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Optimum Design of an Electric Vehicle Charging Station Using a Renewable Power Generation System in South Korea

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Abstract: In the context of global warming and fossil fuel depletion, electric vehicles (EVs) have become increasingly popular for reducing both carbon emissions and fossil fuel consumption. However, as the demand for EV charging power rises along with the expansion of EVs, conventional power plants require more fuel, and carbon emissions increase. This suggests that the goal of promoting EV adoption to mitigate climate change and reduce reliance on fossil fuels may face significant challenges. Therefore, there is a need to adopt renewable energy generation for EV charging stations to maximize the effectiveness of EV distribution in an eco-friendly way. This paper aims to propose an optimal renewable energy generation system for an EV charging station, with a specific focus on the use of an actual load profile for the station, the consideration of carbon emissions and economic evaluation, and the study of a specific case location in Korea. As a case study, an EV charging station in Korea was selected, and its renewable energy fractions (REF) of 0%, 25%, 50%, 75%, and 100% were considered for comparison of carbon emissions and economic evaluation with the help of HOMER software. In addition, the system with 25% REF was analyzed to find the best operating strategy considering the climate characteristics of the case site. The results show that the system configuration of PV/ESS is the most economical among all the REF cases, including PV, WT, and ESS, due to the meteorological characteristics of the site, and that the system with REF below 25% is the most optimal in economic terms and carbon emissions.

Keywords: electric vehicle; electric vehicle charging station; renewable power generation; carbon emission; economical analysis; HOMER

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1. Introduction

Due to the increase in carbon emissions, there has been a global movement to reduce the use of fossil fuels [1]. Since the transportation sector accounts for 24% of global energy consumption [2], the movement to reduce carbon emissions through the dissemination of electric vehicles (EV) is accelerating [3]. After the Paris Agreement, many countries have tried to limit greenhouse gas emissions through their policies and regulations. Korea declared a 37% reduction in greenhouse gas emissions and an expansion of EV supply to 30,000 units by 2030 under the agreement and the Second Basic Plan for Eco-friendly Vehicles in Korea [4,5].

The spread of EVs is due to the perception that electric vehicles are clean in terms of greenhouse gas emissions; however, considering the power generation process for charging electric vehicles, it cannot be seen that it is true. Figure 1 shows Korea's power generation ratio and carbon emissions during power generation. It indicates that 81.4% of the total electricity load was supplied by non-renewable power sources, including nuclear power, bituminous coal, hard coal, oil, LNG, and pumped storage, while the remaining 18.3% was supplied by renewable sources. Since Korea has low energy security due to the lack of fossil fuels, the portion of the power generated by renewables is important [6]. EVs do not generate carbon during operation, but if charged using the power generated, the total amount of greenhouse gases emitted will not significantly differ from that of ordinary vehicles (LPG, diesel, and gasoline) [7]. To reduce carbon emissions and distribute EVs simultaneously, there is a need for charging EVs using renewable power generation instead of conventional power plants that emit carbon. Renewable power can contribute to various purposes, including lowering peak power [8–10], enhancing the resilience [11] of the main grid, demanding response applications [12], and distributing resource operations [13].

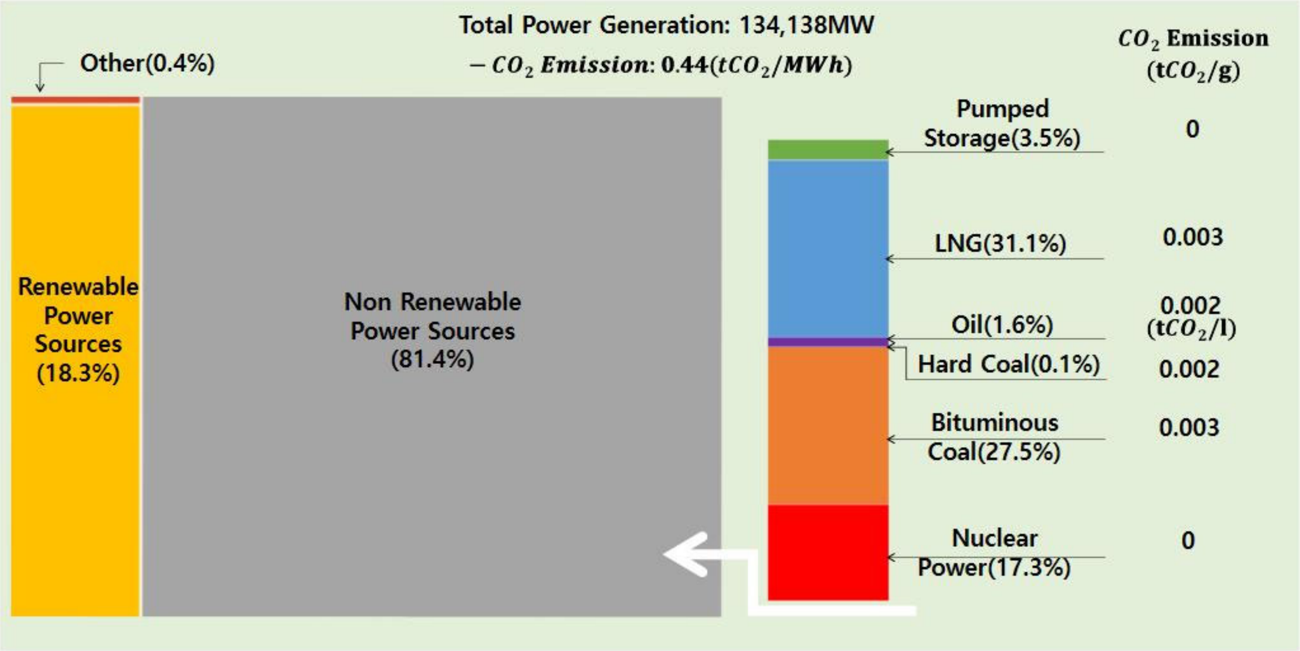


Figure 1. Power production and carbon emissions in Korea in 2021 [14].

To investigate the integration of renewable energy systems into a power grid and their optimization [15–17], the HOMER (Hybrid Optimization of Multiple Energy Resources) software [18] has been widely applied, as shown in Table 1. Kwon et al. proposed an optimal renewable-energy-based hybrid system to supply adequate power to private educational institutions in Korea [1]. Riayatsyah et al. conducted a techno-economic performance and optimization analysis of grid-connected Photovoltaic (PV) panels, wind turbines, and battery packs for Syiah Kuala University located in Indonesia [19]. Al Essa presented a PV-wind-battery system to supply electricity for individual appliances in Iraq [20]. Tiam Kapen et al. conducted a techno-economic assessment of a PV/Fuel Cell/Electrolyzer/Biogas system for energy and hydrogen production in Cameroon [21]. Rahmat et al. conducted a study that aimed to find the best renewable energy technology combined by solar, wind, hydroelectric, and biomass energy for several scenarios in Malaysia [22]. Mas'Ud et al. computed the economic feasibility of installing a PV/wind/diesel/battery system in a remote location in northern Saudi Arabia [23].

In addition, investigations related to renewables-integrated EV charging stations have been conducted. Muna et al. conducted an economic and environmental evaluation of EV charging stations in three cities of Ethiopia, powered by the system configuration of PV/diesel and three different battery technologies [24]. Al Wahedi et al. performed a techno-economic assessment in four cities of Qatar to determine the best configuration of renewables for a novel stand-alone renewables-based charging station [25]. Al Wahedi Ekren, Orhan et al. conducted a case study of a hybrid wind–solar energy charging station in Turkey [2]. Karmaker et al. proposed an optimal EV charging station based on PV, biogas, and battery in Bangladesh [26].

Table 1. Previous studies conducted using HOMER software.

Ref.	Authors	Year	Location	System Components	Facility for the Installation of the System	Considerations for Optimal System Design		
						Total NPC	Actual Load	CO_2
[1]	Kwon et al.	2022	Korea	Wind/Battery/Grid	University	Y	Y	N
[19]	Riayatsyah et al.	2022	Indonesia	PV/Wind/Battery/Grid	University	Y	Y	N
[20]	Al Essa	2023	Iraq	PV/Wind/Battery	Household	Y	N	Y
[21]	Tiam Kapen et al.	2022	Cameroon	PV/Fuel-cell/Electrolyzer/Biogas	Household	Y	N	N
[22]	Rahmat et al.	2022	Malaysia	PV/Wind/Diesel/Battery/Grid	Household	Y	N	N
[23]	Mas'Ud et al.	2021	Saudi Arabia	PV/Wind/Diesel/Battery	Household	Y	Y	N
[24]	Muna et al.	2022	Ethiopia	PV/Wind/Diesel/Battery	EV charging station	Y	N	N
[25]	Al Wahedi et al.	2022	Qatar	PV/Wind/Electrolyzer/Battery/Bio	EV charging station	Y	N	N
[26]	Karmaker et al.	2018	Bangladesh	PV/Battery/Bio	EV charging station	Y	Y	N
This paper	Ihm et al.	2023	Korea	PV/Wind/Battery/Grid	EV charging station	Y	Y	Y

"Y" refers to being considered; "N" refers not to being considered.

From the literature review, the following facts were found. First, an optimal system design was proposed by deriving the scenario with the lowest total NPC (Net Present Cost). Although the total NPC is an important parameter for optimal system design, since electric vehicles are being distributed to reduce carbon emissions, the ratio of renewable power generation and carbon emissions for each system should also be analyzed. Second, research using an actual load profile has been rarely conducted. In most cases, the load was constructed under several conditions. As shown in [20,21], several studies on residential areas constructed load scenarios assuming the capacity and time of household appliances used every day. Most of the studies conducted on electric vehicle charging stations utilized information such as the type of EV that is most widely distributed in the case site, the average mileage of vehicles, and assumptions about the number of vehicles visited and charging capacity to construct the load profile [2,24–26]. In the case of households, load demand may vary depending on the number of people living or the size of the building, but EV charging stations tend to have a constant pattern of load over time and season, particularly in Korea [27]. For this reason, there is a need for conducting system optimization using the actual load profile of the electric vehicle charging station. Third, case studies in Korea are insufficient, and in particular, no study has researched the optimization of renewable energy generation systems for electric vehicle charging stations in Korea.

For this reason, this paper aims to address this research gap by investigating the optimization of the renewable energy generation system for EV charging stations in Korea using the actual load profile, and for the optimization of the system, carbon emission, and the NPC from the ratio of renewable power generation. The rest of this paper is organized as follows. Section 2 introduces the methodology for designing a renewables-integrated EV charging station and the system configuration, including PV panels, wind turbines, an energy storage system (ESS), and a converter. Section 3 describes a case study of a renewables-integrated EV charging station in Korea considering renewable energy fractions (REFs) and proposes an optimal design case under an REF of 25%. Section 4 demonstrates the results of the case study of each REF, the following power flow, economic evaluation, and carbon emissions. Finally, Section 5 presents a further discussion of the case study and concludes this paper.

2. Methodology

This study aims to design a renewable energy generation system for an electric vehicle charging station to intensify the effect of electric vehicle distribution on the reduction in carbon emissions. This study has been performed using HOMER software developed by the National Renewable Energy Laboratory in the United States. HOMER is an effective tool for designing and evaluating a hybrid power system, which consists of various energy sources and loads [1,28].

2.1. System Configuration

For the design of a renewable power generation system-integrated EV charging station, PV panels, wind turbines, ESSs, and converters were used as the major components. The connection to the utility grid was also considered for the comparison of carbon emissions according to the REFs. Figure 2 shows a schema of the system configuration.

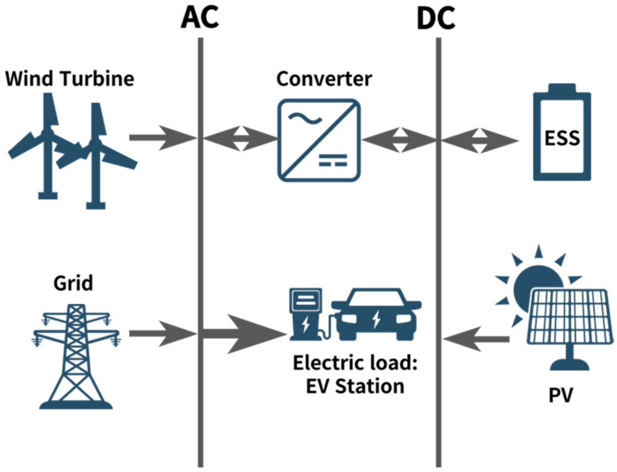


Figure 2. A schema of the proposed system configuration.

Even though connecting the EV chargers directly to the DC bus reduces energy losses and improves charging speed, the infrastructure in the considered EV charging station remains in a legacy system that is not designed to support a direct connection to the DC bus, as shown in Figure 3. The advantages of the direct connection to the AC bus are decentralized operation, less infrastructure, direct connection without going through a station, and short electrical cables, resulting in low electric power loss.

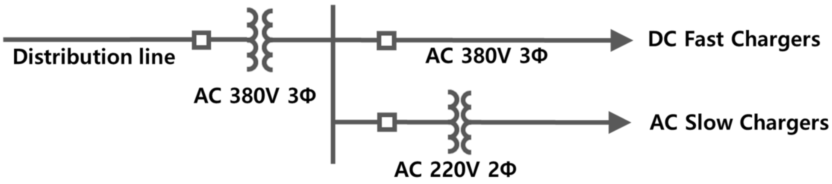


Figure 3. A single-line diagram of the Korean distribution system along with the electric chargers.

2.1.1. Solar PV Panels

PV panels are widely used in sites with abundant solar radiation as a key technology for producing electricity. The rated capacity of the PV array and solar radiation are used as input to calculate the amount of power generated through the PV panels. The effect of temperature on the PV array was not considered in this study, so the PV power generation can be calculated using the equation below [18]:

$$P_{pv} = Y_{pv} f_{pv} \left(\frac{G_T}{G_{T,STC}} \right) \tag{1}$$

where Y_{pv} measured in kW represents the power output of PV under its standard test conditions, f_{pv} measured in % represents the derating factor of PV, G_T measured in $\mathrm{kW/m^2}$ represents the incident solar radiation on the PV array in the current time step, and finally $G_{T,STC}$ denotes the incident radiation at standard test conditions.

2.1.2. Wind Turbine (WT)

The power output of the wind turbine follows the following steps:. First, the wind speed at the hub height of the wind turbine is determined. Second, the amount of power produced by the wind turbine is calculated at the wind speed that was previously obtained at the standard air density. Finally, the power output of the wind turbine at each phase of the process is determined using the features of the case site as the input. The power generated by the wind turbine can be calculated as follows [18]:

$$U_{hub} = U_{anem} \left(\frac{z_{hub}}{z_{anem}} \right)^{\alpha} \tag{2}$$

where U_{hub} turbine measured in $\mathrm{m/s}$ represents the speed of the wind at the wind turbine's hub height, U_{anem} represents the wind speed at the height of the anemometer, z_{hub} measured in meters denotes the hub height of the wind turbine, z_{anem} denotes the height of the anemometer, and α represents the power law exponent.

2.1.3. Energy Storage System (ESS)

The energy storage system (ESS) has been chosen to store excess power and supply it when the generated power does not meet the load. The capacity of the ESS during the charging and discharging modes can be computed as follows [21]:

$$C_{Bcharg}(t) = C_{Bcharg}(t-1)(1-\sigma) + \left\{ P_T(t) - \frac{P_L(t)}{\mu_{conv}} \right\} \mu_{Batt} \tag{3}$$

$$C_{Bdischarg}(t) = C_{Bdischarg}(t-1)(1-\sigma) + \left\{ \frac{P_L(t)}{\mu_{conv}} - P_T(t) \right\} \mu_{Batt} \tag{4}$$

where $P_T(t)$ represents the total output power generated by the system, $P_L(t)$ represents the load demand at the corresponding hour, μ_{Batt} represents the battery efficiency, and μ_{conv} denotes the hub height of the wind turbine.

2.1.4. Connection to Utility Grid

The utility grid is commonly connected to an EV charging station for supplying electric power to the station. To evaluate the economic cost of the system according to the ratio of renewable power generation and to analyze carbon emissions in each REF case, the connection to the utility grid should be considered.

2.2. Economic Evaluation

The optimal power source configuration is suggested based on an economic analysis by applying the climate data of the target area and power generation systems designed within the program [29]. Net Present Cost (NPC) is the main economic indicator of HOMER as a criterion for deriving economically optimal system configurations [30]. The NPC is calculated through the capital cost, replacement cost, and maintenance cost that occurred during the entire project period as follows [7]:

$$C_{NPC} = \sum_{n=0}^{t} \frac{C_n}{(1+r)^n} - I_0 \tag{5}$$

where C_n denotes the total annual cost, r denotes the discount rate, t denotes the project life, and I_0 represents the initial cost.

3. Case Study

3.1. Selection of Charging Station Site

The purpose of this study is to analyze the reduction in carbon emissions and evaluate the economic feasibility of the installation of renewable power systems in a typical type of electric vehicle charging station initially fed by the power grid. For the effective operation of the renewable power generation system, it is important to select a place with a high charging demand among electric vehicle charging stations currently operating in Korea. Therefore, selecting a charging station with a constant load profile and steady vehicle visits among electric vehicle charging stations located in a city with a high penetration rate of electric vehicles is an important criterion. Since electric vehicle charging stations are often located near residential areas, it is likely to select renewable power sources that can be installed in urban areas, such as solar panels and small wind turbines. Because solar radiation and wind speed are important resources for solar and wind power generation, an area with abundant weather resources has been selected among the sites that met the previous conditions.

Based on these criteria, a charging station located in a park in Daegu, Korea, has been selected as the installation site. Daegu has the third-largest supply of electric vehicles and the second-highest solar radiation in Korea [31,32]. Figure 4 shows the location of Daegu, Korea, from the HOMER.

Figure 4. A map of Daegu, Korea in HOMER.

In particular, the selected charging station is in a park near downtown, and there are eight high-speed chargers with a capacity of 100 kW, so there is a steady visit of electric vehicles for charging. In addition, there is idle land nearby, which has the advantage of having space for the installation of renewable power sources. Figure 5 shows a panoramic view of the selected charging station from Google Earth.

Figure 5. A panoramic view of the selected charging station.

3.2. Meteorological Resources

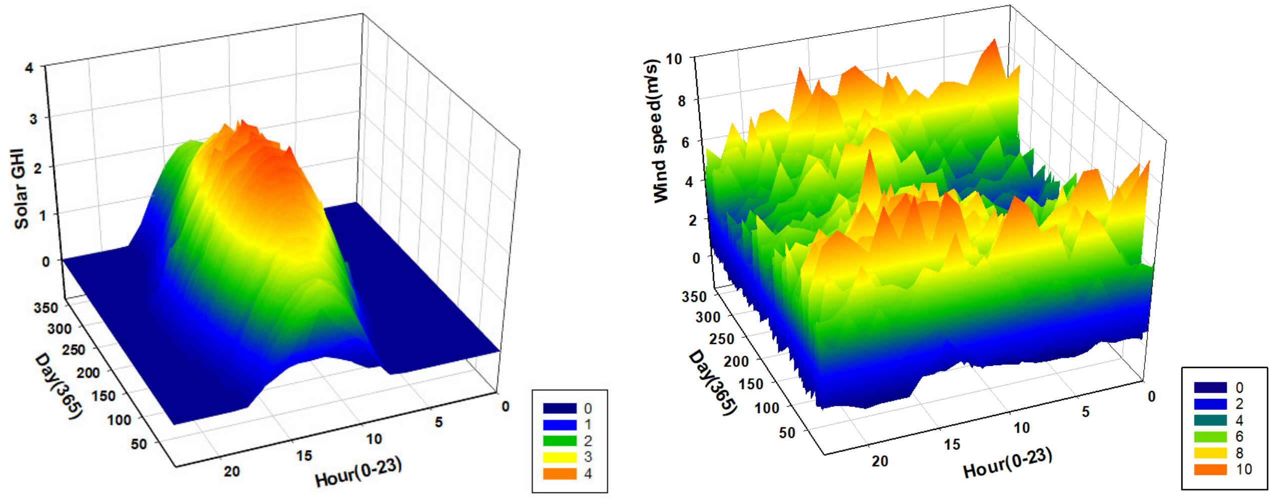
The annual average solar radiation in Daegu is 4.22 kWh/m/day, which has higher potential than other regions in Korea. Its monthly average solar radiation is relatively high during late spring to summer (April to July). Due to the topographical characteristics of Daegu, which belongs to the inland region, its wind speed is lower than the average wind speed of other regions in Korea. It has an average annual wind speed of 2.25 m/s and a relatively high wind speed during winter (December–February) and spring (March–May). Specific meteorological data are shown in Table 2. Figure 6 shows the amount of solar radiation and wind speed in Daegu Metropolitan City according to time and date [32].

Table 2. Average meteorological data.

Month (1–12)	**Solar Radiation (kWh/m^2)**	**Clearness Index**	**Wind Speed (m/s)**	**Temperature (°C)**
January	2.281	0.573	2.533	0.467
February	3.691	0.588	2.699	4.816
March	4.385	0.540	2.417	10.201
April	5.713	0.577	2.907	14.503
May	5.360	0.483	2.456	18.282
June	5.508	0.477	2.227	23.211
July	5.457	0.483	2.177	26.899
August	4.062	0.394	1.633	25.700
September	3.729	0.428	2.051	22,067
October	3.817	0.560	1.569	16.477
November	2.967	0.567	1.980	9.510
December	3.051	0.674	2.362	3.136

3.3. Load Demand

The load profile of the EV charging station has been obtained from the Korea Electric Power Corporation (KEPCO) and its annual average load demand is demonstrated in Figure 7 [33]. It can be seen that the peak load of this station is 89 kW with an average load of 157.61 kWh/day (6.57 kW). On average, this station has a high consumption of electricity at 10 AM and 7 PM.



(**a**) (**b**)

Figure 6. Meteorological data of Daegu. (**a**) Solar GHI. (**b**) Wind speed.

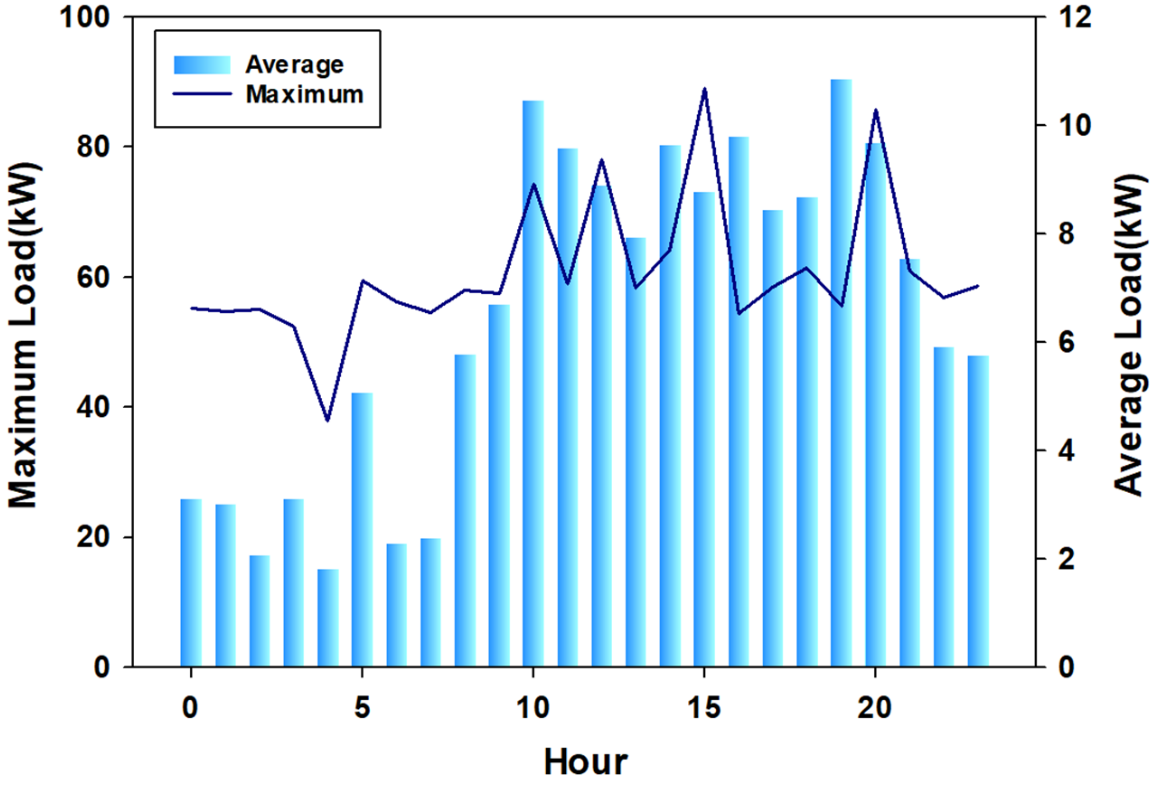


Figure 7. Load demand of the EV charging station.

3.4. Utility Grid and Renewables

The EV charging station's power system is fully powered by the utility grid in which KEPCO operates. As can be seen in Table 3, Korea is applying a system that charges different rates depending on the season and time for the electric vehicle charging station operators [33]. Table 4 shows the specific data of the components for power generation and storage applied in this case study. The derating factor of the PV panels and the hub height of the wind turbine are considered 80% and 17 m, respectively. Five renewable energy fraction (REF) cases, 0%, 25%, 50%, 75%, and 100%, have been selected and simulated for the comparison of carbon emissions and economic evaluation.

Table 3. Electricity charges for the electric vehicle (EV) charging station operators.

	Charge of Electricity (USD /kWh)		
Time Zone	**Summer (Month: 6~8)**	**Spring/Fall (Month: 3~5, 9~10)**	**Winter (Month: 11~2)**
Light load	0.067	0.059	0.075
Heavy load	0.099	0.068	0.09
Maximum load	0.12	0.071	0.10

Table 4. Specific data of the components for power generation and storage.

	PV	**WT**	**ESS**	**Converter**
Rated Capacity	**1 (kW)**	**3 (kW)**	**13.2 (kWh)**	**1 (kW)**
Capital cost (USD)	1400	1800	6480	550
Replacement cost (USD)	1400	1800	5980	450
O&M (USD /year)	20	180	-	15
Lifetime	25	20	10	15
Reference	[18]	[34]	[24]	[18]

4. Results

4.1. Scenarios under Different REFs

Based on the proposed methodology and the conditions of the case study, scenarios under different REFs with variations of 0, 25, 50, 75, and 100% have been simulated. According to the REFs, different system architectures were obtained, as shown in Table 5. The total cost for the operating years, excess electricity and CO_2 emission per year, PV output power, and energy purchased from the grid are also listed for each scenario. Due to Daegu's meteorological characteristics of low wind speed compared to solar radiation, the installation of solar panels was considered a priority over wind turbines in all five scenarios.

Table 5. Optimization results for different REF cases.

Renewable Fraction (%)	**Architecture**			**Cost**	**System**		**PV**	**Grid**
	PV (kW)	**ESS (Quantity)**	**Converter (kW)**	**NPC (USD)**	**Excess Electricity (kWh/Year)**	**CO_2 (kg/Year)**	**Production (kWh/Year)**	**Energy Purchased (kW)**
0	0	0	0	USD 48,318	0	27,038		57,528
25	30	2	18.1	USD 104,756	22,946	20,277	38,593	43,143
50	80	6	49.4	USD 214,821	71,639	13,514	102,914	28,753
75	110	22	65.1	USD 393,207	93,194	6598	141,507	14,038
100	130	37	94.5	USD 560,163	102,589	0	167,235	0

4.2. Optimal Operation Strategy

The ratio of renewable power generation of renewable-based EV charging stations currently operating in Korea is about 25%. In consideration of this, an additional analysis was conducted for the cases with an REF of 25%. Seasonal power flows were simulated for three scenarios, (a), (b), and (c), where the composition of power sources was PV + Grid, PV + WT + Grid, and WT + Grid, respectively. To represent each season, the main flow of the second day of April (Spring), July (Summer), October (Fall), and January (Winter) are shown. All three scenarios have a common point of purchasing 43,143 kWh of power annually from the utility grid.

Scenario (a) consists of a 30 kW PV panel and two ESSs with a capacity of 13.2 kWh. In this scenario, the total amount of power produced by PV is 38,593 kWh annually. In spring and summer, when solar radiations are relatively high compared to other seasons, the average power output of PV panels is 5.37 kW and 4.55 kW, respectively, which is higher than the average power purchased from the utility grid of 3.18 kW and 2.66 kW. On the other hand, in winter when the solar radiation is the lowest, the average PV generation is 4.10 kW and the average power purchased from the utility grid is 5.06 kW. To meet the annual total load demand, it can be seen that the proportion of solar power generation is higher than the electricity purchased from the utility grid in the spring/summer seasons and the proportion of electricity purchased from the utility grid is higher than the solar power generation in the autumn/winter seasons.

Scenario (b) consists of a 25 kW PV panel, five wind turbines, and three ESSs. In this scenario, the total annual amount of power produced by PV is 32,161 kWh, and 2036 kWh of power is generated by the wind turbines annually. Unlike solar panels, which have a large deviation between day and night, wind turbines do not fluctuate much with time, but they appear to vary according to the season. In spring and winter, when solar radiation and wind speed are relatively high compared to other seasons, wind turbines have been shown to assist solar panels during the night and dawn. On the other hand, in summer and autumn, most of the renewable power generation is satisfied by solar panels because of the low wind speed, which is below the reference for wind turbines' minimum power of 4 m/s [18].

Scenario (c) consists of seventy-two wind turbines and forty-six ESSs. Since the average wind speed of the case site is far below the standard for a wind turbine's maximum power output of 14 m/s [18], it was shown that more capacity for a wind turbine should be installed than for a solar panel generating the same amount of power. In the case of scenario (c), the total amount of power produced by the wind turbines is 29,317 kWh annually. In spring and winter, when wind speeds are relatively high compared to other seasons, the average power output of the wind turbines is 5.08 kW and 5.89 kW, respectively, which is higher than the average power purchased from the utility grid of 3.10 kW and 3.94 kW. On the other hand, in autumn, when the wind speed is the lowest, the average wind power generation is 0.66 kW and the average power purchased from the utility grid is 6.44 kW. It can be seen that most of the load demand is satisfied by the power purchased from the utility grid.

Table 6 lists the specific data for the cases with 25% REF. Solar power generation has intermittent characteristics over time, but a certain amount of power generation is observed during the day. In contrast, wind power generation did not change much over time, but there were many differences in daily power generation due to the inconsistent wind speed in Daegu. Because of this reason, scenarios with PV panels had a higher rate of excess electricity compared to the scenario with only wind turbines, but scenarios with wind turbines required even more ESSs compared to the scenario with one PV panel to supply stored excess power when wind generation is not available due to the low wind speed.

Table 6. Specific data for REF 25% cases.

Scenario	**System Components**			**Excess Electricity**	
	PV (kW)	**WT (unit)**	**ESS (unit)**	**Percentage (%)**	**Power (kWh/Year)**
(a) PV + Grid	30	-	2	28.1	22,946
(b) PV + WT + Grid	25	5	3	21.9	16,602
(c) WT + Grid	-	72	46	17.5	12,694

Scenario (b) shows that wind turbines play an auxiliary role in solar power generation at night when there is no sunlight, but compared to the total amount of solar power generation, its role is insignificant. So, when considering the efficiency of the energy production and the initial cost of system components, it is observed that a single operating system of PV panels in scenario (a) is the most efficient system for the charging station. In other words, when operating a renewable generation system for EV charging stations located downtown with low wind speeds, installing a single operating system of PV panels would be appropriate.

4.3. Economic Analysis

In this section, an economic analysis of five different REF cases is presented. Figure 8 shows the initial cost and the cost of operation and maintenance (O&M) according to the increase in REF. As REF increases, the cost of O&M decreases due to the decrease in the power purchased from the utility grid. In contrast to O&M, the initial capital and replacement costs increase because the system requires more capacity for renewable energy generation components for power generation.

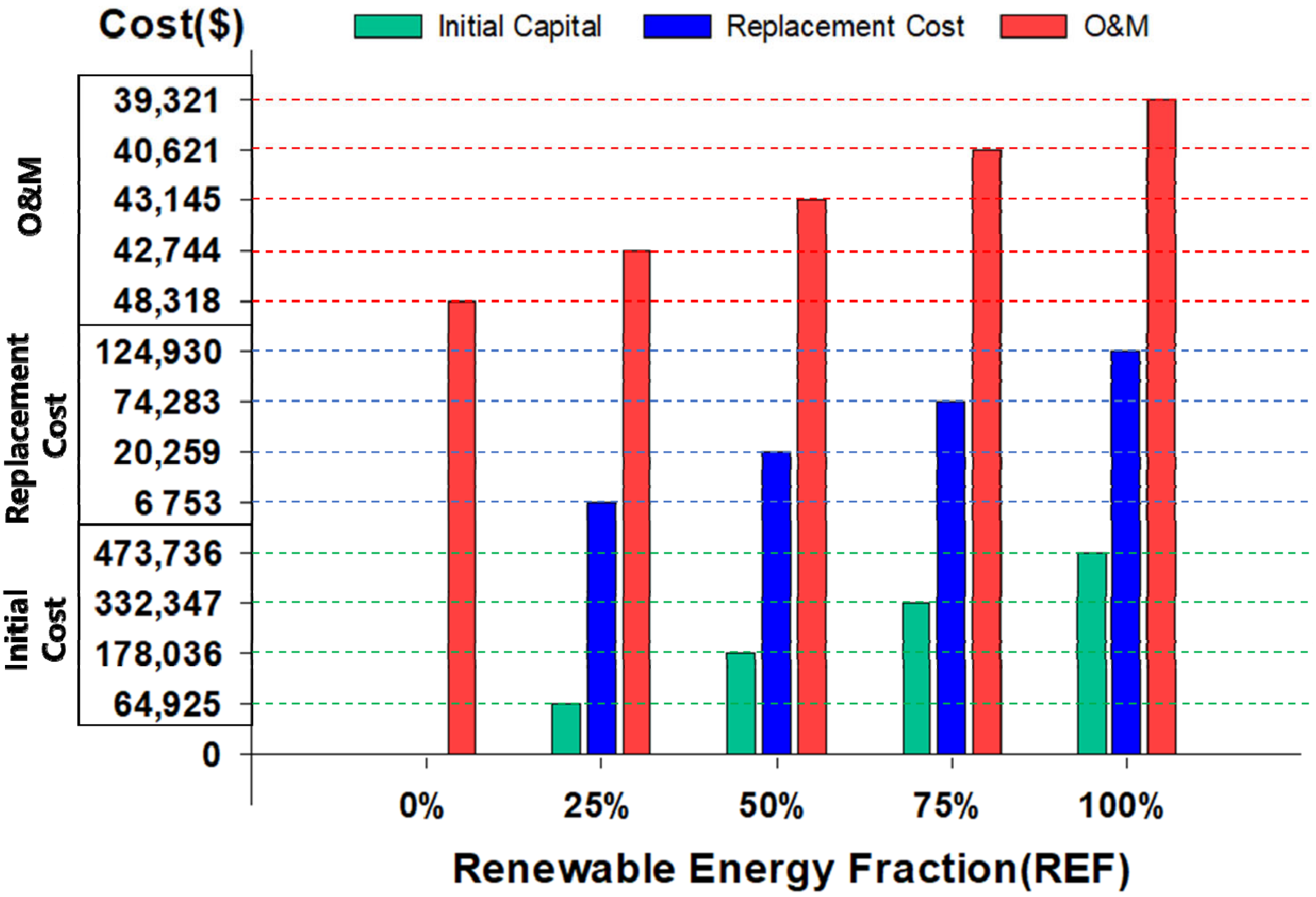


Figure 8. Cost summary of different REF cases.

The total NPC for each case is shown in Figure 9. The total NPC required for each case is USD 4937, USD 10,756, USD 214,821, USD 393,207, and USD 560,163, respectively. Since the capital and replacement costs of the system components are much higher than the fee for purchasing electricity from the utility grid, the total NPC increases as REF increases. As illustrated in Figure 10, the proportion of power supplied through the storage power of the ESS among the total power supplied via renewable power sources increases with an increase in REF. This is because, when REF exceeds 50, the load needs to be satisfied with renewable power even at night when solar power does not occur, so a large capacity of ESS is required compared to the cases of REF below 50. To meet this, the proportion of ESS's NPC of the total NPC tends to increase as REF increases.

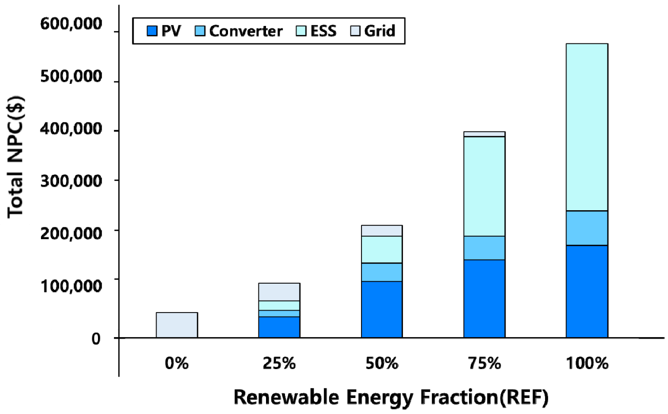


Figure 9. Total Net Present Cost (NPC) of different REF cases.

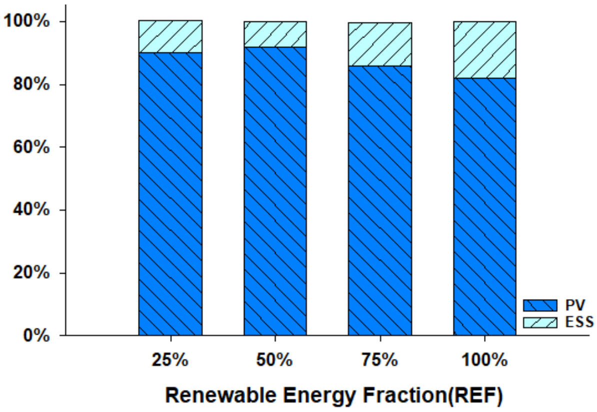


Figure 10. Power production/storage ratio of PV and ESS of different REF cases.

4.4. Correlation Analysis between Carbon Emissions and NPCs According to REF

Figure 11 depicts the carbon emissions and NPC according to the REF. As REF rises from 0% to 100%, the NPC grows, and emissions fall. The total annual CO_2 emissions for each case are 27,038, 20,277, 13,514, 6598, and 0 kg, respectively. It is clear that an increase in the ratio of renewable power led to a decrease in carbon emissions due to the use of EVs.

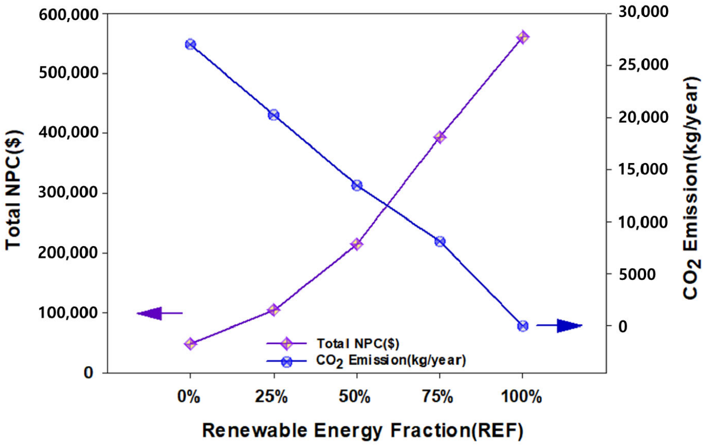


Figure 11. Total NPC and carbon emissions based on REF.

For the section with an REF of 0–25, an increase of 1% in REF reduces carbon emissions by 270 kg per year, and the total NPC increases by USD 16, so an additional charge of USD 0.06 per year is required to reduce carbon emissions by 1 kg. For the section with an REF of 25–50, an increase of 1% in REF reduces carbon emissions by 271 kg per year, and the total NPC increases by USD 327, so an additional fee of USD 1.2 per year is required to reduce carbon emissions by 1 kg. For the 50–75 REF section, an increase of 1% in REF reduces carbon emissions by 277 kg per year, and the total NPC increases by USD 285, so an additional USD 0.97 per year must be paid to reduce carbon emissions by 1 kg. For sections with REFs of 75–100%, an increase of 1% in REF reduces carbon emissions by 264 kg per year, and the total NPC increases by USD 267, so an additional USD 0.99 per year should be paid to reduce carbon emissions by 1 kg. It can be seen that when the REF exceeds 25%, an increase in NPC for a reduction in carbon emissions increases compared to when the REF is less than 25%. This is because of the increase in NPC for additional installation of PV to prepare for situations where the load must be satisfied through solar power generation, but solar radiation is not sufficient.

The larger the renewable power generation ratio, the smaller the carbon emission is, but considering the current situation where the initial cost of renewable power sources is too high compared to power purchased from the utility grid, a system with a REF of 25% or less is considered to be the most optimal system in economic terms.

5. Discussion

The wind speed in Korea is relatively low, so wind turbines in the renewable system seem to have a meaningful effect on overall power production. Therefore, the systems including wind turbines were evaluated as economically low, whereas the system of PV and ESS combination was the most optimal for all REF cases. When REF exceeded 25%, the increase in NPCs for a 1% increase in REF and a 1 kg reduction in carbon emissions was 21 times higher than that of the system with an REF of 25% or less. So, the larger the renewable power generation ratio, the smaller the carbon emission is. Considering the current situation where the initial cost of renewable power sources is too high compared to power purchased from the utility grid, a system with an REF of 25% or less is the most optimal system in economic terms. Considering each simulation result together, it can be determined that scenario (a), with a total NPC of 104,756 and configuration of a 30 kW PV and 2 ESSs, is the most optimal system for a renewable power generation-based electric vehicle charging station.

Since electric vehicle charging stations are restricted by space, power sources that occupy a large amount of space, such as fuel cells and biogas, could not be considered. Additionally, due to the low wind speed in Korea, the influence of wind turbines was very little on the total power system in a techno-economic term. From the system configuration of PV/WT/ESS/Grid, a system that consists of PV, ESS, and Grid has been determined to be the most optimal system. This is a system with an REF of 25%, which purchases 43,143 kWh of power annually.

In terms of policy recommendations, it is important to consider incentives to increase the penetration of electric vehicles. To promote the adoption of electric vehicles and support the development of renewable energy, policymakers can implement various incentives and policies. For example, tax credits, subsidies, and grants can be provided to individuals and businesses that purchase and install EV charging stations with renewable energy generation systems. Additionally, regulations can be established to require new buildings and parking lots to include EV charging infrastructure and renewable energy generation systems. Furthermore, utilities can offer time-of-use rates and other incentives to encourage EV owners to charge their vehicles during off-peak hours, which can help balance the grid and reduce the need for additional conventional power plants.

However, the deployment of charging centers should be distributed optimally to avoid grid congestion and ensure the efficient utilization of renewable energy generation systems. The optimal distribution can be determined based on factors such as the number of EVs in the area, the availability of renewable energy sources, and the capacity of the grid infrastructure. This can help avoid overloading the grid during peak charging times and ensure that the renewable energy generation system is used to its full potential.

Regarding the contribution of clean energies, the REF of the renewable energy generation system can play a crucial role. As shown in this study, the optimal REF for the EV charging station was found to be 25% or less, considering economic evaluation and carbon emissions. However, the optimal REF can vary depending on factors such as the location, climate, and available renewable energy sources. Therefore, it is essential to conduct a thorough feasibility study and consider all the relevant factors to determine the optimal REF for each EV charging station.

Moreover, the efficiency of the renewable energy generation system against the consumption of the conventional electrical grid can be evaluated using metrics such as REF and the levelized cost of electricity (LCOE). These metrics can help assess the economic and environmental impacts of the renewable energy generation system and compare it to the conventional electrical grid. Policymakers and stakeholders can use these metrics to determine the feasibility and potential benefits of adopting renewable energy generation systems for EV charging stations.

In summary, policymakers can implement various incentives and policies to promote the adoption of electric vehicles and support the development of renewable energy. The deployment of charging centers should be distributed optimally to avoid grid congestion and ensure the efficient utilization of renewable energy generation systems. The optimal REF can vary depending on various factors, and it is essential to conduct a thorough feasibility study to determine the optimal REF for each EV charging station. Finally, metrics such as REF and LCOE can help assess the economic and environmental impacts of the renewable energy generation system and compare it to the conventional electrical grid.

6. Conclusions

This study analyzed the techno-economic feasibility of different renewable energy systems for electric vehicle charging stations in Korea. The most optimal system was found to be a combination of photovoltaic panels and energy storage systems, with a renewable energy fraction of 25% or less. Based on the simulation results, the optimal system for a renewable power generation-based EV charging station in Korea was composed of a 30 kW PV and 2 ESSs configurations, with a total NPC of 104,756. The system configuration of PV/ESS/Grid is the most optimal, with an REF of 25%, which purchases 43,143 kWh of power annually in terms of economic evaluation and carbon emissions. This applies to sites that have the same constraints and climatic conditions. This study also suggests that policymakers can implement incentives, such as tax credits, subsidies, and grants for the adoption of electric vehicles and renewable energy systems in EV charging stations. Finally, it is essential to conduct a thorough feasibility study to determine the optimal REF for each EV charging station based on factors such as location, climate, and available renewable energy sources. As there is very little research on the optimization of renewable power generation systems of Korean electric vehicle charging stations, based on actual loads, this study is expected to affect the activation of new and renewable energy-based electric vehicle charging stations in Korea.

The limitation of this work is that we only considered the historical visiting vehicles to the designated electric vehicle charging station. Future expectations of charging demands could be further analyzed to improve the accuracy of our results. As a further study, the case study is to accurately identify the zone of incidence to assess the potential impact of the proposed system on the surrounding area, particularly in terms of traffic flow and congestion. In addition, a traffic simulation will be conducted to better understand the micro-level effects of the system on a local road network. Finally, this study can be improved if we integrate into our future projects the vehicle-to-grid technology, which consists of considering the battery of an electric car as an extension of the distribution network, a reservoir in which the electricity supplier can use this stored energy.

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References

1. Kwon, S.; Gil, H.; Baek, S.; Kim, H. Optimal Solution for a Renewable-Energy-Generation System at a Private Educational Institute in South Korea. *Energies* **2022**, *15*, 9430. [CrossRef]
2. Ekren, O.; Hakan Canbaz, C.; Güvel, Ç.B. Sizing of a Solar-Wind Hybrid Electric Vehicle Charging Station by Using HOMER Software. *J. Clean. Prod.* **2021**, *279*, 123615. [CrossRef]
3. Un-Noor, F.; Padmanaban, S.; Mihet-Popa, L.; Mollah, M.N.; Hossain, E. A Comprehensive Study of Key Electric Vehicle (EV) Components, Technologies, Challenges, Impacts, and Future Direction of Development. *Energies* **2017**, *10*, 1217. [CrossRef]
4. Bodansky, D. The Paris Climate Change Agreement: A New Hope? *Am. J. Int. Law* **2016**, *110*, 288–319. [CrossRef]
5. Ihm, J.; Chun, S.; Park, H. Optimal Scenarios of Renewables and Chargers for an Electric Vehicle Charging Station Using Public Data. In Proceedings of the SCEMS 2022—2022 IEEE 5th Student Conference on Electric Machines and Systems, Busan, Republic of Korea, 24–26 November 2022.
6. Park, H.; Bae, S. Quantitative Assessment of Energy Supply Security: Korea Case Study. *Sustainability* **2021**, *13*, 1854. [CrossRef]
7. McKenzie, K.A. Sun, Wind and Waves: Ev Fossil Fuel Use and Emissions on an Isolated, Oil-Dependent Hawaiian Island. *World Electr. Veh. J.* **2021**, *12*, 87. [CrossRef]
8. Rahman, S.; Khan, I.A.; Khan, A.A.; Mallik, A.; Nadeem, M.F. Comprehensive Review & Impact Analysis of Integrating Projected Electric Vehicle Charging Load to the Existing Low Voltage Distribution System. *Renew. Sustain. Energy Rev.* **2022**, *153*, 111756. [CrossRef]
9. Zhuang, Z.; Jin, T. Capacity Configuration and Control Strategy of EV Charging Station with Integrated Wind Power and Energy Storage Based on SSA. In Proceedings of the 5th IEEE Conference on Energy Internet and Energy System Integration: Energy Internet for Carbon Neutrality, EI2 2021, Taiyuan, China, 22–24 October 2021; pp. 4316–4322. [CrossRef]
10. Zainab, F.; Naz, K.; Mehmood, K.K.; Basit, S.; Bukhari, A.; Wadood, A.; Khalid, H.A.; Park, H. An Optimal Joint Planning of DGs and Electric Vehicle Charging Stations in Grid-Connected and Islanded Microgrids. *IET Renew. Power Gener.* **2023**, *17*, 1623–1634. [CrossRef]
11. Zhang, B.; Dehghanian, P.; Kezunovic, M. Optimal Allocation of PV Generation and Battery Storage for Enhanced Resilience. *IEEE Trans. Smart Grid* **2019**, *10*, 535–545. [CrossRef]
12. Gong, L.; Cao, W.; Liu, K.; Yu, Y.; Zhao, J. Demand Responsive Charging Strategy of Electric Vehicles to Mitigate the Volatility of Renewable Energy Sources. *Renew. Energy* **2020**, *156*, 665–676. [CrossRef]
13. Wu, Z.; Bhat, P.K.; Chen, B. Optimal Configuration of Extreme Fast Charging Stations Integrated with Energy Storage System and Photovoltaic Panels in Distribution Networks. *Energies* **2023**, *16*, 2385. [CrossRef]
14. Korea Institute of Energy Research. Available online: https://www.kier.re.kr/eng (accessed on 28 April 2023).
15. Erdinc, O.; Uzunoglu, M. Optimum Design of Hybrid Renewable Energy Systems: Overview of Different Approaches. *Renew. Sustain. Energy Rev.* **2012**, *16*, 1412–1425. [CrossRef]
16. Saadatmand, M.; Gharehpetian, G.B.; Siano, P.; Alhelou, H.H. PMU-Based FOPID Controller of Large-Scale Wind-PV Farms for LFO Damping in Smart Grid. *IEEE Access* **2021**, *9*, 94953–94969. [CrossRef]
17. Shivarama Krishna, K.; Sathish Kumar, K. A Review on Hybrid Renewable Energy Systems. *Renew. Sustain. Energy Rev.* **2015**, *52*, 907–916. [CrossRef]
18. HOMER Pro—Microgrid Software for Designing Optimized Hybrid Microgrids. Available online: https://www.homerenergy.com/products/pro/index.html (accessed on 6 April 2023).
19. Riayatsyah, T.M.I.; Geumpana, T.A.; Rizwanul Fattah, I.M.; Rizal, S.; Indra Mahlia, T.M. Techno-Economic Analysis and Optimisation of Campus Grid-Connected Hybrid Renewable Energy System Using HOMER Grid. *Sustainability* **2022**, *14*, 7735. [CrossRef]
20. Al Essa, M.J.M. Energy Assessments of a Photovoltaic-Wind-Battery System for Residential Appliances in Iraq. *J. Energy Storage* **2023**, *59*, 106514. [CrossRef]

21. Tiam Kapen, P.; Medjo Nouadje, B.A.; Chegnimonhan, V.; Tchuen, G.; Tchinda, R. Techno-Economic Feasibility of a PV/Battery/Fuel Cell/Electrolyzer/Biogas Hybrid System for Energy and Hydrogen Production in the Far North Region of Cameroon by Using HOMER Pro. *Energy Strategy Rev.* **2022**, *44*, 100988. [CrossRef]
22. Rahmat, M.A.A.; Abd Hamid, A.S.; Lu, Y.; Ishak, M.A.A.; Suheel, S.Z.; Fazlizan, A.; Ibrahim, A. An Analysis of Renewable Energy Technology Integration Investments in Malaysia Using HOMER Pro. *Sustainability* **2022**, *14*, 13684. [CrossRef]
23. Mas'Ud, A.A.; Al-Garni, H.Z. Optimum Configuration of a Renewable Energy System Using Multi-Year Parameters and Advanced Battery Storage Modules: A Case Study in Northern Saudi Arabia. *Sustainability* **2021**, *13*, 5123. [CrossRef]
24. Muna, Y.B.; Kuo, C.C. Feasibility and Techno-Economic Analysis of Electric Vehicle Charging of PV/Wind/Diesel/Battery Hybrid Energy System with Different Battery Technology. *Energies* **2022**, *15*, 4364. [CrossRef]
25. Al Wahedi, A.; Bicer, Y. Techno-Economic Optimization of Novel Stand-Alone Renewables-Based Electric Vehicle Charging Stations in Qatar. *Energy* **2022**, *243*, 123008. [CrossRef]
26. Karmaker, A.K.; Ahmed, M.R.; Hossain, M.A.; Sikder, M.M. Feasibility Assessment & Design of Hybrid Renewable Energy Based Electric Vehicle Charging Station in Bangladesh. *Sustain. Cities Soc.* **2018**, *39*, 189–202. [CrossRef]
27. Kim, J.H.; Moon, S.K.; Lee, B.S.; Seo, I.J.; Kim, C.H. Analysis and Pattern Deduction of Actual Electric Vehicle Charging Data. *Trans. Korean Inst. Electr. Eng.* **2018**, *67*, 1455–1462. [CrossRef]
28. Arunachalam, R.K.; Chandrasekaran, K.; Rusu, E.; Ravichandran, N.; Fayek, H.H. Economic Feasibility of a Hybrid Microgrid System for a Distributed Substation. *Sustainability* **2023**, *15*, 3133. [CrossRef]
29. Bansal, S.; Zong, Y.; You, S.; Mihet-Popa, L.; Xiao, J. Technical and Economic Analysis of One-Stop Charging Stations for Battery and Fuel Cell EV with Renewable Energy Sources. *Energies* **2020**, *13*, 2855. [CrossRef]
30. Amini, S.; Bahramara, S.; Golpîra, H.; Francois, B.; Soares, J. Techno-Economic Analysis of Renewable-Energy-Based Micro-Grids Considering Incentive Policies. *Energies* **2022**, *15*, 8285. [CrossRef]
31. KOSIS Korean Statistical Information Service. Available online: https://kosis.kr/eng/ (accessed on 6 April 2023).
32. Korea Meteorological Administration. Available online: https://www.kma.go.kr/eng/index.jsp (accessed on 6 April 2023).
33. KEPCO MAIN | KEPCO. Available online: https://home.kepco.co.kr/kepco/EN/main.do (accessed on 6 April 2023).
34. Aziz, A.S.; Tajuddin, M.F.N.; Hussain, M.K.; Adzman, M.R.; Ghazali, N.H.; Ramli, M.A.M.; Khalil Zidane, T.E. A New Optimization Strategy for Wind/Diesel/Battery Hybrid Energy System. *Energy* **2022**, *239*, 122458. [CrossRef]