

Article

Comparative Analysis of Charging Station Technologies for Light Electric Vehicles for the Exploitation in Small Islands †

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Abstract: The worldwide growing adoption of Light Electric Vehicles (LEVs) indicates that such technology might in the near future be decisive for improving the sustainability of transportation. The segment of LEVs has some peculiar features compared to electric mobility in general, which then deserve a devoted investigation. Stakeholders are called to implement the most appropriate technology depending on the context, by taking into account multifaceted factors, which are the investigation object of this work. At first, a methodology is formulated for estimating the power and energy impact of LEVs recharging. Based on this, and assessed that the load constituted by LEVs is in general modest but might create some problems in lowly structured networks, it becomes conceivable to develop Charging Station (CS) technologies which are alternative to the grid connection at a point of delivery. Yet, it is fundamental to develop accurate methodologies for the techno-economic and environmental analysis. This work considers a use case developed at the University of Brescia (Italy): a CS operating off-grid, powered by PhotoVoltaics (PV). Its peculiarity is that it is transportable, which makes it more appealing for rural/remote areas or when the charging demand is highly not homogeneous in time. On these grounds, this work specializes to a context where the proposed solution might be more appealing: small isolated islands, in particular Favignana in Sicily (Italy). It is estimated that the adoption of the proposed off-grid CS is by far advantageous as regards the greenhouse gases emissions but it is more economically profitable than the grid connection only if the number of users per day is less than order of 200. Hence this work provides meaningful indications on the usefulness of off-grid CS powered by PV in peculiar contexts and furnishes a general method for their techno-economic and environmental assessment.

Keywords: Light Electric Vehicles; electric mobility; Charging Stations; environmental sustainability; techno-economic analysis; PhotoVoltaics



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1. Introduction

Light Electric Vehicles (LEVs) are a broad class of electric-powered vehicles that include scooters, bicycles, skateboards, and other compact personal transport devices. Their growing diffusion will sensibly contribute to reshaping the world of transportation, as for example by the following points of view [1]:

- Progressively substituting urban car trips with range less than order of 8 km, which are the majority worldwide;

- Reducing the use of cars also in rural areas [2];
- Stimulating a modal shift from private ownership to sharing modes [3];
- Enlarging the audience of potential users to the share of elderly and fragile people [4];
- Fostering the development of the so-called green tourism [5].

As of 2021, approximately 1.1 million e-bikes were sold just in the United States [6]. Projections indicate that the U.S. e-bike market, valued at \$1.98 billion in 2022, is expected to grow at a compound annual rate of 15.6% from 2023 to 2030, reaching approximately \$7.16 billion by 2030 [7].

It is well known that a sensible reduction of the GreenHouse Gases (GHGs) emission in the transportation sector can be achieved only provided that the electricity for recharging the EVs is produced from renewable sources [8]. Yet, the most important renewable sources as solar and wind, are stochastic and hence predictable only within a certain extent, as the EVs load demand is. Hence, the uncertainty in the combination of renewable power generation and EVs load demand might have disrupting consequences on the power grid, summarized for example in [9].

In the case of LEVs, the load is relatively modest and it is energy-intensive rather than power-intensive. This means that their effect on grid frequency and voltage stability is negligible, as they demand relatively lower power per unit, compared to heavy electric vehicles, such as cars [10], buses [11] or trucks. Nevertheless, LEVs might negatively contribute to the the peak demand (as observed in Section 4.1), given that the hours of the day with more charging demands are the same as the peak of household electricity consumptions [12–14]. Hence, it is valuable to attempt at alleviating the power grid from such an additional burden and, given its energy-intensive nature, it is conceivable to exploit distributed renewable power technology coupled with energy storage. This explains why there has recently been a certain attention to the development of charging stations for LEVs which are powered by renewables (mainly PV): see Section 1.1.4 for a detailed discussion. If the charging station is designed to operate off-grid, evidently there is no burden on the power grid, but the quality of service is not assured, as the energy for recharging the vehicle can come solely from the renewable source or possibly from the energy storage.

Based on this line of reasoning, the stakeholders (typically the municipalities) have to take into account multifaceted factors when selecting a particular charging station technology [15], as for example:

- Accessibility;
- Cost;
- Minimum level of desired quality of service;
- Environmental sustainability.

Evidently, there is not a one size fits all solution and the optimal selection depends on the context. Based on this premise, the investigation object of this study is to formulate methodologies aimed at:

- Estimating the power and energy impact of LEVs recharging on the grid;
- Performing a techno-economic analysis of various charging station technologies;
- Assessing the environmental sustainability of the various solutions.

The study conducted in this work employs a use case developed at the University of Brescia (Italy), in the context of a project funded by the European Recovery Plan. The considered charging station operates off-grid and it is powered by PhotoVoltaics (PV). Its most peculiar aspect is that it is transportable, being towed by a vehicle, and this makes it more appealing for rural/remote areas or when the charging demand is highly not homogeneous in time. Given the features of the considered use case, this work specializes to a type of context where the proposed solution might be more appealing: namely, small

isolated islands. Indeed, the selected use case is the island of Favignana, in Sicily (Italy). As will be discussed in more detail in Section 3, the island of Favignana is in line of principle a context in which the benefits from the use of transportable off-grid charging stations powered by PV might be higher:

- The tourism multiplies tenfold the population of Favignana in summer, hence the demand for recharging EVs drastically varies among the seasons;
- The island of Favignana has a lowly structured power grid, which might benefit from even a low alleviation of the burden, especially in the peak hours in summer;
- The electricity in Favignana is produced using diesel generators, hence with an averagely high level of GHGs emissions.

It should be noticed that, despite the formulated methodologies have been applied to a use case where it has been argued the results would have been more interesting, the approach is general and might be useful for EVs stakeholders in the most various contexts.

1.1. Related Work

1.1.1. Carbon Footprint and Electric Mobility

Some recent studies in the literature deal with the estimation of the potential GHG reductions when using PV for producing the electricity for recharging the EVs. For example, in [16], it is argued that it is fundamental to recharge EVs with electricity produced from renewable power sources and that the environmental footprint might more sensibly decrease if adopting smart charging algorithms [17], optimally managing the state of the charge of the vehicles [18] in relation to the electricity prices. In [19], the selected use case is 1.5 MWP floating PV system, which is supposed to be employed for recharging various types of EVs. The results indicate that an E-bike, E-scooter, or E-car can become a net zero emission vehicle in 25.5 months, 12.1 months, and 7.7 months, respectively, when charged from floating PV plant. Also the work in [20] deals with techno-economic and sustainability analysis of integrating PV and battery storage in the charging pipeline. The differences compared to the the present paper refer to the size of the energy systems (centralized vs. decentralized), the attention to EVs rather than LEVs and, most importantly, the architecture (grid-connected vs. off-grid in the present paper). In [21] the design process and some economic and environmental assessments regarding a smart car park—equipped with a 40 kW photovoltaic system and a Li-ion battery storage system (42 kWh)—for electric vehicles in the campus of the University of Palermo is presented, while the work in [22] is based on a philosophy similar to [20], but is closer to the subject of the present paper. Actually, a system with 19.8 kWp of PV and 10 kWh of storage is considered for recharging e-bikes at a University Campus. The architecture of the charging station is grid-connected, marking a difference compared to this work.

1.1.2. Rural/Remote Areas

Rural/remote areas are the investigation object of the study in [23], which deals with a Water-Energy Hub in Kenya. In that paper, it is shown that there is an excess PV production from a 30 kWp system operating off-grid, which could be employed for recharging LEVs, provided that the load management is optimized. Similar considerations are drawn in [24], where the selected use case is a rural area in Uganda.

1.1.3. The Island of Favignana, Its Power Grid and Energy Mix

Attention to small islands and the study of their energy system is a theme particularly explored by the research group in Electrical Energy Systems at the University of Palermo. The geographical and infrastructural characteristics of small islands present unique challenges that make them an important subject of research, particularly regarding energy

generation, distribution, and sustainability. Their isolated nature, coupled with limited availability of energy resources, typically results in overdependence on fossil fuels, in the form of diesel generators for example, which are costly, environmentally impactful, and vulnerable to supply chain fluctuation. Additionally, small islands are also affected by low inertia grid stability, high seasonality of demand, and inadequate or totally exempt interconnection with continents. These are problems that make small islands fertile grounds for research on energy solutions such as the renewable energy penetration, microgrids, energy storage optimization, and demand response management. In several years, the research from the University of Palermo has introduced a multitude of innovations in the management and development of island electricity systems with knowledge that can be applied in common situations as well, such as in the Sicilian power grid. Research has also been directed to enhance grid robustness, increasing renewable energy penetration, and decreasing the reliance on imported fuel so as to create island power systems more independent, efficient in terms of costs, and sustainable. For example, in [25] a methodology was applied for the evaluation of the optimal energy mix on the island of Lampedusa considering the penetration of renewable sources of various kinds, while in [26] the impact on the electrical grid relating to the establishment of RECs in various small-scale scenarios was assessed.

In particular, a few recent studies are devoted to the analysis of the power grid of the island of Favignana in relation to renewable power generation and electrical mobility. For example, in [27] it is argued that the network of Favignana can handle a shift to electrical mobility, even massive, but with the current energy mix (based on Diesel generators, as discussed in detail in Section 3) such shift would end up in increased GHGs emissions. Hence, the need for integrating renewable power generation in the energy mix of Favignana, but in [28] it is argued that 1 MW of installed PV would have negative consequences on the stability of the power grid, thus requiring that the transition to electrical mobility is accompanied by the possibility of establishing Vehicle-To-Grid services [29,30]. In absence at present of the practical implementation of charging station allowing for Vehicle-To-Grid services, one possible strategy for fostering the transition to electrical mobility while diminishing the GHGs emissions without stressing the network of the island is exploiting charging stations powered by renewables which operate off-grid.

1.1.4. Off-Grid Charging Stations Powered by Renewables

A few works in the literature deal explicitly with charging stations for e-bikes which integrate renewable power generation and can operate hybrid or off-grid. In the case of [31,32], the architecture is hybrid and the core of the system is a 48 V DC nano-grid powered by a PV array and equipped with a storage. The focus of the works in [31,32] is the design phase. A similar focus on the design phase characterizes the work in [33], with the difference that the considered charging station is supposed to operate off-grid. Attention is devoted to electrical aspects and to the possibility of having output voltage at 12, 24 or 36 V.

The idea of developing off-grid charging stations for e-bikes, with the additional feature of the transportability, has been developed at the University of Brescia (Italy), in the context of a project funded by the European Recovery Plan. Preliminary studies regarded the proof of concept and the design phase [34], the estimation of the power flows and the expected quality of services for different ICT technologies and battery storage size [35]. Evidently, the achievable quality of service is a critical issue when the charging station is powered by renewables, hence intermittent, because the service can be dispensed only by using the renewable power in real time or passing through a storage. In light of an upcoming experimental campaign, based on the realized prototypes, a preliminary

techno-economic analysis has been realized for the work in [36], of which the present paper represents an extended version.

1.1.5. Related Technologies

For completeness, it should be briefly pointed out that there are several technology issues which are somehow related to the investigation object and methodologies of this work and will likely be addressed in future studies. At least two are worth citing:

- **Battery technology:** recent developments have been achieved about supercapacitor-based installations [37,38], which are especially promising due to higher power densities and faster recharging times than batteries. The assessment of such technology might be promising when generalizing the approach of the present work to city scenarios and electric vehicles with much higher power demand.
- **Communication infrastructure:** since, as discussed for example in [35], the quality of service is not guaranteed when employing off-grid charging stations powered by renewables, smart charging algorithms [39] would be beneficial and this requires to set up adequate communication infrastructures for localizing the e-bikes while en route and for directing them at the most appropriate charging station.

1.2. Research Gap and Highlights

Based on the above brief literature review, a research gap can clearly be identified. Namely, the literature on off-grid charging stations for e-bikes is at its early stages and mainly deals with the design phase. Hence, the present paper conceptually represents a step forward because it deals with the contextualization of such charging station technology, namely by considering its environmental footprint and the interaction with the power grid. To the best of the authors' knowledge, the present is the first study in the literature addressing the following issues:

- The sustainability of PV-powered off-grid charging stations, specifically for the case of LEVs;
- A scrupulous techno-economic analysis regarding the exploitation of prototypes of off-grid charging stations in real-world scenarios, going beyond prototype design phase to which most of the state of the art is devoted;
- The identification of specific contexts (as the selected use case, island of Favignana), where the additional load of LEVs, although modest, might exacerbate the stress on lowly structured and isolated power grids, thus causing economic disadvantages.

The results of this work, discussed in detail in Section 4, shed light in general on the competitiveness of off-grid charging stations powered by renewables, in comparison with standard approaches as the installation of new points of delivery. In particular, touristic areas with lowly structured power grids and low share of renewable power production can be identified as the most appropriate target for the deployment of the proposed charging station technology. Furthermore, from the analyses of this work, it clearly arises that the selection of the most appropriate charging station technology in a specific context is a multi-faceted problem which, in the case of off-grid solutions, has an additional layer of complexity given by the fact that it is not assured that the service might indeed be delivered whenever requested. The methods proposed in this work might guide stakeholders in identifying appropriate techno-economic and environmental targets and, possibly, in designing a new generation of public subsidies, which might remunerate the alleviation of the burden to the power grid.

1.3. Article Organization

The organization of the work is the following. The methods are formulated in Section 2. The use case (charging station prototype and Favignana island) is described in Section 3. The results are collected and discussed in Section 4, while the conclusions are drawn and further directions are outlined in Section 5.

2. Methods

2.1. Power and Energy Consumption Analysis

The first step of the comparative analysis includes an assessment of peak power and energy consumption at different penetration rates of LEVs. The proposed model combines probabilistic approaches with user-defined parameters to estimate peak power demand and daily energy consumption for different LEV adoption and charging station utilization rates. The modeling of daily usage of the charging stations is paramount to the analysis and, in absence of empirical studies on the behavior of tourists and inhabitants of the island of Favignana, the distribution has been hypothesized based on literature. In studies like [12–14], it is argued that the charging demands are concentrated at lunch time and in the evening both in touristic and urban scenarios.

The assumed distribution is then the sum of two Gaussian distributions, which characterize the main peaks of usage during the day: one centered is at 1 Post Meridieum (PM), assuming that the charging events happens during lunches and another centered at 8 PM due to evening arrivals and e-bikes evening deposit. Each curve describing the behavior around the corresponding peak hour is characterized by a mean (μ) and standard deviation (σ), selected to represent the typical user behavior, and the sum of the Gaussians has been normalized such that the total area equals 1, representing the probability distribution of charging service demand during the whole day, Figure 1. The values of σ are selected as 2.5 and 2 (h) for, respectively, the peak at 1 PM and at 8 PM. The rationale for such selection is that a 25% more variability in the users' habits during the day, compared to the evening, has been assumed.

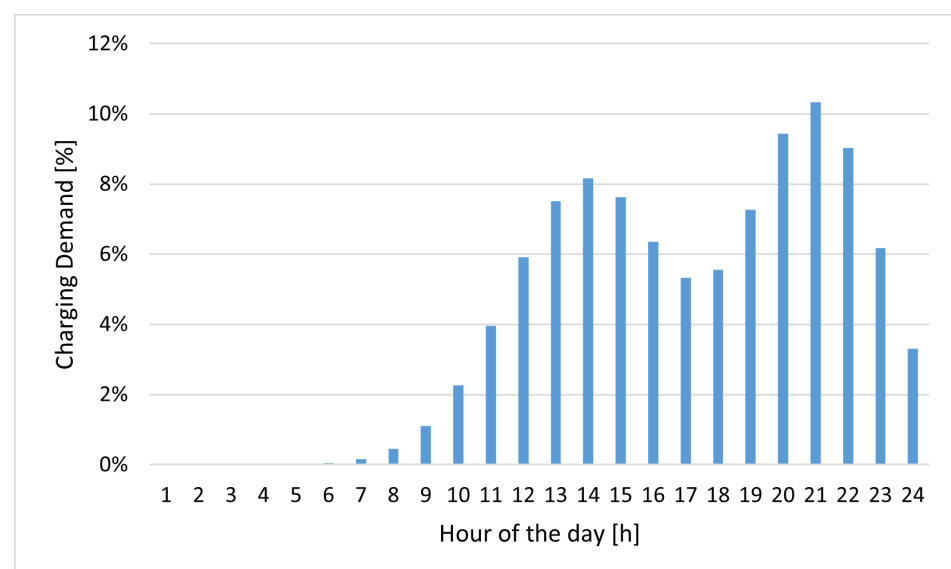


Figure 1. Charging Event Probability Density Function.

The reference population is composed of two groups, consisting of inhabitants and a variable number of tourists, which can vary through the seasons and can reach up to ten times the resident population. Based on the references, it has been considered reasonable not to distinguish the charging demand habits of inhabitants and tourists, who are all

simply considered LEV users. Furthermore, this allowed us to avoid over-complicating the model. LEV adoption is modeled using a variable rate that goes from 1% up to 10%, while the utilization rate of charging stations goes from 10% to 100% each day. As regarding the charging power demand per LEV, a probabilistic distribution is considered, where charging power varies between 0.2 kW and 0.6 kW to better reflect the diversity in battery capacities and charger specifications across different LEV types. In order to account for reactive power components (mainly due to waveform distortion), the apparent power is also adjusted accordingly, considering an average power factor of $\cos(\phi) = 0.7$. Given the charging power range, the corresponding apparent power per charge varies between approximately 0.29 kVA and 0.86 kVA. Actually, it is argued that LEV charging power factor typically falls in the range of 0.65 to 0.75 because of the charging logic (Pre-charge - Constant Current - Constant Voltage). In this way, the apparent peak power per charge corresponds approximately to 0.5 kVA, while the energy consumption per charging cycle is fixed at 0.5 kWh, a parameter in line with most of the e-bike commercially available.

The model estimates apparent peak power and daily energy consumption for every combination of the adoption and utilization rates. It calculates the peak power by the product of the number of charged vehicles, apparent charging power, and the maximum of the summed Gaussian distributions. The total daily energy consumption is calculated by multiplying the number of vehicles charged in a day with energy consumption per cycle. The parameters implied in the model are summarized in Table 1.

Table 1. Energetic Analysis model parameters.

Parameter	Value
Resident Population	Variable
Number of Tourists	Up to 10 times resident population
LEV Adoption Rate	0.01–0.1
LEV Adoption Rate Step	0.005
Charging Station Usage Rate	0.1–1
Charging Station Usage Rate Step	0.05
Mean of the Gaussian 1	13
Mean of the Gaussian 2	20
Standard deviation Gaussian 1	2.5
Standard deviation Gaussian 2	2
Charging Active Power per Vehicle	0.2–0.6 kW
Charging Power Factor	0.7
Apparent Power per Vehicle	0.29–0.86 kVA
Energy per Single Charge	0.5 kWh

2.2. Environmental Analysis

A Life Cycle-based methodology was followed in the case of the environmental analysis of CO₂ emissions, quantifying each operational and infrastructural phase of the two solutions being considered.

The main sources of emission for the mobile station are:

1. photovoltaic panels production, whose data have been derived from reports and estimates based on average energy mixes;
2. production and use of electrochemical storage, considering emissions related to extraction and processing of materials such as lithium and cobalt;
3. electronic system, including inverters and controllers;
4. transportation operations for seasonal station placement;
5. maintenance and management at the end of life.

Regarding emissions associated to the solution with fixed Point Of Delivery (POD), the following emission sources were considered:

1. construction of the underground infrastructure, including excavation and laying cables;
2. electricity generation production, considering the local energy mix for calculations;
3. ordinary maintenance of the infrastructure;
4. network upgrades that could take place in the future.

Emissions relating to the conversion of a each energy source into electricity were estimated in the light of the data on average CO₂ emissions per kWh obtained by reports from national and international institutions. Information procurement was based on a systematic bibliographic search, taking into account scientific articles from the most cited and trusted journals, and from research institutes in the form of technical reports. Preference was given to those of consolidated LCA methodology and with values covering emissions within realistic ranges for the several components analyzed. Further, specific databases were used to give empirical evidence for the calculated emissions in each item.

2.3. Techno-Economic Analysis

In the technical-economic analysis, a structured methodology was adopted for the evaluation of costs and benefits of the two solutions considered. The analysis considered both initial investment costs (CAPEX) and annual operating costs (OPEX), including expenses for maintenance, component replacement, and energy consumption. The CAPEX for the mobile station includes:

1. PV panels purchase cost;
2. the electrochemical storage system purchase cost;
3. the electronic system, which includes inverters and controllers;
4. the cost of assembling and installing the components.

The annual OPEX of the mobile station includes:

1. periodic replacement of batteries estimated over the average life cycle of 5–7 years;
2. panels and electronic component maintenance costs;
3. transportation costs associated with seasonal station repositioning;
4. communication costs for remote monitoring.

For the fixed POD, CAPEX consists of the costs relative to infrastructure realization, such as cable laying and the installation of MV/LV substation plants. These costs have been estimated on the basis of the average data of the cost per kilometer of cable and the average length of the connections, realized through technical reports and case studies. The annual OPEX of the POD includes:

1. energy use for operating for 5 h per day at an estimated cost measured in €/kWh;
2. routine maintenance costs of the underground infrastructure;
3. an annual allowance for future upgrade cost of the network

To annualize the CAPEX, the Capital Recovery Factor (CRF) is applied, converting a one-time investment into a series of equal annual payments over the asset's lifespan. After determining the CRF, it is multiplied by the initial CAPEX to obtain the annualized value. The CRF is calculated as:

$$CRF = \frac{i \cdot (1 + i)^n}{(1 + i)^n - 1} \quad (1)$$

where i is the interest rate and n is the expected lifespan measured in years. Assuming $i = 5\%$ and $n = 15$, the CRF is equal to

$$CRF = \frac{0.05 \cdot (1 + 0.05)^{15}}{(1 + 0.05)^{15} - 1} \approx 0.096 \quad (2)$$

It should be noticed that no public subsidies have been taken into consideration and that, to the best of the authors' knowledge, there are no specific subsidies related to the adoption of off-grid charging stations powered by renewables. Anyway, in case, it would be quite straightforward to incorporate them in the above outlined estimation method.

3. Use Case

3.1. The Off-Grid Charging Station Prototype

The portable charging station for LEVs is a technical solution that integrates renewable energy, modularity and operational flexibility [35]. Designed for use in isolated or high-density tourist contexts, the station is powered by a PV system with a nominal capacity of 1.2 kWp. The energy generated can be stored in a 10 kWh electrochemical storage system. Lithium-ion batteries are selected, due to their higher energy density, efficiency, and lifespan compared to other technologies. A 1.2 kW bidirectional inverter converts the DC energy produced by the panels into AV at a low voltage level (230 V AC), compatible with the charging needs of most vehicles commercially available. As is known, to maximize the production of photovoltaic modules it is necessary to orient the panels towards the South with an azimuth angle equal to 0° . The variable that influences the inclination of the solar modules is the latitude: to maximize production the inclination of the panels must be equal to the latitude L of the place where the system is built, in the specific case of Favignana approximately $37^\circ 55'$.

The battery's charge-discharge strategy has been designed to mitigate the intermittence of solar energy generation while ensuring energy availability for LEVs. The station has a smart energy management system that monitors and regulates charging sessions as a function of real-time solar energy production and battery state of charge. This approach places highest priority on charging vehicles during times of maximum solar generation and implement strategies to optimize battery utilization and extend its lifespan. Protective algorithms are implemented to prevent deep discharge or overcharging in order to safeguard the longevity and efficiency of the battery storage system. The station will be able to work completely off-grid, supporting even automatic regulation to avoid overloads. Output connections will provide for multiple types of low- and medium-power charging sockets, configurable up to 3 kW, depending on the specific needs of electric mobility. Finally, the system is equipped with an IoT communication module, based on a 4G network, to ensure remote monitoring of all the main parameters such as the battery charge status, input and output voltage, energy performances. The electrical block diagram of the station is shown in Figure 2a while the realized prototype is shown in Figure 2b.

3.2. The Context: Favignana Island

Favignana is the largest of the Egadi Islands and has an isolated electrical network. Its energy production is based on diesel generators: similar to many remote islands, such configuration has very high energy costs and a strong environmental impact because of the CO₂ emissions related to fossil fuel electricity generation. The generation system essentially depends on fossil fuels and is powered by 7 diesel generators for a total generation power of approximately 12 MW. Energy distribution takes place via 10 kV medium voltage lines and is carried out through 42 secondary substations arranged in strategic points to power the various users on the island, Figure 3a [27]. The territory is strongly affected by seasonal variations, with tourism peaks of around 40,000 users and 4000 inhabitants present on the island at the same time [40]. This causes all infrastructure to be subjected to severe stress, including the electricity grid, with a load that varies from a minimum of 1 MW in winter days to over 5 MW in summer peaks [28].

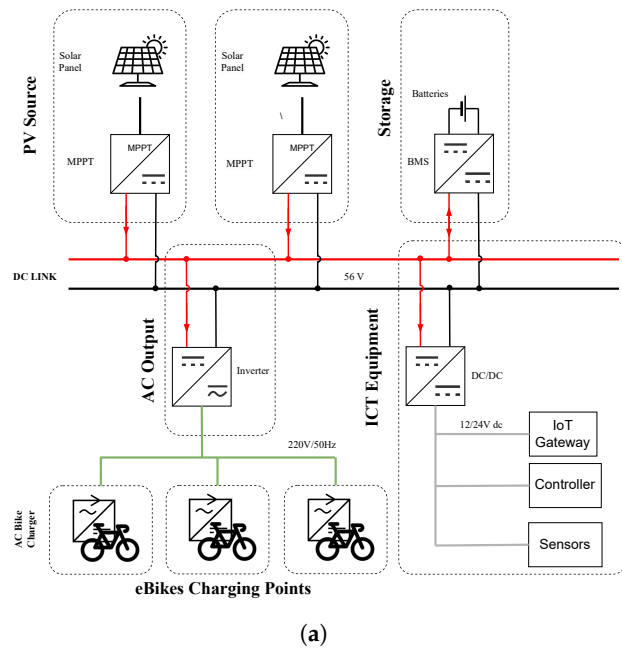


Figure 2. (a) Block diagram of the charging station prototype; (b) Prototype of the charging station in the manufacturer laboratory.

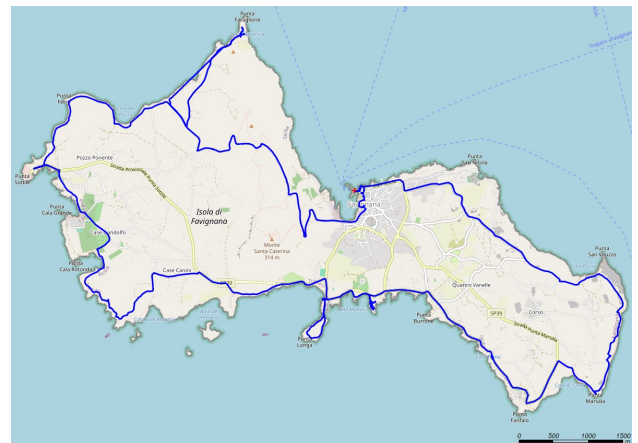
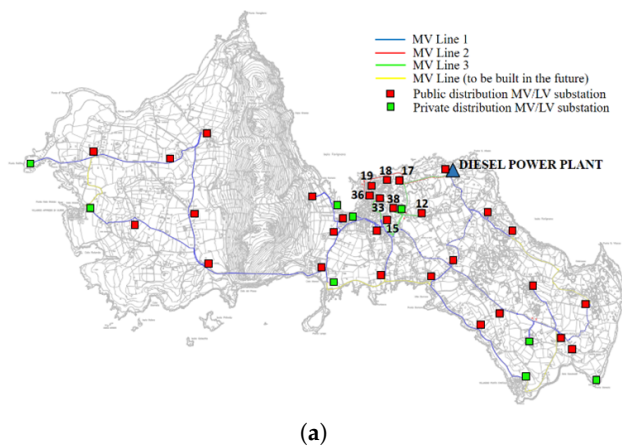


Figure 3. (a) Favignana island electrical grid; (b) Cycling route considered.

In the last years, tourism related to cycling has grown well, thanks to the fact that the island lends itself very well to this type of activity both from a climatic and territorial point of view. The route for cyclists considered in the analysis is about 35 km long and connects the main points of tourist interest, crossing areas characterized by a limited electrical infrastructure, Figure 3b. In this respect, the context is ideal to experiment with off-grid photovoltaic-powered charging stations operating autonomously without further burdening the local network. Portable solar-powered stations are able to support light electric mobility by reducing the need for diesel generators and contributing to a decrease in CO₂ emissions. Their modularity allows flexible distribution along the route, responding to seasonal needs and ensuring sustainable charging for electric vehicles.

The application of the methodology described in Section 2 is subsequent to the creation of a scenario defined as follows: a 35-km cycling route around Favignana, with mostly flat terrain and a single moderate climb, was chosen as it is popular among tourists. With the incorporation of user demand patterns, energy requirements have been calculated across variable numbers of LEVs, data used to determine the equivalent number of stand-alone

charging stations and fixed PODs. First, the infrastructure of the route was analyzed to select the best positions for the charging stations. In the site selection, a number of key factors were considered, such as distances from tourist hotspots, the average range of LEVs, and accessibility to main cycling paths. An assessment of solar energy production was conducted using the PVGIS tool [41], which applies a lumped parameter model for the PV modules. Since the stations are primarily intended for use during the peak tourist season, the estimation focused on solar radiation during the summer months, with data collected from a sample location near the island's center (latitude $37^{\circ}55'41.8''$ N, longitude $12^{\circ}18'54.8''$ E). Further calculation was also made to get the number of PODs which will be needed to provide a matching capacity for the mobile charging stations. Every POD was considered to draw a power of 10 kW, a value assumed to be adequate for this purpose. Relating to the power provided by the charging stations, the power provision from a single POD matches around 8 stations, supporting about 160–170 vehicles.

4. Results

4.1. Power and Energy Consumption Analysis

The results are plotted in two 3D plots as shown in Figure 4.

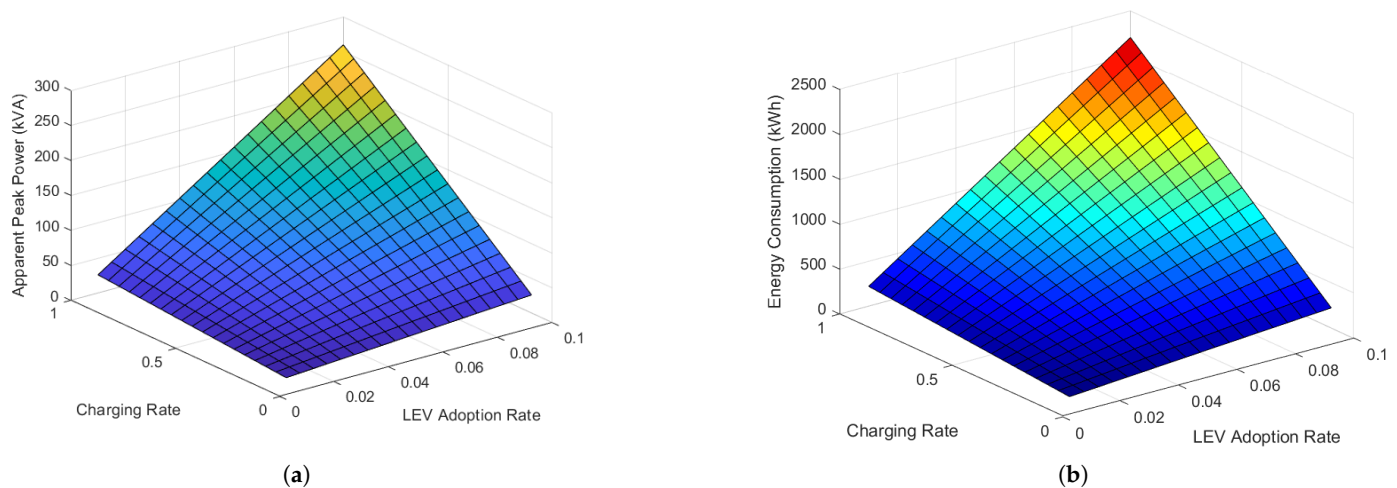


Figure 4. (a) Peak Apparent Power as a function of Adoption Rate and Charging Rate; (b) Energy consumption as a function of Adoption Rate and Charging Rate.

- Apparent Power at peak, Figure 4a: this graph shows the peak apparent power as a function of LEV adoption rate and charging infrastructure utilization rate. It shows the way in which power demand rapidly increases with increasing adoption and utilization rates underlining the importance of proper planning of local electrical grid capacities.
- Total Daily Energy Consumption, Figure 4b: the trend represents the sum of the daily energy consumption, which is linearly dependent on the number of vehicle and on the charging rate.

As can be seen from the figures, the energy analysis performed underlined remarkable values about energy demand and power required in the maximum adoption scenarios of LEVs and at the highest rate of use of the charging stations, that is, charging rate. With an adoption rate of 10% compared to the resident population and tourists, around 44,000 potential users, with a charging rate of 100%, the peak power required is about 260 kVA. From an energy point of view, in the case of an adoption rate of 10% and a charging rate of 100%, the total daily consumption amounts to approximately 2200 kWh, calculated considering an average energy per charge of 0.5 kWh per vehicle. Although the

estimated power and consumption values are theoretically manageable by the Favignana electricity grid, the introduction of such a high additional demand can generate local overloads, especially in the vicinity of the MV/LV electrical substations, which are already limited in capacity. The network, being isolated and characterized by production entirely based on diesel generators, is particularly vulnerable to sudden load variations. Increased demand during peaks can shift generators from their efficiency sweet spot, reducing their performance and increasing specific CO₂ emissions per kWh produced. This behavior results in greater fuel consumption and increased operating costs, compromising economic and energy sustainability. In this context, the implementation of photovoltaic-based off-grid solutions could help reduce overloads, improve the overall efficiency of the network and mitigate the environmental impact of diesel generators.

4.2. Environmental Analysis

The comparative analysis of the CO₂ emissions for the stand-alone charging station powered by photovoltaics against a standard solution with POD presents remarkable differences concerning environmental sustainability. The detailed distribution of the emissions due to the contribution of single components is presented in Table 2.

Table 2. CO₂ emission [g/kWh] per single contribution, minimum:maximum and average values.

Component	Stand-Alone (Min:Max)	Stand-Alone (Average)	Standard POD (Min:Max)	Standard POD (Average)
Photovoltaic panels	6:28	17	-	-
Electrochemical storage	40:70	55	-	-
Electronic system/inverter	5:10	7.5	-	-
Maintenance and disposal	5:10	7.5	10:20	15
Transportation	1.5:9	4.9	-	-
POD construction	-	-	27:137	82
Diesel generation	-	-	650:750	700

4.2.1. Mobile Charging Stations

Emissions from the stand-alone station originate mainly from the production of PV panels and the electrochemical storage system. PV modules are an important emitter at the average of 17 g CO₂/kWh, but such production emission is compensated for by the renewable energy they produce during their life cycle. The SolarPower Europe report entitled “Sustainable Solar: environmental, social, and governance actions along the value chain” [42] puts these emissions at between 6 and 28 g CO₂/kWh, depending on the energy mix used for production. The end-of-life disposal of PV modules and the related environmental and economic costs are already factored into the modules’ initial purchase cost. In accordance with the European Parliament’s 2012/19/EU Directive [43], it is the module manufacturer’s obligation to take care of their disposal and recycling procedure under waste electrical and electronic equipment compliance requirements. Several sources, like [44,45], point out that recycling of PV modules remains a complicated and under-regulated process, and it is challenging to provide a clear and universally agreed CO₂ footprint at the end of life. Given that there is no standard recycling process and there are differences in material recovery efficiency, CO₂ emissions from module disposal continue to be enveloped by significant uncertainty.

The electrochemical storage system contributes an average of 55 g CO₂/kWh, a value that accounts for the extraction and processing of critical materials such as lithium and cobalt [46–48]. Minor emissions are associated with electronic systems and inverters, which contribute approximately 7.5 g CO₂/kWh [49], and maintenance and disposal operations, estimated between 5 and 10 g CO₂/kWh [50]. Changes and fluctuations in parameters

such as PV module efficiency, location, battery life, conversion efficiencies, and utilization rates are already incorporated within the cited references, which is why CO₂ emission calculations are presented as minimum-maximum values.

A plus of the stand-alone solution is that its transportation currently contributes 8.2 g CO₂/kWh, based on monthly movements of 50 km using a diesel vehicle emitting 500 g CO₂/km [51]. An alternative scenario considers the moving the mobile charging station with an electric vehicle instead of a diesel vehicle. Based on references [22,52], emissions from electric vehicle transport are evaluated at 93 g CO₂/km under the assumption of the European energy mix. This would entail a lower CO₂ impact associated with transport compared to internal combustion engines. However, for more precise estimation, the energy mix of all the concerned islands should be studied as local power generation could be quite different. Where there are more renewables, emissions could be reduced even more, but fossil fuel-driven grids might increase the indirect CO₂ emissions associated with recharging the electric car. For the purpose of this research, a European average condition is considered, thus evaluating this voice of emission at 1.55 g CO₂/kWh.

4.2.2. Fixed POD

In contrast, the traditional POD, which is predominantly powered by energy produced from fossil fuels, has an average of 742 g CO₂/kWh of emissions—which range from 737 to 857 g CO₂/kWh. The majority of this is due to diesel generation at an average of 700 g CO₂/kWh [53,54]. Other contributions are the emissions by construction of infrastructure (cables, substations, etc.), which can be as low as 27 g CO₂/kWh and as high as 137 g CO₂/kWh, depending on the complexity of the site [55]. A comparison of the total emissions for the two solutions is summarized in Table 3. It follows that the stand-alone station reduces CO₂ emissions by about 66% with respect to the standard solution. This is mainly due to renewable energy production, which compensate the initial emissions related to the production and realization of components. For this reason, this characteristic makes the stand-alone station particularly suitable for island or tourist contexts where environmental sustainability is a priority.

Table 3. Total CO₂ emission comparison [g/kWh], minimum, maximum and average values.

Solution	Minimum Emissions	Maximum Emissions	Average Emissions
Stand-alone station	88	258	215.2
Standard POD	737	857	742

4.3. Techno-Economic Analysis

4.3.1. Mobile Charging Stations

The cost of a stand-alone mobile charging station, including PV panels, batteries, controllers, and assembly, is estimated at €8000 per station, this cost represent its Capital Expenditure (CAPEX). The estimate is derived from market prices and cost analysis of similar off-grid photovoltaic-powered charging systems. Fixed installations have grid connection infrastructure investment, while mobile charging stations don't, so they can be deployed immediately with minimal installation expense. This flexibility makes them particularly valuable in applications where permanent alteration of infrastructure is prohibitive or impossible, such as in sites of historical or ecologically sensitive significance. Operating Expenditures (OPEX) include annual maintenance, battery replacement, transportation expenses for seasonal deployment, communication fees for remote monitoring, and other miscellaneous expenses. The maintenance of PV panels alone costs between €160 and €240 annually, while batteries must be replaced every 5 to 7 years, which amounts to an amortized cost of €400–€560 annually [56]. This lifespan is

evaluated accordingly to the aspected value of Lithium-Ion batteries, corresponding to the type used for the station. Other operational expenditures, such as 4G communications (€120–€180 annually) and periodic transport and repositioning (€1000–€1500 annually), result in a total estimated OPEX of €2000 to €3000 annually. A sensitivity analysis based on an assumption of 5 to 7 years for the battery and inverter lifespan indicates that the annual cost of these components varies from €500 (with a 5-year lifespan) to €357.14 annually (with a 7-year lifespan). This means that increasing the useful life by 20–30% can contribute in lowering the OPEX, hence making the mobile charging station economically viable in the long term. The lesser lifespans of components means increased cumulative expense over time, one possible remedy could be making use of high-quality materials and efficient energy management to increase the component useful life. Similarly, employing higher-efficiency inverters with extended lifetimes could reduce unplanned replacement costs and system downtime even further, contributing to overall economic feasibility for mobile stations. As a result of modularity in mobile stations, scalability is highly flexible, with investment being feasible incrementally as user demand increases. This feature is in contrast to the high capital expenditure required by fixed PODs, thus rendering mobile stations highly cost-effective for settings with uncertain or variable patterns of demand, such as regions with seasons of heavy traffic. The benefit of modularity is that operators can increase charging capacity incrementally without over-allocating resources, thus preserving economic efficiency in diverse adoption patterns. Furthermore, their mobility enables them to actively adapt to fluctuations in demand, such that stations can be relocated to accommodate use patterns and maximize utilization efficiency in the long term.

4.3.2. Fixed POD

In the case of fixed PODs, the estimated CAPEX is much higher due to construction costs, especially related to underground cabling and associated infrastructure. These costs show a strong dependence on the length of the connection line and its type, among other variables. To estimate the CAPEX for the POD, some assumptions were made. As explained before, only the underground cable solution was considered, whose costs were taken from [57]. In order to calculate an average installation cost, several MV/LV cabins on the island were assessed and located along the designated route. The distances from these cabins to possible panoramic points on the island where new charging points could be installed for light vehicles were measured and an average distance of 0.504 km was obtained. Based on this distance, the CAPEX for a single POD was found to be €56,780. Hence, such amount includes the expense of connection to the grid. It was calculated according to the tariff schedule of Italy's biggest electricity distributor with the aim of encompassing all the infrastructure costs incurred, such as underground cabling, installing a transformer and, of course, connection [57].

Annualizing this with the previously calculated CRF gives €5471.59 per year.

In addition, the OPEX is relatively high, largely because energy depends on market-priced generations. Generally, this kind of infrastructures finds their economic convenience on utility-scale projects, which is why it is wanted to look for valid alternatives for low-demand applications. A 10 kW POD operating for 5 h daily consumes approximately 18,250 kWh annually. A rate of €0.30 per kWh has been assumed, summing up to an annual energy cost of €5475. Such assumption corresponds to the average national price in the time frame from late 2023 to early 2025, as in [58]. This is an assumption based on the Italian tariff compensation mechanism so that, despite the generation cost in the island being 3–4 times higher, consumers are paying the same as households in mainland Italy. Thanks to this system, price stability is guaranteed and inflated prices for inhabitants of remote regions such as Favignana are avoided. Maintenance of underground infrastructure

incurs an additional cost of €1000–€2000 per year, while an annual provision of €500 is allocated for future grid upgrades. Consequently, the total OPEX for fixed PODs ranges between €6500 and €8000 annually.

4.3.3. Comparison

The comparison between fixed PODs and mobile charging points reported in Table 4 shows that there is a fundamental trade-off between initial cost and modularity. Mobile stations provide scalability, incremental and demand-driven deployment while fixed PODs present high up-front capital but full service continuity. Figures 5 and 6 show the CAPEX, OPEX, and number of users per day, illustrating how the critical point between the two solutions is a function of the number of vehicles. In small-scale applications or regions, characterized by seasonal fluctuations in demand, mobile stations remain more economical, since their modularity prevents over-investment in unused capacity. This advantage is particularly significant in markets where adoption rates are uncertain since mobile stations facilitate incremental investment planning, lowering financial risks and matching infrastructure to demand in real time. However, as the daily number of users increases, the cost per user for fixed PODs begins to decline, eventually surpassing mobile solutions in terms of economic efficiency. The analysis reveals that for demand levels exceeding approximately 210 recharges per day, fixed PODs become more cost-effective due to their higher capacity and lower long-term OPEX. This result highlights that for the station to remain competitive compared to traditional solutions, it is essential to focus on minimizing operational costs as much as possible. The other important factor to consider is the operating site and its environment. Mobile charging stations are independent and off-grid and do not depend on existing grid infrastructure, making them appropriate for deployment in remote or temporary locations. Fixed PODs, on the other hand, require a stable and well-developed electric grid, which may not always be accessible or economically feasible in geographically constrained environments such as historical areas, nature reserves, or small islands. In addition, the cost-effectiveness of the fixed PODs is highly volatile with respect to electricity prices and grid-connection costs. Despite grid electricity normally being cheaper compared to off-grid solar power, when variations in grid electricity prices occur by policy adjustments or higher fossil fuel prices, relative advantage of the fixed PODs could be put aside in favor of renewable energy-driven mobile stations.

Table 4. CAPEX and OPEX comparison between the proposed solutions.

Cost Item	Mobile Charging Station [€]	Fixed POD [€]
CAPEX	8000	Variable
CAPEX (Annual)	771.20	Variable
OPEX (Annual)		
- Maintenance	400–540	1000–2000
- Battery Replacement	400–560	0
- Energy Costs	0	5475
- Transportation & Installation	1000–1500	0
- Communication (4G)	120–180	0
- Grid Upgrade Fund	0	500
- Insurance & Storage	100–200	0
Total OPEX (Annual)	2000–3000	6500–8000

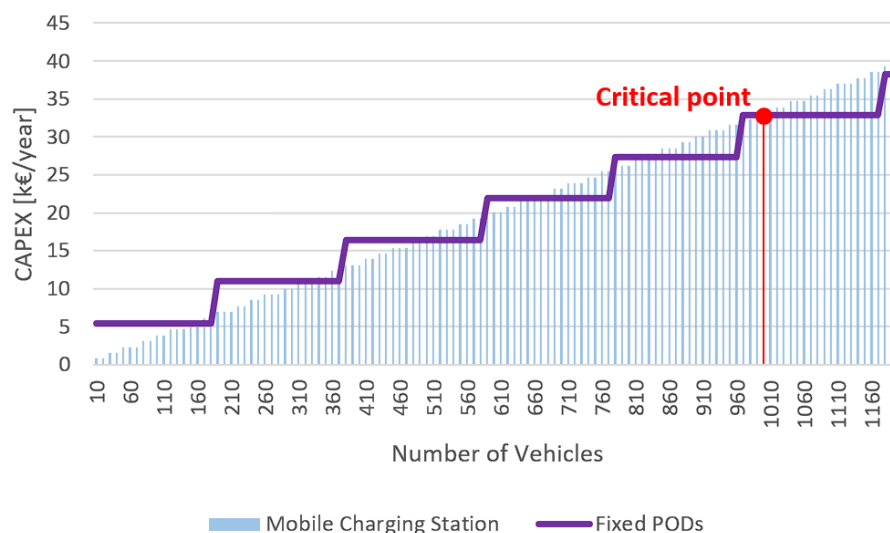


Figure 5. CAPEX comparison of the two solution as a function of daily vehicles.

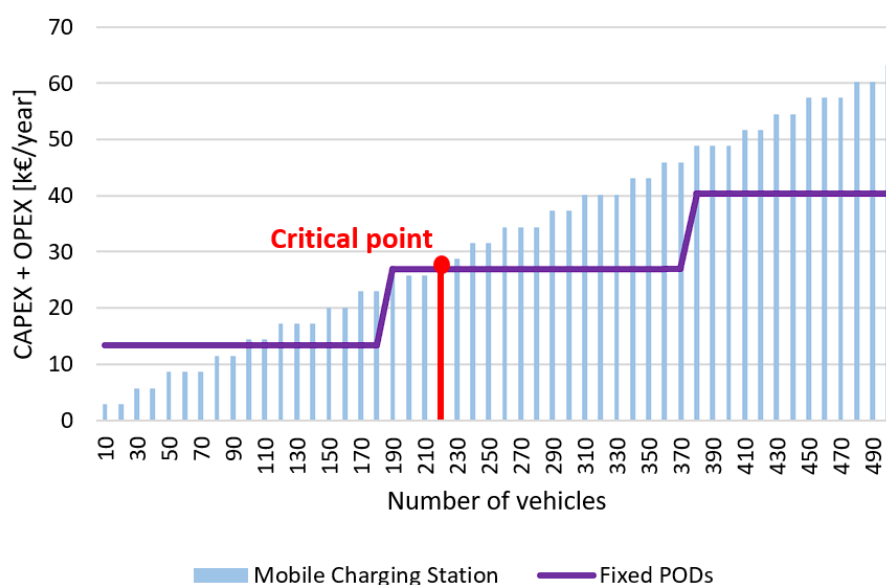


Figure 6. CAPEX + OPEX comparison of the two solution as a function of daily vehicles.

4.4. Discussion

The conducted analyses indicates the advantages of considering short- and long-term implications when selecting a charging solution. Mobile charging stations, while at first stage being less expensive and easier to access, incur greater perational costs of transportation and mantainence and thus suit lower-demand or sporadic usage cases better. In contrast, fixed PODs require widespread adoption to sustain their high CAPEX, present lower operational expenses but possess limited flexibility. One of the key findings is that interdependence between OPEX and CAPEX is an economic feasibility determinant. Mobile deployments allow incremental investment, while fixed PODs require a better understanding of the user base before their installation becomes economically feasible. Additionally, the results show that local conditions, grid structures, and price models for energy have a strong influence on the economic feasibility of every solution. The economic models will be refined in the future with field testing being conducted on the Favignana island in real environments, observing charging station efficiency, rate of adoption of users,

and long-term economic impact. These observations will refine the economic models and optimize deployment planning for similar remote or seasonal sites.

As a final output of this research, is within the scope of the dissertation to evaluate a generalized approach to evaluate the deployment of mobile charging points in different environments in relation to the conditions of the sites and of the grid. The proposed methodology includes the following main steps:

1. **Site Selection and Demand Assessment:** select sites based on mobility patterns, grid connectivity, and seasonal demand fluctuation. Conduct questionnaires or obtain historical mobility data to forecast probable LEV adoption.
2. **Technical Feasibility Analysis:** evaluate solar (or in general renewable) potential and energy demand based on geographic location, shading, and seasonal fluctuation, assess the battery storage sizing according to anticipated charging cycles and energy demand variations, check integration with existing renewable energy sources or microgrids, where possible.
3. **Economic and Environmental Analysis:** estimate CAPEX and OPEX for various deployment scenarios, conduct LCA-based emissions study to evaluate the environmental impacts of the two options, consider possible incentives, regulatory structures, and local electricity pricing regimes to calibrate economic feasibility.
4. **Pilot Deployment and Testing:** deploy mobile charging stations to collect empirical data on usage patterns and performance, track changes in charging demand fluctuations, energy use, and power reliability over time, measure user behavior, station accessibility, and practical limitations influencing station repositioning.
5. **Performance Evaluation and Scalability Model:** analyze collected data to support predictive models of energy usage, economic impact, and CO₂ savings, develop a scalability plan that identifies proper conditions for mobile charging station expansion, compare results from many test sites to further establish future deployment decision-making criteria.

Besides the research environment, intellectual property protection potential has also been considered, particularly with regard to the design and development of mobile off-grid charging stations. While formal protection by means of patent is beyond the scope of the project, some key technological advancements are worthy of attention. These include energy management methods, modular scalability for dynamic charging infrastructure expansion, and IoT-based remote monitoring and control systems. These developments may form the basis for subsequent commercialization attempts towards increasing the efficiency, flexibility, and marketability of mobile charging solutions in remote or high-tourism areas.

5. Conclusions

This paper has provided a techno-economic and environmental analysis of mobile stand-alone PV-powered charging stations for LEVs compared to fixed PODs for small isolated islands. The analysis was conducted in a case study of Favignana island, where the particular grid infrastructure and topology and intense seasonal mobility demand fluctuations make the selection of an alternative charging solution particularly relevant. The following are the main conclusions:

- From an economical point of view, results indicate that mobile charging stations offer a cheap and modular solution in low- and medium-demand environments, particularly in areas with seasonal trends of tourism fluctuations. Although their CAPEX per unit is significantly lower (€8000 per unit) compared to fixed PODs (€56,780 per unit), their OPEX is slightly greater due to periodic battery replacement, transportation, and maintenance costs (€2000–€3000 per year). Fixed PODs, by contrast, become

economical only if over approximately 210 users charge per day, with lower operating costs per user but a massive initial investment.

- From the energy and grid point of view, stand-alone charging points provide a reasonable off-grid alternative that is not going to burden the existing diesel-based grid, cutting down additional emissions and stress on the grid. However, large-scale usage of LEVs might increase peak energy demand, requiring additional regulation of diesel generator operation to minimize loss of efficiency.
- The environmental analysis assesses that PV-powered stations significantly reduce CO₂ emissions compared to grid-connected charging points, especially if, for fixed PODs, the greater part of the electrical energy is generated from fossil fuels.
- By a methodological point of view, a proposal has been formulated to assess the feasibility of using mobile charging points in different contexts ensuring that constraints such as energy potential, economic investments, environmental impact, are addressed in a multi-faceted way. The strategy presents a scalable framework that can be extended to different off-grid and seasonal contexts to support future research and decision-making for sustainable mobility use cases.

Based on these results, the next phase of the project has already started and will involve the real-world deployment of mobile charging stations in Favignana during the upcoming summer season. This field implementation will allow for empirical validation of the study's theoretical results, offering valuable insights into user behavior, station performances, and long-term feasibility and the compatibility with more energy-intensive vehicles, such as e-scooters, pedelecs, and so on. The collected data will contribute to further refining the methodology and optimizing the integration of off-grid charging solutions in small islands and remote areas.

Another further development of this work, which at present is being pursued, regards the refinement of the methodology for the assessment of the environmental sustainability of the off-grid charging stations. Indeed, a methodology is being implemented, which considers in detail the logic of the service provision and of the battery charge/discharge, and estimates the PV power production based on real-world long-term environmental measurements collected at the site of interest and elaborated through the Perez anisotropic model [59] and the PV electrical model. Such further directions are at present being pursued and will constitute the basis for a more rigorous formalization of the multi-objective analysis conducted in this work, for example through optimization algorithms.

Finally, this study clearly highlights that the selection of charging station technologies is a multi-faceted problem, which needs to take into account economic considerations, the environmental sustainability, the operation of power grids and issues related to the expected quality of service provided to the end of users. The findings of this study might inspire the formulation of specific public subsidies which, depending on the context, advantage certain choices.

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