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Konstantinidis, George, Paspatis, Alexandros, Katsigiannis, Yiannis and Karapidakis, Emmanuel (2025) Analysis of off-grid fast charging stations with photovoltaics, wind turbines, and battery energy storage systems along highways for electric vehicles. In: 14th Mediterranean Conference on Power Generation Transmission, Distribution and Energy Conversion (MEDPOWER 2024), 3 November - 6 November 2024, Athens, Greece.

DOI: https://doi.org/10.1049/icp.2024.4629

Publisher: Institution of Engineering and Technology (IET)

Version: Accepted Version

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Analysis of Off-Grid Fast Charging Stations with Photovoltaics, Wind Turbines, and Battery Energy Storage Systems along Highways for Electric Vehicles

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Keywords: Electric Vehicle, Off-Grid Fast Charging Stations, Hybrid Energy Systems

Abstract

Fast-charging stations play a crucial role in the transition to e-mobility, particularly those located along highways that are expected to replace conventional gas stations. However, these charging stations require significant amounts of electricity due to the high-power demand of the fast chargers. In some cases, grid availability may be limited or non-existent. This study examines the impact of various capacities of renewable energy sources (RES) and battery energy storage systems (BESS) on charging time and environmental footprint. The simulations indicate that there must be a trade-off between charging time, environmental footprint, and energy rejection, depending on the priorities set by the investor.

1. Introduction

Countries worldwide, in their attempt to decrease their environmental footprint, promote e-mobility, as one potential solution to decarbonize the transportation sector. However, adopting electric vehicles (EVs) also creates challenges, such as the amount of energy required for charging, and the accessibility of charging stations (CSs) to avoid constraining EV drivers in certain areas [1].

One solution to mitigate these challenges is to power CSs with renewable energy sources (RES) and/or battery energy storage systems (BESS). Combining RES with BESS can enable sustainable charging, as the BESS capacity can provide energy when RES production is not synchronized with charging demand.

Authors in [2] determined the optimal ESS capacity for a fast electric vehicle CS (FEVCS) by taking into account peak reduction, EV resilience enhancement, and energy storage unit (ESS) cost minimization. A hybrid storage system, comprised of BESS and superconducting magnetic energy storage is proposed in [3] to cover the needs of fast charging, high response, and energy capacity. In [4], a FEVCS integrated with photovoltaic system (PV), wind turbine (WT), and energy storage system (ESS) is proposed to address power quality issues and investment costs. Two ownership models were examined, one from the viewpoint of the wind farm owner and one from the fast-charging stations (FCS) owner. Sun et al. [5] proposed an optimization framework for capacity allocation and energy management of FEVCT with WT, PV, and ESS applied in Inner Mongolia, China. This approach uses demand response to adjust electric vehicle charging schedules based on time-of-use electricity prices. Combining multi-objective particle swarm optimization (MOPSO) with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method, it aims to balance cost savings and environmental benefits. An optimization framework to maximize the expected profit of a FEVCS is proposed in [6]. This framework considers factors like vehicle arrival patterns, the intermittency of solar PV generation, customer satisfaction, and ESS management. It identifies the optimal investment configurations and daily power scheduling under different environmental conditions for a grid-connected charging station.

In case there is no electrical grid in the area of interest or the grid has limited capacity, an off-grid CS can provide the required energy to the EV. The electrical grid uses BESS and generators to ensure a stable energy supply because of the stochastic production of RES. The study in [7] examines the effect of the integration of RES and ESS on a FEVCS. A FEVCS model is designed, and using Genetic Algorithms, it analyzes the impact of different combinations (like the on-grid and off-grid connections, the deployment setups of various RES and ESS) on economic factors and the grid's demand/response. The authors of [8], ran a feasibility study for powering an off-grid EV charger of 3.6 kW with a RES hybrid system comprising PV, WT, and BESS. According to [9], the proposed off-grid DC fast-charging station, with one 100 kW DC charging unit integrated with a 140 kWh lithium-ion battery and an optimized PV capacity, demonstrates a higher net present value and return on investment compared to conventional grid-tied fast-charging stations. The researchers of [10], propose a novel reflector-based PV system to enhance the sustainability and efficiency of an off-grid fast charger EV CS.

Although several studies have explored the integration of hybrid RES with storage units to power electric vehicle

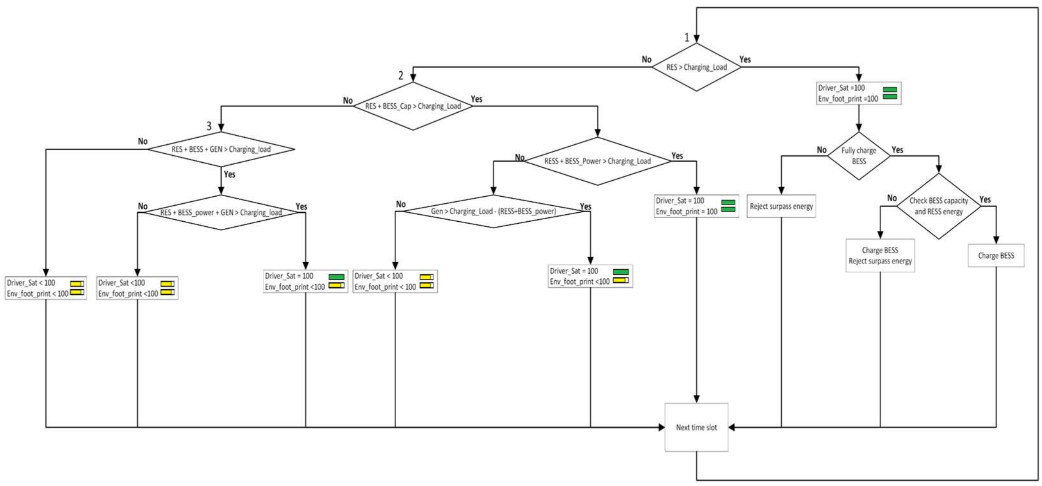


Figure 1 Flow chart of the FEVCS operation

charging stations (EVCSs), few have specifically examined how to meet the changing demands of fast EV charging stations in terms of charging time and "green" charging. This study addresses that gap by measuring the charging time and evaluating the extent to which the energy used is renewable, especially when the RES alone is insufficient to fulfill the demand. The rest of this paper is structured as follows: Section 2 describes the methodology and the assumption of the input data; Section 3 simulation results -obtained for several indicative operation scenarios- are presented and discussed; Section 4 concludes the paper.

2. Methodology

Different capacities of each component are utilized to evaluate the impact of PV systems, WT, and BESS on an off-grid supply. The case study focuses on a midpoint of the highway connecting Greece's two largest cities, Athens and Thessaloniki, located at coordinates 38.949°N, and 22.876°E, respectively.

Two indicators were considered to compare each scenario: driver satisfaction and environmental footprint. Driver satisfaction refers to the waiting time at the CS. To achieve complete driver satisfaction (100%), the charging time should be as if the charger operates at 100% capacity throughout the charging process. Conversely, the driver will be completely dissatisfied (0%) if there is no availability from PV, WT, and BESS, and the generator distributes the available power among all chargers, resulting in the maximum possible charging time. The environmental footprint indicator reflects the percentage of energy used to charge the EV from the generator.

2.1. EV and EV chargers

Four DC chargers, each with 100 kW power, are selected due to the high demand for fast charging along highways to minimize waiting times. Generally, fast charging is essential for the adoption of EVs [11]. Additionally, it is assumed that an EV is always waiting to charge, ensuring that the chargers are consistently in use. Only the two chargers are constantly in use and the other two are in use, from 10.00 am to 10.00 pm as the traffic is reduced at night. For the overnight charge, a charger with a lower power capacity will be preferred.

It is considered that the average EV battery capacity is 72 kWh [12], so the incoming EV battery capacities are randomly chosen within the range of 52 kWh to 92 kWh. The same approach is used to determine the state of charge (SoC) of arriving EV, which ranges from 10% to 30% of their SoC. Finally, the departure SoC is randomly chosen to be either 90% or 100% of the EV SoC. Four lists of 20.000 EVs data are created, one for each charger.

2.2. PV, WT, BESS and Generator selection

Two different capacities of PV, WT, and BESS were chosen, respectively, and one for the generator.

The PV power was calculated via PVGIS, version 5 [13]. The configuration made is:

- selected the examined area (38.949°N, 22.876°E)
- selected solar radiation database (PVGIS-SARAH2)
- year (2019)
- mountain type (fixed) with optimized slope and azimuth
- PV technology (Crystalline Silicon)
- Installed peak PV power (400 kWp and 600 kWp)
- System loss (14%).

A polyonymic equation (equation (1)) was created for the WT to fit the power curve of Enercon's E82 WT [14]. The wind speed at 10m height was also taken from PVGIS for the exact location and year [13]. The wind speed (m/s) in hub height, which was taken at 85m, was calculated from the equation (2).

$$u_x = u_{10}\left(\frac{x}{10}\right)^a \qquad (2)$$

Where $\mathbf{u_x}$ is the wind speed at WT's hub height, u_{10} is the wind speed at the reference height of 10 meters, x is the WT's hub height, and a is the wind shear exponent, which depends

$$WT(x)=\begin{cases} 0, & x \leq 1 \\ 0.00302472*u_x^7 - 0.13108*u_x^6 + 2.2062*u_x^5 - 18.6407*u_x^4 + 86.4213*u_x^3 - 204.554*u_x^2 + 230.106*u_x - 95.2238, & x > 1 \end{cases} \qquad (1)$$

on the surface roughness. The examined area is in an open terrain; hence, it was considered 0.14.

In the case of the BESS, capacities of 500 kWh and 1000 kWh were considered. The power output of the BESS was set at a rate of 1 to 3 times their capacity. Additionally, only 80% of the BESS capacity was utilized, and the battery charging/discharging efficiency was considered to be 93%. Finally, the power of the generator was considered 100 kW.

2.3. Operation of the Charging Station

The flow chart of the CS operation is shown in Figure 1. The first step (1) is to examine whether the energy from the PV and WT is sufficient to meet the charging load of all the chargers. If so, the EVs will charge on time, and subsequently, this charging will be considered "green". Additionally, the process will determine if the BESS needs to be charged and how much energy will be stored or rejected. If the energy from PV, WT, and BESS is insufficient to meet the charging load (2), the BESS capacity will be checked against its adequacy to contribute, even if the BESS power output is insufficient. In this scenario, the generator will cover the remaining charging load if deemed appropriate. Finally, the process will verify the extent of the generator's contribution and whether it is enough to cover the charging load.

The PV, WT, and BESS energy is distributed equally among all chargers in each case. If a charger requires less energy during a specific time slot, the surplus energy is redistributed evenly among the other chargers. The same principle applies to the generator's power.

3. Results and discussion

To assess the impact of varying capacities of PV, WT and BESS, on both the driver satisfaction and the environmental footprint of the HEVCS, eight scenarios were examined as shown in Table 1. The examined period spans across one year.

Table 1 Examined Cases

Case	PV (kWp)	WT (kW)	BESS (kWh)	Gen (kW)
1	400	2000	500	100
2	400	2000	1000	
3	400	4000	500	
4	400	4000	1000	
5	600	2000	500	
6	600	2000	1000	
7	600	4000	500	
8	600	4000	1000	

3.1. Effects on EV serviced and energy rejection

The number of EVs serviced, the total energy required for charging, and the energy rejected are all presented in Table *4*. Chargers 1 and 2 service nearly twice as many EVs as Chargers 3 and 4, due to their operation for twice the amount of time. This is similarly reflected in the energy consumption patterns.

The number of EVs charged at the station increased from Case 1 to Case 8 by up to 18.69%, while energy rejection increased significantly from Case 2 to Case 7, with a peak increase of 2847.96%. Table 2 presents the impact of BESS, WT, and PV on the total number of EVs charged at the station and the amount of energy rejected.

Table 2 Impact of BESS, WT, and PV on the total number of EVs charged and FEVCS energy rejection.

	Cases	EV number (%)	Rejection (%)
BESS	1→2	0.50	-35.89
	3→4	0.74	-14.17
	5→6	2.26	-24.09
	7→8	2.45	-11.52
WT	1→3	5.57	375.89
	2→4	5.87	537.20
	5→7	4.52	138.96
	6→8	4.72	178.53
PV	1→5	10.84	690.86
	2→6	12.83	836.51
	3→7	9.74	297.11
	4→8	11.61	309.37

As anticipated, higher capacities of RES present a positive correlation with the increased energy rejection. However, as BESS capacity increases, energy rejection decreases. Specifically, by increasing BESS capacity, energy rejection decreased by 35.89% between Cases 1 and 2, and 11.52% between Cases 7 and 8. This reduction occurs since any additional BESS capacity allows more excess energy storage. However, a simultaneous and uneven increase in RES can lead to higher rejection rates, as BESS may not be able to store all excess energy when it is fully charged or due to potential BESS power limitations. Additionally, increasing PV capacity results in higher rates of EV service and energy rejection than increasing WT capacity. An example of the PV and WT contribution to the charging load can be observed in *Figure 2* Power distribution of PV, WT, BESS, and Generator to cover charging demand on April 15th (a) Case 1, (c) Case 8; and on October 15t (b) Case 1 and (d) Case 8.Figure 2.

3.2. Effects on driver satisfaction and environmental footprint

The effects of each FEVCS configuration on driver satisfaction and environmental footprint are presented in Table *5*. Regarding driver satisfaction and environmental footprint, it was observed that Chargers 1 and 2 provide higher driver satisfaction compared to Chargers 3 and 4, albeit with a greater environmental footprint. Despite the absence of PV production at night, Chargers 1 and 2 utilize the remaining energy sources without sharing with the other two chargers, which enables them to serve EVs more quickly during the night. However, the generator typically operates continuously at night to meet charging demands, contributing to a higher environmental impact. As RES capacity increases, the difference in driver satisfaction between Chargers 1 and 2 and Chargers 3 and 4 diminishes, as more energy is available during the day, allowing all chargers to operate closer to their nominal power. Conversely, the environmental footprint between these two groups of chargers tends to increase. Increased RES capacity raises the likelihood of fully charging the BESS to contribute to night-time charging. As a result, the environmental impact decreases, but not as significantly as during daytime, when PV contribution is a critical factor in reducing generator operation and, by extension, the environmental impact.

Generally, driver satisfaction increased by up to 14.12% from Case 1 to Case 8, while the environmental footprint decreased by up to 46.4%. As illustrated in Table 3, PV plays a significant role in enhancing driver satisfaction and reducing the environmental footprint of the HEVCS, particularly when combined with high BESS capacity (Case 2 → Case 6).

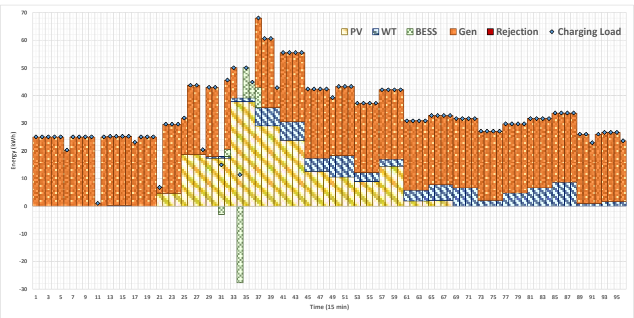
Table 3 Impact of BESS, WT, and PV on driver satisfaction and environmental footprint.

	Cases	Driver sat. (%)	Env. Footprint (%)
BESS	1→2	0.48	-1.83
	3→4	0.73	-3.79
	5→6	1.94	-10.65
	7→8	2.03	-13.27
WT	1→3	4.43	-16.75
	2→4	4.69	-20.03
	5→7	2.33	-14.08
	6→8	2.42	-18.91
PV	1→5	8.95	-28.88
	2→6	10.52	-35.27
	3→7	7.10	-28.10
	4→8	8.48	-35.19

Finally, Figure 1 illustrates the energy distribution at the charging station for a typical day in the middle of spring and autumn. In Case 1, where the RES capacity is lower than in Case 8, the generator operates for nearly the entire day. In contrast, in Case 8, the generator operates primarily when PV production is low, and the BESS has more opportunities to charge throughout the day compared to Case 1.

3.3. *Effects on driver satisfaction and environmental footprint*

Different scenarios may be suitable depending on the specific circumstances under which the CS will be designed. If the CS has a grid connection that feeds excess energy into the grid, profitability will be achievable in all scenarios, particularly for Cases 7-8, where rejected energy exceeds 750 GWh. If a grid connection is not possible, Cases 1-2 will be preferable due to the smaller investment required. However, the environmental footprint will be more significant.



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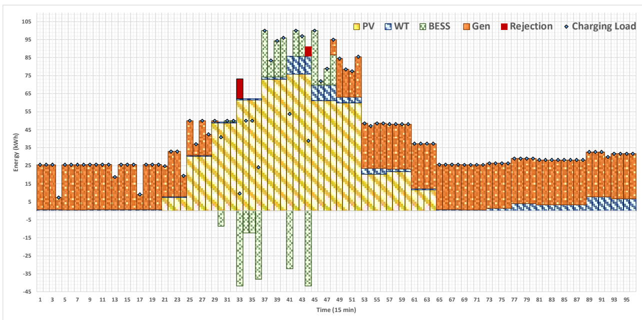

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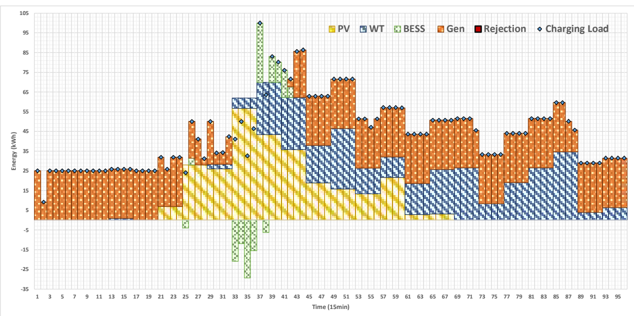

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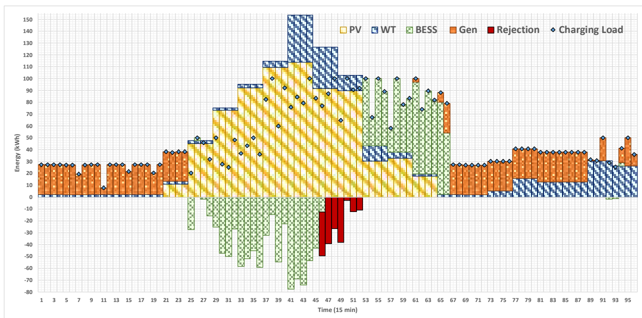

(d)

Figure 2 Power distribution of PV, WT, BESS, and Generator to cover charging demand on April 15th (a) Case 1, (c) Case 8; and on October 15t (b) Case 1 and (d) Case 8.

Table 4 EV number, total charging energy and energy rejection for each case.

Case		Charger 1	Charger 2	Charger 3	Charger 4	Total
1	EV number	9,143	9,175	4,548	4,545	27,411
	EV charging energy (kWh)	494,494.11	495,496.50	245,238.69	245,055.10	1,480,284.40
	Energy rejection (kWh)					45,525.07
2	EV number	9,181	9,193	4,568	4,592	27,534
	EV charging energy (kWh)	496,525.51	496,439.86	246,333.98	247,624.35	1,486,923.70
	Energy rejection (kWh)					29,184.15
3	EV number	9,613	9,617	4,844	4,863	28,937
	EV charging energy (kWh)	519,733.71	519,358.58	261,353.80	262,232.04	1,562,678.13
	Energy rejection (kWh)					216,649.53
4	EV number	9,669	9,688	4,894	4,899	29,150
	EV charging energy (kWh)	522,863.34	523,264.94	264,123.54	264,237.11	1,574,488.93
	Energy rejection (kWh)					185,960.93
5	EV number	9,996	10,002	5,186	5,198	30,382
	EV charging energy (kWh)	540,583.00	540,069.27	280,083.34	280,572.06	1,641,307.67
	Energy rejection (kWh)					360,039.13
6	EV number	10,157	10,198	5,343	5,369	31,067
	EV charging energy (kWh)	549,206.52	550,601.79	288,313.86	289,897.97	1,678,020.14
	Energy rejection (kWh)					273,313.43
7	EV number	10,441	10,454	5,425	5,435	31,755
	EV charging energy (kWh)	564,679.92	564,581.00	292,803.84	293,335.98	1,715,400.74
	Energy rejection (kWh)					860,337.98
8	EV number	10,627	10,652	5,616	5,639	32,534
	EV charging energy (kWh)	574,582.67	575,426.43	303,217.45	304,305.84	1,757,532.39
	Energy rejection (kWh)					761,265.68

If minimizing the environmental footprint is the key goal, Cases 7-8 will be more suitable. In any case, a more comprehensive study should be conducted, taking into account the economic aspects of each scenario and the land area required for each design. In scenarios with higher RES penetration and more significant energy rejection, connecting to the grid or increasing the battery's capacity is recommended.

Table 5 Driver satisfaction and environmental footprint for each EV charger.

Case		Charger 1 (%)	Charger 2 (%)	Charger 3 (%)	Charger 4 (%)	Mean (%)
1	Driver sat.	78.20	78.18	74.93	74.85	76.54%
	Env. footprint	46.88	46.85	34.01	33.90	40.41%
2	Driver sat.	78.54	78.32	75.33	75.47	76.91%
	Green charging	46.23	46.26	33.18	33.01	39.67%
3	Driver sat.	81.42	81.19	78.68	78.46	79.94%
	Env. footprint	41.23	41.24	28.23	28.22	34.73%
4	Driver sat.	81.74	81.58	79.37	79.39	80.52%
	Env. footprint	40.31	40.42	26.53	26.40	33.41%
5	Driver sat.	83.86	83.73	82.92	83.06	83.39%
	Env. footprint	36.07	35.90	21.58	21.41	28.74%
6	Driver sat.	84.81	84.88	85.14	85.20	85.01%
	Env. footprint	33.71	33.82	17.52	17.66	25.68%
7	Driver sat.	86.30	86.17	84.97	84.99	85.61%
	Env. footprint	31.58	31.58	18.32	18.39	24.97%
8	Driver sat.	87.38	87.40	87.34	87.26	87.35%
	Env. footprint	28.98	29.08	14.24	14.32	21.66%

4. Conclusion

This article presents an analysis of the impact of various capacities of RES and BESS on an off-grid fast electric vehicle charging station (FEVCS). Each scenario has its advantages and disadvantages. Higher RES penetration improves charging times and reduces the environmental footprint, but it also leads to increased energy rejection, and vice versa.

A more comprehensive study that includes the economic aspects of the investment and the characteristics of the investment area could provide further insights into which scenario is most feasible for implementation.

5. Acknowledgements

This work was supported by the project "Enhancing resilience of Cretan power system using distributed energy resources (CResDER)" (Proposal ID: 03698) financed by the Hellenic Founda-tion for Research and Innovation (H.F.R.I.) under the Action "2nd Call for H.F.R.I. Research Projects to support Faculty Members and Researchers.

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