. Homeowners can effectively manage and control energy flow through the utilization of HEMSs, which monitor, manage, and optimize energy usage within the household, ensuring the efficient distribution and utilization of energy resources. Furthermore, the presence of home charging infrastructures for EVs not only benefits homeowners, but also extends advantages to neighbors and local communities. This shared infrastructure enables convenient access to charging facilities, promoting the wider adoption of EVs and reducing reliance on traditional fuel-powered vehicles. The transition to EVs in Australia not only yields environmental benefits, but also holds immense potential for job creation and industry growth. By combining solar PV systems, EVs, and HEMSs, households can achieve significant energy savings and reduce energy costs. This integrated approach not only contributes to individual cost savings, but also fosters a more sustainable and environmentally conscious society by reducing reliance on fossil fuels and minimizing carbon emissions.

In the context of grid-connected solar PV smart homes integrated with EVs, this study highlighted the importance of rapid transitions to electric road transport and 100% renewable electricity. These transitions are essential for achieving energy savings, low energy costs, and reduced carbon emissions at the residential level. Immediate and strong action is necessary to accomplish this transition. However, the future research should focus on investigating the specific policy settings that can facilitate the required changes. Detailed insights into these policy settings are essential to effectively guide the transition and maximize its benefits. In terms of the future works, there is a need to focus on the development of smart communities that integrate renewable energy, electric vehicles, and energy management systems, and the role of aggregators in facilitating the integration of these energy sources.

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Abbreviations

AC: Alternating Current, BEV: Battery Electric Vehicle, BSS: Battery Storage System, CO_2: Carbon Dioxide, DRPs: Demand Response Programs, DC: Direct Current, ESS: Energy Storage System, EVs: Electric Vehicles, G2V: Grid to Vehicle, GHG: Greenhouse Gas, GW: Giga Watts, H2V: Home toVehicle, HEMS: Home Energy Management System, kWh: Kilo Watt Hour, MPPT: Maximum Power Point Tracking, MJ: Mega Joule, PEV: Plug-in Electric Vehicle, PV: Photovoltaic, RES: Renewable Energy Source, SM: Smart Meter, SOC: State of Charge, V2G: Vehicle to Grid, V2H: Vehicle to Home, V2X/X2V (X = Home, Grid).

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