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Rituraj, Gautam; Chandra Mouli, Gautham Ram; Bauer, Pavol

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A Comprehensive Review on Off-Grid and Hybrid Charging Systems for Electric Vehicles

GAUTAM RITURAJ [1] **(Member, IEEE), GAUTHAM RAM CHANDRA MOULI** [1] **(Member, IEEE), AND PAVOL BAUER** [1] **(Senior Member, IEEE)**

Electrical Sustainable Energy Department, Delft University of Technology, 2628 CD Delft, The Netherlands

CORRESPONDING AUTHOR: Gautam Rituraj (e-mail: g.rituraj@tudelft.nl).

ABSTRACT In recent years, the research interest in off-grid (standalone mode) and hybrid (capable of both standalone and grid-connected modes) charging systems for electric vehicles (EVs) has increased. The main reason is to provide a seamless charging infrastructure in urban and rural areas where the electrical grid is unreliable or unavailable so that EV adoption can be increased worldwide. In this regard, this article reviews the state-of-the-art architectures of the off-grid and hybrid charging systems and investigates their various subsystems, such as single or multiple energy sources, power electronics converters, energy storage systems, and energy management strategies. These subsystems should be optimally integrated and operated to achieve low-cost and efficient EV charging. Moreover, each subsystem is explored in detail to find the current status and technology trends. Furthermore, EV charging connectors, their power level, and standards for all kinds of EVs (ranging from one-wheeler to four-wheelers) are reviewed, and suggestions are discussed related to the non-standardization of charging plugs. Finally, conclusions show the continuous efforts of the researchers in improving the systems in various aspects, such as cost reduction, performance improvement, longevity, negative environmental effect, system size minimization, and efficient operation, and highlight challenges for both charging systems.

INDEX TERMS Biomass, EV charging, off-grid, grid-connected, solar, and wind.

I. INTRODUCTION

The mass adoption of electric vehicles (EVs) in urban and rural areas of various countries lies in seamless, widespread, and fast charging solutions. Most EV batteries are currently charged from the utility grid (UG) at a residential, public, or semi-public (like workplace) charging station [1]. Moreover, the available commercial EV charging stations also use UG as a primary energy source [2]. However, dependency on only UG may not solve the purpose of the electrifying transportation sector (so-called EVs). The UG is not 100% reliable in several places, and it is not accessible in several areas. Moreover, if UG is predominantly powered by fossil fuels, then charging EVs from such UG shifts the emissions from the vehicle to the power plant. Therefore, renewable energy sources (RESs), such as wind, solar, and biomass [3], [4], should be used (according to their availability at the site) as a primary energy source in EV charging stations.

According to the data published by the World Bank in 2019, about 760 million people globally do not have access to electricity [5]. On the other hand, a limited number of countries have the highest quality of electricity supply in 2019 [6]. The remaining countries have an unreliable grid. Thus, there is a need for off-grid and hybrid charging systems in the developing world, and motivated to research this field.

A. DEFINITION OF TERMS 'OFF-GRID' AND 'HYBRID'

There are two types of EV charging systems: off-grid and hybrid. In the context of this paper, a hybrid charging system (HCS) can function in both standalone and grid-connected modes depending on the availability of UG. It should be noted that many articles use the term 'hybrid' differently, for example, when multiple sources of energy or storage are used or when the same inverter is used for solar photovoltaic (PV)

array and battery, etc. In contrast to HCS, an off-grid charging system (OGCS) operates in the standalone mode because of the absence of UG. Further, in HCS and OGCS, various subsystems, such as energy sources (RESs and fossil fuels), energy storage system (ESS), power electronics converters (PECs), and energy management strategy (EMS) are generally used [7]–[10].

B. LITERATURE SURVEY

Various architectures of hybrid and off-grid charging systems for EVs have been studied and investigated in the literature. These architectures are AC-based, DC-based, and both AC and DC-based, according to the type of bus or (micro) grid (i.e., AC or DC) used for the collection and distribution of power [7], [11]–[15]. In the literature, AC-based, DC-based, and AC and DC-based architectures of HCSs for EV applications have been reviewed in various aspects, such as converter topologies, socio-economic, architecture, and control, etc. [16]–[20]. Reference [16] presented a comprehensive review of PECs topologies for integrating PV, UG, and EV in AC-based architecture of HCS. For a DC-based architecture of HCS, [17] presented an overview of PECs topologies for PV/EV/Grid integration with a specific focus on Z-source converters. Moreover, reference [18] has discussed various aspects of a PV-grid integrated dc fast-charging system with a particular emphasis on the multiple components of the system, architecture, operational modes, and control. Furthermore, in [19], a comprehensive analysis of DC-based architecture of HCS having PV, UG, and EV has been presented. Here, the various aspects, such as the deployment in the world, methodology, operation mode, and EV energy management, are covered in the analysis. For AC and DC-based architecture of HCS having PV, grid, and EV, different possible system configuration to provide both AC and DC charging has been investigated and compared [20]. Based on this, a review of PECs has been presented for PV, EV, and grid integration. Then, a multi-port converter for PV, EV, and grid interconnection is proposed, which uses a common dc-link.

As far as the review of the various architectures of OGCSs is concerned, the researchers reported only DC-based architecture of OGCS separately or combined with a DC-based architecture of HCS [21]–[25]. In [21], an energy-efficient DC-based architecture of OGCS is reviewed for lighting appliances, plug and play solar PV home systems, and EVs and discussed the worldwide demand for the same. The DC-based architecture of OGCS and HCS are reviewed for different applications in [22]–[25]. In [22], both types of charging systems having PV and battery storage (and UG) are summarized with a focus on EV fundamentals, batteries, and PV systems. Moreover, a MATLAB simulation-based case study is presented for both charging systems focusing on the technical and the economic feasibilities. In [23], various power converter topologies that can be used in both types of charging systems having PV, wind, and battery storage, are reviewed. Reference [24] presented a technological review on DC charging using both types of charging systems having PV, battery

storage, and UG. The PECs (focused on V2G), charging standards, and control for both charging systems are discussed here. In [25], both types of EV charging systems having PV, energy storage, and UG are discussed and reviewed, focusing on their control architectures. Moreover, the impact of various EVs connected to UG has been studied, and the different EV charging scheduling techniques have been analyzed.

Apart from the system level review, few works have provided an in-depth review separately for different subsystems, such as EMS, PECs, and EV charging topologies. In [26], various energy management strategies are reviewed for the hybrid RESs based microgrid system. However, EV charging application is not considered in this work. In [27], an in-depth review of grid-tied converter topologies for PV systems is presented, which is also not focused on EV charging applications. Reference [4] focuses on reviewing EVs interaction with RESs in smart grid based on cost-aware, efficiency-aware, and emissions-aware while interacting between RESs and EVs. In [3], the essential methods and assumptions for the integration of EVs, UG, and RESs are reviewed. Here, EVs' environmental, economic, and grid impacts have also been discussed. Reference [28] presented a review on DC-DC converter topologies for EVs, Plug-in Hybrid EVs, and fast-charging stations. Here, the review evaluates the architecture, merits, and demerits of converter topologies.

As far as connectors are concerned, it is one of the essential parts of any plug-in EV charger. It plays a vital role in transferring the power of different levels and providing communication between the EV charger and charging stations [29], [30]. Few works have reviewed and discussed the standards of plugs and power levels adopted by various countries [29]–[32]. However, these works do not report a review of their usage by the different off-grid and hybrid charging systems.

C. CONTRIBUTIONS

The abovementioned literature survey shows that none of the work has reviewed various architectures of off-grid and hybrid charging systems for EV applications. Besides that, the review of each subsystem for these charging systems is also missing in the previous work. Therefore, to fill this literature gap, a comprehensive review of various architectures of off-grid and hybrid charging systems for EVs has been done in this article, and the following contributions are made:

- Various architectures of off-grid and hybrid charging systems for EVs are critically reviewed for the first time.
- Moreover, the reported works are investigated based on subsystems, such as RESs, ESS, PECs, and EMS. ESS are intensively analyzed in terms of battery technology, rated power and energy, and the EMS strategies in terms of EMS algorithms used and the control objective; RESs are investigated in terms of their type and rated power; PECs are discussed in terms of isolation, topology, AC or DC interconnection bus.
- Furthermore, EV charging power level, connectors, and their standards for one to four-wheelers are also discussed, and the usages of these connectors in off-grid

TABLE 1. Summary of Various Architectures of OGCS Reported in Literature

Reference(s)	OGCS based on			Expt./Sim.
	AC Fig. 2	DC Fig. 3	AC & DC Fig. 4	Both
[11]	Yes	-	-	–
[8], [33]–[37]	Yes	-	-	Sim.
[12], [38]–[43]	-	Yes	-	Sim.
[44]	-	Yes	-	-
[45]	-	Yes	-	Expt.
[46]	-	-	Yes	-
[7]	-	-	Yes	Sim.

TABLE 2. Summary of Various Architectures of HCS Reported in Literature

Reference(s)	HCS based on			Have both modes implemented?	Expt./Sim.
	AC -	DC -	AC & DC Fig. 7		Both
[47]	Yes	-	-	Yes	Sim.
[48]–[51]	Yes	-	-	-	Sim.
[13], [52]	Yes	-	-	Yes	Expt.
[53]	Yes	-	-	Yes	Both
[54]	Yes	-	-	-	Both
[14], [55]–[62]	-	Yes	-	-	Sim.
[63]–[65]	-	Yes	-	Yes	Sim.
[66], [67]	-	Yes	-	-	Expt.
[68]–[71]	-	Yes	-	Yes	Expt.
[72]–[78]	-	Yes	-	-	Both
[20]	-	Yes	-	-	-
[9], [10], [79], [80]	-	-	Yes	Yes	Expt.
[15]	-	-	Yes	Yes	Both

FIGURE 1. Various components used in OGCS. The hidden part (Utility grid) is for the HCS, which is discussed in Section II-C.

the published articles related to the different architectures of the off-grid and hybrid charging systems, respectively.

A. UG CHARGING INFRASTRUCTURE

UG charging infrastructure is commonly used in areas where a reliable UG is present. Here, one has to plug the connector of EV charger in their home or at the commercial place(s), and the UG supplies the AC power [81]. This AC power is available for the on/off-board EV chargers from the AC single-phase or three-phase input. This infrastructure is well studied and reported in the literature, and commercial systems are widely available [82]. Therefore, it is not reviewed in this article and is also not the primary objective.

B. OFF-GRID CHARGING INFRASTRUCTURE

In off-grid charging infrastructure, various energy sources, such as fossil fuel and renewable sources, are used individually or in combination to generate electricity locally and consume locally. An OGCS can have an energy buffer (local backup), such as the battery bank, a fuel cell system, and supercapacitors [43]. This system has no interface with UG and is suitable in areas where UG is absent. The various components used in such a system are shown in Fig. 1 namely energy source(s), EMS, PECs, ESS, and EV charger. An OGCS can offer both AC and DC charging to EV via AC and DC connectors, respectively. If adequately designed, this system can also supply power for local loads, such as individual appliances and homes.

The OGCS can be classified into three types based on the nature of the power supply (i.e., AC and DC), and related works are summarized in Table 1:

1) AC-based architecture of OGCS (Fig. 2);
2) DC-based architecture of OGCS (Fig. 3); and
3) AC and DC-based architecture of OGCS (Fig. 4).

1) AC-BASED ARCHITECTURE OF OGCS

Fig. 2 shows an example of the AC-based architecture of OGCS. Here, diesel generators (DG), biomass generators (BG), PV array, wind turbines, or a combination of these sources generates the AC power, which is collected on the AC bus; then distributed to the load(s). However, converting AC power from the DC sources, such as PV array, requires a power conversion stage (DC-AC converter), which impacts

and hybrid charging systems are reviewed to evaluate the trend.

D. ARTICLE ORGANIZATION

The remainder of this article is organized as follows: Section II presents the category of charging infrastructure. Furthermore, it reviews the different architectures of off-grid and hybrid charging systems for EVs reported in the literature. Section III discusses the various energy sources used in off-grid and hybrid charging systems. Section IV provides the overview of different ESSs in these charging systems. Section V reviews the different types of power electronics converters used in off-grid and hybrid charging systems for EV. Section VI summarizes the various types of energy management strategies used in these charging systems. Section VII reviews EV charging connectors, power levels, and standards, which are widely used by various countries. Finally, Section VIII gives the conclusions and provides the direction of future research.

II. CLASSIFICATION OF CHARGING INFRASTRUCTURE

Based on the availability and reliability of the grid, the charging infrastructure can be divided into three categories: UG, off-grid, and hybrid. Moreover, these charging infrastructures can be further classified as AC, DC, or a combination of AC and DC architectures based on the nature of the power supply required for EV charging. Tables 1 and 2 summarize
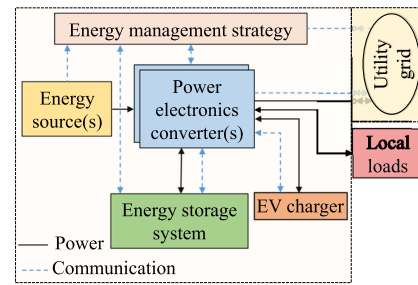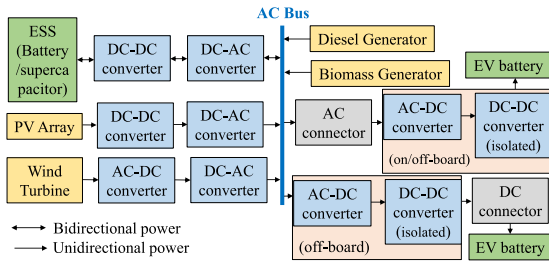
FIGURE 2. An Example of AC-based architecture of OGCS for EVs having a DG, BG, PV array, wind turbine, or a combination along with/without an ESS.
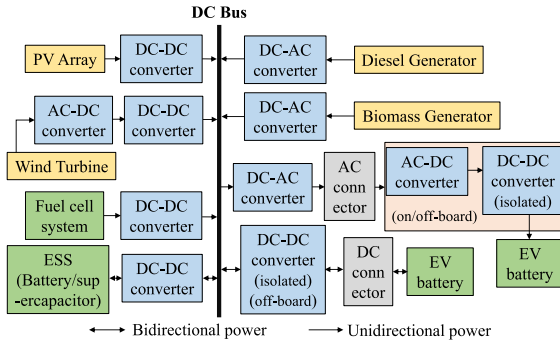

FIGURE 3. Illustration of DC-based architecture of OGCS for EVs having PV array, wind turbine, fuel cell system, DG, BG, or a combination along with/without an ESS.
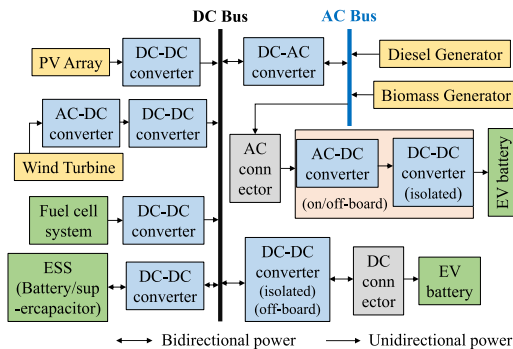

FIGURE 4. AC and DC-based architecture of OGCS for EVs having PV array, wind turbine, fuel cell system, DG, BG, or a combination along with/without an ESS.

the cost, complexity, size, and efficiency of the system as per the selected power level [75]. In Fig. 2, an ESS can also be used to provide uninterrupted charging at the time of outage of other sources. Depending upon the selected voltage level of the ESS and PV array, the DC-DC converter between the AC bus and ESS (or PV array) can be removed (i.e., only a DC-AC converter is enough).

The use of this architecture (Fig. 2) can be found in [8], [11], [33]–[37], where mostly simulation-based work is reported, as summarized in Table 1. In these works, the PV array is used as one of the energy sources. Moreover, ESS is also used in most of these works as a local backup so that the charging system can provide uninterrupted power.

2) DC-BASED ARCHITECTURE OF OGCS

Fig. 3 presents an example of a DC-based architecture of OGCS. Here, the power exchange happens through the DC bus. Since PV, fuel cell system, ESS, and EV battery are DC by nature, they can be connected to a DC bus via only a DC-DC converter. In other words, this architecture removes the need for a DC-AC converter compared to those required in the AC-based architecture of OGCS. Thus, it can save installation space and be a cost-effective and reliable charging system compared to the AC-based architecture of OGCS.

If DG, BG, or both are used in this (DC-based) architecture, an extra power converter(s) (AC-DC) is needed for their connection to the DC bus. This increases the cost and requires more installation space than the AC-based off-grid architecture. Moreover, using DG, BG, or both in this architecture can impact the system efficiency depending on its operating condition.

Furthermore, with this architecture, one can do both AC and DC charging similar to the AC-based architecture of OGCS. However, AC charging of EVs requires two additional power conversion stages in converting DC to AC (for input to AC charger) and then from AC to DC (inside AC charger, before isolated DC-DC) as compared to DC charging. Hence, AC charging should be less preferred for efficient and low-cost charging with this charging system. This architecture is studied in [12], [38]–[45], as summarized in Table 1.

3) AC AND DC-BASED ARCHITECTURE OF OGCS

In the AC and DC-based architecture of OGCS, the AC and DC power generation from the different energy source(s) are directly fed to AC and DC buses, respectively, as shown in Fig. 4. Further in Fig. 4, the AC and DC loads can be connected to their respective buses. Moreover, the power exchange between AC and DC buses happens through a single bidirectional DC-AC converter. This architecture provides AC and DC charging of EVs simultaneously through AC and DC buses, respectively, preventing the need for additional power conversion. Hence, it is more advantageous than the AC-based and DC-based architectures of OGCSs in terms of efficiency, charging flexibility, and reliability. In spite of this, very few works have been reported on AC and DC-based architecture of OGCSs in recent years [7], [46].

C. HYBRID CHARGING INFRASTRUCTURE

HCS is a result of an interface between UG and OGCS, as shown in Fig. 5. In other words, an OGCS can also be connected with the UG. Therefore, HCS can operate in both standalone and grid-connected modes (depending on UG availability). In this system, the source of electricity generation can be UG, renewable resources, and fossil fuel. In the case of overgeneration, excess power is sent to the UG and withdrawn to provide uninterrupted EV charging when other energy resources are low. This advantage reduces/removes the necessity to use massive ESS as used in the OGCSs. This charging
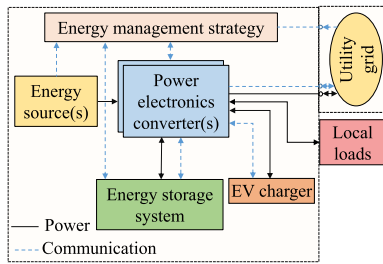
FIGURE 5. Various components used in HCS and its interconnection.

FIGURE 6. A bipolar DC-based architecture of HCS with balancing ESS [75].

FIGURE 7. AC and DC-based architecture of HCS.

system is mainly found in areas where an unreliable UG is present.

A HCS can also be classified similarly to the OGCSs, as discussed in Sections II-B1-II-B3 (i.e., AC based, DC-based, and AC- and DC-based architectures). Table 2 shows the related works on such HCSs [9], [10], [13]–[15], [20], [47]–[80]. Among them, the work on both standalone and grid-connected modes implementation in their selected architecture of a HCS can be seen in [9], [10], [13], [15], [47], [52], [53], [63]–[65], [68]–[71], [79], [80]. However, the remaining works have shown only grid-connected mode [14], [20], [48]–[51], [54]–[62], [66], [67], [72]–[78]. Among these works, few works have considered ESS in the used architecture [14], [48], [49], [56], [58], [59], [62], [72], [74]–[78]. Whereas, other works have not considered ESS in their selected architecture [20], [50], [51], [54], [55], [57], [60], [61], [66], [67], [73]. Nevertheless, if the control of both modes is implemented in an architecture used in the grid-connected mode works, then due to ESS, a standalone mode can function for a much longer period than that given architecture where no ESS has been considered. In other words, for standalone mode, the backup of the architecture where no ESS has been considered depends on the available duration of RESs. Hence, this type of hybrid architecture should not be preferred for a reliable charging system.

Compared to AC-based architecture of OGCSs, AC-based architecture of HCSs have been broadly researched in the literature [13], [47]–[54]. In [13], [47]–[49], [51]–[54], the used renewable source is only PV, whereas only wind source is used in [50]. The work reported in [13], [47]–[54] for this charging system is based on either simulation, experiment, or a combination of both, as shown in Table 2.

The DC-based architecture of HCS has been extensively investigated among other architectures of hybrid and off-grid charging systems [14], [20], [55]–[74], [76]–[78]. Moreover, in [75], a bipolar (having two DC-buses) DC-based architecture of HCS has been proposed and investigated, as shown in Fig. 6. Here, MATLAB simulation of a 1.38 MW charging station is presented, and a scaled-down prototype is used to validate the proposed approach.

Fig. 7 shows the architecture of AC and DC-based HCS. In the literature, high interest in research for AC and DC-based architecture of HCSs is seen than the AC and DC-based architecture of OGCS [9], [10], [15], [79], [80]. Here, it is observed
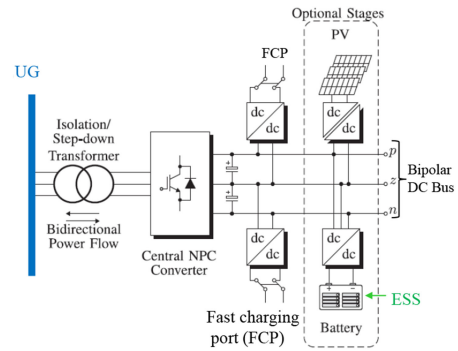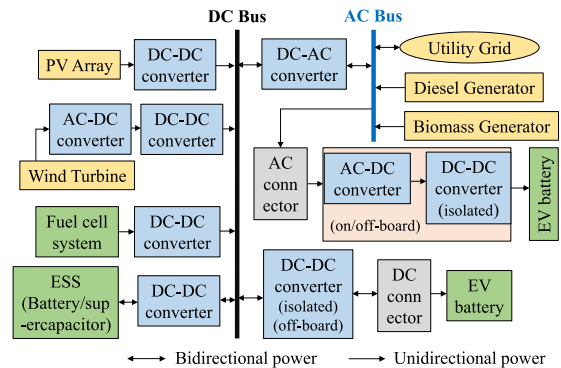
that all works are based on experimental validation. However, the maximum charging power of EV is limited to 3.7 kW, which is reported in [79].

From Tables 1 and 2, it can be seen that various architectures of HCSs have been widely researched with more experimental work as compared to different architectures of OGCSs. The researchers in their paper(s), as summarized in Tables 1 and 2, have worked on various objectives, such as designing charging systems, optimizing ESS, development and comparison of PECs, integration of different RESs, and various EMS for EV applications. Among the discussed architectures, DC-based architecture for EV charging can be suggested as the best configuration when the energy source is DC. Other subsystems, such as the ESS and the load (EV battery), are by nature DC. Being these subsystems in DC removes the need for power conversion from AC to DC and vice-versa, which not only can save cost, space, and power conversion losses but can also improve the efficiency and reliability of the system. However, when the output of the energy source is AC, then based on the geographical location and appropriate analysis, the suitability of the architecture (AC-based, DC-based, or AC and DC-based) can be decided.

III. ENERGY SOURCES
Different energy sources, such as RESs, fossil fuel-based sources (for example, DG), and UG, are used (by the designer) according to the requirements in off-grid and hybrid charging

TABLE 3. Summary of Energy source(s) and ESS Used in OGCSs

| Ref.	Architecture	(Energy sources) + (ESS)	Ratings	Sim./ Expt.
[37]	AC	(PV)+ (None)	(320 kWp) + (None)	Sim.
[34]	AC	(PV) + (Li-ion batteries)	(7.675 kW) + (1-15 kWh)	Sim.
[33]	AC	(PV) + (Battery)	(281.52 kWp) + (420 kWh)	Sim.
[35]	AC	(PV, wind) + (Li-ion battery, FCs–H2)	(251 kWp, 250 kW) + (650 kW, 200 kWh)	Sim.
[11]	AC	(PV, wind, DG) + (LiFePO_4 battery)	(-, -, -) + (-)	-
[8]	AC	(PV, DG1, DG2) + (Lead-acid batteries)	(13 kW, 31 kW, 20 kW) + (64 kWh)	Sim.
[38]	DC	(PV) + (None)	(1 kW) +(None)	Sim.
[44]	DC	(PV) + (Battery)	(-) +(-)	-
[12]	DC	(PV) + (Li-ion battery)	(1 kW) + (1.44 kWh)	Sim.
[40]	DC	(PV) + (Battery)	(24 kWp) + (15 kWh)	Sim.
[45]	DC	(PV) + (FCs)	(24 kW) + (10 kW)	Expt.
[43]	DC	(PV, wind) + (Battery–gel type, FCs–proton)	(3.36 kW, 2.4 kW) + (920 Ah, 6 kW)	Sim.
[39]	DC	(PV, wind) + (Battery)	(250 kWp, 25 kW) + (500 kWh)	Sim.
[41]	DC	(PV, wind, biomass) + (Battery–powerwall)	(468 kWp, 250 kW, 33 kW) + (654 kWh)	Sim.
[46]	AC&DC	(PV, DG) + (FCs–H2)	(-, -) + (-)	-
[7]	AC&DC	(PV, wind, local AC grid) + (Battery)	(100 kW, 10kW) + (24 kWh)	Sim.
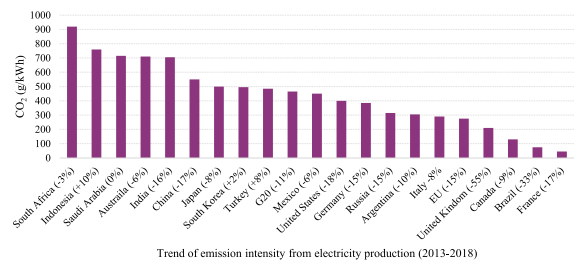
FIGURE 8. Emission intensity of the power sector in the G20, 2018. Source:Enerdata 2019.

systems. For producing one kWh of electricity in the UG, equivalent CO_2 emission (in grams) of various countries is shown in Fig. 8. It also shows the change in emission intensity during 2013-2018. Charging a high number of EVs through UG will increase the power demand, contributing to further CO_2 emissions at the power plant unless RESs is used in UG [83]. Thus, to meet the future charging demand while keeping CO_2 emission as low as possible, it is encouraged to use more RESs in EV charging applications. The possible RESs are wind, biomass, and solar.

A wind turbine is used to convert wind energy into electric energy [73]. Wind turbines require a suitable location with vast space for installation, which can not be achieved in urban areas [18]. However, rural areas can fulfill these requirements. Therefore, it is primarily used in OGCSs as compared to HCSs (see Tables 3 and 4). Nevertheless, the highly fluctuating nature of wind speed makes it a less preferred choice among other RESs.

On the other hand, biomass energy could be an excellent alternative to wind energy because it is convenient to store and use when required [41], [84]. The commonly used biomass materials for producing biomass energy are wood, waste, and plants (known as biomass feedstocks) [18]. However, the

electricity production from biomass feedstocks makes the environment high-polluting due to greenhouse gas emissions [84]. Therefore, it is inappropriate for densely populated areas.

Solar energy is easy to access in rural and urban areas through solar PV arrays. Besides producing electricity, the PV panel provides shelter from the sun and rain and does not require separate space for installation; it can easily be mounted on the roof of a building or in parking places [18]. Moreover, integrating to UG allows selling the excess power during the daytime and drawing power when the low PV output.

Tables 3 and 4 show the combination of different energy sources used (with their ratings) in various architectures of off-grid and hybrid charging systems for EVs reported in the literature. From Table 3, it is observed that PV has been widely used in all architectures of OGCSs. The maximum rating of 468 kWp PV has been utilized in designing the OGCS (DC-based). Besides PV, wind energy (wind turbine power ranges from 2.4-250 kW) is also used in a few works, but in combination with PV. The use of biomass energy is also seen in the reported OGCS (DC-based) [41], with a rating of 33 kW. Few works have used DG-sets in combination with PV and wind with a maximum rating of 31 kW [8], [11], [46]. From Table 3, it is also noticed that most of the works are based on simulation except [45]. Furthermore, from Table 4, it is observed that PV has been mostly used as one of the energy sources in various architectures of HCSs except [50] and [73]. References [50] and [73] use only wind energy with UG. However, few works have used a combination of PV and wind in the DC-based and AC and DC-based architectures of HCSs [10], [58], [70]. The maximum used power rating of PV and wind is seen to 1100 kW and 330 kW. Few works have also used a combination of PV and DG with UG [9], [13], [15], [52]. A 3.7 kW DG-set has been used in these works, and implementation has been done in the hardware. Moreover, the use of biomass energy

TABLE 4. Summary of Energy source(s) [other Than UG] and ESS Used in HCSs

Ref.	Archit-ecture	(Energy sources other than UG) + (ESS)	Ratings	Sim./Expt./Both
[54]	AC	(PV) + (None)	(-) + (None)	Both
[51]	AC	(PV) + (None)	(1100 kW) + (None)	Sim.
[47]	AC	(PV) + (Battery)	3.6 kWp + (35kWh)	Sim.
[53]	AC	(PV) + (Lead-acid battery)	(6.4 kW) + (7.2 kWh)	Both
[49]	AC	(PV) + (Battery)	(22 kW) + (200 kWh)	Sim.
[48]	AC	(PV) + (Battery)	(400 kWp) + (500 kWh)	Sim.
[13]	AC	(PV, DG) + (Battery)	(4.3 kWp, 3.7 kW) + (8.4 kWh)	Expt.
[52]	AC	(PV, DG) + (Battery)	(4.3 kWp, 3.7 kW)+ (8.4 kWh)	Expt.
[50]	AC	(Wind) + (None)	(-) + (None)	Sim.
[57]	DC	(PV) + (None)	(200 W) + (None)	Sim.
[55]	DC	(PV) + (None)	(2 kWp) + (None)	Sim.
[68]	DC	(PV) + (None)	(3.7 kW) + (None)	Expt.
[69]	DC	(PV) + (None)	(3.77 kWp) + (None)	Expt.
[20]	DC	(PV) + (None)	(10 kW) + (None)	-
[66]	DC	(PV) + (None)	(10 kW) + (None)	Expt.
[60]	DC	(PV) + (None)	(10 kW) + (None)	Sim.
[67]	DC	(PV) + (None)	(24 kW) + (None)	Expt.
[61]	DC	(PV) + (None)	(180 kW) + (None)	Sim.
[59]	DC	(PV) + (Li-ion battery)	(-) + (-)	Sim.
[75]	DC	(PV) + (Ultracapacitor)	(-) + (845.64 Wh)	Both
[72]	DC	(PV) + (Battery)	(-) + (100 kWh)	Sim.
[72]	DC	(PV) + (Battery)	(90 Wp) + (45 W)	Expt.
[77]	DC	(PV) + (Lead-acid battery)	(275 W) + (-)	Expt.
[77]	DC	(PV) + (Lead-acid battery)	($\sim$5.5 kW) + ($\sim$7 kW)	Sim.
[74]	DC	(PV) + (Battery)	(400 W) + (450 W)	Both
[71]	DC	(PV) + (Battery)	(3.77 kW) + (1.2 kW)	Expt.
[64]	DC	(PV) + (LiFePO_4 battery)	(5 kW) + (35 kWh)	Sim.
[63]	DC	(PV) + (Battery)	(280*28=7.87 kWp) + (9072*8=72.58 kWh)	Sim.
[76]	DC	(PV) + (Battery)	(12 kW) + (6 kWh)	Both
[78]	DC	(PV) + (Battery)	(20 kWp) + (19.2 kWh)	Both
[65]	DC	(PV) + (Battery)	(45 kWp) + (-)	Sim.
[62]	DC	(PV) + (Li-ion Battery1, Li-ion Battery2)	(70 kW) + (-, -)	Sim.
[56]	DC	(PV) + (Lead-acid battery)	(119 kWp) + (22.9 kWh)	Sim.
[58]	DC	(PV) + (Battery)	(1200 kW) + (3000 kWh)	Sim.
[73]	DC	(Wind) + (None)	(10 kW) + (None)	Both
[70]	DC	(PV, wind) + (None)	(2.14 kW, 2 kW) + (None)	Expt.
[14]	DC	(PV, wind) + (Battery)	(25 kW*11.23, 30 kW*11) + (25 kWh*30)	Sim.
[79]	AC&DC	(PV) + (battery)	(2.6 kWp) + (9.5 kWh)	Expt.
[80]	AC&DC	(PV) + (battery)	(4.5 kW) + (8.4 kWh)	Expt.
[10]	AC&DC	(PV, wind) + (None)	(3.7 kW, 1.1 kW) + (None)	Expt.
[9]	AC&DC	(PV, DG) + (Battery)	(2.92 kW, 3.7 kW) + (5.04 kWh)	Expt.
[15]	AC&DC	(PV, DG) + (Battery)	(3.7 kW, 3.7 kW) + (5.04 kWh)	Both

is not found in the reported HCSs, as given in Table 4. Compared to OGCSs, the majority of works in HCSs have implemented hardware. However, the reported works on high power rating are based on simulation for both types of charging systems.

IV. ENERGY STORAGE SYSTEM

ESS is the crucial part of operating OGCSs to provide uninterrupted charging power to EVs. It becomes critical in delivering charging power in HCSs when it works in standalone mode (from the grid-connected mode). Moreover, ESS in grid-connected mode is used to mitigate the power fluctuation of RESs. ESS can be equipped with different types of energy storage technologies, such as a battery bank, hydrogen energy storage/fuel cell, ultracapacitors, or a combination of these three. The use of these storage technologies in various architectures of off-grid and hybrid charging systems can be seen in Tables 3 and 4, respectively.

A. BATTERY

From Tables 3 and 4, it can be seen that battery is widely adopted in ESS due to for both types of high energy and power density, compact size, and reliability [85], [86]. In battery-based ESS, lead-acid chemistry in [8], [53], [56], [77], and Li-ion chemistry in [12], [34], [35], [59], [62] are reported. However, some other works (in Tables 3 and 4), where battery-based ESS are used, have not mentioned the battery chemistry. The lead-acid battery is a low-cost and technically mature energy storage device [87]. However, it suffers in terms of various aspects, such as low energy (50-80 kWh/m^3) and power density (90-700 kW/m^3), short lifetime (250-1500 cycles), high maintenance requirements, and toxicity material consumption [86], [87]. On the other hand, the Li-ion battery has high energy (1300-10000 kW/m^3) and power density (300-750 kWh/m^3), long lifetime (500-10000 cycles), short response time, low memory effect, and is recyclable [87]. Although Li-ion batteries are more expensive

than lead-acid, they can handle higher C-rates than lead-acid batteries. Furthermore, from Table 3, the maximum power rating of battery storage in AC-based architecture of OGCS is observed to 650 kW, whereas, in DC-based and AC and DC-based architectures of OGCSs, the maximum capacity of the battery is used to 654 kWh and 24 kWh, respectively. All these (maximum) ratings are implemented in simulation only. Furthermore, from Table 4, the maximum capacity of batteries is found to be 500 kWh for AC-based [48], 3000 kWh for DC-based [58], and 9.5 kWh for AC and DC-based architectures of HCSs [79]. Here, except [79], other references (i.e., [48] and [58]) implemented these maximum capacity of batteries in simulation.

B. ULTRACAPACITOR
Ultracapacitors have higher power density over battery because the charges are stored at the electrodes physically [85]. Moreover, it has a longer lifetime and requires low maintenance, resulting in cost savings. However, it has low energy density and safety issues. Thus, it can only be used for the places requiring a fast response in short-duration, such as grid voltage maintenance [86]. From Table 4, it can be seen that reference [75] uses an ultracapacitor (of 845.64 Wh) in ESS for a downscaled prototype. Whereas the use of ultracapacitors in OGCSs is not observed (see Table 3).

C. HYDROGEN ENERGY STORAGE/FUEL CELL SYSTEM
Fuel cells convert chemical energy to electricity. It uses the oxidant (like oxygen), the fuel (like hydrogen) and the electrolyte for electricity generation [86]. This hydrogen fuel is supplied from the hydrogen storage tank, which is refilled by the electrolyzer [35]. Various types of electrolyzers, such as alkaline, proton exchange membrane, and solid oxide, are used to create hydrogen (through electrolysis of water) [88]. The fuel cell has a longer life and is environmentally safe but suffers from the high initial cost [88]. Nevertheless, references [45] and [46] use only FC system in ESS, as shown in Table 3. From the study in [45], FC system based ESS in OGCS is found to be a cost-effective and sustainable solution over batteries-based ESS in the long run. However, in HCSs, none of the works uses FC system (see Table 4).

D. COMBINATION OF STORAGE TECHNOLOGIES
According to need in terms of response time, fast and slow charging, long-duration storage, one can use the combinations of the abovementioned storage technologies. A combination of FC system and batteries based ESS can be seen in [35], [43] (see Table 3). Thus, batteries can be favorable for day to day and hour to hour storage, capacitors for a min to min or hour to hour, while FC systems are more suitable for seasonal storage.

V. POWER ELECTRONICS CONVERTERS
Power electronics converters are essential elements of the off-grid and hybrid charging systems in converting power from AC to DC and DC to AC. There are several types of converters, such as DC-DC, DC-AC, and AC-DC are widely
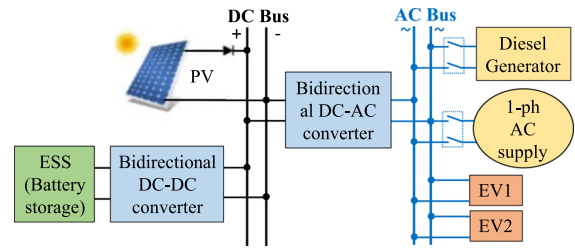
FIGURE 9. A HCS (AC-based) for EVs having PV array MPPT without a unidirectional DC-DC converter [52].

used in these charging systems [9], [17], [20], [36], [39], [47], [55]–[59], [67], [73], [74], [79], [89], as shown in Fig. 7. This section reviews the uses of such PECs in both charging systems.

A. DC-DC CONVERTERS
According to the direction of power flow, two types of DC-DC converters are used in the off-grid and hybrid charging systems: unidirectional and bidirectional DC-DC converters. These converters could be either isolated or non-isolated, and their use depends on the applications. Tables 5 and 6 summarize these types of converters with their location of use in both types of EV charging systems.

1) UNIDIRECTIONAL DC-DC CONVERTERS
A non-isolated unidirectional conventional DC-DC boost converter (UCDDBC) is commonly used in between PV array and DC bus [18], [90], [91], as shown in Fig. 7 and Tables 5 and 6. But, few works have used buck, T-source, and buck-boost converters in this stage (i.e., PV to DC bus) [38], [53], [74]. Besides that, isolated (highlight in blue color in Tables 5 and 6) unidirectional DC-DC converter, such as flyback converters, is also used in this stage [45].

The DC-DC converter between PV to DC bus uses maximum power point tracking (MPPT) controller to ensure the maximum power extraction from PV under various environmental conditions [92], [93]. Different types of MPPT algorithms have been reported in [94]–[98]. Among them, perturb and observed (P & O) is the most popular strategy [12], [42], [74], [98] due to its fast response and simplicity [18].

Besides conventional boost converter (CBC), interleaved boost converter (IBC) [57], [89], [99] and coupled inductors IBC (CIIBC) [69], [100] can also be used between PV to DC bus. IBC has paralleled CBC that minimizes current in each leg and reduces conduction losses. IBC has a high efficiency at light load, reduced EMI, higher power density, and improved reliability. However, these advantages are at the cost of a higher number of power electronics components. The modified version of IBC is CIIBC, which has a lower number of inductors due to coupled inductors. CIIBC has reduced winding and core losses and also has reduced overall size. Moreover, it also has improved input and inductor ripple current.

Furthermore, no MPPT unidirectional DC-DC converter is connected in between PV to DC bus in [52], [69], [70], as shown in Fig. 9. With the arrangement shown in Fig. 9, the

TABLE 5. Summary of Power Electronics Converters Used (And Their Location) in Various Off-Grid Architectures for EV Charging. Here, Ab = AC Bus, Db = DC Bus, Es = Energy Storage, Ev = EV, Ez = Electrolyzer, Fc = Fuel Cell, Pv = Photovoltaic, W = Wind, Lg = Local Grid, and Symbol '→' and '–' Inside Bracket Represents Unidirectional and Bidirectional Power, Respectively

Ref.	Arch-itec-ture	DC-DC converter		Bidirectional AC-DC converter	Other types of converter used/proposed	EV charger / EV connected at
		Unidirectional (Isolated/Non-isolated)	Bidirectional (Isolated/Non-isolated)			
[37]	AC	-	-	-	Central off-grid inverter (pv→ab)	AC bus
[34]	AC	-	-	-	Grid tie inverter (pv→ab)	AC bus
[33]	AC	-	-	(es–ab)	DC-AC (pv→ab)	AC bus
[35]	AC	step down (pv→ez)	-	-	AC-DC (w→db), DC-AC (db→ab)	AC bus
[11]	AC	-	-	(db–ab)	-	AC bus
[8]	AC	-	-	(es–ab)	PV inverter (pv→ab)	AC bus
[38]	DC	Buck (pv→db), boost (db→ev)	-	-	-	DC bus
[44]	DC	(pv→db)	(es–db), (db–ev)	-	-	DC bus
[12]	DC	Boost (pv→db)	Buck-boost (db–es)	-	-	DC bus
[40]	DC	Boost (pv→db)	Buck-boost (es–db & db–ev)	-	-	DC bus
[45]	DC	Flyback (pv→db & fc→db)	-	-	-	DC bus
[43]	DC	-	-	-	-	DC bus
[41]	DC	(pv→ez)	-	-	AC-DC (w→db), DC-AC (db→ev)	DC bus
[39]	DC	(pv→db, db→ev)	-	-	AC-DC (w→db)	DC bus
[46]	AC&DC	-	-	-	-	ab & db
[7]	AC&DC	Boost (pv→db & w→db)	Buck-boost (es–db & db–ev)	-	DC-AC (db→ev), AC-DC (ab→ev)	ab & db

TABLE 6. Summary of Power Electronics Converters Used (And Their Location) in Various Architectures of HCSs

Ref.	Arch-itec-ture	DC-DC converter		Bidirectional AC-DC converter	Other types of converter used/proposed	EV charger / EV conn-ected at
		Unidirectional (Isolated/Non-isolated)	Bidirectional (Isolated/Non-isolated)			
[54]	AC	-	-	-	DC-AC (pv→ab), AC-DC (ab→ev)	AC bus
[47]	AC	(pv→db)	(es–db)	(db–ab)	-	AC bus
[53]	AC	Buck-boost (pv→db)	-	-	Solar inverter (db→ab)	AC bus
[49]	AC	-	-	(es–ab)	DC-AC (pv→ab)	AC bus
[48]	AC	-	-	-	-	AC bus
[13]	AC	-	Buck-boost (es–db)	H-bridge (db–ab)	-	AC bus
[52]	AC	-	Buck-boost (es–db)	H-bridge (db–ab)	-	AC bus
[51]	AC	-	-	-	Suntree 30000 TL inverter (pv→ab), AC-DC (ab→ev)	AC bus
[50]	AC	-	-	-	-	AC bus
[57]	DC	-	-	-	DC-AC (db→UG), isolated voltage multiplier (high gain boost) (pv→db)	DC bus
[55]	DC	FB LLC resonant (db→ev)	-	-	Quasi Z-source inverter (pv→db-UG)	DC bus
[68]	DC	Boost (pv→db)	Buck-boost (db–ev)	3-ph VSC (db–UG)	-	DC bus
[69]	DC	-	Buck-boost (db–ev)	H-bridge (db–UG)	-	DC bus
[66]	DC	-	-	-	Three-port (with isolation) (pv→ev–UG)	DC bus
[60]	DC	-	-	-	Three-port (with isolation) (pv→ev–UG)	DC bus
[67]	DC	Step-up (pv→db)	FB (db–ev)	3-ph VSC (UG-db)	-	DC bus
[61]	DC	(pv→db)	-	(UG–db)	-	DC bus
[59]	DC	(pv→db, db→ev)	(es–db)	(db–UG)	-	DC bus
[75]	DC	(pv→db), (db→ev)	-	grid tied NPC (UG–db)	-	DC bus
[72]	DC	(pv→db, db→ev)	(es–db)	(UG–db)	-	DC bus
[77]	DC	Boost (pv→db)	Buck-boost (db–ev)	H-bridge (UG–db)	-	DC bus
[74]	DC	(pv→db, db→ev)	(es–db)	(UG–db)	-	DC bus
[64]	DC	-	(es–db, db–ev)	(db–UG)	-	DC bus
[63]	DC	(pv→db)	(es–db)	-	DC-AC (db→UG)	DC bus
[76]	DC	Boost (pv→db)	Buck-boost (es–db, db–ev)	H-bridge (UG–db)	-	DC bus
[78]	DC	T-source (pv→db, db→ev)	T-source (es–db)	(UG–db)	-	DC bus
[65]	DC	-	-	-	-	DC bus
[71]	DC	Boost (pv→db)	Buck-boost (ev–db)	3-ph VSC (UG–db)	-	DC bus
[62]	DC	(pv→db)	2*(es–db)	-	AC-DC (UG→db)	DC bus
[56]	DC	Boost (pv→db), buck (db→ev)	Buck-boost (es–db)	-	DC-AC (db→UG)	DC bus
[58]	DC	(pv→db)	(es–db)	(UG–db)	-	DC bus
[73]	DC	Boost (w.dc→db)	FB (db–ev)	3-ph VSC (UG–db)	AC-DC (w→dc)	DC bus
[70]	DC	Boost (w.dc→db)	Buck-boost (db–ev)	H-bridge (ab–db)	AC-DC (w→dc)	DC bus
[14]	DC	(pv→db)	-	(ab–db)	AC-DC (w→db)	DC bus
[20]	DC	-	-	-	Multi-port with isolation (pv→ev–UG)	DC bus
[79]	AC&DC	Flyback(db→ev)	-	-	Hybrid inverter (db–ab–ev), DC-AC (db→ev)	ab & db
[80]	AC&DC	-	Buck-boost (es–db, db–ev)	3-ph VSC (db–ab)	-	ab & db
[10]	AC&DC	Boost (pv→db, w.dc→db)	Buck-boost (es–db, db–ev)	H-bridge (db–ab)	AC-DC (w→dc)	ab & db
[9]	AC&DC	Boost (w.dc→db)	Buck-boost (db–ev)	H-bridge (db–ab)	AC-DC (w→dc)	ab & db
[15]	AC&DC	Boost (pv→db, db→ev)	-	H-bridge (db–ab)	-	ab & db

MPP is achieved by the voltage source converter in grid-connected mode/DG set connected mode and bidirectional DC-DC converter in islanded mode [52]. The advantage of doing this is that it removes one DC-DC converter, which saves cost, space, and maintenance and makes the charging system more efficient. However, MPP with both converters in different modes can increase the control complexity and have a limited operating range.

Between PV and electrolyzer (for hydrogen production), a unidirectional DC-DC converter has been used in [35], [41]. Here, [35] adopts a step-down DC-DC converter for this purpose. Moreover, an isolated DC-DC converter (flyback) is used in between the fuel cell system and DC bus, as shown in Fig. 7 [45].

Furthermore, between the wind turbine and DC bus, a unidirectional boost DC-DC converter (after AC-DC converter), as shown in Fig. 7, is used to maintain voltage at DC bus [9], [10], [14], [41], [70], [73]. Among these works, [41] uses an isolated boost converter (in OGCSs), whereas other works use non-isolated boost converters (in HCSs).

As per standards, the EV battery needs to be isolated from the grid for safety reasons in both AC and DC charging. Therefore, an isolated DC-DC converter has to be used in EV charging [20]. This converter is connected between the DC bus and EV (in the case of AC charging, it is located between AC/DC stage and EV battery), as shown in Fig. 7. An isolated unidirectional DC-DC converter, such as full-bridge (FB) LCC resonant and flyback converters, is used between DC bus and EV [55], [79]. However, many works have neglected the isolation requirement and used a non-isolated buck or boost converter for the same, as shown in Tables 5 and 6.

2) BIDIRECTIONAL DC-DC CONVERTERS

A non-isolated bidirectional DC-DC converter (BDDC) is commonly used between the ESS and DC bus, as shown in Fig. 7. The main purpose of this converter is to store the excess energy in ESS at the time of overgeneration and give it back to the load when other energy sources are low. Generally, a buck-boost converter is used for this purpose, as tabulated in Tables 5 and 6. However. in [78], a bidirectional T-source converter is implemented between the ESS and DC bus.

Moreover, isolated BDDC is suggested to use between DC bus and EV for bidirectional power flow. In this way, EV can be used as an ESS. However, most of the works have used a non-isolated BDDC except [44], [58], [73], as summarized in Tables 5 and 6.

B. AC-DC OR DC-AC CONVERTERS

AC-DC converter (rectifier) is used between the wind turbine and DC bus (before the DC-DC converter), as shown in Fig. 7. Moreover, it is also used to convert DC power from UG to fed into DC bus [62].

The DC-AC converter (inverter) converts DC power to AC power. Between PV to AC bus, an inverter is used with various names, such as central off-grid inverter, grid-tie inverter,
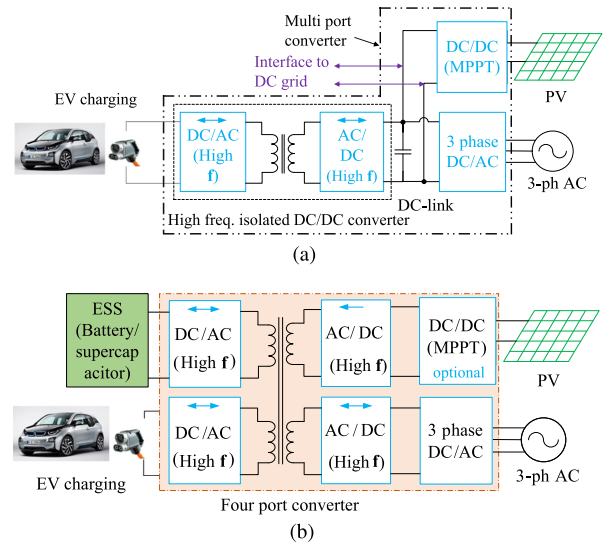

FIGURE 10. Multi-port converters. (a) Three-port converter based on common DC link voltage [20]. (b) Four-port converter with inherently decoupled power flows [102].

and PV inverter [8], [34], [37]. Moreover, in the case of AC charging of EV, an inverter is used between the DC bus and AC charger of EV in [7], [41]. In some of the works, it is connected between DC bus and UG for feeding power into UG [56].

On the other hand, a bidirectional AC-DC converter is used to do both (rectification and inversion) with a single converter. Such converter is used between AC bus and DC bus for power balance between these buses. For a single-phase system, few works have used H-bridge bidirectional AC-DC converter [9], [10], [13], [13], [15], [52], [69]. Besides that, a 3-phase voltage source converter (VSC) is used in a 3-phase system [67], [68], [73], [80]. In a bipolar DC-based architecture of HCS, a grid-tied neutral-point-clamped (NPC) converter is used between AC bus and DC bus [75].

C. MULTI-PORT CONVERTERS

The integration of multiple RESs, ESS, and loads (EVs) in Fig. 7 can also be done through multi-port converters, as shown in Fig. 10. This converter reduces power conversion stress, improves efficiency, gives higher power density, and reduces material billing [20], [66], [101], [102]. Fig. 10(a) shows a multi-port converter, which is based on a common DC-link voltage. Here, it has three ports that connect PV, UG, and EV (with isolation) through a common DC-link and also provides a connection to interface with DC bus [20]. This converter has been used in a DC-based architecture of HCS in [20], [66]. Moreover, Fig. 10(b) shows a four-port converter, which is derived from the dual-active bridge and a generalized four-port converter is thoroughly investigated in [102]. It provides complete isolation among all ports and does not require a common dc-link voltage. This converter can be used in the AC-based architecture of HCS.

TABLE 7. Summary of Reported Energy Management Strategies for the Off-Grid and Hybrid Charging Systems

| Ref.	Architecture	EMS technique	Objective
[43]	DC off-grid	Fuzzy logic via MATLAB/Simulink	● Mainly to provide economic load sharing between sources and to operate FC safely and efficiently.
[39]	DC off-grid	Convex optimization via CPLEX 12.7	● To maximize the utilization of RESs and optimizing the use of ESS to reduce local grid's peak power demand and save the charging cost.
[7]	AC & DC off-grid	Algorithm based on various modes of operation via MATLAB/Simulink	● To regulate RESs, EV charging demand, and battery SOC (of ESS).
[13]	AC hybrid	Different control algorithms via dSPACE-1006	● To manage power among various energy sources, regulating EV charging, and voltage & frequency regulation of the generator for optimal operation of the charging system.
[47]	AC hybrid	Intelligent; based on estimation and forecast via LabVIEW software	● To reduce UG's peak power demand and maximize PV power for EV charging.
[48]	AC hybrid	Contract capacity optimization via MATLAB	● To coordinate the energy exchange between UG and PV array for reducing the cost of EV charging.
[49]	AC hybrid	Coordinated control (various operation modes) via simulation	● To reduce the overloading impact of EV charging load demand on UG connecting transformer to AC bus by coordinated control of PV and battery ESS.
[14]	DC hybrid	Hybrid optimization algorithm via MATLAB/Simulink	● To minimize cost of electricity and pollution emissions.
[56]	DC hybrid	Decentralized control (model predictive control for PV and ESS) via MATLAB/Simulink	● To regulate the energy flow among the PV system, the battery storage and UG to achieve the efficient charging of EVs.
[58]	DC hybrid	Consensus network based learning algorithm via simulation	● To maintain the average available capacity of the storage battery in CS, and to maximize the EV charging power.
[59]	DC hybrid	Rule-based algorithm via MATLAB	● To maintain uninterrupted charging at a constant price under various operating conditions.
[60]	DC hybrid	Mixed-integer linear programming via CPLEX v12.6	● To minimize charging cost while reducing stress on UG and increasing PV self-consumption.
[61]	DC hybrid	Distribution algorithm based on stackelberg game, heuristic algorithm, & back-propagation neural network via simulation	● Collecting and recording the information of charging station's each unit & broadcasting the inner price to all the chargers.
[64]	DC hybrid	Intelligent; based on estimation & control via simulation	● To optimize the use of PV and UG for EV charging, and to reduce the peak power demand from UG and energy exchange between the other sources and UG.
[65]	DC hybrid	Algorithm based on various modes of operations via MATLAB/Simulink	● To allocate instant power to each plugged EV depending on its initial SOC, desired SOC, battery capacity, and departure time while minimizing the use of UG power.
[69]	DC hybrid	Sliding mode control (DC-bus voltage regulation) via dSPACE-1006	● To provide uninterruptible charging and power to household loads.
[76]	DC hybrid	Based on different modes of operation via MATLAB/Simulink	● To minimize the usage of UG power and store PV power when no EV is available for charging.
[77]	DC hybrid	Based on different modes of operation via MATLAB/Simulink & LabVIEW platform	● To balance power between the different sources (including EV battery; used as ESS) and the home load and to reduce the unexpected peak power demand.
[9]	AC & DC hybrid	Based on the energy balance of the DC bus via dSPACE-1006	● To achieve uninterruptible charging at minimized charging cost.

D. CRITICAL OBSERVATIONS

Thus, from the above review, it is observed that most of the works use conventional converters in various power conversion stages, as shown in Fig. 7 and Tables 5 and 6. However, very few works have proposed/implemented different converters to make the system compact, efficient, and cost-effective. As far as standalone mode operation for AC-based or AC and DC-based architectures of both off-grid and hybrid charging systems is concerned, the following points need attention.

- At the time of PECs design, the overload capacity for a few seconds during startup should also be considered.
- Among the various reported work for standalone mode operation, references [80] and [68] have used three-phase configuration in their architecture. However, in these works, three-phase inverter control (in standalone mode) has been neglected for an unbalanced load, which further research should also consider.

TABLE 8. AC and DC Charging Plugs and Power Levels in Europe, USA, and China [103]–[108]

Plug	Charging	Number of power pins (pps) and communication pins (cps) Here, PP–Proximity pilot, CP–Control pilot	Voltage, Current, Power
Type 1-SAE J1772	AC	3 pps – L1, N, E and 2 cps – CP, PP (PWM over CP)	1Φ 120 V, $\leq$ 16 A, 1.9 kW and 1Φ 240 V, $\leq$ 80 A, 19.2 kW
Type 2-Mennekes	AC	4 pps – L1, L2, L3, N, E and 2 cps– CP, PP (PWM over CP)	1Φ 230 V, $\leq$ 32 A, 7.4 kW and 3Φ 400V, $\leq$ 32 A, 22 kW $\leq$ 63 A, 43 kW
Type 4-CHAdeMO v2.0	DC	3 pps – DC+, DC-, E and 7 cps – for CAN communication	200-1000 V, $\leq$ 400 A, 350 kW
ChaoJi-CHAdeMO v3.0	DC	3 pps – DC+, DC-, E and 4 cps	200-1500 V, $\leq$ 600 A, 900 kW
SAE-CCS/Combo	DC	3 pps – DC+, DC-, E and 2 cps – CP, PP (PLC over CP, PE)	200-1000 V, $\leq$ 350 A, 350 kW
Tesla US	AC & DC	3 pps – (DC+, DC-, E) or (L1, N, E) and 2 cps – CP, PP	Supercharger V2, $<$ 500 V, up to 250 kW
Chinese GB/T	DC	3 pps – (DC+, DC-, E), 2 pps for LV – A+, A- and 4 cps – CAN-H, CAN-L, PP	up to 950 V, $\leq$ 250 A, 250 kW
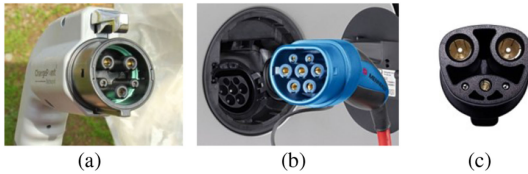
FIGURE 11. Plug for AC charging- (a) US Type 1 SAE, (b) European Type 2 Mennekes, and (c) Tesla plug. Image courtesy: Mennekes, Michael Hicks on Wikipedia, Tesla.

- In addition, power quality, including harmonics, will be an essential factor in converter design, primarily used in hybrid charging systems.
- The transition between standalone and grid-connected modes needs to be quick and smooth.

VI. ENERGY MANAGEMENT STRATEGY

In the off-grid and hybrid charging systems, optimal operation of different energy sources, ESS, and loads (i.e., EVs) is essential for minimizing the cost of charging, maximizing the system efficiency, and providing an uninterruptible charging power. In this regard, multiple EMSs, reported in the literature for both types of charging systems, are reviewed in this section. Table 7 summarizes numerous reported EMSs for different architectures of off-grid and hybrid charging systems.

A. EMS FOR OFF-GRID CHARGING SYSTEMS

From Table 7, it can be seen that very few works have attempted EMS for OGCSs [7], [39], [43]. In these works, the primary focus of EMS is on the operation of ESS so that uninterruptible power can be provided in case of no RES(s) power. Besides ESS, the other objectives, such as reducing the charging cost, maximizing the utilization of RESs, and meeting the charging demand, have also been considered while developing the EMS. References [43] and [7] use a rule-based approach in their EMS and are implemented using MATLAB/Simulink (see Table 7). Moreover, in [39], an optimization-based approach is used for the EMS of OGCS, and it uses CPLEX 12.7 for implementation.

B. EMS FOR HYBRID CHARGING SYSTEMS

A significant amount of works have been reported in the literature for HCSs compared to OGCSs, as shown in Table 7. From Table 7, it can be seen that EMS of DC-based architecture has been widely researched among various architectures of HCS.

In the AC-based architecture of HCS, the main focus was the optimal operation of various energy sources. As per the objective(s) of EMS in [13], [47]–[49], various EMS techniques are used, which are rule-based ([13], [47], [49]) and optimization-based ([48]). References [48] and [49] have realized their EMS in simulation. Whereas, references [13] and [47] have used real-time platform dSPACE-1006 and LabVIEW, respectively.

In the DC-based architecture of HCS, the EMS is focused on various objectives, such as regulation of various energy sources, charging at minimized cost, uninterruptible and efficient charging, and minimizing the use of UG power [14], [56], [58]–[61], [64], [65], [69], [76], [77]. Among these works, references [14], [56], [58], [60], [61], [69] use optimization-based approach (global or real-time) in their EMS, whereas rule-based approach is used in [59], [64], [65], [76], [77], as summarized in Table 7. These EMS techniques in [14], [56], [58]–[61], [64], [65], [76] are implemented in simulation, mostly in MATLAB/Simulink (except [58], [59], [61], [64]). In [59], CPLEX 12.6 is used, whereas references [58], [61], and [64] have not revealed the used simulation software. Moreover, a real-time implementation of EMS in [69] is done using dSPACE-1006. Furthermore, both simulation and real-time implementation of the developed EMS in [77] is done using MATLAB/Simulink and LabVIEW platform, respectively.

For AC and DC-based architecture of HCS, the only focus is given to achieve uninterruptible charging at minimized cost while developing EMS in [9], which is based on the energy balance of the DC bus. Here, the developed EMS is implemented in real-time using dSPACE-1006.

VII. EV CHARGING CONNECTORS, POWER LEVELS, AND STANDARDS

Conductive charging of EV can be done today with AC or DC charging [109], [110]. In both methods, the utility grid's power is converted from AC to DC and recharges the battery inside the vehicle. The EV battery is typically a few kWh in the case of a plug-in hybrid electric vehicle (PHEV) and is tens of kWh in the case of a plug-in electric vehicle (PEV). A few examples are BMW car i8 PHEV with 7.1 kWh battery, Brompton E-Bike M6L with 300 Wh battery, Tesla Model S car PEV with 85 kWh battery, Hero electric Photon HX scooter with 72 V / 26 Ah battery, Ather 450X scooter with 2.9 kWh battery, etc.

FIGURE 12. Plug for DC charging- (a) CCS/Combo for US, (b) European, (c) CHAdeMO, and (d) Chinese GB/T. Image courtesy: SAE and CHAdeMO.
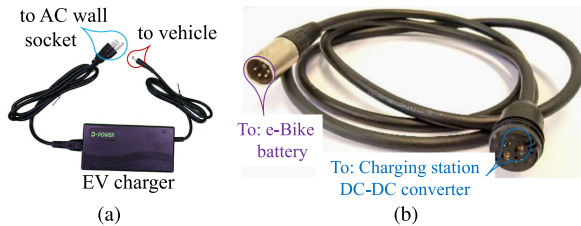

FIGURE 13. (a) Non-standard EV charger for personal mobility. (b) Non-standard connectors for E-bike charging.

The DC charging power P_{ch} is fed in terms of a charging current I_{ev} to charge the batteries with a voltage, V_{ev}:

$$P_{ch} = V_{ev}I_{ev}. \quad (1)$$

The energy delivered to the battery E_{ch} over a time period t_{ch}

$$E_{ch} = \int_0^{(t_{ch})} P_{ch}dt. \quad (2)$$

Table 8 summarizes the currently existing AC and DC charging plugs, communication standards, and power levels for large vehicles, such as cars, buses, and trucks, which typically require high power charging above 1.9 kW. Based on Table 8, a discussion on AC charging and DC charging is presented in Section VII-A and VII-B, respectively. Besides this, the charging of one-, two-, and three-wheelers is discussed in Section VII-C.

A. AC CHARGING

AC charging of EV is done using the on-board AC/DC power converter through a single-phase or three-phase AC connection. There exist four types of AC chargers; however, currently, three types are used globally [103]–[107], as shown in Fig. 11 and Table 8.

Most countries have adopted one of these plugs for their AC charging systems. In the US, the Type 1 plug provides single-phase charging using three power pins a namely phase (L1), neutral (N), and earth pin (E). The Type 2 plugs used widely in Europe support three-phase charging using five power pins, i.e., three-phase pins (L1, L2, L3), neutral (N), and earth pin (E). The main difference is that the European Type 2 plug provides much higher charging powers of up to 43 kW (up to 63 A) through a three-phase UG connection. The control pilot (CP) and proximity pilot (PP) are used for communication between the charger and the EV in Type 1 and Type 2 chargers. The Type 3 EV charger of the EV plug

alliance (not listed in Table 8) has been abandoned in favor of Type 1 or 2 by nearly all EV manufacturers.

The IEC61851-1 standard defines the charging mode for AC charging, namely Mode 1, Mode 2, and Mode 3. In Mode 1 and Mode 2, the charging power is derived from a standard non-dedicated power socket, and Mode 2 has an additional in-cable protection device built into it. Mode 3 uses dedicated EV supply equipment, which has both built-in control and protection functionality. It is the preferred charging mode for public charging stations and residential charging at high power.

1) Type1, single phase charger, SAE J1772-2009, commonly used in USA;
2) Type 2 Mennekes VDE-AR-E 2623-2-2, single and three phase chargers, commonly used in Europe; and
3) Tesla dual charger for single-phase AC and DC used in the USA.

Due to weight and space restrictions on the EV, the on-board AC charger is usually limited to up to 22 kW charging power levels in commercial EVs. The only exception is when the drivetrain propulsion power electronics, typically of a much higher power rating (80-500 kW), are re-used for EV charging. These are referred to as 'on-board integrated' chargers [103], [109]. The integrated chargers use a combination of the drivetrain inverter and the windings of the propulsion motor for the EV charging. An example is the integrated Caméléon the charger of the Renault Zoe, which was rated for 43 kW for model years up to 2018-19. DC charging is preferred for high-power EV charging beyond 50 kW, which uses an off-board charger.

B. DC CHARGING

DC charging was introduced to facilitate faster charging of EVs (up to 900 kW) and overcome an on-board charger's weight and size limitation. DC charging comes under Mode 4 as defined in IEC 61851-1, where a dedicated off-board AC/DC converter supplies DC power directly to the EVas battery. Currently, there exist many types of DC chargers [29], [106], [107] used globally, as shown in Fig. 12 and Table 8:

1) CCS/COMBO (Combined Charging System, Combo 1 and Combo 2);
2) Type 4 CHAdeMO;
3) Chinese GB/T;
4) The more recent ChaoJi plug coming from the joint efforts of CHAdeMO and GB/T;
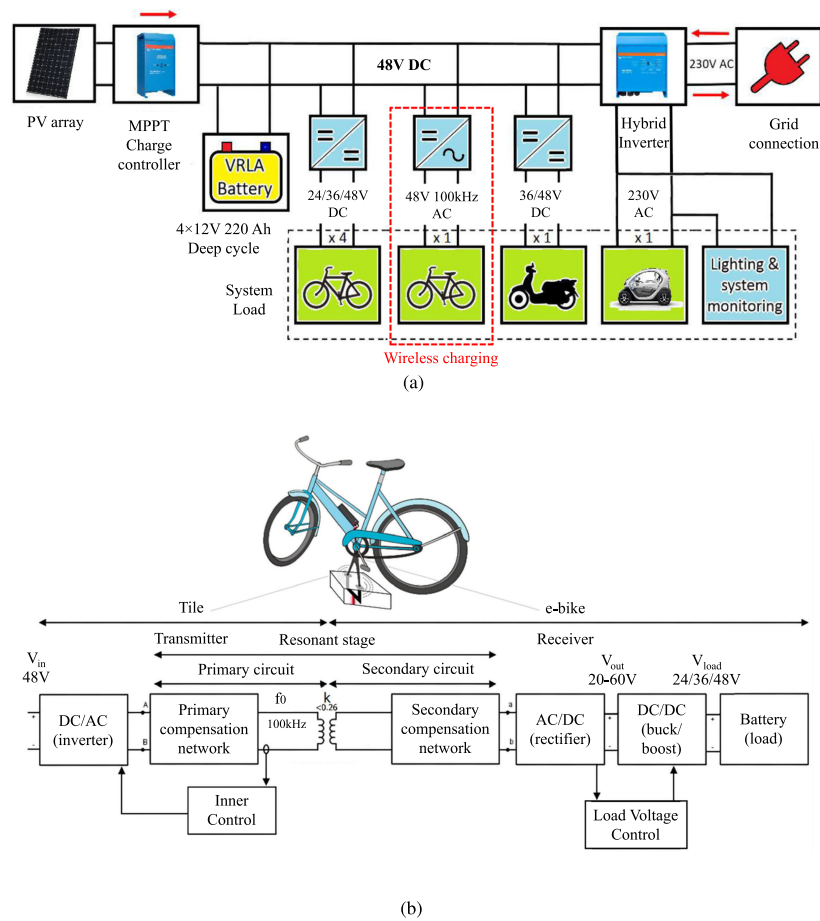5) Tesla dual charger for single phase AC and DC used in USA; and

(a)

(b)

FIGURE 14. (a) AC and DC-based architecture of HCS providing wireless charging to E-bike (highlighted in red color) [79]. (b) Block diagram of WPT system for the E-bike [79].

6) Tesla Type 2 plug used for DC charging in Europe (recently abandoned to make use of CCS Type 2).

The DC charging systems use three power pins to transfer the power: two DC power pins DC+, DC-, and one earth pin (E). They differ, however, in the communication and control protocol used. For example, CHAdeMO uses CAN bus communication, seven pins for control, and communication, while CCS uses Power Line Carrier communication (PLC) and two communication pins. CCS/COMBO is unique in that the same plug has the AC charging pins at the top and the DC charging pins at the bottom. This results in CCS having two types of charging plugs referred to as CCS Type 1 and CCS Type 2 depending on whether the AC part of the connector is the AC Type 1 or AC type 2 connector.

The charging system of Tesla is unique because it uses the same two power pins for both single-phase AC and DC and two communication pins. The Tesla coupler and interface are designed to charge the EV using a Tesla charger (either AC or Supercharger) or an adapter from a Type 1 SAE J1772 charger or a CHAdeMO charger.

The extremely high charging power levels, which are possible in DC charging, means an EV with a typical battery capacity of 20–100 kWh can be charged in 5-20 mins in the constant current charging region. The very high charging currents (100-600 A) require the cables to be liquid-cooled

so that the size and weight of the cable are manageable for a human to lift and connect to the vehicle. In case of charging heavy-duty vehicles like busses or trucks, catenary-based charging using a catenary up or down approach is also used to avoid liquid-cooled cables or cables altogether at the charging depot.

A key advantage of DC charging is that the charger can be made bidirectional for implementing vehicle-to-everything (V2X) [111], [112]. V2X is a generic name that refers to V2G (grid), V2B (building), V2H (home) or V2L (load) [113]–[115]. V2G is a particular case of smart charging, and V2G opens up a plethora of opportunities, such as using the EV for storing renewable energy, participation in energy markets, and providing ancillary services [111], [116]–[118]. Hence, bidirectional off-board DC chargers are being developed for implementation of V2G, and both CHAdeMO and CCS/Combo support V2G [29].

C. CHARGING OF ONE-, TWO-, AND THREE-WHEELERS

While the charging plugs and pins, power levels, and communication between the vehicle and the charger are relatively standardized for AC and DC charging of large vehicles, as described in Sections VII-A and VII-B, this is not the case for electric one-wheeler, two-, and three-wheelers. This

TABLE 9. Summary of EV Charging Done From the Off-Grid and Hybrid Charging Systems in the Literature (See Table I)

Ref.	EV charging (AC / DC / both)	Specifications of energy storage in EV		Specifications of EV Charging ports		Sim./ Expt. /Both
		storage type	rating	total number	rating of each	
OGCSs						
[37]	AC	Li-ion	32-95 kWh	100	3.7 kW	Sim.
[34]	AC	Li-ion	36 kWh	1	10.23 kW	Sim.
[33]	AC	Li-ion	60 kWh	1	50 kW	Sim.
[35]	AC	Li-ion	35 kWh	4–6	-	Sim.
[11]	AC	-	2 kWh	50/day	27.09 kW	-
[8]	AC	-	4 kWh	1	3.3 kW	Sim.
[38]	DC	$LiMn_2O_4$	24 kWh	1	980 W	Sim.
[44]	DC	-	-	3	-	-
[12]	DC	Li-ion	600 W, 1.2 kW, 1.8 kW	1	260.2–780 W	Sim.
[40]	DC	-	-	1	-	Sim.
[45]	DC	Li-ion	6.25 kWh	4	5 kW	Expt.
[43]	DC	-	-	1	3 kW	Sim.
[39]	DC	-	-	1	8 kW	Sim.
[41]	DC	-	35 kWh	80/day	-	Sim.
[46]	AC & DC	-	-	-	-	-
[7]	AC & DC	-	-	3	- (AC), 50 kW for EV1 & EV2 (DC)	Sim.
HCSs						
[54]	AC	-	-	-	-	Both
[51]	AC	$LiFePO_4$	63.36 kWh	1	-	Sim.
[47]	AC	-	-	1	6.6 kW	Sim.
[53]	AC	-	-	1	-	Both
[49]	AC	-	-	2	-	Sim.
[48]	AC	-	44 kWh	-	7 kW	Sim.
[13]	AC	-	-	2	-	Expt.
[52]	AC	-	-	2	-	Expt.
[50]	AC	-	60 kWh	12	-	Sim.
[57]	DC	-	-	1	-	Sim.
[55]	DC	-	-	1	3.3 kW	Sim.
[68]	DC	Lead-acid	8.4 kWh	1	-	Expt.
[69]	DC	Lead-acid	8.4 kWh	1	0.95 kW	Expt.
[20]	DC	-	-	1	10 kW	-
[66]	DC	-	-	1	10 kW	Expt.
[60]	DC	-	2.2(min.)–45(max.) kWh	6	-	Sim.
[67]	DC	Li-ion	1.2 kWh each	15	1.2 kW	Expt.
[61]	DC	-	60 kWh	48	-	Sim.
[59]	DC	-	-	150/day	-	Sim.
[71]	DC	-	1.2 kW	1	-	Expt.
[75]	DC	Ultracapacitor	845.64 Wh	1	-	Expt.
[75]	DC	-	-	-	-	Sim.
[72]	DC	-	-	1	-	Sim.
[72]	DC	Electronic load#	-	1	-	Expt.
[77]	DC	Lead-acid	3.564 kWh	1	-	Expt.
[77]	DC	-	-	1	4.692 kW	Sim.
[74]	DC	Electronic load#	-	1	-	Expt.
[74]	DC	-	-	-	-	Sim.
[64]	DC	$LiFePO_4$	35 kWh	1	2.72 kW	Sim.
[63]	DC	-	-	-	-	Sim.
[76]	DC	-	-	3	1 kW	Both
[78]	DC	-	-	2	-	Both
[65]	DC	-	16–60 kWh	10	-	Sim.
[62]	DC	-	-	3	60 kW	Sim.
[56]	DC	Li-ion	19.6 kWh each	2	48 kW	Sim.
[58]	DC	-	64 kWh	20	-	Sim.
[73]	DC	Li-ion	1.2 kWh each	15	1.2 kW	Both
[70]	DC	-	8.4 kWh	1	1 kW	Expt.
[14]	DC	-	-	-	-	Sim.
[79]	AC & DC	Li-ion	396 Wh (EVs1-5), 1.92 kWh (EV6), & 6.1 kWh (EV7)	7	3.7 kW (AC) & 100 W, 200 W (DC)	Expt.
[80]	AC & DC	-	-	2	2 kW (AC) & 1 kW (DC)	Expt.
[10]	AC & DC	-	8.4 kWh each	2	1.1 kW each	Expt.
[9]	AC & DC	Lead-acid (EV3)	3.36 kW (EV3)	3	3.41 kW (EV1), 1.21 kW (EV2)(AC) & 0.677 kW (EV3; DC)	Expt.
[15]	AC & DC	-	-	2	1.35 kW each	Both

It is used in place of a battery in the experiment to emulate different modes, such as constant current, constant voltage, constant power, and constant resistance.

non-standardization is because this segment of personal (and often shared) mobility is broad and includes electric scooters, steps, segway, e-bikes, e-motor bikes, tuk-tuks, and small vans from various products and market players. Typically, the battery voltage levels are in the range of 12-48 V but can go up to 120 V, and charging power levels are in the range of 50 W and go up to a few kW depending on the device.

These vehicles are characterized by a charger that is like a laptop charger, i.e., the charger connects to the AC wall socket on one side, convert the power to DC and then connect to the vehicle on the other side, as shown in Fig. 13. The vehicle-side connector is usually of a proprietary design using a non-standard communication posing a fundamental challenge both within the same country/region and between regions. Alternately, the complete charger is on-board, and

there is a plug from the vehicle that directly connects to the AC wall socket (like AC charging, Mode 1, or Mode 2). However, it will consume space in the vehicle with additional weight on it.

D. WIRELESS CHARGING

Wireless charging of EVs can be a more straightforward solution over different standards (and non-standards) plugs and power levels of AC and DC conductive charging, as discussed in Sections VII-A – C. For the wireless power transfer (WPT) system, standards are set internationally for their design and operation, such as the coil design (including power level and air gap), operating frequencies (as per SAE J2954 standard), and electromagnetic field exposure (as per ICNIRP) [119]. Thus, the WPT system makes EV charging simpler and safer (due to contactless operation) for any power level than the plug-in charger.

Implementation of a high-power WPT system has various challenges, such as electromagnetic safety, EMI, cybersecurity, and foreign object, which are the current focus in the wireless community. However, implementing a WPT system for the power level required by one-, two-, and three-wheelers is widely available. Therefore, it can be used in place of non-standard conductive chargers for one-, two-, and three-wheelers. For example, in [79], a hardware implementation of wireless charging for E-bike has been presented in AC and DC-based architecture of HCS, as shown in Fig. 14. Besides this, more details on the different designs of WPT systems for high power EV charging can be looked into a comprehensive review presented in [120].

E. CRITICAL INSIGHTS ON CHARGING PLUG AND POWER LEVEL IN BOTH CHARGING SYSTEMS

1) CHARGING PLUG

Among the various architectures of off-grid and hybrid charging systems, as summarized in Table II, a very few works have considered the above discussed charging connectors in their presented architectures [33], [38], [53], [66], [77]. In [33], CCS and CHAdeMO charging standards are used for the fast charging of EVs through the AC-based architecture of OGCS. For the DC-based architecture of OGCS, CHAdeMo is used by the authors in [38]. Moreover, for AC-based architecture of HCS, [53] uses Type-1 connector. Furthermore, in DC-based architecture of HCS, [77] considers CHAdeMO connector, whereas CHAdeMo and COMBO are used in [66].

2) CHARGING POWER LEVEL

Table 9 shows the current status of charging power implemented in the off-grid and hybrid charging systems. For OGCS, only a Li-ion battery of up to 95 kWh is used in the study, as shown in Table 9. Moreover, to charge these batteries in most of the works, the used charging power is from 260.20 W–50 kW at the given number of port(s) (see Table 9). However, in [11], [41], [59], instead of charging port number, the data of a total number of vehicles charged per day is given. From Table 9, it is also noticed that these power levels are

implemented in simulation only except in [45]. In [45], 5 kW DC charging is implemented experimentally.

As far as HCSs are concerned, Li-ion and lead-acid batteries of up to 63.36 kWh and 8.4 kWh, respectively, are mostly used in the reported works, as shown in Table 9. Lead-acid batteries [9], [68], [69], [77], ultracapacitor [75], and electronic load [72], [74] are used for lab experiments to represent the EV charging. However, few works have considered Li-ion for the same while performing experiments [67], [73], [79], whereas all simulation works are based on Li-ion batteries only. Few works reported both (sim. and expt.) had descaled the power level while performing the experiments [72], [74], [77]. The works used both (AC and DC charging) are completely based on the hardware implementation of a maximum 3.7 kW charging power. This power level is generally suitable for two- or three-wheelers; however, slow charging of the car can also be performed.

Besides that, the reported power level of DC charging for a single plug is limited to 50 kW in the case of OGCS and 60 kW in the case of HCS. These power levels are significantly less as per the standards of the DC charging plug's maximum rating (i.e., 250–900 kW). Therefore, attention should be given to the design and implementation of high power ratings per port in both types of charging systems so that DC fast charging can be done.

VIII. CONCLUSION AND OUTLOOK

This article has studied and reviewed the various architectures of the off-grid and hybrid charging systems for EVs. Moreover, it also reviewed and investigated their different subsystems, such as energy sources, ESS, PECs, EMS, and charging connectors (their power level and standards) for various vehicle types, in Sections III–VII, respectively. Furthermore, critical insights and trends are provided at each section's end. Nevertheless, a few more crucial points and outlook are summarized here as follows:

- From the review, it is found that numerous works have been reported for HCSs in comparison to OGCSs. However, for the success of the EV program worldwide, attention should also be given to OGCSs so that the area where the UG is absent can also adopt EV.

- PV and battery are in the current trend in energy sources and ESS subsystems, respectively. It is also seen that a few works use a combination of PV, wind, and DG in energy sources and battery and FC system in ESS. In one of the reported works [45], it is suggested that in off-grid systems, using FC system in ESS is a cost-effective and sustainable solution in the long run than batteries. Therefore, it is recommended to research FC system based ESS for safer and more efficient use.

- Biomass can be a great energy source in rural areas and advantageous for OGCSs. However, very few works (i.e., [41]) have focused on biomass and its integration with other RESs. Therefore, it can be a potential area to explore further in OGCSs.

- In the PECs subsystem, the commonly used converter topologies in both types of EV charging systems are unidirectional boost DC-DC, bidirectional buck-boost DC-DC, full-bridge rectifier, H-bridge, and 3-phase voltage source converters. However, few works have used/proposed different design/topologies to integrate RESs, ESS, EV, and grid, as shown in Tables 5 and 6. The hardware verification of these converters is done in very few works of various architectures of OGCS, AC-based, and DC-based architectures of HCS. In contrast, all reported works for AC and DC-based architecture of HCS have performed hardware verification, as shown in Tables 3 and 4. Besides that, the isolation of EV chargers is missed in most of the works, leading to safety concerns. Moreover, V2G chargers are not often implemented though it could be critical in OGCSs to provide backup power.

- Many works on EMS have been reported for HCSs, whereas minimal attention has been paid to OGCSs, as shown in Table 7. The EMS's commonly used objectives in OGCSs were the optimal operation of ESS, charging cost reduction, maximizing the utilization of RESs, and meeting the charging demand. Whereas regulation/optimal operation of energy sources, charging cost reduction, efficient and uninterruptible charging, and minimizing UG use were the commonly used objectives in HCSs. For achieving these objectives, various approaches on optimization-based and rule-based are implemented either using simulation, real-time, or both. From the review, it is observed that the EMS technique based on estimation or different modes of operation is in trend. It is suggested to explore the EMS for OGCSs to deal with power outages and low-cost charging uncertainties.

- The review also shows that the charging power levels and connectors for four-wheelers are well standardized, varying from country to country. However, one-, two-, and three-wheelers, which make up a large portion of the EV market, still use non-standard charging connectors at the vehicle-side. This could be a problem for EV manufacturers, which have international reach in the market. Therefore, in the case of off-board charger, it is recommended to standardize vehicle-side connectors (like for smartphone charging ports, such as USB Micro-B and USB Type-C) or use other alternatives, such as wireless charging for these EVs.

- From Table 9, it can be seen that in most of the works, charging power of up to 60 kW per port is implemented in simulation. However, very few works have experimentally implemented a charging capacity of up to 10 kW per port. Therefore, it is recommended to develop a charging system prototype that can provide high charging power per port so that fast charging can be done.

In conclusion, there are many research opportunities in the OGCSs and HCSs, which need to be addressed for seamless charging of EVs in rural and urban areas of various countries.

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GAUTAM RITURAJ (Member, IEEE) received the B.Tech. degree in electrical engineering from Uttar Pradesh Technical University, Lucknow, India, in 2012, and the Ph.D. degree from the Indian Institute of Technology Guwahati, Guwahati, India, in 2021. He is currently a Postdoctoral Researcher with the DC systems, Energy Conversion and Storage Group, Department of Electrical Sustainable Energy, Delft University of Technology, Delft, The Netherlands.

His research interests include off-grid EV charging systems, analysis and design of wireless power transfer systems, coil design and modeling, and developing the power electronic circuits for EV charging. He is an active Reviewer of many journals, including the IEEE TRANSACTIONS OF POWER ELECTRONICS, IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION, IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS, and IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS. He was the recipient of the Gandhian Young Technological Innovation Appreciation 2021 for his doctoral work.

GAUTHAM RAM CHANDRA MOULI (Member, IEEE) received the bachelor's degree in electrical engineering from the National Institute of Technology Trichy, Tiruchirappalli, India, in 2011, the master's degree in electrical engineering from the Delft University of Technology (TU Delft), Delft, The Netherlands, in 2013, and the Ph.D. degree from the TU Delft in 2018, for the development of a solar-powered V2G electric vehicle charger compatible with CHAdeMO, CCS/COMBO and designed smart charging algorithms (with PRE, ABB and UT Austin). From 2017 to 2019, he was a Postdoctoral Researcher with TU Delft, pursuing his research on power converters for EV charging, smart charging of EVs, and trolley busses. He is currently an Assistant Professor with the DC systems, Energy Conversion and Storage Group, Department of Electrical Sustainable Energy, TU Delft.

His research interests include electric vehicle charging, PV systems, power electronics, and intelligent control. He was awarded the Most significant innovation in electric vehicles award from IDtechEx in 2018 and the Best Tech Idea of 2018 by KIJK. He was awarded the Best Paper Prize in the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS in 2018, Best Poster prize at Erasmus Energy Forum 2016, The Netherlands, and Best Paper prize at the IEEE INDICON Conference 2009, India. He is involved in many projects with industrial and academic partners at national and EU level concerning electric mobility and renewable energy such as PV charging of electric vehicles, OSCD, Trolley 2.0, Flexgrid, Flexinet and NEON. He is the Coordinator and a Lecturer for the Massive Open Online Course (MOOC) on Electric cars on edX.org with 175,000 learners from 175 countries. He is the Vice-chair of the IEEE Industrial Electronics Society Benelux chapter.

PAVOL BAUER (Senior Member, IEEE) received the master's degree in electrical engineering from the Technical University of Kosice, Koice, Slovakia, in 1985, and the Ph.D. degree from the Delft University of Technology, Delft, The Netherlands, in 1995. He is currently a Full Professor with the Department of Electrical Sustainable Energy of Delft University of Technology and the Head of DC Systems, Energy Conversion and Storage Group. He is also a Professor with the Brno University of Technology in Czech Republic and a Honorary Professor with Politehnica University Timişoara, Timişoara, Romania. From 2002 to 2003, he was partially with KEMA (DNVGL, Arnhem) on different projects related to power electronics applications in power systems. He authored or coauthored more than 120 journal and 500 conference papers in his field (with H factor Google scholar 40, Web of Science 26). He is the author or coauthor of eight books, holds seven international patents and organized several tutorials at the international conferences. His main research interests include power electronics for charging of electric vehicles and DC grids. He has worked on many projects for industry concerning wind and wave energy, power electronic applications for power systems, such as Smart-trafo and HVDC systems, projects for smart cities, such as PV charging of electric vehicles, PV and storage integration, contactless charging, and participated in several Leonardo da Vinci, H2020 and Electric Mobility Europe EU Projects as Project partner (ELINA, INETELE, E-Pragmatic, Micact, Trolley 2.0, OSCD, P2P, Progressus) and a Coordinator (PEMCWebLab.com-Edipe, SustEner, Eranet DCMICRO). He is the former Chairman of Benelux IEEE Joint Industry Applications Society, Power Electronics and Power Engineering Society chapter, Chairman of the Power Electronics and Motion Control (PEMC) council, Member of the Executive Committee of European Power Electronics Association (EPE), and also Member of international steering committee at numerous conferences.