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ELECTRIC VEHICLE CHARGER STATION WITH SECOND-LIFE BATTERY STORAGE SYSTEM

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ABSTRACT

EV car sales experienced a major increase recently and are proposed to have a prominent share of global car sales in the next decade. Hence, a high volume of EV batteries reaches their first end of life every year when they resume their 70-80% capacity. At this juncture, EV manufacturers face three options for the used batteries: recycling, disposing, or reusing them in their second life. Reutilization of EV batteries in their second life provides the most economical and environmental option for EV manufacturers. In this paper, we propose to use LiFePo4 (LFP) type second-life batteries as an energy storage solution (ESS) in an EV charger station with photovoltaic panels and a power grid connection. The system provides charging of two EVs in AC/DC simultaneously. The energy management system (EMS) controls the battery packs and manages the AC/DC conversion for DC charging of battery modules and AC charging of EVs via the power grid. The battery management system parameters such as state of health (SoH), state of charge (SoC), and temperature are provisioned to the cloud system via the telemetry module. The proposed system is currently under development at the technology readiness level (TRL) 5-6 level for demonstration purposes as part of a European project.

Key Words: Second-Life Battery Systems, Battery Energy Storage Systems, EV Charger, Battery Management System BMS.

1. INTRODUCTION

The Electric Vehicle (EV) market trend is predicted to accelerate in the upcoming years. Electric car sales globally were approximately 14 million in 2023, 95% of the total sales were in China (60%), Europe (25%), and the United States (10%) **Error! Reference source not found.**. In Türkiye, 68700 EVs were sold in 2023 which was 8 times more than the EV sales in 2022, and this was 10% share of the national car sales market last year [2]. The European Union (EU) declared a zero emissions target for the new manufactured cars by 2035. In an estimated scenario for EU countries, EVs will reach a market share of 75% by 2030, and one in four vehicles in the European Union (EU) market will be electrically operated by 2030. The electricity demand resulting directly from the charging of passenger and commercial EVs in the EU could increase from nine terawatt hours in 2021 to 165 terawatt hours in 2030. The EU will need at least 3.4 million operational public charging points by 2030. The EV-charging infrastructure which includes installing new charging points, upgrading power grids, and increasing renewable-energy generation capacity may cumulatively cost upward of €240 billion by 2030 in the EU alone[3].

Consequently, the yearly demand for lithium batteries is experiencing swift growth, nearing an estimated annual consumption of 5.7 terawatt-hours globally by 2035 [4] . A typical battery electric car produces approximately half the carbon emission as conventional ICE equivalent cars during its lifetime. Thus, wide range adoption of electric vehicles will contribute to achieving the net zero carbon emission target of the International Energy Association (IEA) by 2050.

The second life of batteries refers to their extended life after completing the first life in an EV. The batteries have a challenging life in an EV with continuous charge and discharge cycles. The accepted life for a battery pack is 70-80% of its original capacity and the second life remains till the battery's SoH is 30%. Consequently, there exists a major opportunity to utilize the remaining life of batteries in stationary applications like energy storage systems (ESS) or EV charging stations.

However, challenges exist in managing second-life batteries in their remaining life. These challenges can be grouped as diagnosis of the health of battery cells, installation and grouping in a storage system, control of different types of batteries in a BMS system, total energy management in a charger system, and the functional safety requirements of the second-life battery system. Every challenge can be a topic of R&D work in a literature paper. We propose an EV charger station with a battery energy storage system (BESS) composed of second-life battery modules, photovoltaic panels, and a power grid connection. The BESS system consists of battery modules of LFP-type batteries. Photovoltaic panels charge the battery modules in DC. The power grid connection also charges the battery modules with AC/DC conversion and provides AC charging of EVs. The hardware and software development for the EV charger station is currently in progress. The charging system parameters such as SoH, SoC, temperature, voltage, and current measurement readings via BMS will be provisioned to the cloud system of the European KDT-JU (Key Digital Technologies- Joint Undertaking) project, namely OPEVA (Optimization of Electric Vehicle Autonomy).

The work here is part of an overall R&D project, OPEVA, that aims to enhance the electric vehicle domain to move from conventional to sustainable EVs by working on six objectives. These objectives can be stated as energy-efficient power train, energy-efficient dynamic routing, accurate range prediction techniques, improved EV grid integration, efficient charging technologies, and wider EV adoption [5]. In the project context, 9 demonstrations with 26 key technologies will be implemented on multiple demonstrator sites. This article presents one of the 9 demonstrations that will be implemented in the OPEVA project.

2. LITERATURE REVIEW

A DC-based microgrid EV charging station with renewable energy sources such as photovoltaic panels and wind turbines is implemented along with second-life batteries for charging in case of power source shortages [6]. Related simulation models were prepared to predict the behavior of the system. An EV charging station equipped with photovoltaic panels and a battery energy storage system (BESS) was designed and implemented in [7] . Environmental sustainability, specifically focusing on carbon emissions reductions is also discussed in detail. The strategies encompassing first-life, second-life, and no-battery solutions within an eight-year time horizon are explored. The findings indicate that the second-life battery-based EVSE solution reduced carbon emissions by 15% and 10% compared to the first-life batteries and no-battery solutions, respectively. The optimal design of EV charging stations with wind, solar photovoltaic, and battery energy storage systems (BESS) was studied to determine the capacity configuration of the components and the power requirements [8]. The study concluded that modeling and simulation of such a system, in conjunction with the utility grid and demand response strategies, yield optimized capacity values for system components, including wind turbines, photovoltaic panels, and BESS. The techno-economic feasibility of using second-life ESS in an EV charging station is studied in [9]. The determination of the quantity of second-life battery modules for Energy Storage System (ESS) deployment is achieved via a novel methodology. The study compares the economic evaluation of dedicated versus shared battery solutions for EV charging, concluding that the shared second-life battery solution results in a 13% reduction in the annual cost of energy.

A generic energy management strategy is implemented in [10] to manage the power demand among multiple second-life batteries with varying power levels and disturbances. A multi-port converter was designed to integrate three second-life battery modules with different sizes, capacities, and chemistry types. The proposed energy management strategy with DC/DC and DC/AC converters, a battery management system (BMS), and related hardware setup, manages performance inequality between 5% and 45% SoC among the second-life battery modules. A fast charge station nanogrid with a photovoltaic system, second-life ESS, and limited connection to the utility grid is developed in [11]. An energy management system (EMS) with fuzzy logic is implemented to manage and control the power requirements of the nanogrid system. A novel simulation tool that combines deterministic and stochastic elements is employed to analyze the energy requirements of the fast charge station.

An evaluation framework is introduced for the end-of-life batteries of EV/PHEV in a BESS implementation [12]. This framework consists of the battery degradation model, the battery retirement process model, and the model of BESS in power system applications. The cost is better optimized for power generation in the battery's second life, and it is observed that BESS with second-life batteries has higher cost savings for PHEV. Hence, battery health is better preserved in its first life with the proposed battery degradation model. A centralized charging station (CCS) is proposed to provide delivery and charging of the battery modules from swapping stations of EVs [13]. This CCS consists of photovoltaic solar panels and secondary life battery modules to support the charging of the serving battery modules. An operational strategy is proposed to optimize the operations between the CCS and battery swap stations. Since second-life batteries have varying SoH after retiring from their first life in EVs, they require reconditioning to balance the SoH of the battery modules. The economics and cost analysis of reconditioning second-life batteries with novel methods are studied in [14]. It is concluded that ESS utilizing reconditioned batteries is more cost-effective than brand-new Li-Ion batteries in an ESS.

A recent review of the technical challenges associated with second-life battery applications reveals a focus on economic and environmental issues rather than technical ones [15]. The technical challenges discussed include modeling battery performance degradation, developing SoC/SoH algorithms, and applying AI for battery cycle aging. It is suggested that specific battery management systems (BMS) should be designed for second-life battery modules due to their unique performance degradation behaviors. The review also lists recent European projects that have implemented second-life battery modules in grid-based ESS and EV charging stations.

3. SYSTEM ARCHITECTURE

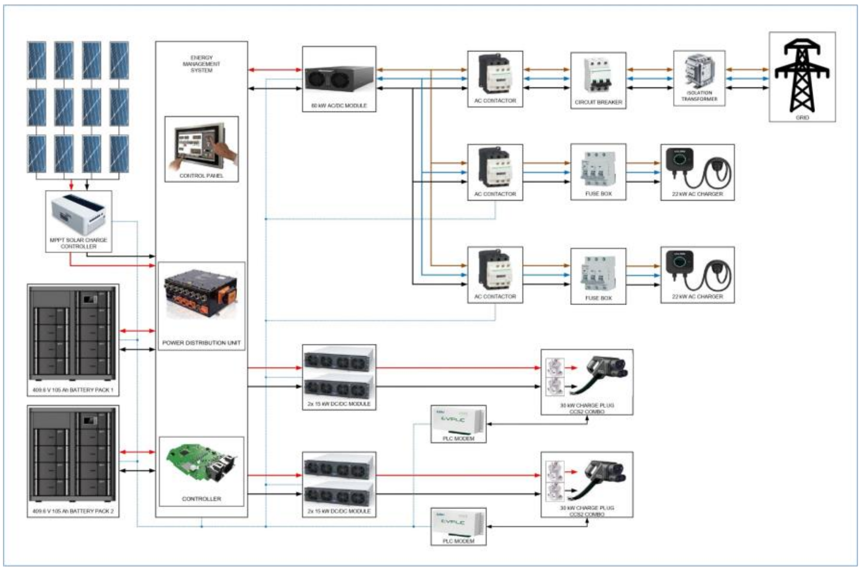

Figure 1 : EV charger system with second-life battery storage

The block diagram showcases an advanced EV charging station integrated with solar photovoltaic panels, the power grid and second-life battery packs in Figure 1. Solar photovoltaic panels generate renewable energy regulated by an MPPT Solar Charge Controller. This energy is stored in two 409.6V/105Ah second-life battery packs, managed by a Power Distribution Unit (PDU). The system includes a 60 kW AC/DC module and 2x15 kW DC/DC modules for efficient power conversion and distribution. It supports three 22 kW AC chargers and two 30 kW DC chargers (CCS Combo), connected through AC contactors, fuse boxes, and circuit breakers for safety. The Energy Management System (EMS) oversees the entire setup, interfacing with a control panel and PLC modem for real-time monitoring and control and connects to the utility grid to ensure continuous power supply and grid stability.

3.1 Second-life Battery Modules

The second-life batteries utilized in this study are Lithium Iron Phosphate, $LiFePO_4$ (LFP) batteries, characterized by their robust performance and safety features. The two types of batteries possess specific attributes as outlined in Table 1 and Table 2.

Table 1: Second-life battery 1st type

Item	Specifications
Nominal Capacity	105Ah
Nominal Voltage	3.2V
Nominal Current	52A
Geometry	Prismatic
Dimensions WxHxD (mm)	135x215x30

Table 2: Second-life battery 2nd type

Item	Specifications
Nominal Capacity	90Ah
Nominal Voltage	3.2V
Nominal Current	45A
Geometry	Prismatic
Dimensions WxHxD (mm)	128x212x30

These second-life batteries were procured from a prominent national Original Equipment Manufacturer (OEM) within the automotive sector. Prior to their deployment in the battery module, a rigorous series of tests and controls are conducted to ensure their suitability. These tests include the measurement of internal resistance and voltage values to confirm that they fell within the expected operational range. The construction of each battery module involves connecting sixteen battery cells in series. Consequently, each battery module comprises a total of sixteen LFP cells to achieve the desired electrical characteristics. This configuration is depicted in Figure 2.

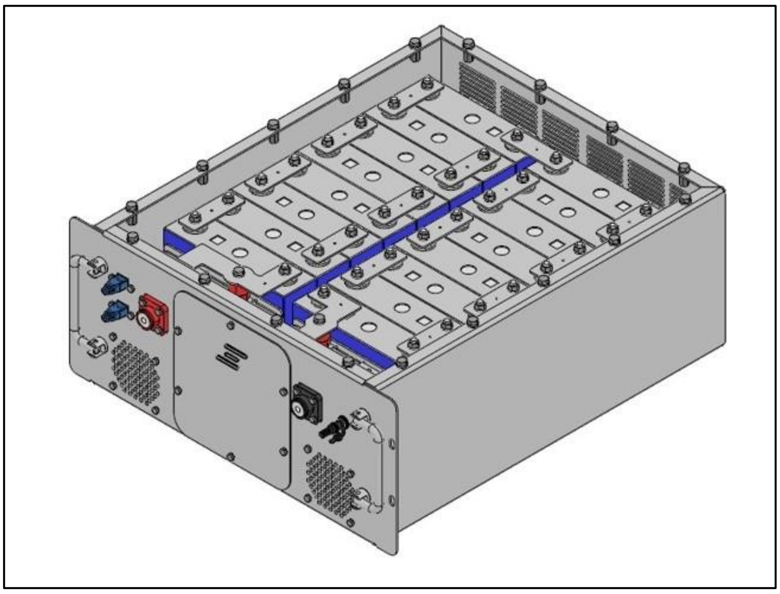

Figure 2: Second-life battery module

Furthermore, the battery pack comprises eight such battery modules connected in series, which forms a robust and high-capacity energy storage solution. The entire system consists of two battery packs connected in parallel, thereby delivering a cumulative output of 410VDC, and providing a total energy capacity of approximately 80 kWh. This arrangement ensures a substantial energy reserve capable of supporting significant charging demands. The structural and operational layout of the battery pack is illustrated in Figure 3.

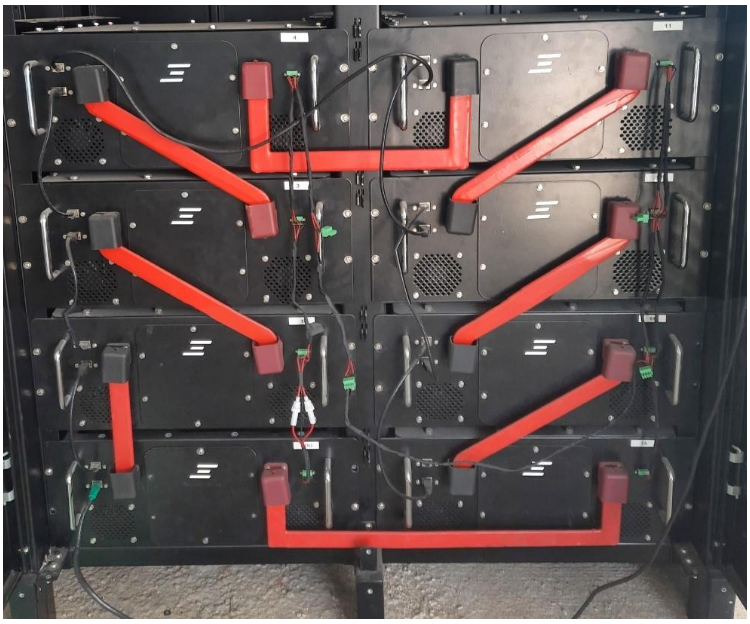

Figure 3: Second-life battery pack

The implementation of second-life batteries in this manner not only promotes environmental sustainability by reusing battery cells that have reached the end of their initial lifecycle but also offers a cost-effective solution for large-scale energy storage needs. This approach aligns with current trends in renewable energy integration and sustainable energy management practices.

3.2 Power Distribution Unit (PDU)

The power distribution unit (PDU) is the main controller unit of the second-life battery EV charger system. The PDU architecture can be visualized in Figure 4.

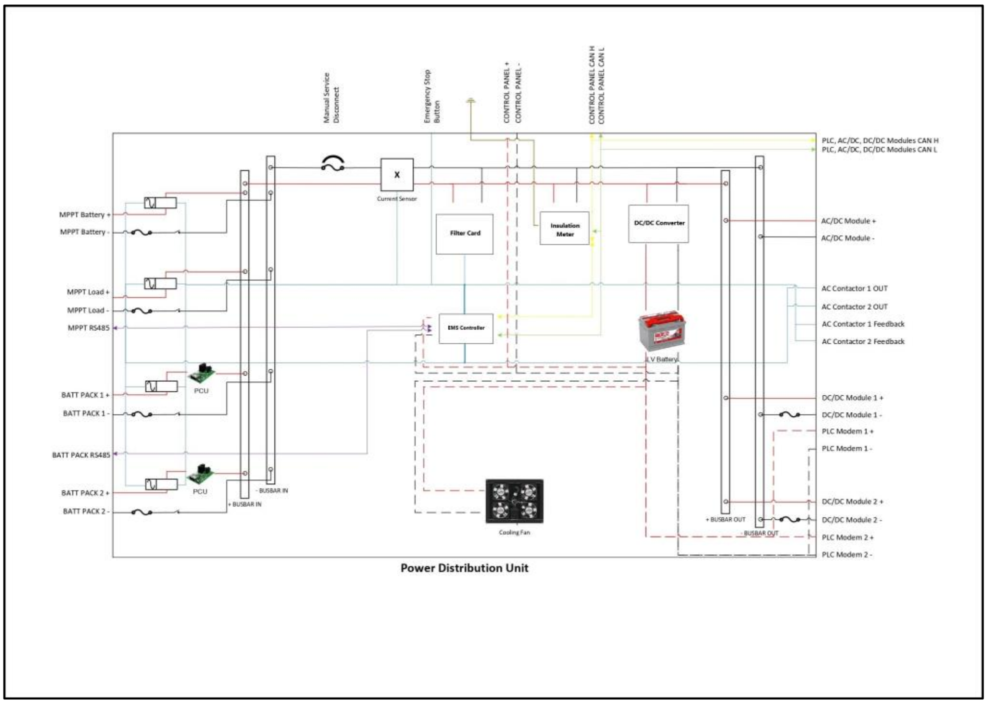

Figure 4: Power distribution unit (PDU) Architecture

PDU comprises multiple hardware control units to control the system's power requirements. The power control unit (PCU) manages and controls the individual battery packs and feeds into busbars that serve as central distribution points. MPPT (Maximum Power Point Tracking) controller connection for the solar photovoltaic panels and the PDU. The system incorporates a current sensor for monitoring flow and a manual service disconnect for safety, The energy management system (EMS) controller manages the power output of the PCUs, DC charging output, AC output from the power grid, DC/DC converter module, the human-machine-interface (HMI) unit, and the cooling fans. The control panel supports communication via CAN lines with PLCs, AC/DC, and DC/DC modules. The provided diagram is a schematic of the power distribution unit displaying the connections and components involved in managing and distributing electrical power within a system.

3.3 Solar Photovoltaic Cells

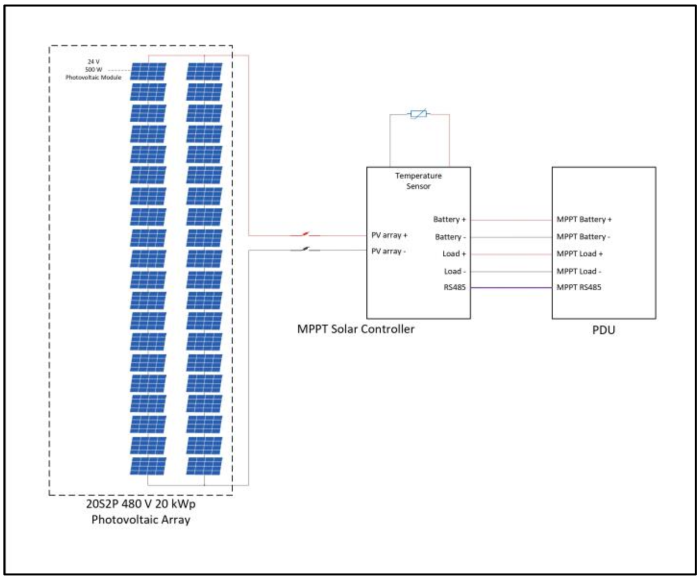

Figure 5: Solar photovoltaic cells

The solar controller architecture can be visualized in Figure 5. The diagram shows a solar power system featuring a photovoltaic (PV) cell array, an MPPT solar controller, and the power distribution unit (PDU). The PV cell array, consisting of multiple 24V, 500W cell modules configured in a 20 series and 2 parallel arrangements (20S2P) to produce 480V and 20 kWp, converts sunlight into electricity. This electricity flows into the MPPT solar controller, which optimizes power output and manages battery charging through its battery connections. The controller also supplies power to various loads via its load connections and communicates data through an RS485 port. A temperature sensor connected to the controller monitors thermal conditions to ensure safe operation. The PDU distributes the regulated power to the connected loads, completing the system that efficiently manages and distributes solar-generated energy.

3.4 Thermal Management System

The battery packs produce heat when providing DC output for EV charging. The thermal management of the system is implemented via a liquid cooling system shown in Figure 6

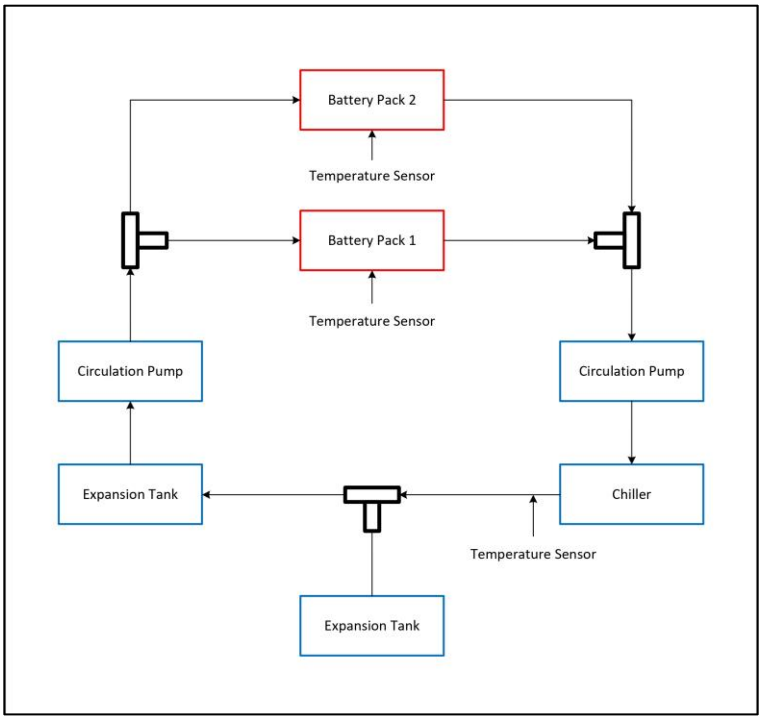

Figure 6: Battery thermal management system

This diagram represents a thermal management system for cooling battery packs. The thermal management components can be explained as follows:

- Battery Packs that are mentioned in the section 3.1. Each battery pack has an associated temperature sensor to monitor its temperature.

- Temperature sensors that are located on each battery pack and the chiller and monitor the temperatures to ensure the system remains within operational limits.

- Circulation pumps that circulate the coolant through the battery packs and circulate the coolant through the chiller. These pumps ensure that coolant is continuously moving through the system, helping to dissipate heat from the battery packs.

- Expansion tanks that accommodate the thermal expansion and contraction of the coolant, maintaining proper pressure and preventing air pockets within the system.

- Chiller that is responsible for cooling the coolant. The coolant flows through the chiller, which is cooled down before circulating back to the battery packs.

Coolant is pumped from the expansion tank by the first circulation pump. It flows through the battery packs, absorbing heat from them. The heated coolant then flows through the second circulation pump. It is then directed to the chiller, where it is cooled down. The cooled coolant is returned to the expansion tank, completing the loop. This closed-loop system ensures that the battery packs remain within a safe temperature range by continuously circulating cooled coolant through them, absorbing, and dissipating the heat generated during operation. Temperature sensors allow for real-time monitoring and adjustment, ensuring optimal thermal management.

4. CONCLUSIONS and RECOMMENDATIONS

In this work, we presented a novel electric vehicle (EV) charging system utilizing a second-life battery system with LiFePO4 (LFP) type battery modules and the implementation details. The charging system proposes an innovative architecture with battery packs controlled in a standalone setup. Power distribution unit (PDU) components manage and control the power in the EV charger system. Photovoltaic panels provide the DC charging of the battery packs, and the power grid provides the AC charging of the EVs. The thermal management system cools and maintains the operating temperature requirements of the battery packs. The overall EV charger system along with the provisioning telemetry unit and functional safety implementation are presently under development and will be implemented during the lifecycle of the OPEVA project.

The proposed system aims to reduce charging station expenses, enhance energy efficiency, and prolong the range and lifespan of the battery. Consequently, leveraging second-life batteries promises increased efficiency, cost-effectiveness, and environmental sustainability across the entire battery lifecycle. The widespread adoption of second-life batteries will bolster driver confidence, lower EV costs, foster greater acceptance of electric vehicles, and contribute to the EU's carbon neutrality initiatives.

Different types of EV batteries with varying chemistries such as LFP and NMC could be the topic of research and development work for another literature paper. AI / ML algorithm development for SoC/SoH estimation on BMS of the EV charger station is also considered for future work.

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