SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2023
ORGANIZATION AND MANAGEMENT SERIES NO. 184

ASSESSING THE EFFICIENCY OF HYBRID ENERGY FACILITIES FOR ELECTRIC VEHICLE CHARGING

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Purpose: The aim of the study is to evaluate the efficiency of using conventional energy facilities based on renewable energy sources to provide energy to battery swapping stations and charging stations for electric vehicles in one of the selected countries. As part of the work, the following tasks are solved:

- A mathematical model of charging stations or battery swapping stations, electrical installations based on renewable energy, and general energy facilities operating parallel to the electrical grid and autonomously is developed;
- A methodology has been developed, verifying the structures and parameters of energy facilities based on renewable energy sources for charging batteries of electric vehicles;
- The efficiency of using generation facilities based on renewable energy sources to battery charging stations in rural areas of such a large country is evaluated;
- The number of hybrid energy facilities based on renewable energy sources and charging stations is evaluated.

Design/methodology/approach: The examined power plant facilities serve electric vehicles in cities, recreation areas, industrial enterprises, and highways. Service types such as charging the battery and replacing discharged batteries of electric vehicles with pre-charged batteries are used at charging stations for electric vehicles. The efficiency of using conventional energy installations as part of charging stations is evaluated in regions with different climatic conditions.

Findings: The results show an increase in profit when participating in the ancillary service market.

Originality/value: In the following research paper were presented the optimization objective function that maximizes the profit.

Keywords: Hybrid Energy Facilities, Electric Vehicle Charging, Efficiency Assessment, Renewable Energy Integration, Energy Security.

Category of the paper: Research article.

1. Introduction

The number of cars polluting the atmosphere with exhaust gases is increasing every year (Wang et al., 2020). In Turkey, 17% (91 Mt of CO_2e in 2021) of the total amount of pollutants entering the atmosphere comes from motor vehicles, and in large cities, this figure sometimes reaches 60% (Turkish Statistical Institute, 2022). New-generation hybrid electric vehicles (EV) and electric vehicles developed with today's technology are important options for reducing harmful emissions. Today, the electric vehicle market is developing rapidly in the world, and this process has also started in Turkey. According to September 2023 data, the five nations boasting the largest proportion of electric vehicle (EV) sales are Norway (all-electric vehicles made up 80% of passenger vehicle sales in 2022), Iceland (41%), Sweden (32%), the Netherlands (24%) and China (22%) (Joel, 2023). Just over 41.393 electric vehicles (0.3%) are used in Turkey (Turkish Statistical Institute, 2021). For the operation of electric vehicles, suitable grid charging stations are required, which today are represented by two types:

- Stations for swapping rechargeable batteries, where discharged batteries of electric vehicles are replaced with pre-charged rechargeable batteries at these stations (Ali et al., 2022),
- charging stations where rechargeable batteries of electric vehicles are recharged (Rajendran et al., 2021).

The network of charging stations has already become widespread around the world. According to 2023 data, there are more than 138,000 stations in the USA, more than 1.5 million in China, around 49,000 in Germany, and more than 8,800 stations of the first type in Turkey.

As the production and use of new-generation hybrid electric vehicles and electric vehicles begin to become widespread, the demand for electrical power is expected to increase in parallel. Nowadays, most charging stations and all battery swapping stations (Ali et al., 2022) operate with electricity obtained from the electrical grid. This means that the impact of reduced emissions due to switching to electric vehicles is offset by emissions from thermal power plants providing increased power for the new consumer. In order for the use of electric vehicles to have a significant environmental impact, it is recommended to provide energy to charging stations in energy production facilities based on renewable energy sources. In the structure of charging electric vehicles, energy facilities based on renewable energy sources contribute to:

- saving fossil fuels,
- improving the environmental situation in the regions,
- increasing the energy security and energy independence of the region.

It is known that there are very few charging stations in the world today that work only with renewable energy sources. Unfortunately, such stations are not yet available in Turkey. Therefore, it is quite important to evaluate the feasibility of building facility energy facilities based on renewable energy sources to power charging stations and battery swapping stations

(Ali et al., 2022). In this case study, it is assumed that the stations use conductive charging technology. In general, electric vehicle (EV) chargers can be categorized into two main groups: indoor and outdoor chargers, and further divided into one-way and two-way chargers. Figure 1 illustrates the various EV charging technologies, which are typically organized into the following three distinct categories.

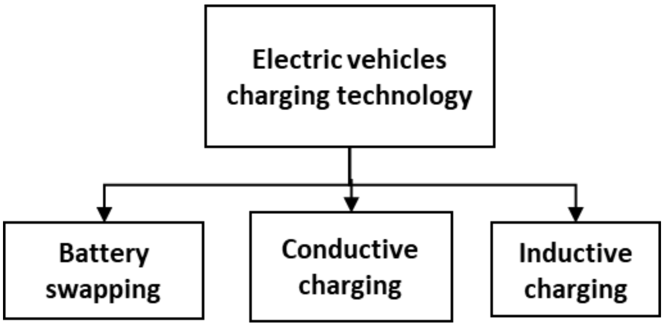

Figure 1. Categories of technology related to EV charging.

2. Methods

The aim of the study is to evaluate the efficiency of using conventional energy facilities based on renewable energy sources to provide energy to battery swapping stations and charging stations for electric vehicles in Turkey. As part of the work, the following tasks are solved:

- A mathematical model of charging stations or battery swapping stations, electrical installations based on renewable energy, and general energy facilities operating parallel to the electrical grid and autonomously is developed;
- A methodology has been developed, verifying the structures and parameters of energy facilities based on renewable energy sources for charging batteries of electric vehicles;
- Turkey's surface area is 783,562 km^2. The efficiency of using generation facilities based on renewable energy sources to battery charging stations in rural areas of such a large country is evaluated;
- The number of hybrid energy facilities based on renewable energy sources and charging stations is evaluated.

Above listed tasks are solved using the following methods:

1. The examined power plant facilities serve electric vehicles in cities, recreation areas, industrial enterprises, and highways.
2. Service types such as charging the battery and replacing discharged batteries of electric vehicles with pre-charged batteries are used at charging stations for electric vehicles.
3. The efficiency of using conventional energy installations as part of charging stations is evaluated in regions with different climatic conditions.

3. Mathematical model of hybrid energy systems

The research problem, which is the focus of this work, was solved using an improved mathematical model of integrated energy facilities consisting of power plants based on renewable energy sources and charging stations or battery swapping stations. In this case study, a microgrid makes effective use of information and communication technologies to oversee various components, such as electricity generators, energy storage systems, and electrical loads as depicted in Figure 2. To be more specific, a microgrid can be segmented into distinct subsystems, encompassing elements like wind power generators, photovoltaic (PV) solar power generators, distributed generators, battery energy storage systems, and electric vehicle (EV) charging stations. Solar-powered batteries serve as a valuable solution for meeting the unpredictable demands of grid electricity. These demands often involve rapid charging, discharging, and intermittent periods of full charge. The microgrid controller takes on the pivotal role of orchestrating the operations of all these subsystems and coordinating power distribution. Several research endeavors have been undertaken to explore methods associated with microgrids that incorporate EVs in conjunction with renewable energy sources.

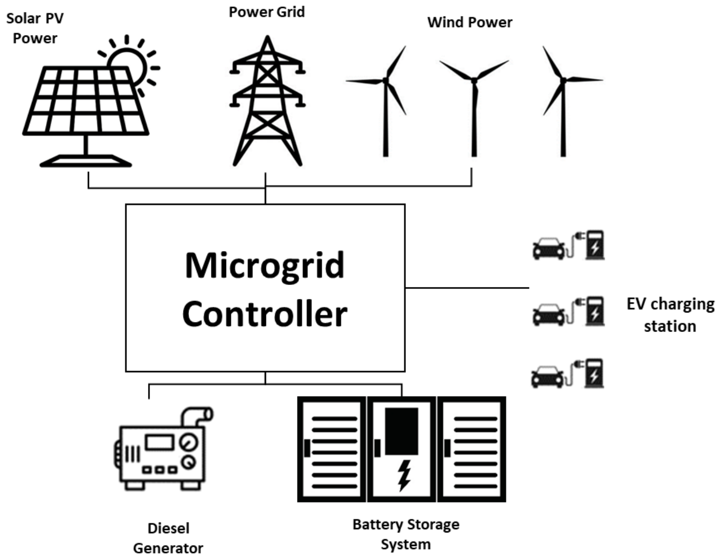

Figure 2. Charging station interacting with renewable energy sources in microgrid.

Since solar and wind resources are considered renewable energy sources in the study, the mathematical model of energy facilities includes the resource and technological models of wind energy and photovoltaic facilities. Resource models are represented by well-known data on solar and wind energy, while technical models are represented by the known dependence of the generation of power plants on the mode of energy received from renewable energy sources.

Analysis of scientific studies (Al Wahedi, Bicer, 2022; Lee et al., 2015; Li et al., 2022; Luo et al., 2018; Marinescu, 2022) on charging electric vehicles has shown that modeling such energy consumers as charging stations has not received enough attention in the world to date. In this study, various energy consumers are modeled such as day/night stations, battery swapping stations serving the taxi and factory fleet, battery swap stations serving the vehicle fleet in the area, and autonomous battery swapping stations. The difference between such stations is characterized by different work schedules, as well as some indicators of the degree of controllability by the station owner.

- Daytime charging stations are located in car parks, near train stations, shopping areas, sports centers, etc., where demand is highest during daylight hours;
- The location of the night charging station in public or private parking lots located near residential buildings and where the demand for recharging vehicles is highest at night;
- There are charging stations at gas stations, and peak demand occurs during daylight hours;
- Battery swapping station serving the fleet of taxi companies and factories;
- Battery replacement station serving the vehicle fleet in the shopping mall parking area.

Modeling of charging and battery replacement stations is carried out by taking into account the time-of-day dependence of the demand for charging or replacing the battery of electric vehicles and the daily electricity consumption schedules by these stations. An example of the time dependence of demand-simulating charging stations is shown in Figure 3. The electric vehicle charging station's own internal needs such as lighting and heating are also included.

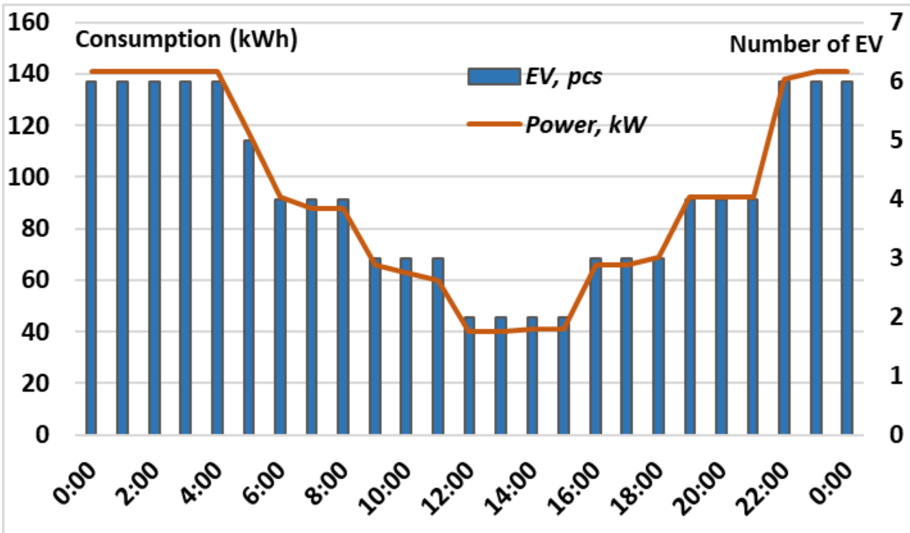

Figure 3. Daily electricity consumption of the charging station and the dependence of charging of electric vehicles on the time of day.

Mathematically, the model of energy facilities includes the constraints and conditions that must be met during the operation process. Thus, the operating mode for energy facilities, including charging stations, is described in a simplified form depending on the number of batteries ($nrech_{bat}$).

Here we are talking about standard rechargeable batteries that accumulate energy from renewable energy sources and later supply to facilities and charge electric vehicles.

Two operating mode options are possible in energy plants with charging stations:

1. When batteries are not included in energy facilities, ($nrech_{bat} = 0$). Then the power consumed by the electrical grid is determined as follows:

$$P_c(t) = l_{fac}(t) - p_{ren}(t) \cdot \eta_{eq} \text{ at } \frac{l_{fac}(t)}{n_{inv}} > P_c(t) \cdot \eta_{con} \tag{1}$$

where:

$P_c(t)$ – consumed power from grid (kWh),

$l_{fac}(t)$ – the load of facilities (kWh),

$p_{ren}(t)$ – generated power from renewable sources (kWh),

η_{eq} – total efficiency (%),

n_{inv} – efficiency of inverter (%),

η_{con} – efficiency of converter (%).

2. In cases where batteries are located in centralized energy facilities, two options are taken into account when determining the power consumed by the network:

If the generated power of renewable energy sources is not enough to ensure the power balance, electricity is consumed from the grid.

$$P_c(t) = l_{fac}(t) - (p_{ren}(t) \cdot \eta_{conv} + p_{bat}(t)) \cdot \eta_{inv} \text{ at } \frac{l_{fac}(t)}{n_{inv}} - P_c(t) \cdot \eta_{con} > p_{bat}(t) \tag{2}$$

where $p_{bat}(t)$ – battery power (kW).

For battery swapping stations, the operating mode is also described in a simplified form depending on the number of batteries in the power plants. In this case, electric vehicle batteries serve as energy accumulators for renewable energy sources. In the future, some of these batteries will be used to provide energy to power plants, and some will be installed in electric vehicles to replace discharged batteries. In this case, the power consumed for energy facilities at battery renewal stations will be as follows:

$$P_c(t) = l_{fac}(t) - p_{ren}(t) \cdot \eta_{con} \text{ at } l_{fac}(t) > P_c(t) \cdot \eta_{con} \tag{3}$$

In this case, the minimum permissible number of fully charged electric vehicle batteries that must be available for battery replacement is taken into account. If the number of batteries is greater than the minimum permissible number of fully charged electric vehicle batteries, the following options are possible for powering grid-connected energy facilities:

- The generation of renewable energy sources is not sufficient to both ensure power balance and provide power to the electric vehicle power supply system

$$l_{fac}(t) > p_{ren}(t) \cdot \eta_{conv} \tag{4}$$

$$p_{cap}(t) > p_{ren}(t) \cdot \eta_{conv} \tag{5}$$

where:
$p_{cap}(t)$ – power capacity of hybrid energy facilities (kW),
$p_c(t) = 0$ where the number of fully charged batteries is sufficient to cover both the battery replacement demand and the nominal capacity of the hybrid energy facilities.

If the number of charged batteries is not sufficient to power the capacity of the facility, the missing part of the power supply is consumed from the grid.

$$p_c(t) = p_{cap}(t) - p_{ren}(t) \cdot \eta_{conv} - dis_{bat} \cdot ch_{le} - hyb_{bat} \cdot p_{bat} \quad (6)$$

where:
dis_{bat} – number of discharged batteries, (pcs.),
ch_{le} – current charge level of the battery, (kW),
hyb_{bat} – the number of batteries that can be used to supply power; to hybrid energy facilities, (pcs.),
p_{bat} – the total power of the battery, (kW).

- When the number of fully charged batteries is not sufficient to meet the demand for battery replacement, the power required not only for the capacity of the plant but also to recharge the required number of batteries is consumed from the network.

$$p_c(t) = p_{cap}(t) - p_{ren}(t) \cdot \eta_{conv} - dis_{bat} \cdot ch_{le} - nrech_{bat} \cdot p_{bat} \quad (7)$$

where $nrech_{bat}$ – number of rechargeable batteries, pcs.

When the generated energy from renewable sources is sufficient to ensure the capacity of the facility or to achieve power balance.

$$l_{fac}(t) > p_{ren}(t) \cdot \eta_{eq} \quad (8)$$

  - if the number of charged batteries is sufficient to satisfy the demand for battery replacement, $p_c(t) = 0$.
  - if the number of fully charged batteries is not enough to satisfy the demand for battery replacement, then excess power from renewable energy sources, and/or power from the grid, is used to recharge the discharged batteries:

$$p_c(t) = p_{cap}(t) - p_{ren}(t) \cdot \eta_{conv} + rech_{bat} \cdot p_{bat} \quad (9)$$

- The battery's state of charge (SOC), represented in the following model, must remain within its minimum and maximum thresholds and should attain a specified target within a designated timeframe.

$$SOC_i(t) = SOC_i(t-1) + (S_{ch}\eta_{ch})P_{EV} \quad (10)$$

$$SOC_{min,i} \le SOC(t-1) \le SOC_{max,i} \quad (11)$$

$$SOC(t_{d,i}) \ge SOC_{d,i} \quad (12)$$

where:
η_{ch} - the efficiency of the charger,
S_{ch} - an indicator binary state variable that equals to 1 when charging and 0 otherwise,
$SOC_{d,i}$ - desired value,
$t_{d,i}$ - certain time.

The development of hybrid energy facilities based on renewable energy sources and charging stations is a critical step towards achieving sustainable and clean energy systems. To conduct a feasibility study for such facilities, it's essential to consider various models and their operating conditions. In summary, a feasibility study for hybrid energy facilities based on renewable energy sources and charging stations should encompass various models, data sources, and considerations to evaluate technical, financial, environmental, and regulatory aspects. This comprehensive analysis will help stakeholders make informed decisions about the viability of such projects.

4. Results

In this study, the equipment shown in Table 1 is selected for a numerical analysis of the structure and parameters of hybrid power facilities.

Table 1.
Equipment included in the typical versions of the hybrid energy facility

PV Manufacturer number	**Sunpays Mono 9BB**	**Sunpays Mono 11BB**
Nominal Power	450kW	550kW
Module efficiency	20.7%	21.3%
Diesel Generator Manufacturer number	**Aksa AP 500**	**Aksa AVP 350**
Standby Rating	400kW	288kW
Fuel Cons. Prime With %100 Load	95lt/hr	63,5lt/hr
Wind turbine Manufacturer number	**Hummer H100KW**	**DeimosWind DT 2169**
Rated power	100kW	60kW
Cut-in wind speed	2,5 m/s	3,2m/s
Rated wind speed	10m/s	8,5m/s
Cut-out wind speed	20 m/s	25m/s
Battery Manufacturer number	**SMART ESS 500**	**SMART ESS 250**
Output Power	500 kW	250kW
Capacity	280AH	280AH
Cycle lifetime at 30% D.O.D.	16000 times	16000 times
EV model	**Togg T10X**	**Tesla Model Y**
Battery capacity	88,5 kWh	78.1 kWh
Battery range	523 km	415 km

The developed algorithm provides the opportunity to evaluate different options for the composition of the equipment of hybrid energy plants for different regions of the case study. The results of the calculations are presented in Figures 5 and 6. The results describe the analysis of the relationships between the composition and characteristics of hybrid energy systems and their efficiency, especially in terms of electricity consumption from the power grid and electricity production from the diesel power plant.

This study allows us to determine the optimal amount and type of equipment to minimize diesel fuel consumption or achieve maximum savings when using a diesel power plant as a backup power source instead of the traditional electricity grid. These results are important for the development and optimization of hybrid energy systems that can be effective in situations where access to electricity is limited or electricity supply from the main grid is unstable. They can help reduce fuel costs and increase the efficiency of energy systems.

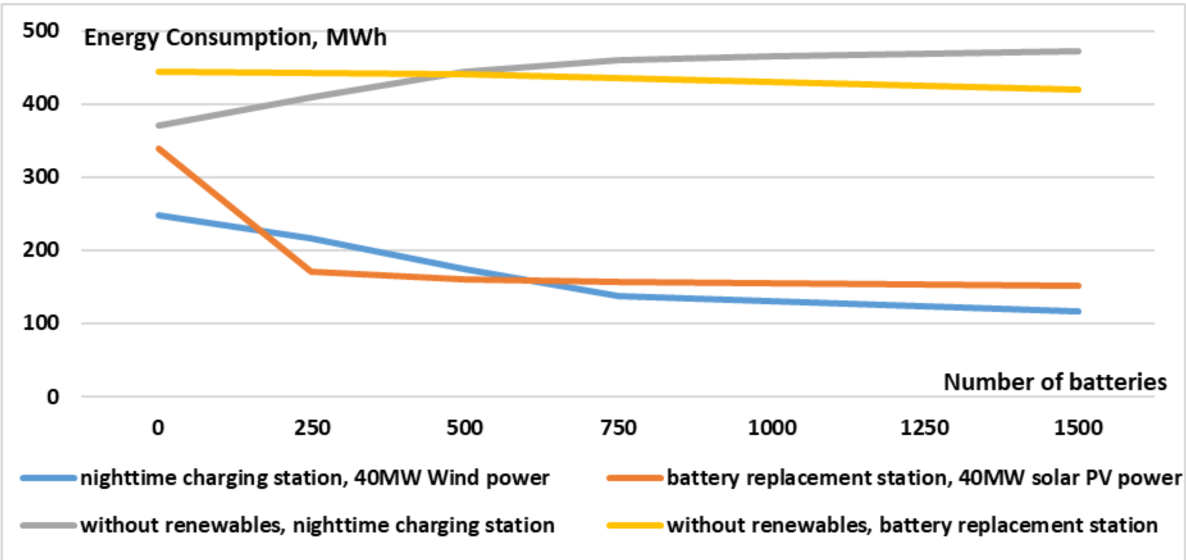

Figure 5. Energy consumed from the grid per year.

The obtained results show that with fuel consumption per 100km drive of 7-10 liter and power consumption of Togg T10X and Tesla Model Y electric vehicles per 100 km run of 16.9 and 14.5 kWh, respectively, the cost of charging an electric car is in some cases less than the cost of refueling a car.

Economic efficiency is evaluated by comparing the cost of recharging the battery of an electric car with the cost of refueling a car of the same class with gasoline according to the results of calculations of operating modes of hybrid energy facilities.

To evaluate the comparative economic efficiency of charging electric vehicles from hybrid energy installations based on renewable energy sources compared to refueling vehicles with gasoline, the electricity tariff sold to consumers was changed during the calculations.

5. Conclusions

This study addresses the pressing issue of transitioning to cleaner energy sources in the face of rising pollution from conventional vehicles. The research sheds light on the evolving landscape of electric vehicle adoption and charging infrastructure, highlighting the growing need for sustainable energy solutions. The results obtained from this study can be listed as follows:

- The mathematical models and analyses presented in this study provide a comprehensive framework for evaluating the efficiency of hybrid energy facilities and their potential impact on reducing diesel fuel consumption in electric vehicle charging stations or battery swapping stations. These insights are valuable for decision-makers, especially in regions with limited access to stable grid electricity, as they can help optimize energy systems and minimize costs.
- The study on the influence of the composition and parameters of hybrid energy installations on their operating modes has shown that grid-connected hybrid energy installations are most effective for charging stations where the highest energy consumption occurs in the evening and at night.
- In grid-connected facilities; hybrid energy facilities based on wind power plants and a charging station or battery swapping station are effective at an average annual wind speed of more than 4 m/s; solar photovoltaic stations and hybrid energy facilities with battery replacement station are effective with an average annual solar radiation of more than 680 kWh/m^2.
- In facilities not connected to the grid, it is more effective than similar hybrid energy facilities with diesel power plants, with an average annual wind speed of 5 m/s.
- The developed recommendations for determining the optimal structure of typical hybrid energy facilities based on charging stations and renewable energy sources allow for assessing the efficiency of using such hybrid energy facilities in various regions of Turkey. This assessment is based on the assignment of specific values of gross renewable energy potential and the conditions for utilizing hybrid energy facilities for each respective area in Turkey.
- However, it is evident that there is a scarcity of charging stations globally that exclusively rely on renewable energy sources, a gap that also exists in Turkey. Therefore, the study underscores the need to explore the feasibility of constructing complex energy systems based on renewables to support these charging stations. Such initiatives hold the potential to not only decrease the carbon footprint but also enhance energy independence and security.

The presented research focused on assessing the efficiency of the use of conventional energy facilities, based on renewable energy sources, to power battery replacement stations and vehicle charging stations electrical in one of the selected countries. Against the background of scientific considerations, the question must be answered whether such a model of behavior can be replicated in other countries, including Poland? According to researchers, the adoption of this vision should certainly be verified with broader analyses, from an interdisciplinary perspective, including: taking into account the number of vehicles and charging stations, the management of cable and transmission infrastructure and the energy efficiency of renewable energy installations in various urban and rural areas.

To sum up, the presented research on the assessment of the efficiency of the use of conventional energy facilities, based on renewable energy sources, to power battery replacement stations and vehicle charging stations electricity in one of the selected countries do not fully cover the essence of this issue. The market will certainly take care of their verification, indicating whether the presented solutions will be implemented in practice in the near future.

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